PROTECTING VISIBILITY

AN EPA REPORT TO CONGRESS

EXECUTIVE SUMMARY AND CHAPTER 1

Executive Summary

INTRODUCTION

This report is prepared in response to the requirements of Section 169A(a) of the Clean Air Act. In this section, which was added to the Act in August 1977, 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." The Act requires a study and report to Congress on methods for meeting the visibility goal, including methods for determining visibility impairment, modeling and other methods for evaluating source impacts, methods for preventing and remedying pollution-derived visibility impairment, and a discussion of pollutants and sources that may impair visibility. In addition to this report, the Act requires the following activities:

1. The Department of the Interior, in consultation with other Federal Land Managers, must compile, and the Environmental Protection Agency (EPA) must promulgate, a list of mandatory class I Federal areas in which visibility is an important value. The list, which includes 156 of the 158 class I areas, was promulgated in November 1979, and is included as Appendix A to this report.

2. EPA must promulgate regulations that (a) provide guidelines to the States on appropriate techniques for implementing the national visibility goal through State Implementation Plans (SIPs) and (b) require affected States to incorporate into their SIPs measures needed to make reasonable progress toward meeting the national visibility goal. The regulations and guidelines must require that certain major stationary sources, likely to impair visibility, install best available retrofit technology (BART). The regulations must also require that the SIPs include a long-term (10-15 year) strategy for making reasonable progress toward the visibility goal. The long-term strategy may require control of sources not otherwise addressed by the BART provision. The Act states that costs, energy and non-air environmental impact, and other factors must be considered in determining BART and reasonable progress.

The language of the national visibility goal and the legislative history of the Act indicate that the national goal of Section 169A mandates, where necessary, control of both existing and new sources of air pollution. It is apparent, however, that adverse visibility impacts from proposed major new or modified sources are to be dealt with through the procedure for prevention of significant deterioration (PSD) mandated in Section 165(d) of the Clean Air Act.

In addition to the activities required of EPA and the States, the Clean Air Act requires that the Federal Land Managers (the Department of Interior and Department of Agriculture, through the National Park Service, the Fish and Wildlife Service, and the Forest Service) play an important role in visibility protection. Land Manager responsibilities include reviewing the adequacy of the state visibility protection strategies and determining whether proposed major air pollution sources have an adverse impact on visibility in Class I areas.

In establishing the national visibility goal, Congress called for explicit recognition of the value of visibility in special class I areas. By requiring consideration of “significant” impairment in BART decisions, “adverse” effects of proposed new sources, and “reasonable progress” in implementing the national goal, Congress has, in effect, mandated that judgements be made on the value of visibility in the context of specific decisions on control and location requirements for sources of visibility impairing air pollution. Preliminary economic studies of the value of visibility and research in recreational psychology and human perception support the notion that visibility is an important value in class I areas and suggest that several approaches are available for estimating the value of an incremental improvement or deterioration in visibility. Such work, however, will require a number of years. Currently, the regulatory process mandated under the Clean Air Act, involving the Federal Land Managers, the States, EPA, and the public, represents the best means for considering visibility benefits in the context of associated costs.

DEFINITION OF VISIBILITY IMPAIRMENT

Although Congressional guidance on the definition of visibility impairment is significant, a number of important areas are left open for additional specification, interpretation, and judgement. Section 169A indicates that visibility impairment includes reduction in visual range and atmospheric discoloration. Visual range, long used as an index of visibility in airport observations, is generally defined as the farthest distance from which one can see a large black object against the horizon sky. Atmospheric discoloration can qualitatively be defined as a pollution-caused change in the color of the sky, distant mountains, clouds, or other objects. Conceptually, virtually any type of visibility impairment could ultimately be expressed as a reduction in visual range or atmospheric discoloration. However, because these effects are often the results of the same pollution impact, it is useful to categorize anthropogenic* visibility impairment into three general types: (1) widespread regionally homogeneous haze that reduces visibility in every direction from an observer, (2) smoke, dust, or colored gas plumes that obscure the sky or horizon relatively near sources (this class is also termed “plume blight”), and (3) bands or layers of discoloration or veiled haze appearing above the surrounding terrain. Examples of these types of impairment are illustrated and discussed in Section 1.5.

The location, degree, and the spatial and temporal extent of visibility impairment must be addressed in the visibility protection programs. In areas such as the Southwest, anthropogenic air pollution occurring outside class I area boundaries can obscure long distance vistas normally visible from within the class I area. Anthropogenic impairment may be frequent, last for long time periods, and be readily apparent to all observers. Conversely, anthropogenic visibility impacts may be so infrequent, short in duration, or small in degree that it is difficult for the unaided observer to distinguish them from existing impairment caused by natural sources. For the purpose of this report, EPA adopts the following position on visibility impairment:

1. Certain vistas extending outside class I area boundaries are important to visitor experience and are part of the visibility value of the area. Such views should be included in the national goal.
2. Anthropogenic visibility impairment in the context of the national visibility goal is defined as any perceptible** change in visibility (visual range, contrast, atmospheric color, or other conveniently measured visibility index) from that which would have existed under natural conditions.

Therefore, in the context of specific control decisions, an increment (or decrement) in visibility impairment must as a minimum be perceptible to be significant or adverse. Further judgements with respect to the significance and adversity of perceptible impairment must be made, at least in part, on a case-by-case basis and must address the degree and spatial and temporal extent of the incremental change. For this reason, and because such judgements must involve States, Federal Land Managers, and the public, it is not possible at this time to specify comprehensive criteria for defining significant or adverse impairment.

CURRENT STATUS OF VISIBILITY IN CLASS I AREA

Some insight into general visibility condition in class I areas can be obtained by examining the regional airport visibility (visual range) data depicted in Figure 1. Although some limitations in airport observations exist, the information is indicative of regional trends. The best visibility occurs in the mountainous Southwest, where annual median visibility exceeds 70 miles (110 km). East of the Mississippi and south of the Great Lakes annual median visibilities are less than 15 miles (24 km), and significantly lower in the summertime. Figure 1 does not address plume blight or discoloration. Ironically, these latter problems can be more severe in “clean” regions. For example, in the Southwest, the region of highest visual range, visible plumes can be seen from great distances.

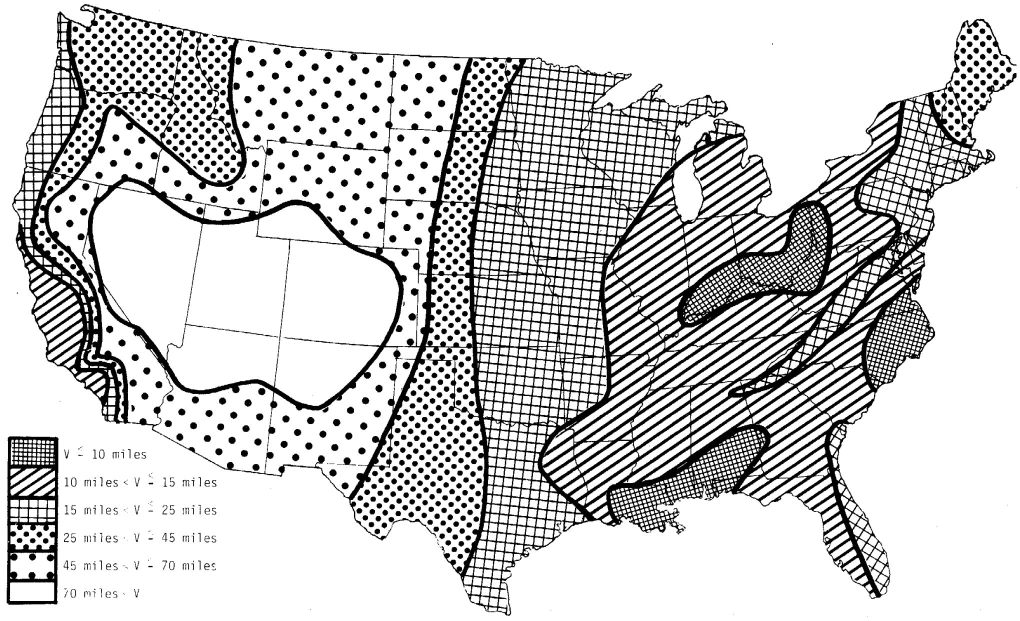

Figure 1. Visual range (V) isopleths for suburban non-urban areas, 1974-76 (Trijonis and Shapland, 1978).

A preliminary analysis of visibility in class I areas has been provided by the Federal Land Managers. The analysis represents observations by individual managers of visual impairment and their subjective judgements on the desirability or acceptability of existing conditions. Because the level of experience, perception, and criteria for judgement vary significantly among these individuals, the results are preliminary and must be confirmed by more detailed analysis. The results are summarized in Figure 2. Class I areas are grouped into regions of similar status. In regions where a number of areas were reported as having undesirable visibility conditions, the major categories reported by the Land Managers are listed.

Approximately one-third of the class I area managers reported undesirable visibility conditions and/or the need to evaluate suspected man-made impacts. The remaining two-thirds of the areas were reported as having desirable or acceptable conditions at all or more of their vistas. On the other hand, it appears that few if any of the class I areas are free from at least some potentially observable anthropogenic visibility influence. Over 90 percent of the class I area managers reported that one of more views from within the area looking outside the area may be, to some degree, important. Nearly all of the managers indicated the need to prevent existing visibility conditions from deteriorating as a result of new source impacts.

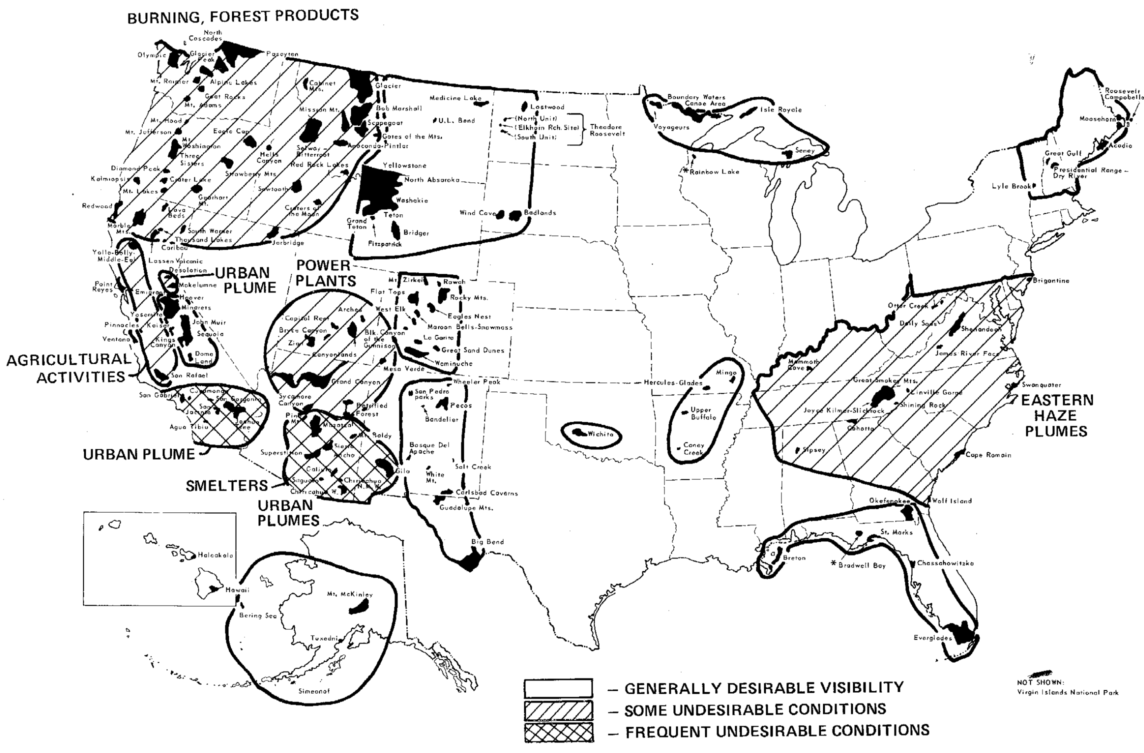

Figure 2. Preliminary class I area visibility status reposted by Land Managers.

VISION IN THE ATMOSPHERE

The ability to define, monitor, model, and control anthropogenic visibility impairment is dependent on available scientific and technical understanding of the factors that affect atmospheric visibility. Because visibility involves the human perception of the physical environment, evaluation of the effects of air pollution on visibility must include:

1. Specification of the process of human visual perception and

2. Quantification of the impacts of air pollution on the optical characteristics of the atmosphere.

Chapter 2 summarizes pertinent information on these areas.

From a scientific and technical point of view, deterioration of visual air quality is probably the best-understood and most easily measured effect of air pollution. However, many important uncertainties and limitations exist in available knowledge. Significant implications of current understanding of vision in the atmosphere may be summarizes as follows:

1. Visibility impairment is caused by the scattering and absorption of light by suspended particles and gases. Fine solid or liquid particles (atmospheric aerosols) and to a

lesser extent nitrogen dioxide are the most important anthropogenic causes of degraded visual air quality. Air molecules, weather variables, and natural emissions also affect visibility.

2. Light scattering and light absorbing pollutants reduce the amount of light received from viewed objects and scatter ambient or "air" light into the line of sight. This scattered air light is perceived as haze. Because these effects vary with the wavelength of light, discoloration can result.

3. These effects can be quantified or approximated through use of theoretical mathematical treatments and experimentally derived pollutant/optics relationships.

4. The perceptibility of pollution effect on light depends on human eye-brain responses. Studies of the eye-brain response to contrast indicate that typical observers can detect a 0.02 (2%) or greater contrast between large dark objects and the horizon sky. Preliminary studies suggest that observers may be able to detect a 0.02 to 0.05 change in apparent contrast caused by incremental pollution. Roughly, this indicates that a reduction in visual range of as little as 5 percent may be perceptible. Additional work is needed on human perception of pollution increments.

5. The perception of color in the atmosphere is less well understood than is contrast. For this reason, theoretical calculations of atmospheric discoloration are useful only as crude indices and guides for experimental measurements. Studies of atmospheric color perception conducted over the next few years should provide an adequate means of predicting atmospheric discoloration, even if a comprehensive theoretical treatment remains unavailable.

6. In many Southwestern class I areas, visibility on some days can approach the theoretical limit imposed by air molecules (blue sky) scattering (200 miles visual range). Visibility in such areas is extremely sensitive to in creased emissions. The addition of 1 microgram per cubic meter of fine particles, spread throughout the viewing path, to such a clean atmosphere could reduce visual range by about 30 percent. Addition of the same amount to a dirtier background (20-mile visual range) would produce only a 3-percent reduction in visual range.

7. Since viewing distances in most class I areas do not exceed 50-100 kilometers (60 miles), a reduction in calculated visual range from, for example, 200 km (120 miles) to 150 km (90 miles) would be noticed principally because of the reduction in contrast and discoloration of nearby objects and sky (haze). Increased haze causes objects to appear "flattened," the horizon sky is whitened, and *the aesthetic value of the vista can be degraded even though the viewing distances are small relative to the visual range.*

8. When particles and light absorbing gases are confined to an elevated haze layer or a coherent plume, the main visual impact will be a discoloration of the sky or a white, gray, or brown plume. The perceived impact depends on a number of factors such as sun angle and condition of background sky. Contrast and brightness effects of elevated haze and plumes can be approximated by available techniques. Additional work is needed to predict the perceived color impacts.

MONITORING

Visibility monitoring is necessary for establishing base line visibility to be used in evaluating impacts of proposed sources or controls, assessing the relative impacts of man-made air pollution and natural sources, identifying specific sources contributing to visibility impairment, and monitoring the effectiveness of visibility protection programs. Meeting these objectives requires measurement of optical parameters, meteorological variables, pollutant characteristics, and scenic characteristics.

The most important optical parameters to be measured include the apparent contrast of distant objects and the extinction coefficient, a parameter related to the light scattering and absorption characteristics of the atmosphere. The basic optical methods include:

Human Observation — measures perceived air quality, visual range (if targets available)

Photography — documents perceived visual air quality

Multiwavelength Telephotometer — measures apparent contrast between target and horizon or other objects, is useful over long path, up to 50 to 100 kilometers

Transmissometer — measures transmission and extinction of light over a fixed path, 10 to 20 kilometers

Nephelometer — measures light scattering by particles at a single point, estimates Extinction coefficient

Each of these measurement approaches has inherent strengths and limitations, which are summarized in Chapter 3. EPA recommends that comprehensive visibility monitoring programs in class I areas include:

1. Baseline monitoring conducted for a year (preferably a meteorologically typical year) or more;

2. Visibility monitoring including color photography, human observation, integrating nephelometer, and a multi-wavelength telephotometer; and

3. Evaluation of anthropogenic and natural source/receptor relationships including a two-stage size-segregating particulate sampler or other device compatible with fine particulate mass and compositional analysis, meteorological measurements, and when necessary, a nitrogen dioxide monitor.

Such comprehensive monitoring is not needed in all class I areas. The results of intensive monitoring in characteristic regions of the country and instrument development over the next few years may indicate some smaller set of measurements, which will be sufficient. Programs with limited resources should rely on structured human observations, photographic documentation, and, where possible, suitable meteorological measurements. Other instruments should be chosen with due consideration of their limitations.

EMPIRICAL METHODS FOR ASSESSING POLLUTION-DERIVED IMPAIRMENT

Relating visibility impairment to its emission sources is a central problem for making progress towards the national visibility goal. Some important general understandings include:

1. Light scattering and particle related light absorption are caused principally by fine aerosols (those smaller than 2.5 micrometers). Understanding the sources of general haze in most areas thus reduced to identification of sources of fine particle mass.

2. High relative humidity significantly increases light scattering of certain water-soluble aerosols.

3. Much of the fine particle mass is of *secondary* origin; that is, most fine particles are formed in the atmosphere from their "precursor" gases, sulfur oxides, nitrogen oxides, and organics. Hence, the emission rate of secondary particles cannot be measured at he source. Furthermore, the gas-to-particle conversion process depends on factors such as solar radiation, the presence of other pollutants, and humidity. Thus, the amount of secondary material formed from a given rate of precursor gases is not constant but depends on the environment.

4. The residence time of fine particles in the atmosphere is through to be about a week or more, and their transport distance can exceed 500 kilometers.

5. The long-range transport of the fine particle/precursor chemical complex results in the superposition and chemical interaction of emissions from different types of sources (e.g., power plant and urban plumes). Many of these interactions currently cannot be adequately predicted on a regional scale.

6. The qualitative evaluation of source receptor relationships will require collection and analysis of monitoring data. Properly calibrated mathematical models are necessary to predict the impact of controls on existing sources or the impact of new sources in a new location.

Empirical approaches to evaluation source impacts range from simple observation of visible plumes to sophisticated aircraft sampling and satellite imagery. The approaches discussed in Chapter 4 include: evaluation of haze chemical composition, analysis of historical trends of emissions and haziness, evaluation of haze/wind-direction relationships, aircraft plume sampling, and application of diagnostic models. Important conclusions from application of these techniques to date include:

1. Direct measurements and statistical analysis indicate that fine sulfate aerosols account for 30 to 60 percent of fine particle related visibility reduction in areas as diverse as the Northeast United States, Los Angeles, and the Southwest mountain states.

2. Other fine particle constituents are also important and can dominate scattering in various regions. IN the Pacific Northwest, for example, carbon-containing aerosols from wood or other vegetative burning and motor vehicles appear to be significant components of light scattering aerosols.

3. Studies of trends in eastern airport visibility indicate that, while wintertime visibilities improved in some northeastern locations, overall eastern visibility declined. Summer, often the season of best visibility in the early fifties, is currently the worst season. From 1948 to 1974, summertime haze (extinction) increased by more than 100 percent in the central Eastern States, 50 to 70 percent for the Midwest and Eastern Sunbelt States, and by 10 to 20 percent for the New England area. Although the results of airport surveys should be viewed with caution, the results are consistent from site to site.

4. Very close parallels have been noted between the geographical/seasonal features of airport visibility trends and the geographical/seasonal features of trends in atmospheric sulfate concentrations, sulfur oxide emissions, and coal use patterns. These parallels provide strong circumstantial evidence that the historical visibility changes in the East were caused, at lest in part, by trends in sulfate concentrations and sulfur oxide emissions.

5. Similar analyses of visibility trends in the Rocky Mountain Southwest, a region containing numerous class I areas, indicate a gradual decline in visibility with a recent improvement, so that current levels are similar to those in the late forties. A strong, statistically significant association exists between these visibility trends and regional sulfur oxide emissions from copper smelters. The increase in visibility from 1972 to 1976 paralleled significant decreases in smelter emissions due to pollution controls and decreased production. Although the statistical studies do not show causality, the results are consistent with theory and experimental results

6. During a nine-month copper smelter strike, significant increases in Southwestern visibility and decreases in sulfate concentrations were noted at great distances from the smelters. Notably, sulfates dropped by about 60 percent at the Grand Canyon and Mesa Verde, 300 to 450 kilometers from major smelter locations.

7. Aircraft measurements of the plumes of large power plants, smelters, and major urban areas have tracked the visibility impact of these sources to 50 to 200 kilometers downwind. The apparent transformation of SO_2 to light scattering sulfate has been observed in both Eastern and Western plumes.

8. Episodes of regional scale haziness have been observed in the Eastern United States. Examination of airport data, pollution measurements, and satellite photography indicate that these hazy air masses move across the Eastern United States in the manner of high-pressure systems, causing significant visibility reductions in areas with little or no air pollutant emissions.

PREDICTIVE MODELS

Although empirical approaches can be used to identify the impact of manmade air pollution, predictive models are necessary to evaluate the effects of alternative controls on existing sources and the potential impacts of proposed new sources. Visibility models adapt the atmospheric dispersion and transformation features of other air pollution models for the prediction of fine particles and NO_2 concentrations across a sight path. The concentration patterns are coupled with optical equations to predict visibility impacts. Visibility models deal with essentially two distance and time scales: transport of plumes from single sources for short to moderate distances (10 to 100 km) and regional scale transport of single and multiple sources over medium to long range distances (100 to over 500 km).

Important uncertainties in visibility models include:

1. Prediction of atmospheric dispersion characteristics becomes less reliable as distance from the source increases. Mountainous and hilly (complex) terrain, common near class I areas, poses a particularly difficult analytical problem. Nevertheless, because concentration across a sight path and not at a single point is the important parameter, visibility models can be somewhat less sensitive to dispersion assumptions than are conventional air quality models.

2. The chemical transformation and removal processes for sulfur and nitrogen oxides have been experimentally estimated, but are difficult to predict under varying environmental conditions.

3. The models are sensitive to base line visibility conditions. Until monitoring programs provide data for class I areas, base line conditions must be derived from rough estimates.

4. The models are subject to the uncertainties in current understanding of human visual perception and the optical characteristics of modeled air pollutants.

5. An incomplete understanding of large-scale meteorological processes, uncertainties in boundary conditions, and lack of adequate inventories of natural and anthropogenic emission sources significantly limit modeling of regional scale transport of pollutants.

6. Visibility models have generally not been verified through intensive environmental monitoring. Major experimental efforts are under way to confirm the theoretical predictions.

Despite these uncertainties, visibility models can and should, within certain limits, be used to evaluate point source impacts. Single source models can estimate the range of expected visibility impacts of primary particle emissions at distances of up to 50 to 100 kilometers from the source. These models can also be used for relatively isolated sources located in clean environments to provide rough estimates of the impacts of sulfur and nitrogen oxide emissions at similar distances. Thus, the degree of visibility improvement resulting from controls on major, obvious sources of plume blight can be predicted, and the visibility impacts of proposed major facilities can be addressed. In the case of new sources proposing to locate within 100 to 150 kilometers of class I areas, an analysis of prevailing meteorological conditions, background visibility, and application of available single source plume models can provide an improved basis for siting decisions.

Models for evaluating the impact of control of existing or proposed sources on a regional scale require further refinement and validation before they can be used for regulatory applications. Empirical data analyses coupled with mathematical modeling exercises are useful for identifying the scales of time and distance upon which visibility impact may occur. Roughly, changes in the regional emissions of fine particles and sulfur oxides will produce changes in regional visibility levels, although the extent, duration, and location of these changes as a function of emissions cannot be adequately predicted. As noted above, pristine regions such as the Southwest will be most sensitive to the addition of new sources or reductions in regional emissions through control.

MAJOR SOURCES

Vision in the natural "unpolluted" atmosphere is restricted by blue sky scattering, by curvature of the earth's surface and by suspended liquid or solid natural aerosols. The important sources of natural aerosols include water (fog, rain, snow), windblown dust, forest fires, volcanoes, sea spray, vegetative emissions, and decomposition processes. These sources must be addressed in estimating base line visibility in class I areas. The extent to which these natural sources control existing visibility levels in the United States is not well known. Nevertheless, it is reasonable to conclude that manmade sources contribute significantly to visibility impairment in most regions of the country and in some cases dominate visibility.

Anthropogenic emission sources of particulate matter, sulfur oxides, nitrogen oxides, and volatile organics are of some significance to visibility impairment. The significance of volatile organics (hydrocarbons), however, is not well understood. Major sources, projected growth, and controls are discussed in Chapter 6. The most important source categories of visibility-impairing pollutants include utilities, industrial fuel combustion, smelters, pulp mills, urban plumes (the result of point sources, space heating, mobile and other urban sources), fugitive dust from agricultural activities, mining, unpaved roads, off-road recreational vehicles, and the managed use of fire including prescribed burning associated with forestry and agricultural burning. The significance of these sources on an individual and collective basis varies throughout the country. Many of them are not readily amenable to further control.

CONTROL STRATEGY IMPLICATIONS

The results of the preliminary Federal Land Manager analysis of visibility in class I areas provide important implications for control programs. These include:

1. Few, if any, of the class I areas are currently free from some anthropogenic influence on visibility. Given resource limitations and the lack of adequate information on impairment, however, those areas with current or projected unacceptable visibility conditions should receive highest priority in control programs. If, as preliminary subjective Land Manager judgements suggest, current visibility is generally acceptable in two-thirds of the class I areas, there will be little impetus for completely eliminating perceptible man-made impairment. This appears to be consistent with Congressional intent.

2. Protection of integral views extending outside class I areas is important for a number of class I areas. A number of managers reported, however, that the haze occurring in large urban areas are visible from some vantage points within the class I area. It is not clear that Congress intended to remedy these kinds of visibility impairment. Case-by-case judgements can address these issues.

3. The kinds of sources that tend to dominate visibility impairment vary greatly throughout the country. Visibility control programs must account for the diverse nature of sources. Particularly difficult problems include regional haze in the Eastern United States, regional emissions in the Southwest, the impact of urban plumes, and prescribed burning activities. The Land Managers themselves utilize fire as a means for enhancing the production of timber, improving wildlife habitats, and preventing catastrophic natural fires. Such activities impair visibility on a temporary basis.

4. Assessment of existing visibility conditions and projected growth indicate that the highest priority for visibility protection programs in class I areas is the evaluation of the impacts of new sources of visibility impairment. Many of the class I areas in the Western United States are likely to be influenced by increased energy development and utilization, population and urban growth, and associated emission increases. Once such sources are constructed, it is very difficult to mitigate their impacts.

Although available models are limited, they should be used to evaluate new source impacts. The alternative allowing construction of new sources without such analyses as long as prescribed class I increments are met, is not acceptable. Available scientific information supports the contention of the House Committee Report that "mandatory class I increments do not protect adequately visibility in class I areas" in all cases.

Programs for the prevention of significant deterioration will address the impact of major facilities on class I area visibility. These requirements, however, do not adequately deal with the visibility impacts of increases in emissions associated with population growth, such as increased urbanization, automotive emissions, and space heating, or with activities such as agricultural growth and highway construction. Additional studies are needed to quantify the influence of these activities on visibility before adequate guidance can be considered. Control of such sources may ultimately prove to be necessary for making progress toward the national goal.

REGULATORY STRATEGIES

Conceptually, visibility protection under Sections 169A and 165(d) includes the following components:

1. Proposal and promulgation of visibility regulations and guidelines for the States by EPA.

2. Assessment of class I area visibility by the States, Federal Land Managers, EPA, and affected industries.

3. Judgments on significance and adversity of impairment caused by existing and proposed new sources and the need to improve existing conditions in class I areas by the Federal Land Managers, States, and EPA.

4. Development of control strategies by the States, assisted by EPA

5. Monitoring progress toward the national visibility goal.

NEED FOR PHASED APPROACH

Because of the lack of base line visibility data in class I areas, the limitations in scientific and technical understanding of source/air quality perception relationships, the need to consider visibility improvements in the context of control costs, and limitations in resources available to States, EPA, and the Federal Land Managers, EPA recommends a phased approach to visibility protection. Although regulations and guidelines for the States must encompass the full range of Clean Air Requirements, they should, to the extent possible:

1. Permit State control programs to focus initially on the most clearly defined cases of existing impairment and on strategies to prevent future impairment and,

2. Allow for the evolution of guidelines and control strategies made possible with expected improvements in scientific understanding of source/impairment relationships.

Although available information is not adequate to develop control strategies that demonstrate ultimate attainment of the national goal, enough is known to develop a series of corrective and preventive measures. An evolutionary or phased regulatory approach would permit these steps to be taken while delaying those actions for which the technical basis is less clear. Moreover, such an approach will allow for a more effective use of the limited manpower and financial resources available to States, Federal Land Managers, and EPA for developing visibility control programs.

In the initial phases of visibility protection, application of BART is likely to be limited to obvious cases of plume blight or single source haze layers. The BART mechanism does not appear to apply to important categories such as prescribed burning, regional power plant and smelter emissions, and urban plumes. Evaluation of new source impacts should focus on major stationary sources, particularly power plants. The visibility impacts of growth of smaller area sources and the effect of regional emission increases from numerous sources are not adequately addressed by current PSD procedures.

LONG TERM STRATEGIES

Because of the limitations in BART and PSD, the eventual development and implementation of long-term strategies will be central to making progress toward the national visibility goal. These strategies should provide for integration of visibility objectives into ongoing air management efforts to account for sources not adequately covered by other mechanisms and to explore innovative approaches for making cost-effective progress toward visibility protection.

A starting point in developing long-term strategies is evaluation of the impact of other air pollution control programs; e.g., standards for air quality, new sources, and mobile sources. The projected impact of existing programs on some of the more difficult visibility impairment problems is outlined below:

1. The Southwestern copper smelters have made progress toward reducing emissions, partially in response to State programs for attaining the National Ambient Air Quality Standards. Although final emission reductions may be deferred, the smelters are under compliance schedules, which should ultimately provide additional reductions in emissions. Preliminary analyses suggest that reductions to date in smelter emissions have resulted in improved regional visibility in the Southwest since 1972.

2. Air quality standards and new source performance standards have halted the general trend toward increased sulfur oxide, particulate, and organic emissions in the Eastern United States. The recently announced new source standard for power plants represents a significant long-term strategy for an ultimate reduction in Eastern sulfur oxide emission levels and a limitation on regional increases in the Western United States. This approach, however, will not begin to effect significant reductions in emissions in the East until after 1995. Accelerated replacement of older uncontrolled oil-fired power plants with coal-fired boilers meeting the new source performance standard under energy initiatives would accelerate the reduction in sulfur oxide emissions.

3. Progress toward meeting air quality standards in urban areas should limit increased impairment and in some cases improve visibility in areas affected by urban plumes.

Once the effect of other regulations on visibility is evaluated, the need for additional control approaches for making progress toward the national goal can be evaluated. Potential long-term control approaches, which may prove desirable in the 1980's, include an accelerated reduction in regional haze occurring in the East, maintaining regional visibility levels in the Southwest and reducing impacts of forest and other burning in the Pacific Northwest. Such approaches must be justified on a technical basis and on a consensus that the improvements are worth the effort. The States and EPA should consider a variety of innovative regulatory strategies for implementing long-term visibility improvement strategies. Some of these include a national secondary air-quality standard for fine particles and economic control approaches, including marketable permits, emission fees, and other economic incentives for improved practices.

VISIBILITY RESEARCH NEEDS

Extension and refinement of visibility protection programs are dependent on improvement of current knowledge and techniques in a number of areas. The most important areas include:

1. Comprehensive characterization of existing visibility conditions in representative regions containing class I areas.

2. Development of improved and simplified visibility monitoring approaches.

3. Field studies of selected single and multiple point and area source impacts.

4. Improvements in predictive models for single sources and for regional scale transport.

5. Studies of human visual perception in clean atmospheres.

6. Studies of the value of visibility.

A combination of programs involving government and the private sector is beginning to address many of these areas. Significant advances in the next several years should enhance our ability to make progress towards the national visibility goal.

1 INTRODUCTION: ESTABLISHING THE NATIONAL VISIBILITY GOAL

1.1 SCOPE OF REPORT

This report is prepared in response to the requirements of Section 169A(a) of the Clean Air Act. In that section, 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." (95^{th} Congress, 1977). The Act requires a study and this report to Congress on available methods for implementing the national visibility goal. The report must include "recommendations for:

A. Methods for identifying, characterizing, determining, quantifying and measuring visibility impairment in (class I) Federal areas, and

B. Modeling techniques (or other methods) for determining the extent to which man-made air pollution may reasonably be anticipated to cause or contribute to such impairment, and

C. Methods for preventing and remedying such man-made air pollution and resulting visibility impairment.

Such report shall also identify the classes or categories of sources and the types of air pollutants which, alone or in conjunction with other sources or pollutants may reasonably be anticipated to cause or contribute significantly to impairment of visibility" (95^{th} Congress, 1977).

This chapter will discuss the establishment of the national visibility goal, including the requirements of the Clean Air Act, the importance of visibility in class I areas, and the definition and nature of visibility impairment.

Chapter 2 will review fundamental scientific concepts related to human perception of light, atmospheric optics, and the means by which man-made air pollutants affect visual air quality. The discussion emphasizes those pollutants that are most important in causing visibility impairment, fine particulate matter (sulfates, "primary" particles, organics, and nitrates) and nitrogen dioxide.

Chapters 3 through 5 discuss and make preliminary recommendations on methods for assessing visibility and relating impairment to sources. Chapter 3 outlines techniques for monitoring visibility. The discussion focuses on operating principles and possible utilization of human observers, photography, telephotometers, nephelometers, and particulate monitoring devices. Existing and planned visibility monitoring networks are also outlined. Chapter 4 reviews the application of several approaches for relating visibility impacts to man-made sources of air pollution. The methods include chemical element balance, statistical studies of air quality, emissions, and visibility trends, diagnostic models, and other empirical approaches. Chapter 5 discusses available mathematical models for evaluating visibility impacts of major sources and assessing alternative controls and siting.

Natural and anthropogenic sources of visibility impairment are discussed in Chapter 6. The general location, impacts, projected growth and possible controls and costs are discussed for major anthropogenic source categories.

Chapter 7 discusses prospects for making progress toward the national goal. A preliminary summary of current class I area visibility status as reported by the Federal Land Managers is presented, key implications of the preliminary summary are discussed, and considerations for developing alternative visibility control strategies are outlined. Chapter 8 summarizes ongoing visibility-related research efforts and makes recommendations for future research.

1.2 STATUTORY REQUIREMENTS AND LEGISLATIVE HISTORY

The Clean Air Act Amendments of 1977 add Section 169A to the Clean Air Act, requiring the following activities of the Federal Government:

1. The Department of Interior, in consultation with other Federal Land Managers, must review all mandatory class I Federal areas and identify those where visibility is an important value of the area. The EP A Administrator, after consulting with Interior, must promulgate a list of mandatory class I Federal areas in which he determines visibility is an important value. The list has been promulgated and is " included as Appendix A to this report.

2. EPA must prepare this report to Congress on methods for meeting the visibility goal, including methods to identify visibility impairment, modeling, and other methods for evaluating source impacts, methods for preventing and remedying pollution related visibility impairment, and a discussion of pollutants and sources that may impair visibility.

3. EPA must promulgate regulations which will (a) provide guidelines to States on appropriate techniques and methods for implementing Section 169 requirements through the State Implementation Plans (SIP) where needed, and (b) require SIPs for affected States to include emission limits, schedules for compliance, and other measures as may be necessary to make reasonable progress toward meeting the national visibility goal.

These regulations must require sources which have been in operation less than 15 years as of August 1977 and which emit any air pollutant that may reasonably be anticipated to impair visibility in the selected class I areas to procure, install, and operate the best available retrofit technology (BART) no later than 5 years after SIP approval.

The regulations must also require that the SIPs include a long-term (10 to 15 years) strategy for making reasonable progress toward the visibility goal. The long-term strategy may require control of sources older than 15 years or sources not otherwise controlled under the BART provisions. BART must be determined for each source by the State (or Administrator, in some cases). In the case of a fossil fuel-fired generating power plant having a total generating capacity of least 750 MW, the emission limitations (BART) must be determined pursuant to EPA guidelines. Guidelines for determining BART must take into consideration the costs of compliance, the pollution control technology in use at the source, the remaining useful life of the source, and the degree of improvement in visibility that may reasonably be anticipated to result from the use of such technology. BART can be expressed as an emission limit or operating practice and must be incorporated into a revised State Implementation Plan.

Enactment of the visibility section of the Clean Air Act was stimulated by public concern about the deterioration of visibility in scenic areas. Examination of the legislative history of the visibility provision indicates that Congress was particularly concerned about evidence submitted by the National Parks and Conservation Association, stating, "that some areas that in the past had 100-mile (160-km) visibility now have only an average of 30-mile (48-km) visibility. Much of this probably can be attributed to emissions from power plants, such as the Navaho and Four-Corners plants." (House Report, 1977). In addition to the recognized threat of power plants to long-range visibility in the western United States, Congress was concerned about reports that "the hazes found in high vegetation areas of the southeast are not dominated by natural organic compounds but by sulfate particles, probably from the oxidation of SO2 emitted from regionally distributed sources. " (House Report, 1977).

As stated in the Conference Report (1977), "a major concern which prompted the House to adopt a visibility protection provision was the need to remedy existing pollution in Federal mandatory class I areas from existing sources. Issues with respect to visibility as an air quality related value and application to new sources are to be resolved within the procedures for prevention of significant deterioration. " This statement is clarified in an attachment to technical changes to the 1977 Clean Air Act Amendments by Congressman Paul Rogers: " ...it does not state or imply that existing sources were the only concern...new sources were also 1-2 of concern. This point is underscored by the statutory language of Section 169A(a)(I), retaining as a national goal: the prevention of any future impairment. ." (Rogers, 1977). With respect to new-sources, Section 165(d)(2)(B) of the Clean Air Act makes it clear that the Federal Land Manager responsible for the management of class I area(s) "shall have an affirmative responsibility to protect the air quality related values (including visibility) of any such lands within a class I area and to consider, in consultation with the Administrator, whether a proposed major emitting facility will have an adverse impact on such values.” Thus, the national goal of Section 169A applies to both existing and new sources; implementation includes both 169A(a) and 165(d).

Congress noted that the current national ambient air quality standards were not adequate to protect visibility in class I areas. Congress also recognized that, as a matter of equity, it would be impractical to require the same national ambient air quality standard for visibility protection in cities such as New York or Los Angeles as for areas such as the Grand Canyon or Yellowstone National Park (House Report, 1977). In requiring an analysis of the visibility values in various class I regions before determining whether visibility protection would be required, Congress recognized that it might be unreasonable to have uniform visibility objectives even for all national parks or other class I areas.

1.3 IDENTIFICATION OF CLASS I AREAS

Mandatory class I areas are defined by the Clean Air Act as including all international parks, national wilderness areas, and national memorial parks exceeding 5,000 acres and national parks exceeding 6,000 acres. Such areas that were in existence when that Act was passed may not be redesignated. The original 158 class I areas are depicted in Figure 1-1. The Department of the Interior used an II-step process for applying criteria to determine whether visibility is an important value in each of these areas. The areas were examined with respect to the following:

1. Legislation establishing the area and authorizing the boundaries to determine whether protection of visibility was intended in designating the area a park or a wilderness area;

2. Importance and character of scenic values;

3. Degree of visual impairment from known natural sources (e.g., fog, terpene haze).

The resulting list (see Appendix A) of 156 areas in which visibility is an important value was transmitted to EPA by the Secretary of the interior in February 1978 (Andrus, 1979). EPA reviewed the Department of Interior analysis and, after proposal and public comment, promulgated the same list of156 areas in November of 1979 (Blum, 1979, Costle, 1979).

The 156 areas include 36 national parks, one international park, one national memorial park, and 118 wilderness areas. The total area protected includes over 29 million acres throughout 37 States and territories of the United States. The lands are managed by the Departments of Interior and Agriculture through three Federal land managing services; the National Park Service (45 class I areas), the Fish and Wildlife Service (23 class I areas), and the U.S. Forest Service (88 class I areas). Although the need to preserve scenic character for recreational and/or aesthetic reasons is common to all 156 areas, there are additional objectives that vary with area and land managing agency. Some of these objectives include maintaining and enhancing wildlife habitat, preserving important archeological sites and national monuments, and maintaining areas in a wilderness condition.

In addition to listing the areas in which visibility is an important value, the National Park Service, the Fish and Wildlife Service, and the Forest Service have each conducted a preliminary analysis of the visual values potentially impaired by air pollution. The analysis specifies the more important vistas associated with the area, tentatively identifies apparent natural and anthropogenic sources of impairment, and provides preliminary subjective judgments of the status of visibility in the area. This preliminary analysis is summarized in Chapter 7.

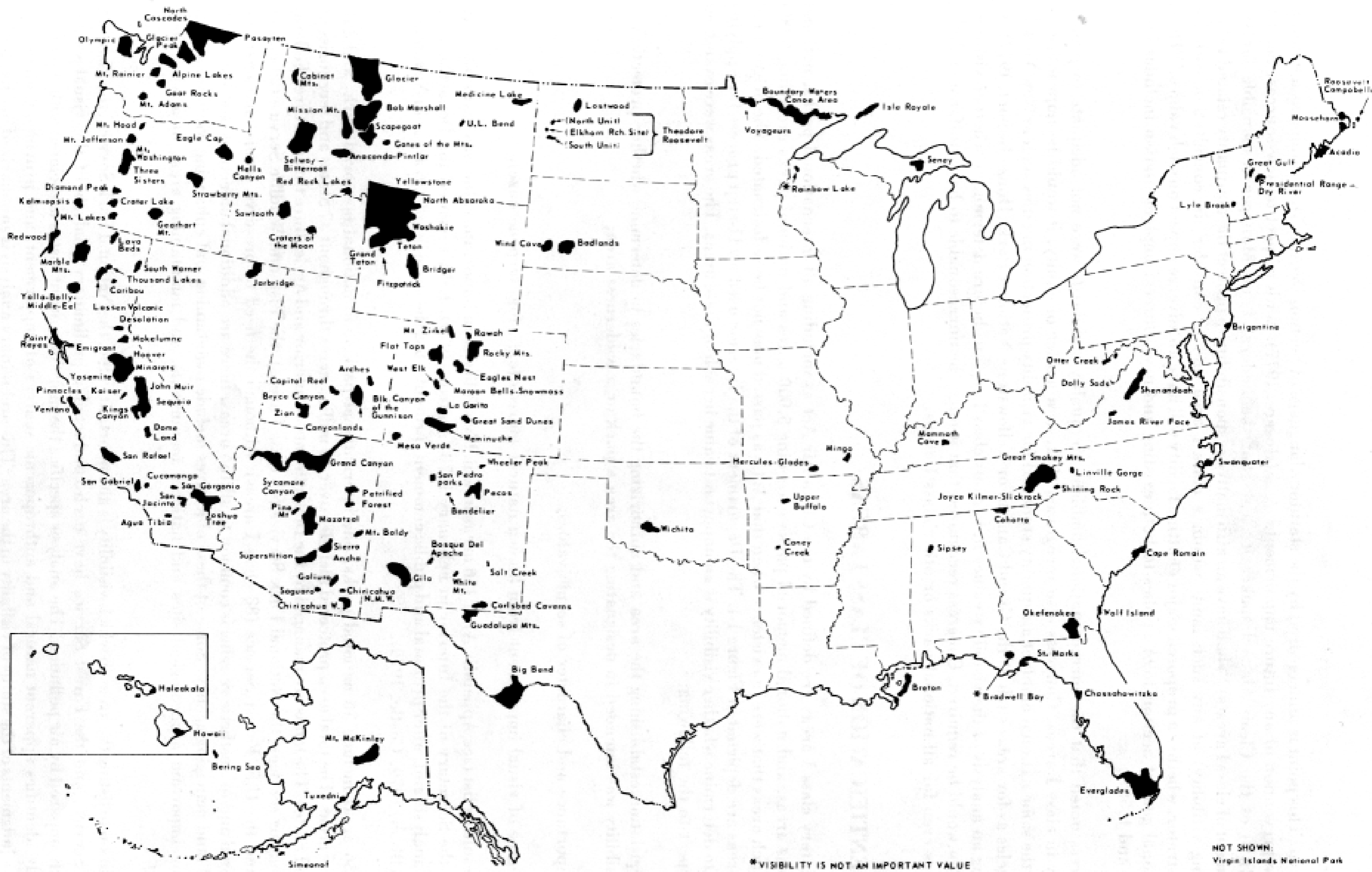

Figure 1-1. Mandatory class I areas.

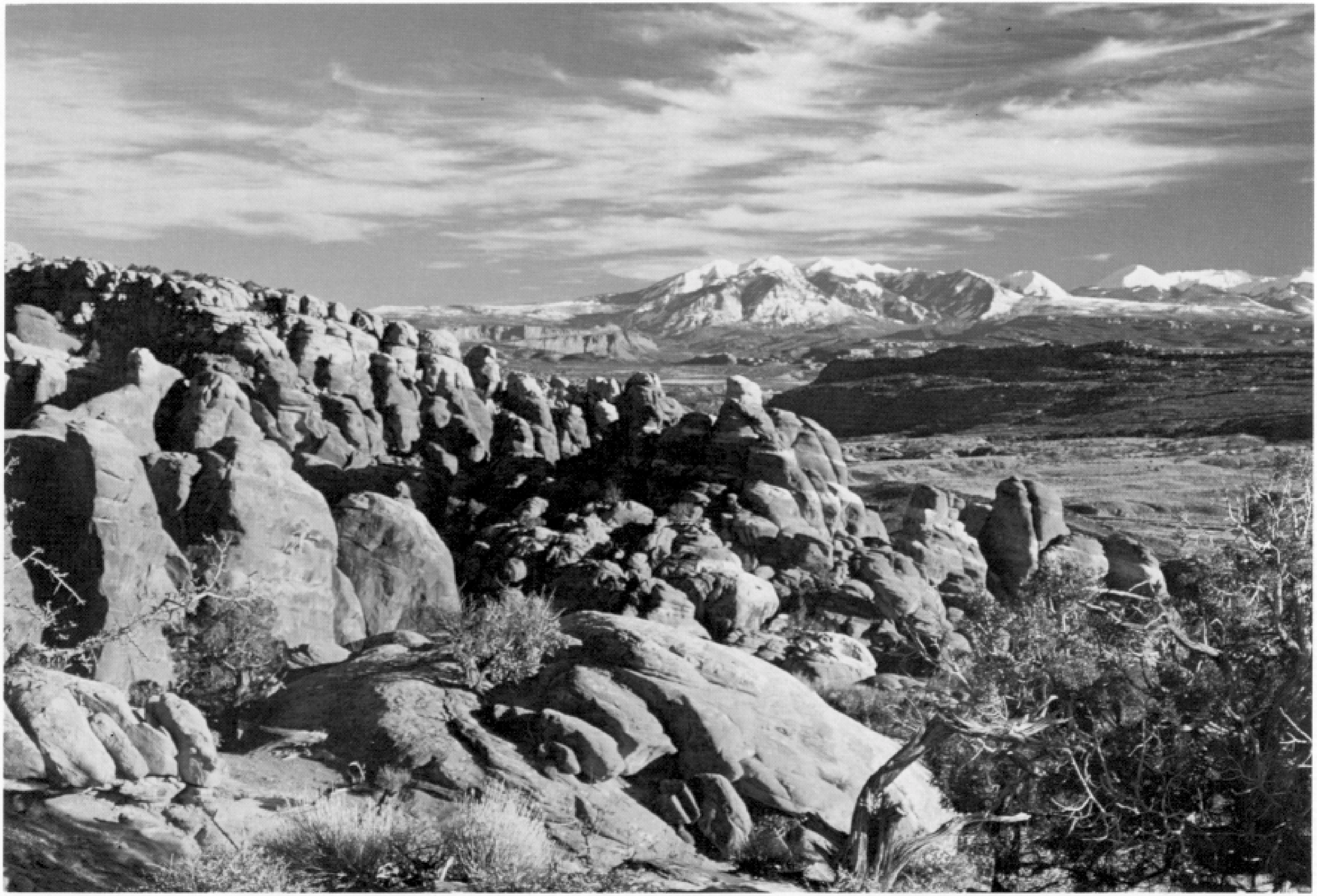

Figure 1-2. La Sal Mountains, southern Utah. This view illustrates the value of unimpaired visibility in a natural setting (Anderson, 1979).

1.4 THE VALUE OF VISIBILITY IN CLASS I AREAS

1.4.1 Background

The value of the "wilderness experience" and the importance of preserving our natural heritage have long been recognized in the United States (Grasvenor, 1979). For example, the National Park Service Act of 1916 created the National Park Service, directing it to "conserve the scenery and the natural (objects) and provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired..." (Andrus, 1978).

In establishing the national visibility goal, Congress called for explicit recognition of the value of visibility in these special (class I) areas. In requiring consideration of "significant" impairment, "adverse" effects and "reasonable progress" in implementing the goal, Congress has, in effect, mandated judgments on the value of visibility in the context of specific decisions on control and location requirements for sources of visibility impairing air pollution. The Department of Interior has taken the first step in valuing visibility by specifying the 156 class I areas in which visibility is an important value. Because of their key role in implementing the national goal, the Federal Land Managers have also initiated a number of activities to assist in making visibility value judgments for control and siting decisions. The following discussion of the concept of the value of visibility and some value measurement techniques is largely based on a workshop supported by the Forest Service, National Park Service, and Bureau of Land Management held in February 1979 on the subject of the Social Values of Visibility (Fox, Loomis, and Greene, 1979).

1.4.2 Establishment of Visibility Values: Overview

A major challenge in establishing visibility values is to develop ways to measure quantitatively visibility impairment as perceived by the human eye. Recent research on environmental quality indices has developed procedures for relating such indices to measurable quantities. Craik (1979) outlines the steps required based on soliciting opinions from users of “visibility” in class I areas. A successful perceived environmental quality index must relate the human perceived experience to a physical setting, and the experience should be integral to or typical for that setting. Peterson's (1979) discussion at the visibility values conference serves as a prototype for relating visibility to the more comprehensive human experience of a class I area. The Park Service in their brochure entitled "My Eyes Need a Good Stretching" (NPS, 1978) attempted to summarize this relationship between visibility and experience by relating the views of artists, humanists, and scientists on the subject of visibility degradation.

Establishing visibility values must, therefore, involve relating the whole visual experience to indices such as visual range, contrast transmittance, and color alteration. Such human visual experiences might be protected by different levels of these visibility related parameters in different locations. Although the visual experience is a significant component of, for example, visits to both the Grand Canyon and Great Smoky National

Parks, protection of that experience might require different magnitudes of visibility protection for each area. Both the perception of anthropogenic impairment and visibility related values are likely to vary from location to location.

It is difficult to estimate the number of people who are affected by class I area visibility. The numbers of scenic area users are rather high; for example, estimated visitor days in 1978 for all Park Service management units are approximately 277 million and for Forest Service Wilderness areas 7 .6 million visitor days. The Park Service collected a total of approximately $17 million in entrance and use fees in the same year (Fox, 1979). Research done in 1966 suggests that approximately $1 per visitor day is an appropriate estimate of the economic benefit of recreation. (Beardsley, 1970). This estimate is of course, subject to considerable inflation by 1979. These numbers provide an indication that direct use of class I areas is high and significant economic impacts are involved. Forest Service estimates on various forms of dispersed recreation use suggest a minimum of 50 percent and a maximum of 250 percent increase over current use in the next 50 years (Fox, 1979). Since a prime philosophy in the preservation of wilderness and establishment of parks is not the concept of use but rather the concept of preserving the existence of unique areas for the benefit of society at large, the value of visibility in class I areas is greater than that suggested by current use estimates alone.

Although the value of visibility may prove to be intangible, it is conjectured that it is to some extent quantifiable (can be identified as a discrete point on a scale) and, hence, can be generalized for display to the public. Given the lack of consistent units for the evaluation of aesthetic qualities such as visibility, values can be categorized according to: 1) economic criteria, the dollar cost/benefit associated with visibility, 2) psychological criteria, the individual need and benefits resulting from visibility and 3) social/political criteria, community opinions and attitudes held in common with regard to visibility. Preliminary results of past studies in each of these areas and suggestions for future work are discussed below.

1.4.2.1 Economic Criteria - Economists have made some progress toward quantifying the values of visibility using dollars as the measure. While in the market place, the market value or price reflects marginal value; total value can be estimated from revealed consumer preference either in a market or market like simulation.

The economic value of visibility can be broken into sub-categories, depending on the nature of benefits anticipated. These anticipated benefits or values could be classified as activity, option, and existence benefits. One may be willing to pay $X to actually visit the Grand Canyon without any visibility impairment (an activity value), $Y for keeping the Grand Canyon's visibility sufficiently clear so that one might enjoy it in the future (an option value) and $Z simply to know that the Grand Canyon will never have degraded visibility (an existence value).

The principal approach to economic evaluation of visibility has been the "iterative bidding technique." Brookshire (1979) explains the iterative bidding technique as "a direct determination of economic values from data which represent responses of individuals to contingencies posited to them via a survey instrument. "

The iterative bidding technique in the current form was first developed and applied by Randall et al. (1974 a, b) in the Four Corners region of the Southwest. Three contingencies were considered: (a) limited visibility reductions and a view of a power plant with limited visible emissions; (b) moderate emissions from the plant, moderate visibility reductions and moderate existence of unreclaimed soil bank and transmission lines; and (c) extensive emissions, visibility reductions and unreclaimed soil bank and transmission lines. Given this selection of scenarios, the results cannot be disaggregated into component values for visibility, power plant location, and unreclaimed soil banks and transmission lines. Employing a sales tax vehicle, the yearly mean bids were $85 (a to c) and $50 (b to c) per household. No bias tests were conducted in this experiment.

The Lake Powell experiment (Brookshire et al., 1976) addressed the potential visibility reduction from the proposed Kaiparowits power plant, which would have impaired the scenic vistas of the Glenn Canyon National Recreation Area. An estimate using the iterative bidding techniques was obtained for the aggregate visitor willingness to pay to prevent construction of the proposed Kaiparowits power plant. One of the principal motivations for the study in addition to the Kaiparowits power plant issue was an attempted replication of a subset of the Randall study results. Three scenarios depicted by verbal description and picture sets were employed in the Lake Powell experiment where visibility and plant sitting varied from best (a) to worst (c). The study tested for strategic bias in the bidding procedure and concluded that the bias was not prevalent in this experiment. Using entrance fees as a vehicle, the aggregate marginal willingness to prevent one additional power plant near Lake Powell was over $700,000. Employing the bids and considering the assumptions and structure of the experiment, an indication of worth via the preferences expressed in the study of the canyon lands of southeastern Utah can be obtained. Extrapolating to recreation areas within a hundred mile radius, the aggregate bid for a similar visibility reduction would be up to $20 million per year (Brookshire, 1979).

The Farmington experiment (Blank, et al., 1978) attempted to value visibility in the Four Corners Region of the Southwest. The study had three principal goals which represented extensions of the previous experiment: (1) to attempt to link visible range and the valuation measures, (2) to develop a theoretical cross check for the iterative bidding process and (3) to systematically test for a vehicle, starting point and information bias in the iterative bidding process. Starting point and vehicle bias in varying degrees were detected in the results. Later Thayer and Schulze (1977), Brookshire and Randall (1978) and Brookshire et al. (1978), biases and found none. Various reasons have been suggested as to why only the Farmington experiment encountered multiple biases. One possibility is the definition of the "good" being valued was poorly specified.

The South Coast Air Basin, California (SCAB) experiment (Brookshire et al., 1978) was the first urban test of the iterative bidding technique. The SCAB experiment included several improvements in the experimental process. The results of the study did not suffer from vehicle starting point information or strategic bias. The dollar bid per household per month was $29 for a 60 percent improvement in air quality. In addition, the independently conducted property value study produced the same order of magnitude valuation results as the iterative bidding portion. Air quality was partitioned into an aesthetic effect, including visibility, and acute and chronic health effects. Utilizing the aggregate bids for all sample areas, 22 to 55 percent of the total for aesthetic effects. The result suggests that, indeed, the aesthetic component of visibility is a of visibility valuation. Furthermore, this result is for an urban area where the preliminary reason for residence is not vistas as would be the case upon a visit, for example, to the Grand Canyon. One might infer that aesthetics, not health effects, would be the principal consideration for scenic national vistas.

These preliminary studies are subject to a number of uncertainties and limitations. The preliminary results largely represent *activity* values for use of class I areas in view of the situations where the iterative approach ate. Option and existence values are more complex concepts, which have not been studied for visibility. Moreover, to say that visibility is worth, for example, $30 to $80 per annum per household does not convey the total magnitude of the visibility issue. There is more to the enjoyment of the visibility in the natural can be qualified with dollars. Nevertheless, the economic studies support the notion that visibility is an important value in class I areas and in urban areas as well.

1.4.2.2. Psychological Benefits - There are certain psychological benefits, actual or perceived, associated with class I areas which would be foregone if visibility were degraded. At the visibility values workshop, the area of psychological benefits received considerable attention and a number of research formats address the quantification of these benefits. Currently, assessment of the benefits is related or can be derived from more general studies. For example, for many years scientists have attempted to measure the psychological benefits of outdoor recreation, including enjoyment of scenic vistas unencumbered with obvious signs of human development.

Driver et al. (1979) have identified a number of direct and indirect psychological benefits and behavior related to visibility in class I areas. The benefits of viewing a scenic vista include a variety of user activities. There are also psychological benefits associated with options or existence values. For example, many people wish to preserve the option for a clear view into the Grand Canyon. Some derive psychological benefits from just knowing that pristine areas exist, even though there is no intention of visiting all or any of them.

Several approaches to quality and quantity psychological benefits were suggested at the visibility values et al., 1979). These include:

1. Scenic Beauty Estimation Index (Daniel, 1979),
2. Psychophysiological Measurements (Ulrich, 1979),
3. Perceived Psychological Benefits (Driver et al., 1979) and

4. Social Value Estimation (Loomis and Green, 1979).

Application of these and other techniques of valuing visibility for use in visibility protection programs represent a considerable challenge, which will require a number of years of research.

1.4.2.3 Social Benefits - Available economic studies suggest mechanisms for developing the value of visibility. The discussion of human perception and psychological benefits discussions at the Visibility Values Workshop provide research perspectives and a list of very general techniques, which could be employed to estimate psychological benefits of scenic vistas and of unimpaired visibility. In one sense, social benefits represent the aggregate of individual benefits and any associated disbenefits. In order to resolve these extremes, there exists a value seeking system which functions well in practice, namely the political process. As noted above, the presence of the visibility provisions in the Clean Air Act Amendments suggests that the political process has ascribed significant value to the protection of class I area vistas. It has also mandated mechanisms for considering visibility benefits and associated societal costs. These decision-making mechanisms must involve the Federal Land Managers, States, and the general public.

Additional research is needed in understanding the economic, psychological, and social benefits and costs of class I visibility protection. This research must be tied to studies of human perception of various forms of visibility impairment. The results of such work will significantly enhance the decision making process.

1.5 Definition of Visibility Impairment

In establishing the national goal, Congress provided the following guidance on the definition of visibility impairment:

1. Visibility impairment "include(s) reduction in visual range and atmospheric discoloration";

2. The goal applies to impairment from man-made (as opposed to natural) air pollution;

3. The visibility impairment must be observed from a vantage point within a mandatory class I area (as opposed to a vantage point outside a class I area);

4. The ultimate goal is to remedy or prevent "any" man-made impairment;

5. In the application of controls or restrictions to pollution from man-made sources of impairment, consideration must be given to the "significance" of the impairment from existing sources and whether a new source visibility impact is "adverse."

This general guidance is significant, but a number of important areas are left open for additional specification, interpretation, and judgment. Examples of visibility impairment, areas requiring further resolution, and preliminary recommendations are illustrated and discussed below.

1.5.1 Categories of Visibility Impairment (Latimer, et al., 1978)

Although it may be desirable and useful to classify visibility impairment in a number of ways (Charlson et al., 1978; Latimer et al., 1978; Malm, 1979a), virtually any type of visibility impairment can ultimately be expressed as a reduction in visual range or atmospheric discoloration. Visual range is generally defined as the farthest distance at which one can see a large, black object against the sky at the horizon. Airport weather observers and others often use the term "visibility" synonymously with visual range. One can make subjective evaluations of "visibility" every time objects are viewed outdoors. Although large black objects are not generally available for observing and evaluating visual range, dark objects such as buildings, television towers, hills, or mountains can be viewed against the horizon sky.

Even if no distant objects are within view, subjective judgments about visual range can be made by noting the coloration and light intensity of the sky and nearby objects. For example, one perceives reduced visual range if a distant mountain that is usually visible cannot be seen, if nearby objects look "hazy" or have diminished contrast, or if the sky is white, gray, yellow, or brown rather than blue. In this latter case, both reduced visual range and atmospheric discoloration are apparent.

Atmospheric discoloration, "unlike visual range, has not been routinely defined or quantified in traditional pollution programs. Qualitatively, atmospheric discoloration is a pollution-caused change in color of the sky, distant mountains, clouds, or other objects. This statement implies that some natural or “not discolored” of atmospheric colors can be defined. Obvious examples of atmospheric discoloration include hazes associated with reduced visual range, distinct haze bands or layers, and visible brown, black, gray, or white plumes.

Because visual range reduction and atmospheric discoloration are often the results of the same pollution impact, it is useful to categorize anthropogenic visibility impairment into three general types: (1) widespread, regionally homogeneous haze that reduces visibility in every direction from an observer, (2) visible smoke, dust, or colored gas plumes that obscure the sky or horizon relatively near sources (this class is also termed "plume blight,” and (3) bands or layers of discoloration or veiled haze appearing well above the surrounding terrain.

Figure 1-3 shows an example of general haze conditions in the Grand Canyon. As seen in this photograph, range is detectable because the distant features of the canyon are difficult to distinguish. The contrast between the given object (part of the canyon) and the background (the horizon or a more distant terrain feature) is reduced by light scattered from particles in the intervening atmosphere. Even if terrain features were not discernible, the intensity and coloration of the scattered light would degrade the aesthetic quality of the atmosphere. In the Western United States, where most of the class I areas are located, spectacular scenery is enhanced by generally excellent visibility, which makes the colorful terrain features stand out with great clarity. Even in flat areas (e.g., the big sky country of the Northern Great Plains), however, a slight reduction in visual range or a slight atmospheric discoloration can change what originally appeared to be an "infinite" horizon to a white, yellow, gray, or brown horizon.

Figure 1-3 General Haze in the Grand Canyon. The source of light scattering particles (natural or manmade) is unkown (Anderson, 1979).

Figure 1-4 provides a "before and after" comparison of the impact of regional haze. Although the visual range is significantly reduced in 1-4b, the distant mountains are visible in both pictures. The most noticeable effect is the overall reduction in contrast and detail.

Near-source visibility impairment or plume blight is illustrated in Figure 1-5. The spatial extent of visibility impairment is defined by the dimensions of the plume. The plume is visible because the light intensity and color of the plume are different from those of the clouds and sky in the background. Because of the resultant relatively sharp boundary between the plume and the background, the visual impact on the observer is dramatic. Light scattering and absorbing particles are responsible for these impacts. Figure 1-6 shows a different kind of plume blight: a coherent brown plume. The discoloration in this case may be due to light absorption by NO_2 gas and/or particle scattering.

Bands of discoloration (Figure 1-7) can result from the transport and mixing of plumes. Airplane travelers are familiar with the noticeable boundary between the more polluted "mixing layer" and cleaner upper air. In Figure 1-7, the haze layers are clearly visible because of the sharp demarcation line between them and the clean air "sandwich." Figure 1-8 shows an example of possible discoloration, the source of which is unclear.

1.5.2 Causes of Visibility Impairment

It is obviously important to distinguish the causes of visibility impairment and, in particular, whether the cause is natural or anthropogenic. Clearly, Congress has been concerned only with anthropogenic visibility impairment. Reducations in visual range caused by precipitation, fog, clouds, windblown dust, sand, snow, or "natural" aerosols are natural occurrences and cannot be controlled by man. Indeed, some forms of natural visibility impairment may contribute to the enjoyment of class I areas. Examples of such phenomena are the blue haze of forested areas and the fog and hazes along the California and Oregon coast. Natural sources are discussed more fully in Chapter 6.

1.5.3 Location of Impairment

The location of visibility impairment is extremely important in terms of visibility protection because the national goal states that visibility *in* class I areas is to be restored and protected. It is uncertain whether this definition includes impairment caused by pollution outside of a class I area. It is reasonable and consistent with traditional (airport) usage to assume that visibility in an area includes the view of unobstructed objects located inside and outside of the area. Figure 1-9 shows a visible haze layer surrounding Navajo Mountain. The mountain, not in a class I area, is usually visible from Bryce Canyon. In EPA's view, important views extending outside the boundaries of class I areas are part of the visibility value of the area, and are included in the national goal. This issue is discussed further in Chapter 7.

1.5.4 Degree and Extent of Impacts Constituting Impairment

Each of the three major categories of visibility impacts can be further specified with respect to degree as well as to spatial and temporal extent. Judgments are necessary to specify where a pollution impact becomes impairment and whether the impairment is significant or adverse.

The degree of impairment can be characterized by the reduction in visual range from some reference value, by a reduction in contrast between an object and the horizon sky at a known distance from the observer, or by a shift in coloration or light intensity of the sky or distant objects, such as clouds or terrain features, compared to what is perceived on a "clear" day. In all cases, the magnitude of visibility impairment can be characterized by the change in light intensity or coloration of an object (or part of the sky) compared to that of some reference object. For example a distant mountain is visible because the intensity and coloration of light from the mountain is different from that of the horizon sky. Another example is a plume or haze layer seen against the background sky or terrain features. The pollution is visible (perceptible) only if the light intensity or coloration of the plume contrasts with that of the surrounding sky or terrain.

Figure 1-4 (a). La Sal Mountains from EPA monitoring site in Canyonlands. Visual range was estimated to be approximately 260 km. Under these conditions, visual range must be calculated because curvature of the earth limits horizontal viewing distances to less than the visual range. Mountains are about 50 km from camera.

Figure 1-4 (b). Same view as in (a). Estimated visual range approximately 110 km. Although visual range is significantly lower, the major visual impact is the reduction in contrast between sky and mountain. The comparison is made difficult because of the difference in snow cover in this scene (Malm, 1979b).

Figure 1-5. Near-source visibility impairment. Plume blight from particulate emissions extends downwind from the Four Corners Power Plant in New Mexico. As the plume mixes to ground level, the visibility of distant terrain features is degraded (Anderson, 1979).

Figure 1-6. Coherent brown plume. Plume is from the Navajo Power Plant near Paige, Arizona. The plume coloration may be due to absorption of blue light by NO_2 and/or back scattering of brown light by particles. (Williams, 1979).

Figure 1-7. Layered haze. A band of blue sky is visible between two haze layers near the Southern California Desert. The origin of the layers in this case is transport of Los Angeles area urban plume (Niemann, 1978).

Figure 1-8. Atmospheric discoloration? The yellowish brown coloration in this view from Mesa Verde National Park is characteristic of NO_2 absorption. Because of photographic limitations, the actual coloration and cause cannot be specified (Malm, 1979b).

Figure 1-9. Navajo Mountain from Bryce Canyon (Niemann, 1978).

The spatial extent of visibility impairment is important to both the perception and the significance of impairment to observers in class I areas. The sensitivity of an observer to brightness and color differences between objects depends on the spatial relationship between the objects. If each of the objects is uniformly colored and there is a sharp line of demarcation between the objects, such as when a mountain is viewed against a horizon sky, a smaller change in light intensity or color can be perceived than if the boundary between the two objects is vague, as in the case of a plume viewed against the horizon sky. If the observer is located in a uniformly colored atmosphere, atmospheric discoloration is perceived, not by comparison of two colored fields but by comparison with the recollection of a clear atmosphere.

The temporal extent (duration, frequency of occurrence, and time of occurrence) is of great importance in determining the significance of air pollution levels. Short term or infrequent phenomena or both are less likely to be of concern. Visibility impairment occurring during times of maximum visitor attendance is of greater significance than the same impact during minimum attendance. With sufficient measurements, the frequency of occurrence can be characterized as the number of days or hours in a year that the degree of visibility impairment is greater than some specified amount.

Qualitatively, the degree and extent of anthropogenic impairment increases through four levels: 1) natural baseline, no anthropogenic pollution; 2) a measurable or predictable pollution increment that is so small or short that it is not perceptible by human observers; 3) an observed or predicted perceptible impact which, because of degree or extent, is generally considered to be insignificant; and 4) an impact that is generally considered significant or adverse.

For the purpose of this report, EPA interprets man-made visibility impairment, in the context of the national visibility goal, as any *perceptible* change in visibility (visual range, contrast, atmospheric color or other index) from that which would have existed under natural conditions. Judgments with respect to the *significance* and *adversity* of perceptible impairments should consider the degree and the spatial and temporal aspects of impairment in the context of control programs. Such judgments must be made, at least in part, on a case-by-case basis. For this reason and because these judgments must involve States, Federal Land Managers and the public, it is difficult at this time to specify general criteria. As a minimum, however, significant or adverse impairment must be perceptible. These issues are discussed further in Chapter 7.

1.6 OVERVIEW OF CURRENT U.S. VISIBILITY

Until recently, visibility parameters have not been routinely monitored in any class I area. Some insight into general visibility conditions in these locations can, however, be obtained by examining available regional airport visibility data throughout the United States. The status of visibility in class I areas is discussed further in Chapter 7.

Figure 1-10 presents median yearly visibilities and visibility isopleths (Trijonis and Shapland, 1978). The data represent midday, median visual ranges for 1974-1976 from 100 suburban and non-urban locations. Visibilities at 93 of the locations are determined from airport observations.

The airport data were checked for consistency, quality, and completeness. Instrumental visibility measurements from seven sites in the southwest are also included. Although some uncertainties arise from the use of airport data*, there is reasonably good consistency between airport observations within regions and between airport and in instrumental results in the Southwest.

The best visibility (70+ miles, 110 km) occurs in the mountainous Southwest. Visibility is also quite good (45-70 miles) north and south of that region, but sharp gradients occur to the east and west. Most of the area east of the Mississippi and south of the Great Lakes exhibits median visibilities of less than 15 miles (24 km) annually.

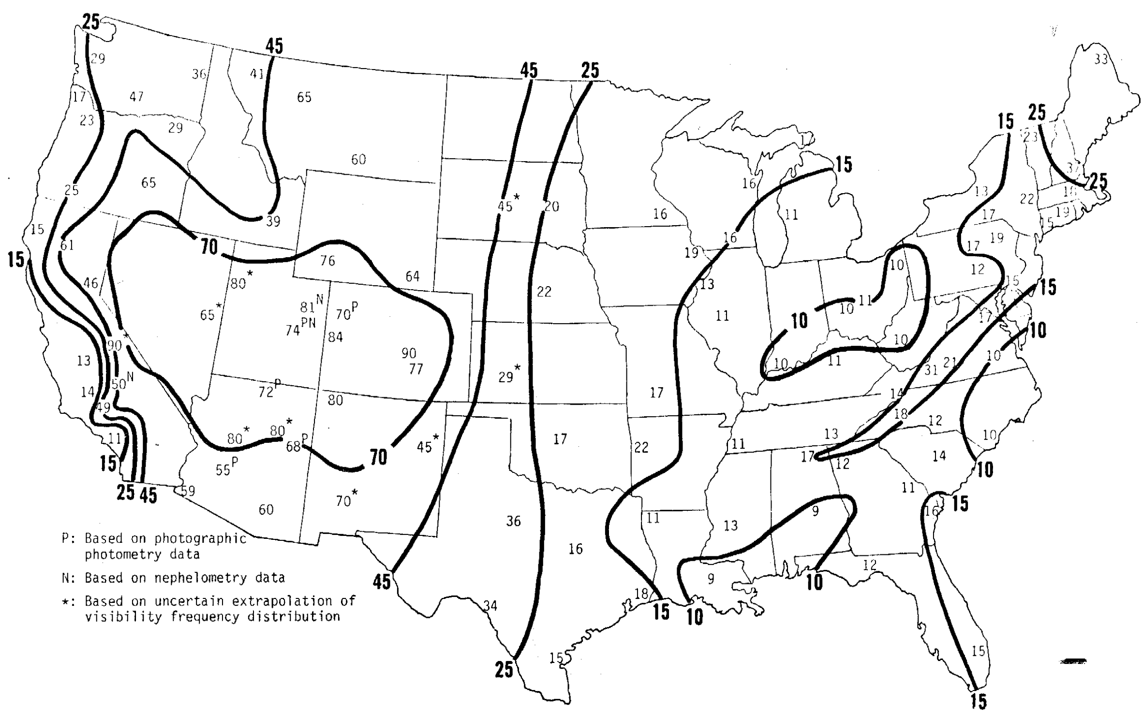

Figure 1-10. Median yearly visual range (miles) and isopleths for suburban /non-urban Areas, 1974-76 (Trijonis and Shapland, 1978).

Figure 1-11 represents median summertime (third quarter) visibilities for the same data. Comparison of these figures shows that summertime visibility is significantly lower than yearly visibility in the East. Most of the Western states show little change in the summer, with mixed increases and decreases. Visibility increases, however, during the summer in the Pacific Northwest.

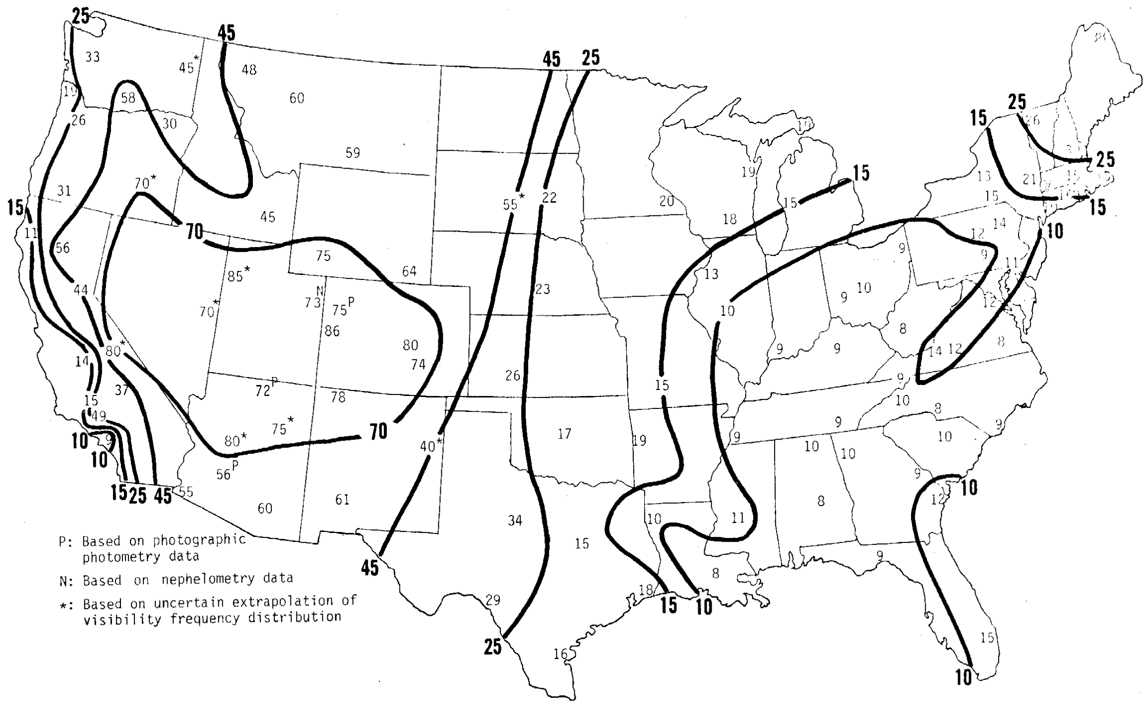

Figure 1-11. Median summer visual range (miles) and isopleths for suburban/ non-urban areas, 1974-76 (Trijonis and Shapland, 1978).

Although natural sources of visibility impairment and prevailing meteorological conditions are undoubtedly an important factor in producing these geographical and seasonal patterns, analysis of visibility trends and other information discussed in later sections suggest that man-made air pollution has a significant impact. The regions with the best existing visibility levels are most sensitive to additional impairment and most responsive to incremental pollution reductions. The reasons for this are discussed in the next chapter.

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PROTECTING VISIBILITY

AN EPA REPORT TO CONGRESS

CHAPTER 2

2 FUNDAMENTALS OF ATMOSPHERIC VISIBILITY IMPAIRMENT

"Therefore, O Painter, make your smaller figures merely indicated and not highly finished, otherwise you will produce effects opposite to nature, your supreme guide. The object is small by reason of the great distance between it and the eye; this great distance is filled with air, that mass of air forms a dense body which intervenes and prevents the eye from seeing the minute details of the objects." –Leonardo da Vinci, Six Books on Light and Shade.

2.1 INTRODUCTION: VISION IN THE ATMOSPHERE

Our ability to define, monitor, model and control anthropogenic visibility impairment is dependent on understanding of the scientific and technical factors that affect atmospheric visibility. Visibility involves an observer's perception of the physical environment. The fundamental factors that determine visibility are illustrated in Figure 2-1 and include:

1. Illumination of the scene by the sun, as mediated by clouds, ground reflection, and the atmosphere;

2. Reflection, absorption, and scattering of incoming light by the target objects and sky resulting in inherent contrast and color patterns at the target location;

3. Scattering and absorption of light from the target and illumination source by the atmosphere and its contaminants;

4. Psychophysical response of the human eye-brain system to the resulting light distribution, and

5. Subjective judgment of the perceived images by the observer.

Evaluation of the effects of air pollution on visibility thus involves two steps: 1) specification of the process of human visual perception and 2) quantification of the impacts of air pollution on the optical characteristics of the atmosphere. The characteristics of illumination and targets can be important to both steps.

2.2 HUMAN VISUAL PERCEPTION

2.2.1 Brightness and Contrast

The eye receives image-forming radiation from the environment and converts it into electrical impulses, which are further interpreted and perceived by the brain. The perception of brightness, contrast, and color is not determined simply by the pattern and intensity of incoming radiation; rather, it is a dynamic searching for the best interpretation of the available data (Gregory, 1978).

A candle in a brightly lit room is scarcely noticeable; but, if the room is dim to start with, the candle itself appears bright. Similarly, sunlit treetops may appear dark against the horizon sky but bright when viewed against the shadowed forest floor. These examples show that the absolute intensity of radiation has little to do with or brightness perception of visible objects. The eye normally senses and intensity difference *relative* to the overall intensity level; that is, it detects the contrast. Thus, trees that appear darker than background cliffs in bright sunlight will also appear darker than the cliffs in moonlight or heavy overcast.

The detection of contrast between an object and its surroundings is fundamental to visibility. Without contrast, as for example in a thick fog, objects cannot be perceived. As the contrast between object and background is reduced (for example, by increased pollution), the object becomes less distinct. When the contrast becomes very small, the object will no longer be visible. This liminal or *threshold contrast* has been the object of considerable study. The threshold contrast is of particular interest for atmospheric visibility, since it influences the maximum distances at which various components of a scene can be discerned. Of equivalent importance to threshold contrast is the smallest perceptible change in contrast of a viewed scene caused by a small increment in pollution haze.

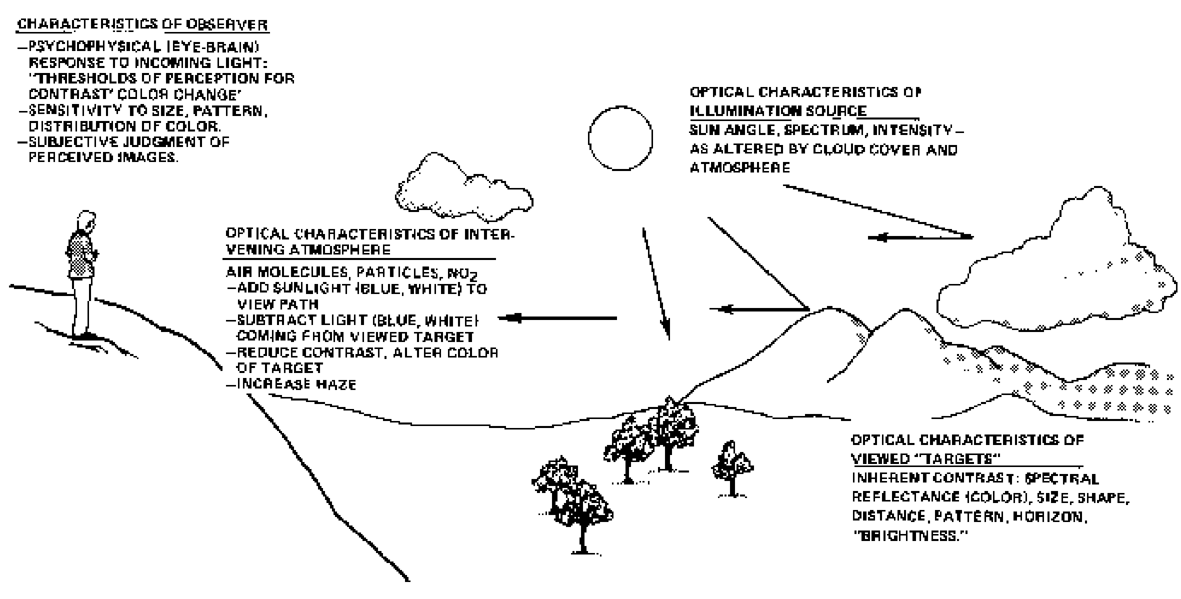

Figure 2-1. Vision in the atmosphere.

The physiology of threshold contrast detection is illustrated in Figure 2-2, showing a bright horizon (I + ΔI) against which a "hazy" mountain (I) is being detected. Laboratory experiments indicate that for most daylight viewing intensities, contrasts (ΔI / I+ΔI) as low as .018 to .03 (1.8 to 3 %) are perceptible (Figure 2-3).

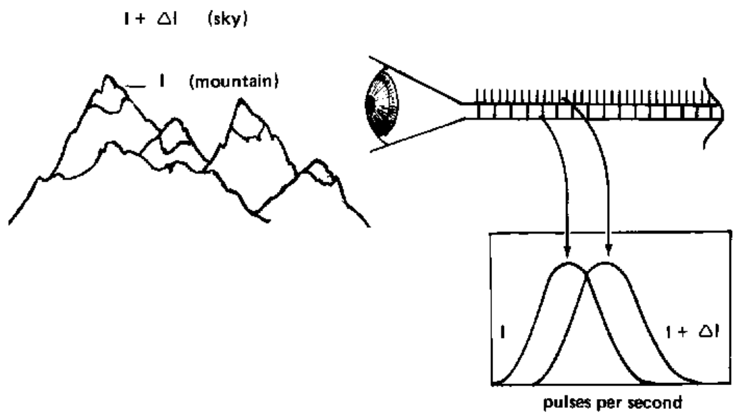

Figure 2-2. Physiological response of the eye to an increment in light intensity is an increase in the number of signals sent to the brain. The detection of threshold contrast involves discrimination of the signal field (I) from its brighter background (I + ΔI) (Gregory, 1978).

Middleton's measurements of observer threshold contrasts for viewing large, dark distant objects in the atmosphere produced similar results, although some variability in observer sensitivity was noted (Figure 2-4). This study, however, was conducted in a relatively polluted urban area. Similar experiments to evaluate contrast thresholds in pristine areas are needed.

The preceding discussion of thresholds was limited to contrast between objects and backgrounds of relatively large apparent size. For "smaller" objects, however, the size of the visual image on the retina of the eye also plays an important role in the perception of contrast. We all know from experience that, as an object recedes from us and apparently becomes smaller, details with low contrast become difficult to perceive. The reason for this loss of contrast perception is not only that the relative brightness of adjacent areas changes but also that the visual system is less sensitive to contrast when the spacing of contrasting areas decreases. If the contrast spacing is regular, a "spatial frequency" can be readily determined. The human visual system is much more sensitive to contrast at certain spatial frequencies than to contrast of other spatial frequencies.

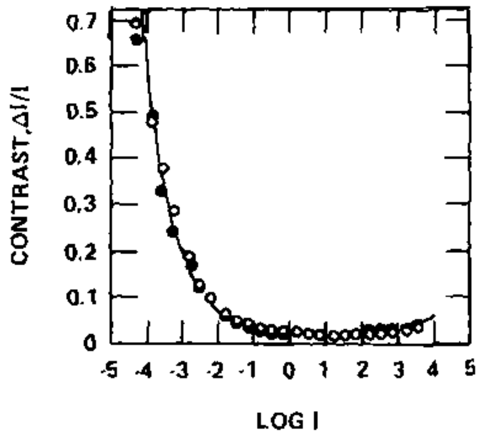

Figure 2-3. The minimum perceptible (threshold contrast ΔI/ΔI is between .018 and .03 for about four orders of intensity change. Evidently, at low intensities, the statistical 'noise' of retinal signals becomes important; at very high intensities, blinding deteriorates the contrast sensitivity ((Konig and Brodhum, 1889).

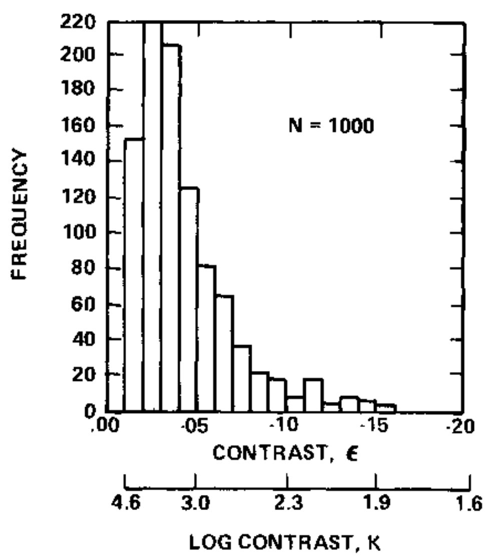

Figure 2-4. Measured threshold contrast of large, dark targets identified in 1000 determinations of visual range by 10 observers. Variability is due to both differences in observer thresholds and the discrete nature of the marker set (Middleton, 1952).

Figure 2-5 shows the contrast sensitivity (inverse of contrast threshold) of the eye-brain system to a standard test pattern with varying spatial frequency. Although several factors affect the location of the curve, the contrast sensitivity is generally highest for periodic visual patterns if the spacings are about 0.33 degrees (20 minutes) apart. This corresponds to clumps of vegetation viewed at a distance of 10 km. The figure indicates that as the visual targets become smaller and their spacing increases, the threshold contrast steadily increases. Measurements of the perceived threshold contrast for individual circular targets suggest a similar relationship (Taylor, 1964). The threshold contrast increases for single targets occupying less than 0.5 degrees (30 minutes) of arc but remains constant (at about 0.3%) for larger targets. The moon and sun occupy about 30 minutes of arc.

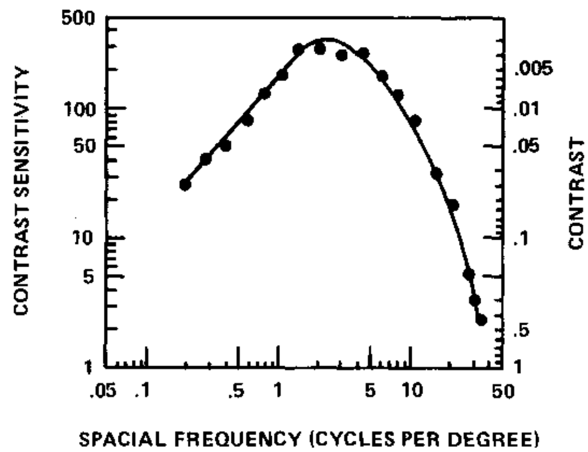

Figure 2-5. Contrast sensitivity of human subjects for sine-wave grating peaks at three cycles per degree corresponding to a contrast threshold of 0.003 or 0.3% (Campbell and Maffei, 1974).

The relationship between perceived contrast threshold and target characteristics (size and pattern) is important for visibility, because a scenic vista usually contains a number of targets of varying sizes and arrangements. The calculation of the perceptibility of all targets would require specification of their angular size distribution. The perception of "texture," consisting of contours of small angular size and high spatial frequency, is particularly affected by this loss of threshold sensitivity. Henry (1977, 1979) has proposed a system for quantifying this effect through the transformation of the contrast details of a scene in conjunction with a specification of the human psychophysical contrast response function (Figure 2-5). This approach, termed MTF*, has some limitations but theoretically could be used to predict the contrast reduction that would cause a just-noticeable (perceptible) difference in the scene.

Although the MTF approach may ultimately improve the specification of perceptible changes invisibility of contrast detail, it has not yet been fully developed or experimentally tested for atmospheric vision. Thus, current visibility models and assessment tools must rely on evaluation of contrast changes for large dark targets as an index of visual degradation. Even for this kid of target, additional experimental verification of perceptible contrast changes is needed. For the purpose of this report the threshold contrast for large dark targets will be assumed to be 0.02. The minimum perceptible contrast change for large targets is less well quantifies and may vary with initial conditions.. Based on preliminary, unpublished data, the minimum perceptible change may range between 0.01 and 0.05 (Malm, 1979b).

2.2.2 Color

The preceding section discussed the response of the eye and brain to the intensity of light, ignoring the spectral (wavelength) distribution. Color is the sensation produced by the eye-brain system in response to incoming light.

The eye has three different types of color sensors (cones) which cover the visible spectrum in three broad, overlapping curves (Figure 2-6). The system operates so that an object that reflects half blue light and half yellow light is identified not as yellow-blue, but rather as a new color, white. As in the case with brightness, the perception of color is not dependent on the absolute flux of radiant energy reaching the eye. The color of objects (e.g. flesh tones) appears similar over a wide range of outdoor and indoor illumination. The eye differs in this regard from photographic film, which can take on a reddish or bluish cast under differing lighting conditions. Moreover, the color of the surrounding scenery can affect the perceived color of a given object. The normalization of color and other aspects of color perception are not fully understood. Although recent approaches to explaining the mechanism of color perception appear promising (Land, 1977), no completely adequate theory of color vision exists (Henry, 1979).

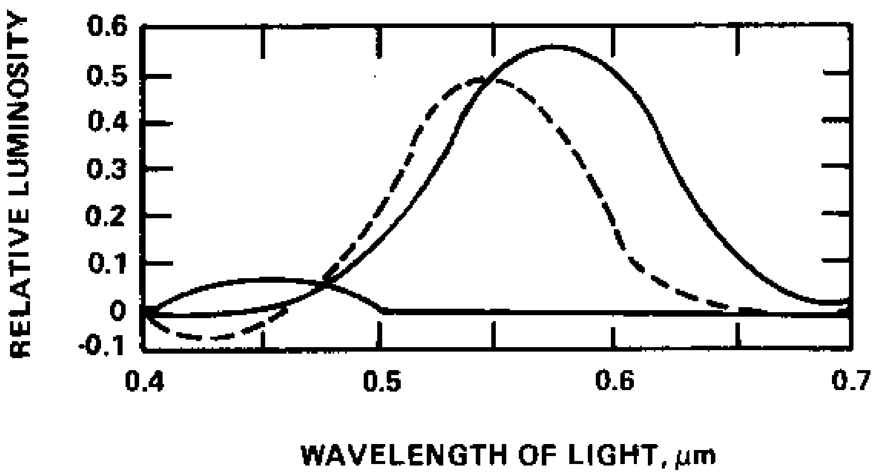

Figure 2-6. The fundamental response curves of the eye (cones). The visible spectrum extends from 0.4 (roughly violet or blue) to 0.7 (roughly red) micrometers. The weighted peak (photopic) response of the eye occurs at a wavelength of 0.55 μm (Gregory, 1978).

The chromaticity diagram (Figure 2-7) was developed to quantify empirically the concept of color. Any three colors, no one of which can be matched by the other two, determine an unambiguous system of coordinates for all colors that can be matched by mixtures of the three; on has only to specify the proportions in the (unique) match. The Commission International de l'Eclairage (CIE) has established two standard schemes, based on three imaginary non-physical colors, by which schemes all colors can be represented as such matches. The CIE primaries, denoted X, Y, Z, are defined in terms of the small field and large field color matching behaviors of a hypothetical "standard observer," whose response to radiation of various wavelengths is near the average of a number of actual observers with normal color perception. This system allows for complete specification of color through its chromaticity coordinates (x, y) and intensity (L*).

The CIE color metrics enjoy wide use in science and industry as international standards. They must not be thought of as methods for describing sensations or a theory of vision but only as means of assigning numbers to colors in such a way that two colors that have the same numerical specifications will appear alike to the standard observer under standard viewing conditions.

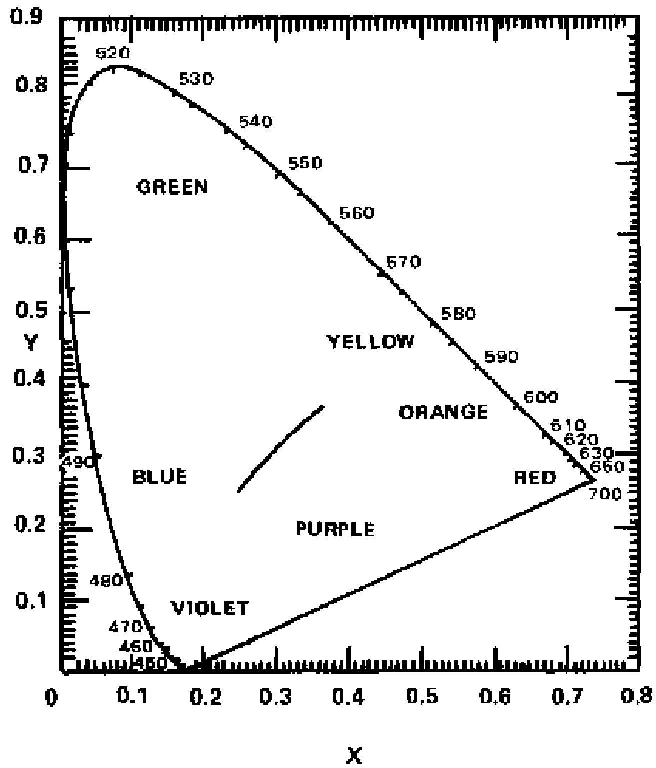

Figure 2-7. The small-field (2°) CIE chromaticity diagram. The curved line is the locus of the spectral colors; all physically realizable colors lie within the closed figure formed by the spectrum locus and the straight line joining its ends. Heavy curve in the middle indicates typical chromaticities of daylight. Intensity or brightness can be represented by a third dimension, perpendicular to the plane of the paper. The corresponding large-field (10°) diagram is similar (adapted from Middleton, 1952).

An attractive feature of the CIE color metrics is that colors that are similar in appearance lie close together on the chromaticity diagrams. A great deal of experimental work has been done on color discrimination thresholds, which are of critical importance to the pain and dye related industries. On the chromaticity diagrams, these thresholds take the form of small ellipses of colors just distinguishable from a given color (Figure 2-8). The differences in colors are specified by a parameter ΔE, which is a function of the change in light intensity or brightness (ΔL*) and the change in chromaticity (Δx, Δy), ΔE can be considered as a distance between two colors in a color "space" such that equal distances (ΔE) between any two colors correspond to equally perceived color changes. It is possible that a threshold, ΔEo, can be found to determine whether a given color change is perceptible. Latimer et al. (1978) have calculated threshold values of ΔE for visible plumes, but he applicability of this system for quantifying perceptible atmospheric discoloration has not yet been experimentally verified.

Factors other than that specified by ΔE (wavelength, intensity) that are of importance to perception include: size of object or area, color of surrounding background, and temporal variations. The well-known effect of background color on perceived color is called chromatic adaptation. In general, if the eye is adapted to a color, e.g. blue sky, a nearby white area may take on the complementary color of the background, in this case a light yellow-brown. This effect may be large enough to explain some of the brown color of atmospheric haze (Henry, 1979).

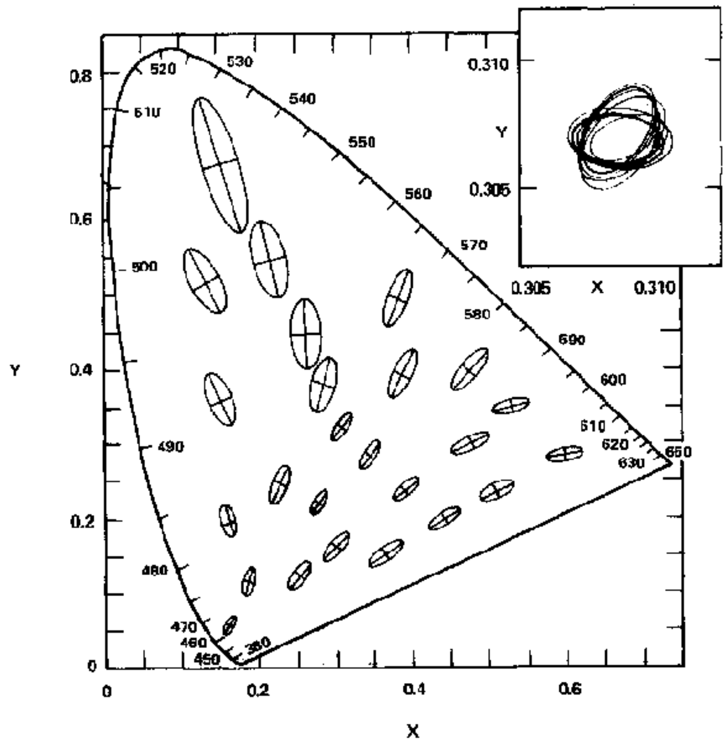

Figure 2-8. Small-field chromaticity diagram showing color-matching ellipses, represented 10 times actual scale for clarity. Each ellipse is the locus of standard deviation in repeated small-field color matching. The diagram summarizes almost 25,000 attempted color matches by a single observer (MacAdam, 1942). Insert: Variability of large-field color-matching ellipsoids among 12 different observers (Brown, 1957).

Because current understanding of color perception is inadequate, theoretical calculations of atmospheric discoloration are useful only as a guide for experimental measurements. Empirical measurements of atmospheric color perception and effects of pollutants over the next few years should provide an adequate means of handling atmospheric discoloration, even without a comprehensive theoretical treatment.

2.3 OPTIAL EFFECTS OF THE ATMOSPHERE AND ITS CONTAINMENTS

2.3.1 Scattering and Absorption

Visibility impairment is caused by the following interactions in the atmosphere:

1. Light scattering -by molecules of air
   -By particles (atmospheric aerosols)

2. Light absorption-by gases
   -By particles

Light scattering by gaseous molecules of air (Rayleigh scattering), which cause the blue color of the sky, is dominant when the air is relatively free of aerosols and light absorbing gases. Light scattering by particles is the most important cause of degraded visual air quality. Fine solid or liquid particles, also known as atmospheric aerosols, account for most of atmospheric light scattering. The aerosols with diameters similar to the wavelength of light (0.1 to 1.0 micrometers) are the most efficient light scatterers per unit mass. Light absorption by gases is particularly important in the discussion of anthropogenic visibility impairment because nitrogen dioxide, a major constituent of power plant and urban plumes, absorbs light. Nitrogen dioxide appears yellow to reddish brown because it strongly absorbs short wavelengths light (blue), leaving longer wavelengths (red) to reach the eye. Light absorption by particles is most important when black soot (finely divided carbon) or large amounts of windblown dust are present. Most atmospheric particles are not, however, generally considered to be efficient light absorbers.

2.3.2 Radiative Transfer

The effect of the intervening atmosphere on the visual properties of distant objects (e.g. the horizon sky, a mountain) theoretically can be determined if the concentration and characteristics of air molecules, aerosols, and nitrogen dioxide are known along the line of sight. The rigorous treatment of visibility requires a mathematical description of the wavelength-dependent interaction of light wit the atmosphere, known as the radiative transfer equation. The description presented here is intended to provide a qualitative understanding of this process. Detailed and summary treatments are available in a number of publications. (Chandraskhar, 1950, Latimer et. al., 1978).

Figure 2-9 (a) shows the simple case of a beam of light (e.g. the sun or a searchlight) transmitted horizontally through the atmosphere. The intensity of the beam in the direction of the observer (I(x)) decreases with distance from the source as light is absorbed or scattered out of the beam. Over a short interval, this decrease is proportional to the length of the interval and the intensity of the beam at that point.

$$-dI = b_{ext} I \, dx \qquad (2\text{-}1)$$

Where –dI = decrease in intensity (extinction)

b_{ext} = extinction coefficient

I = original intensity of beam

dx = length of short interval

The coefficient of proportionality, denoted by b_{ext}, is called the extinction or attenuation coefficient. The extinction coefficient is determined by the scattering and absorption of particles and gases and varies with pollutant concentration and wavelength of light.

Consider now an observer looking at a distant target, as shown in Figure 2-9b. Just as a beam is attenuated by the atmosphere, the light from the target that reaches the observer is also diminished by absorption and scattering. The reduced brightness of distant objects is, however, not usually the primary factor limiting their visibility; if it were, the stars would be visible around the clock, since their light must traverse the same atmosphere night and day. In addition to light originating at the target, the observer receives extraneous light scattered into the line of sight by the intervening atmosphere. It is this air light that forms the diaphanous, visible screen we recognize as haze.

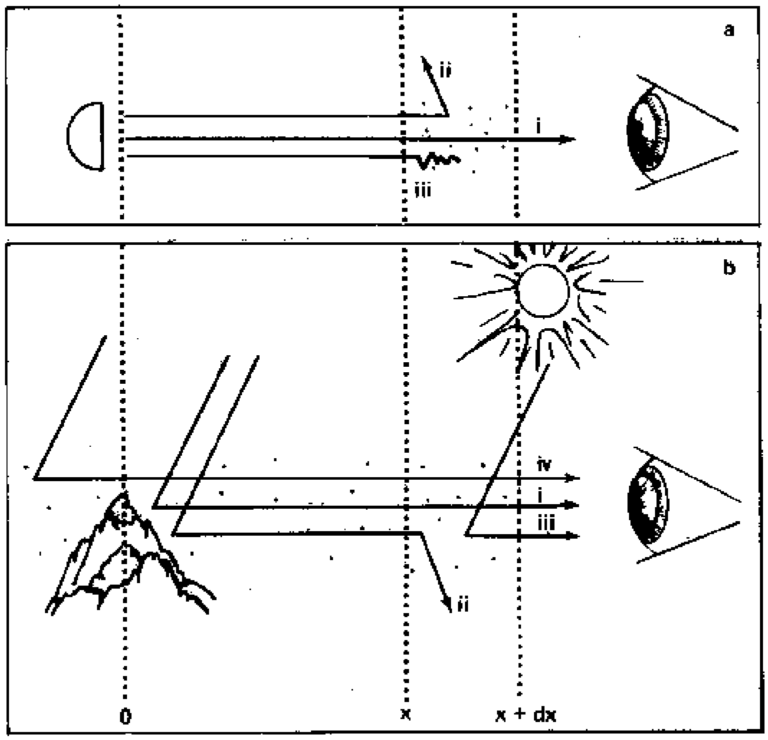

Figure 2-9. (a) A schematic representation of atmospheric extinction, illustrating: (i) transmitted, (ii) scattered, and (iii) absorbed light. (b) A schematic representation of daytime visibility, illustrating: (i) residual light from target reaching observer, (ii) light from target scattered out of observer's line of sight, (iii) airlight from intervening atmosphere, and (iv) airlight constituting horizon sky. (For simplicity, "diffuse" illumination from sky and surface is not shown.) The extinction of transmitted light attenuates the '"signal" from the target at the same time as the scattering of airlight is increasing the background "noise."

The intensity of the air light scattered into the sight path of the observer in Figure 2-9b depends on the distribution of light intensity from all directions, including direct sunlight, diffuse sky light or surface reflection, and the light scattering characteristics of the air molecule and aerosols. Over a short interval, the air light added is given by:

$$dI = b_{ext} \left[W \int Q_v (\theta_v) I_{(v)} \, d\Omega \right] dx \tag{2-2}$$

Where dI = the increase in intensity form added air light

b_{ext} = the extinction coefficient

Bracketed parameters [ ] = the sum of light intensity from all directions scattered into the line of sight. This depends on aerosol and air scattering parameters ($W \Sigma Q_v$), and illumination intensity and angle (I_v, θ_v) summed over all directions (Ω).

dx = length of short interval

Since both extinction coefficient and other scattering parameters vary with wavelength, the added light can produce a color change.

The overall change in light intensity from an object to an observer is governed by the extinction of transmitted light and the addition of air light. The change in intensity for a short interval (dI) is thus:

$$dI = -dI\ (\text{extinction}) + dI\ (\text{air light}) = -\ b_{ext}\ [I\ dx + W \int Q_v\ (\theta_v)\ I_{(v)}\ d\Omega\ dx] \quad (2\text{-}3)$$

This equation, the radiative transfer equation, forms the basis for determining the effects of air pollution on visibility. Its general solution is quite difficult; most visibility models (see Chapter 5) incorporate a number of approximations to simplify calculations and data requirements.

2.3.3. Contrast and Visual Range

The effect of extinction and added air light on the perceived brightness of visual targets is shown graphically in Figure 2-10. At increasing distances, both bright and dark targets are "washed out" and approach the brightness of the horizon. Thus, the apparent contrast of an object relative to the horizon (and other objects) decreases.

An initial object contrast (C_o) can be defined as the ratio of object brightness minus horizon brightness divided by horizon brightness. Assuming a relatively uniform distribution of pollutants and horizontal viewing distance, the apparent contrast of large objects decreases with increasing observer-object distance. As given by Middleton, 1952:

$$C = C_o\ (B_T\ b_{ext}\ x / B_o) \qquad (2\text{-}4)$$

Where C = apparent contrast at observer distance

C_o = initial contrast at object

B_T/B_o = ratio of sky brightness at target object to that at observer (usually 1 for distance less than 50-100 km).

b_{ext} = extinction coefficient

x = observer-object distance

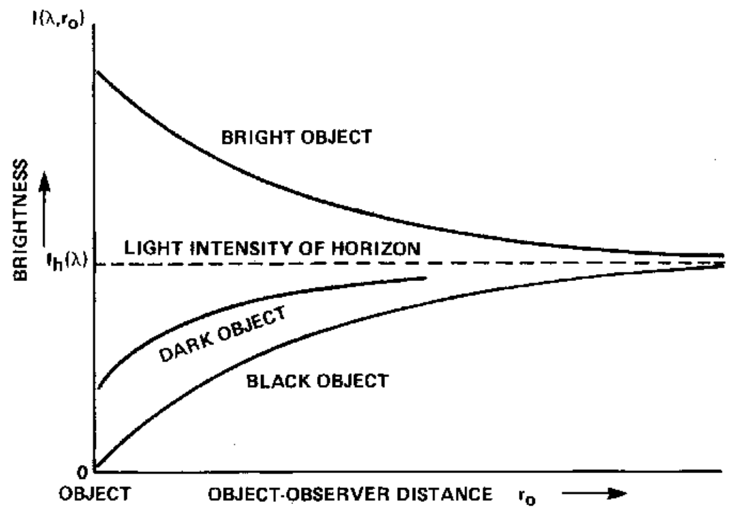

Figure 2-10. Effect of an atmosphere on the perceived brightness of target objects. The apparent contrast between object an horizon sky decreases with increasing distance from the target. This is true for both bright and dark objects (Charlson et al., 1978).

For a black object, the initial contrast is –1 and:

$$C = (-1)\, e^{-b_{ext} x}$$

As discussed in the preceding section, the threshold of contrast perception for large dark targets varies between .01 and .05; for "standard" observers a .02 threshold is often assumed (Malm, 1979). In this case, the distance Vr, at which a large black objet is just visible is given by:

$$.02 = -e^{-b_{ext} Vr} \quad \text{or} \quad Vr = 3.92 / b_{ext} \qquad (2\text{-}5)$$

This is the standard formula for calculating visual range, originally formulated by Koschmieder in 1924.

The Koschmieder relationship gives a valid approximation of visual range only under a limited set of conditions. Important assumptions and limits are listed and discussed below (Charlson, et. al., 1978, Malm, 1979a):

1. Sky brightness at the observer is similar to the sky brightness at object observed;
2. Homogeneous distribution of pollutants;
3. Horizontal viewing distance;
4. Earth curvatures can be ignored;
5. Large black objects; and
6. Threshold contrast of 0.02.

Assumption 1: The effect on visual range of inhomogeneous illumination, such as that under scattered clouds, is difficult to analyze by elementary methods. Limited experimental evidence indicates that this effect may not be great for short visual ranges (less than 50 km). Visual range has been found to correlate with the reciprocal of the scattering coefficient, b_{scat}*, as illustrated in Figure 2-11. The correlation coefficients are commonly in the neighborhood of 0.9, with values for b_{scat} times Vr in the range 2 to 4 as compared to 3.9 in the Koschmieder equation. The studies were conducted in relatively polluted conditions. The effect of scattered clouds or differing sky brightness on visual range in clean areas should be further investigated.

Assumption 2: The Koschmieder equation can be utilized in a non-homogeneous atmosphere (e.g., a ground level plume) if the extinction coefficient in and outside the plume is known. Otherwise, measurements of b_{ext} in areas with strong pollution gradients will produce inaccurate visual range estimates.

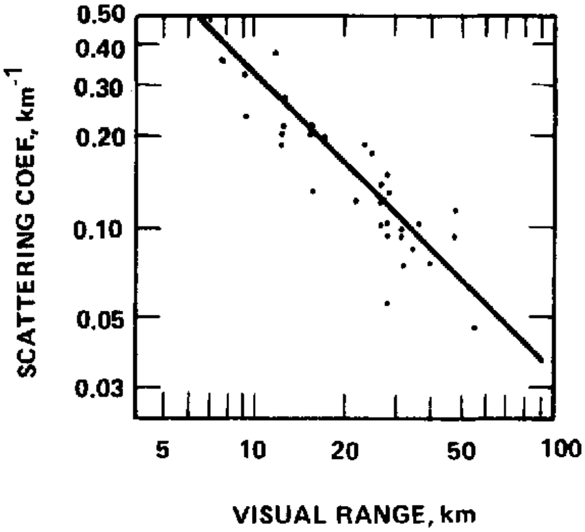

Figure 2-11. Inverse proportionality between visual range and light scattering coefficient (b_{scat}) measured at the point of observation. The straight line shows the Koschmieder formula for non-absorbing ($b_{ext} = b_{scat}$) media, $V = 3.9/b_{scat}$. The linear correlation coefficient for V and b_{scat} is 0.89 (Horvath and Noll, 1969).

Assumptions 3 & 4: Requirements for horizontal viewing distance and curvature of the earth limit the validity of the Koschmieder calculation to cases where visual range is less than about 150-200 km (Figure 2-12). Where no proper targets exist and the extinction coefficient is measured, however, the calculation of visual range is useful in expressing visual air quality in units (miles or kilometers) more readily comprehended by the layman.

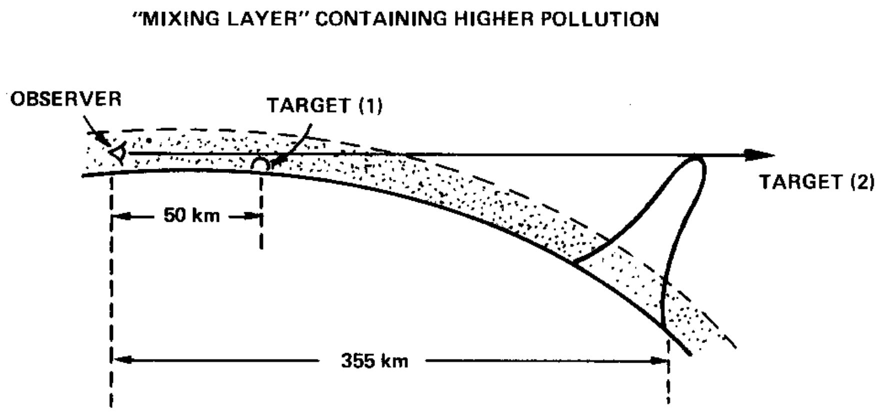

Figure 2-12a. Limitations of Koschmieder relationship. When visual range is short (1), extinction and illumination through sight path is uniform. When true visual range is high (2), Koschmieder equation underestimates visual range because extinction decreases with altitude and illumination (sun angle) at target is different from that at observer. (Dimensions and earth curvature exaggerated for clarity) (Malm, 1979a).

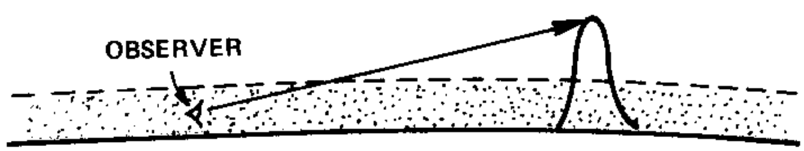

Figure 2-12b. Similarly, when viewing angel is not horizontal, extinction through the site path is nonuniform. Koschmieder equation will underestimate visual range (Malm, 1979a).

Assumption 5: The visual range for nonblack objects depends strongly on initial contrast, which in turn depends on amount and angle of illumination, or if at night depends on the power of the light source. As a result of this ambiguity, visual ranges for nonblack objects or for lights at night cannot be related simply to each other or to optical air quality.

Assumption 6: The effects of target size, texture, and sensitivity of observer are related to the nature of human perception. As discussed in Section 2.1, in general the "visual range" for small targets or contrast detail is significantly less than that for large objects (Table 2-1).

				Visual range (km)	
Detail of objects	Angular size (minutes)	Characteristics sizes at 10 km (m)	Examples for a hillside at 10 km	West Vr = 100 km	East Vr = 20 km[b]
Very coarse (Form)	> 30'	> 100	Hills, valleys, ridgelines	79-100	16-20
Coarse (Line)	17-30'	50-100	Cliffs faces smaller valleys	76	15
Medium (Texture)	9-17'	25-50	Clumps of large vegetation, clearings on forested slopes	62	12
Fine (Texture)	< 9'	< 25	Individual large trees, clumps of small vegetation	22	4

Table 2-1. Visual Range of Contrast Detail[a]. [a]Based on calculations using MTF model of eye-brain response and mathematical transformation of scenic features into a spatial frequency (Henry, 1979). [b]VR sit he assumed background visual range (for large black targets).

2.4 POLLUTANTS THAT IMPAIR VISIBILITY

As indicated above, the air pollution related alteration of the appearance of distant objects (reduction in apparent contrast and visual range) could be estimated if the extinction coefficient, b_{ext}, is known. To the extent b_{ext} varies with the wavelength of visible light, this alteration of appearance includes changes in the apparent coloration of distant objects.

The extinction coefficient represents a summation of the air and pollutant scattering and absorption interactions outlined in 2.3.1.

$$b_{ext} = b_{Rg} + b_{ag} + b_{scat} + b_{ap}$$

Where b_{Rg} is Rayleigh scattering by air molecules;
b_{ag} is absorption by NO_2 gas;
b_{scat} is scattering by particles;
b_{ap} is absorption by particles;

Each of these quantities has inherently different wavelength or color dependence, as will be discussed below. The units of extinction are inverse distance, e.g., 1/mile. The most commonly used units are km^{-1} and ($10^{-4}m^{-1}$). As extinction increases, visibility decreases.

2.4.1 Rayleigh Scatter b

The particle-free molecular atmosphere at sea level has an extinction coefficient of about 0.012 inverse kilometers (km^{-1}) for "green" light (wavelength 0.05 μm), limiting visual range to about 320 km. b_{Rg} decreases with air density and altitude. In some western class I areas, the optical extinction of the atmosphere is at times essentially that of the particle-free atmosphere (Charlson, 1978). Rayleigh scatter thus amounts to a simply definable and measurable background level of extinction against which other extinction components (such as those caused by man-made pollutants) can be compared. Rayleigh scattering decreases with the fourth power of wavelength (Figure 2-13) and contributes a strongly wavelength-dependent component to extinction. When Rayleigh scattering dominates, dark objects viewed at distances of over several kilometers appear behind a blue haze of scattered light, and bright objects on the horizon (such as snow, clouds, or the sun) appear reddened at distances greater than about 30 km.

2.4.2 Absorption by Nitrogen Dioxide Gas (b_{ag})

Of all gaseous air pollutants, only nitrogen dioxide (NO_2) possesses a significant absorption band in the visible part of the spectrum. Nitrogen dioxide and its precursor, nitric oxide (NO), are emitted by high temperature processes such as combustion in fossil-fuel power plants. Nitrogen dioxide is strongly blue absorbing and can color plumes red, brown, or yellow (see Figure 1-6). The hue and intensity of color depend on concentration, optical path length, aerosol properties, conditions of illumination, and observer parameters. In non-urban settings, the area-wide concentration of NO_2 is less important than the levels in coherent plumes. In Figure 2-13, the absorption of 0.1 ppm NO_2, a concentration found in urban areas, is compared to the spectral extinction of pure air. At a wavelength of 0.55 μm, the absorption by NO_2 is comparable to air scattering. The absorption coefficient drops off rapidly with wavelengths, which can give a brownish color when viewed against a white background. However, at concentrations more typical of class I areas, (less than 0.01 ppm) area-wide impacts of NO_2 absorption are unimportant.

2.4.3 Particle Scattering (b_{scat}) and Absorption (b_{ap})

As the particle concentration increases from very low levels where Rayleigh scatter dominates, the particle scattering coefficient bscat increases until eventually $b_{scat} > b_{Rg}$. At this point, particle scattering controls the visual quality of air. In understanding the degradation of visual quality of air two principal problems have been:

1. Defining the size range and other physical characteristics of particles most effective in causing scatter and
2. Defining the chemical composition and, thus, identifying the source of particles in this optically effective size range (Charlson et al., 1978).

2.4.3.1 Light Scattering and Absorption by Single Particles—Particle size, refractive index, and shape are the most important parameters in relating particle concentration and particle derived extinction coefficients, b_{scat} and b_{ap}. If these properties are established, the light scattering and absorption can be calculated. Alternatively, the extinction coefficient associated with an aerosol can be measured directly (see Chapter 3).

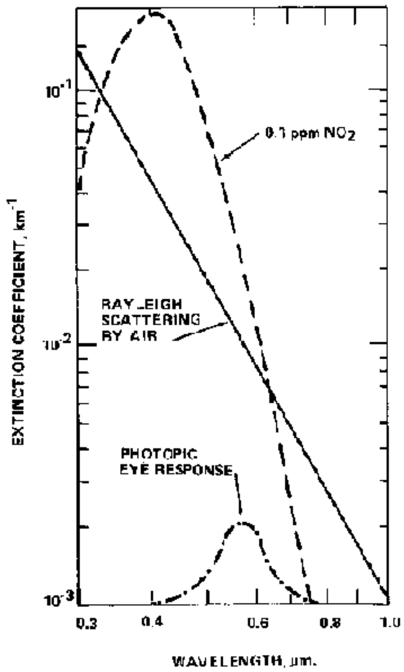

Figure 2-13. Rayleigh scattering by air (b_{Rg}) is proportional to (wavelength)^4 Reduced air density at higher altitudes causes a reduction of b_{Rg}. The NO_2 absorption band peaks at 0.4 μm but vanishes in the red portion of the spectrum (Husar et al., 1979).

The basic interactions between light and atmospheric particles are illustrated in Figure 2-14. For spherical particles of sizes similar to the wavelength of visible light (0.1 to 1 μm), the scattering and absorption of individual particles can be calculated through use of the "Mie" equations (Mie, 1908).

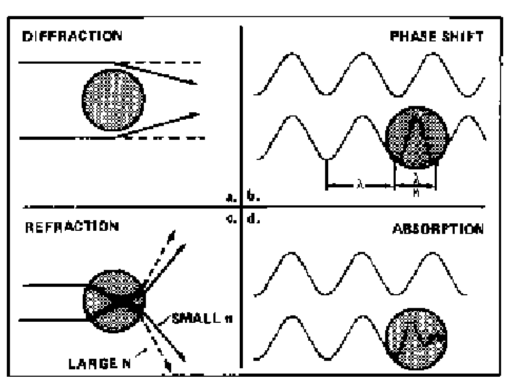

Figure 2-14. Light scattering by coarse particles (>2μm) is the combined effect of diffraction and refraction. A) Diffraction is an edge effect whereby the radiation is bent to "fill the shadow" behind the particle. B) The speed of a wavefront entering a particle with refractive index n >1 (for water n = 1.33) is reduced. This leads to a

reduction of the wavelength within the particle. Consequently a phase shift develops between the wave within and outside the particle leading to positive and negative interferences. C) Refraction also produces the "lens effect." The angular dispersion by bending of incoming rays increases with n. D) For absorbing media, the refracted wave intensity decays within the particle. When the particle size si comparable to the wavelength of light (0.1 - 1 µm), these interactions (a-d) are complex and enhanced. For particles of this size and larger, most of the light is scattered in the forward hemisphere, or away form the light source.

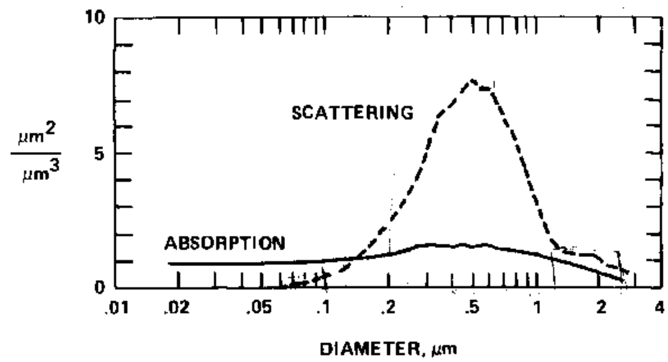

Figure 2-15. Single Particle Scattering and Absorption. For a single particle of typical composition the scattering per volume has a strong peak at particle diameter of 0.5 µm (m = 1.5 - 0.05I; wavelength: 0.55µm). The absorption per aerosol volume however is onlly weakly dependent on particle size. Thus the light extinction by particles with diameter less than 0.1 µm is primrily due to absorption (Charlson et al. 1978). Scattering for such particles is very low. A black plume of soot from an oil burner is a practical example.

Charlson et al., (1978) used Mie theory to calculate the light scattering and absorption efficiency per unit volume of particle for a typical aerosol containing some light absorbing soot (Figure 2-15). As illustrated in the figure, particles in the size range of 0.1 to 1 µm are the most efficient light scatterers. The remarkably high scattering efficiencies of these particles are illustrated by the following examples: a given mass of aerosol of 0.5 µm diameter scatters about a billion times that of the same mass of air; a 1 mm thick sheet of transparent material, if dispersed as 0.5 µm particles, is sufficient to scatter 99% of the incident light, i.e. to obscure completely vision across such aerosol cloud (Husar et. al., 1979).

Atmospheric particles or aerosols are made up of a number of chemical compounds. All of these compounds exhibit a peak scattering efficiency in the same particle size range as that calculated for the typical aerosol of Figure 2-15. Because of differences in refractive index, however, the values of the peak efficiency and the particle size at which it occurs vary considerably among the compounds.

From Figure 2-16 it is apparent that, for relating light scattering to the aerosol, consideration needs to be given to the chemical composition of the scattering and absorbing aerosol. In particular, compounds that tend to draw water in the aerosol phase, such as sulfates, can be very important. Furthermore, the optical properties of a given mass of aerosol collected over the arid western part of he country may be substantially different from those of the same mass of aerosol collected in a humid eastern U.S. air mass.

2.4.3.2 Characteristics of Atmospheric Particles—Investigations of atmospheric aerosols over the past several years have revealed some important regular features (Whitby et al., 1972). A typical atmospheric particle size distribution is shown in Figure 2-17. Most of the aerosol volume and mass is distributed in two modes: a fine mode centered at about 0.3 μm and a coarse mode centered at 5 to 30 μm. The two modes are usually unrelated in that they have different compositions, sources, life times, and removal mechanisms. Figure 2-18 illustrates a pair of measured particle size distributions showing independent variation of fine particle concentration at a single site.

The source of much of the fine mode particles is atmospheric transformation of reactive gases (e.g. sulfur dioxide, volatile organics, and ammonia) into aerosols such as sulfates, particulate organics, and ammonium compounds. Such transformed substances are called *secondary* particles. Other important fine mode sources include direct or *primary* particle emissions from combustion (fires, automobiles, etc.) and industrial processes. Coarse mode particles usually are derived from mechanical processes such as grinding operations or plowing. High winds can suspend large quantities of coarse particles.

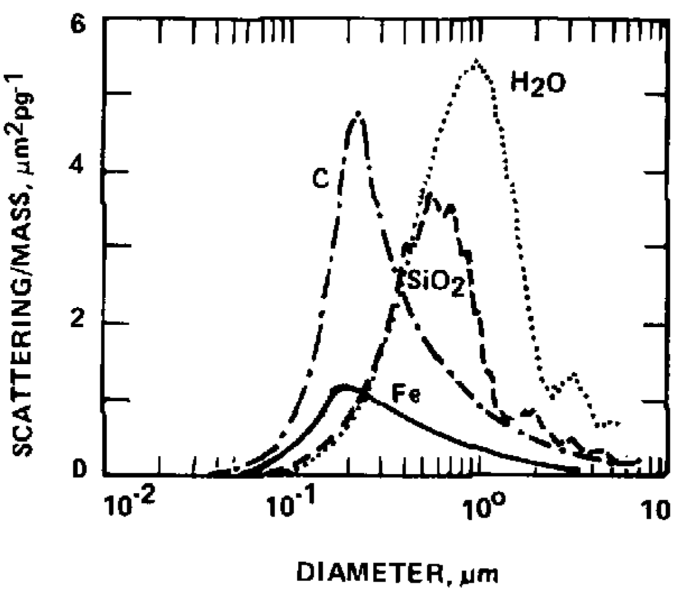

Figure 2-16. Single particle light scattering for several substances. Per unit mass, water scatters more light than SiO2 or iron. Furthermore, the water scattering efficiency peaks at about 1 μm, while the spheres of pure carbon or iron are most efficient scatterers at 0.2 μm (Faxvog, 1975). Carbon is te most efficient light absorbing substance, and hence 0.2μm carbon particles are the most efficient for total extinction (absorption + scatter) (Faxvog and Roessler, 1978).

From the point of view of aerosol optics, a key question is whether an aerosol particle is spherical. For such particles, rigorous Mie theory is applicable and the optical properties can be readily calculated from their size and reflective index. Measurements in St. Louis by Allen et al(1978) show that in the fine mode less than 5% of aerosol population exhibits nonspherical shape. Puschel and Wellman (1978) found that spherical particles also dominate fine mode aerosols near Cedar Mountain, Utah. Coarse particles are almost exclusively nonspherical and therefore the application of the Mie theory to calculate their optical properties is only a crude approximation. Currently there is an extensive body of experimental data on the optical properties of the nonspherical particles (e.g. Pinnick et al., 1976).

2.4.3.3 Light Scattering by Typical Particle Distributions—Measured particle size distributions can be used in conjunction with Mie theory calculations for single particles as shown in Figures 2-15 and 2-16, to determine the contribution of different size classes to extinction. The result of this kind of calculation is shown in Figure 2-19. The peak in single particle scattering per unit volume at 0.3 μm coincides with the peak in observed aerosol volume (mass), so that the fine particles dominate extinction in most cases.

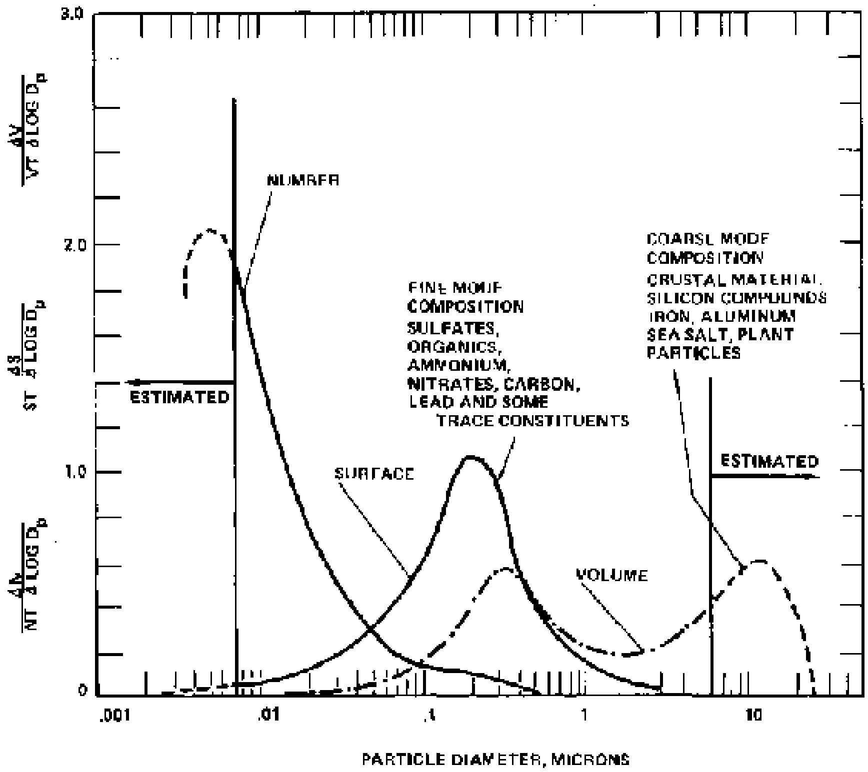

Figure 2-17. Number, Surface, and Volume (Mass) distributions for typical aerosols in the lower atmosphere. They typical chemical consitutents of each mode are also given. The area under each curve segment is proportional to the fraction of the property (number, N; surface, S; volume, V) that is contained within a given size range (Whitby et al., 1972).

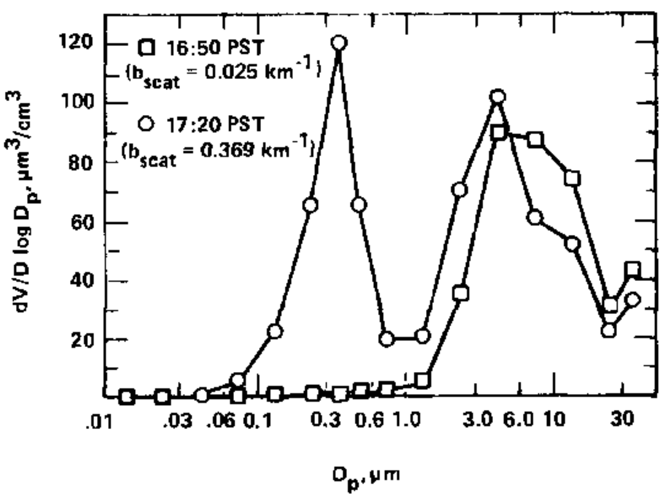

Figure 2-18. Variation in Fine and Coarse Particle Modes. In the California ACHEX study, the measured areosol distributions have shown that the fine and coarse particle modes are essentially independent. In Rubidoux, for example, the size distribution has been observed to change from a fine particle-free distribution at 16:50 (Sept. 25, 1973) to the usual bimodal distribution at 17:20 (Hidy et al., 1975).

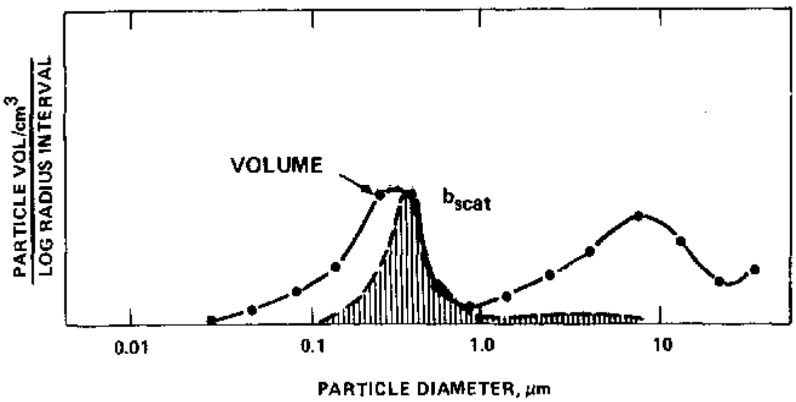

Figure 2-19. Light scattering for a typical aerosol volume (mass) distribution. The calculated light scattering coefficient is contributed almost entirely by the size range 0.1 - 1.0 µm. The total b_{scat} and total aerosol volume are proportional to the area under the respective curves (Charlson et al., 1978).

Because the peak and shape of the bimodal particle mass distribution curve can vary, the light scattering characteristics of a given particle mass might also be expected to vary. As noted by Charlson (1978), however for the observed range of atmospheric particle distributions, the calculated scattering coefficient per unit mass is relatively uniform. Latimer et al. (1978) have determined the scattering efficiency per unit mass for several aerosol distributions. The calculated coefficient changes by no more than 40 percent in the size range of 0.2 to 1.0 µm (Figure 2-20).

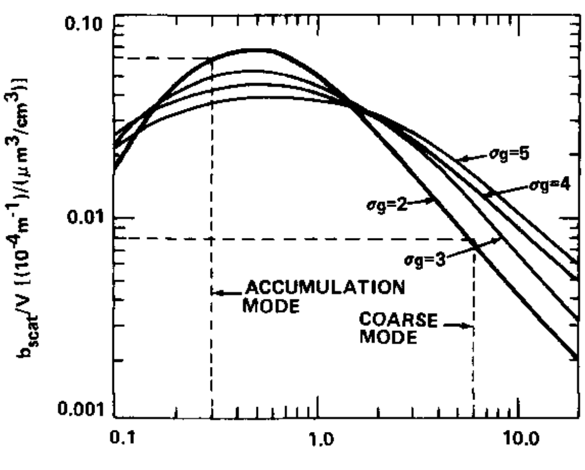

Figure 2-20. The light scattering per unit volume for various aerosol size distributions (σg) is the highest in the 0.2 - 1.0 µm range, and does not vary greatly (Latimer et al., 1978).

The relative consistency of calculated light scattering per unit mass over a range of particle distributions and the dominant influence of fine particles suggest that reasonably good approximations of light scattering coefficients can be obtained by measurements of fine particle mass. Simultaneous monitoring of the two parameters at a number of sites has been conducted by several investigators (Weiss, 1978, Patterson and

Wagman, 1978, Macias et al., 1975, and White and Roberts, 1975). These investigators measured scattering per unit mass ratios of 0.003 $km^{-1}/\mu g/m^3$ to 0.005 $km^{-1}/\mu g/m^3$ at several locations. The Mie calculations of Figure 2-19 suggest a ratio of 0.0033 $km^{-1}/\mu g/m^3$. Moreover, at these locations, correlations between fine particle mass and b_{scat} were consistently 0.95 or better. Figure 2-21 shows the relationship for St. Louis. The high correlations indicate that at the sites studied, fine particle mass dominates particle scattering. The relationship between several chemical components of fine particles and light scattering is discussed in Chapter 4.

Coarse particles are a less significant cause of visibility degradation. Notable exceptions include wind-blown dust, fog, fly ash, and certain plumes. In case of wind-blown dust, for example, Gillette et al. (1978) have reported light scattering to mass ratios more than an order of magnitude lower than the ratios noted above, since coarse dust particles are much less efficient scatterers per unit mass (Figure 2-15). In clean areas where fine particle levels are low, however, coarse mode particle may contribute a non-negligible portion of light scattering. Secondly, it should be noted that a given b_{scat} to mass ratio is only applicable if the refractive indexes of the light scattering particles are the same. It is conceivable that, in the dry and arid western states, the aerosol refractive index and relative amounts of coarse and fine mode particles are sufficiently different that the scattering mass ratios quoted above would not be applicable. Preliminary results from project VISTTA, however (Macias, et al., 1979) suggest b_{scat}/fine mass ratios in the southwest are 0.003 $km^{-1}/\mu g/m^3$, or about the same as measured elsewhere.

The wavelength dependence of light scattering ranges from the very strong blue scattering of air molecules and very small particles <0.05 µm to wavelength independent to “white” scattering for coarse particles > 5 µm. Thus Rayleigh particles (<0.05µm) in the exhaust of a poorly tuned automobile appear blue against a dark background while a fog of coarse water droplets appears white. A typical aerosol size distribution at moderate concentrations tends to scatter more blue light than red, but the wavelength dependence is not as strong as for Rayleigh particles. It has generally been observed that the wavelength dependence of light scattering diminishes as the total light scattering and humidity increases (Husar et al., 1979).

In pristine class I areas on days when Rayleigh scattering dominates (b_{Rg} = 0.012 km^{-1}), an addition of about 4 $\mu g/m^3$ of fine particles (b_{scat} = 0.013 km^{-1}) would cause substantial “whitening” of the natural blue Rayleigh haze and the horizon sky (Charlson et al., 1978). At a fine particle level of 30 $\mu m/m^3$ (0.1 km^{-1}), the wavelength dependent scatter would be controlled by the aerosol itself.

2.4.3.4 Light Absorption by Typical Particle Distributions—Particle absorption (b_{ap}) appears to be on the order of 10 percent of particle scattering (bscat) in clean background areas (Bryce Canyon, Utah) and up to 50 percent of composition and particle size distribution (Waggoner, 1973, Bergstrom, 1973). The most important contributor to this absorption (in cities) appears to be graphitic carbon in the form of soot (Novakov et al., 1978). The source of this highly absorbing submicrometer soot appears to be the combustion of liquid fuels, particularly in diesel engines; coal combustion may not be a major contributor (Charlson et al., 1978).

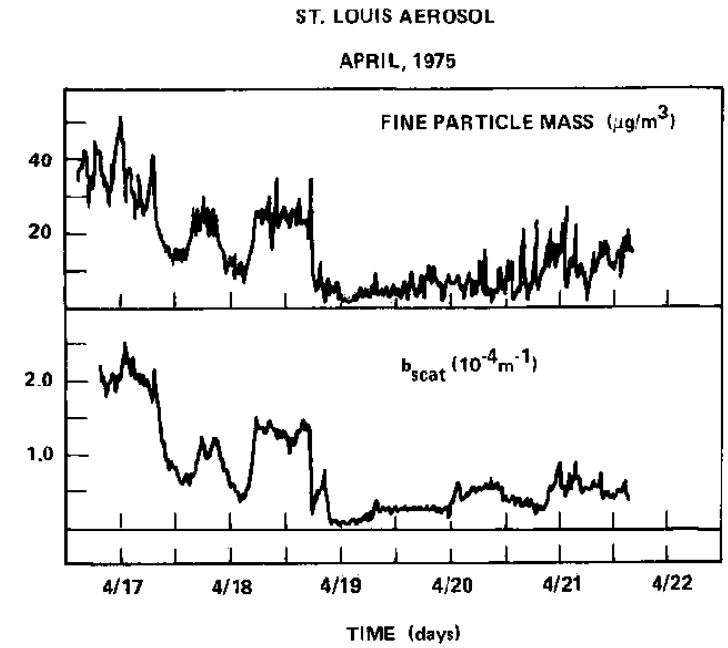

Figure 2-21. Light scattering vs. fine particle mass. Simultaneous monitoring of bscat and fine particle mass in St. Louis showed a high correlation coefficient of 0.96, indicating that bscat depends primarliy on the fine particle mass concentration (Macias et al., 1975).

2.5 POLLUTANT/IMPAIRMENT RELATIONSHIPS

The scattering and absorption from an aerosol cloud depend on the wavelength of incident light, the angle of observation, and the concentration and size distribution of the light scattering and absorbing aerosol and gases. The role of these parameters will be examined briefly as applied to the three major types of visibility impairment: general haze, plume blight, and atmospheric discoloration.

2.5.1 General Haze—Visual Range, Contrast, Color

Visibility in the atmosphere of pristine class I areas is extremely sensitive to incremental additions of fine aerosol. The sensitivity of clean atmospheres to change is illustrated in the graph of visual range versus extinction (fine particle mass) in Figure 2-22.

However, in many class I areas, where viewing distances are 50 to 100 km, a reduction in calculated visual range (for example, from 350 km to 250 km) will not be the most noticeable impact of incremental pollution. The reduction in apparent contrast and discoloration of nearby objects and sky are the main effects perceived in such areas.

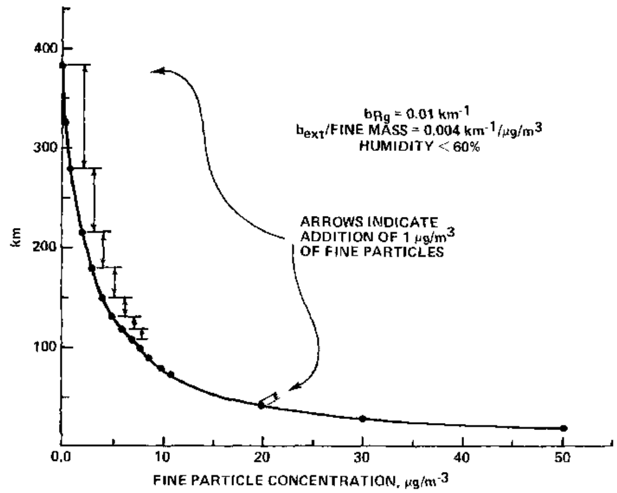

Figure 2-22. Effects of fine particle increments on calculated visual range. Addition of 1 μg/m^3 to a clean atmosphere reduces visual range by 30 percent. Addition of the same amount when bckground visual range is 35 km (20 miles) produces a 3 percent reduction.

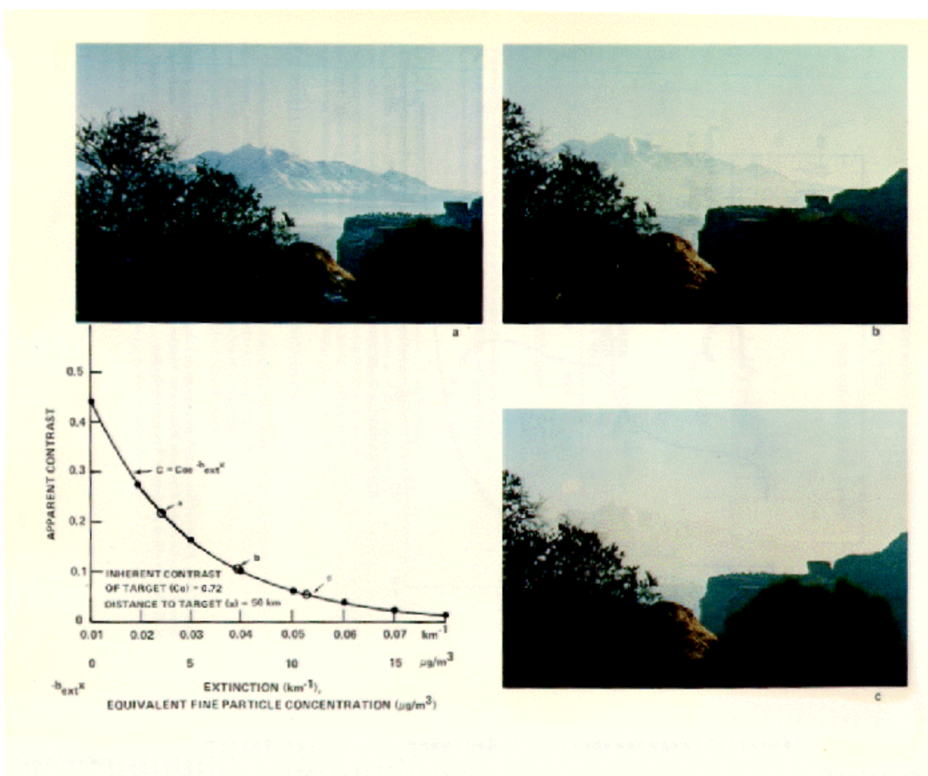

Figure 2-23. Effect of fine particle increments (calculated) on apparent contrast (measured) between sky and target (mountain) (Malm, 1979b).

Figure 2-23 shows that apparent contrast between an object and sky also decreases rapidly with increasing extinction in clean atmospheres. The graph also indicates the calculated concentration of fine particles spread throughout the viewing distance associated with the listed extinction coefficient. The accompanying photographs show the dramatic changes in contrast detail of even a 3 to 5 $\mu g/m^3$ increment of fine particles. A similar increment in a relatively polluted area (20 $\mu g/m^3$ of fine particles) might not be perceptible. Calculation of contrast changes (for large targets) accompanying incremental particle levels indicate that the maximum decrease in contrast will occur for objects located at distances of about one-fourth of the visual range from the observer (Malm, 1979a). Thus, in an initially clean atmosphere, a fine particle increment produces maximum contrast reduction for large objects 50 to 100 km away. A reduction in visual range of 5 percent would result in a reduction in contrast of 0.02 for those objects. As discussed in Section 2.2.1, such a change may be just perceptible. The contrast detail (texture, small objects) and coloration of closer objects in contrast may, however, be affected to a greater degree (Henry, 1979, Malm, 1979a).

The perceived color of objects and sky is also changed by the addition of aerosols. Because of the difficulties and uncertainties in specifying perceived color, only a qualitative description is possible. In general, the apparent color of any target fades toward that of the horizon sky with increasing distances from the observer. Without particles, scattered air light is blue, and dark objects appear increasingly blue with distance. The addition of small amounts (1 to 5 μg/m3) of fine particles throughout the viewing distance tends to whiten the horizon sky making distant dark objects and intervening air light (haze) appears grayer. According to Charlson et al., (1978), even though the visual range may be decreased only slightly from the limit imposed by Rayleigh scattering the change from blue to gray is an easily perceived discoloration. The apparent color of white objects is less sensitive to incremental aerosol loadings. As for contrast, incremental aerosol additions produce a much greater color shift in cleaner atmospheres (Malm, 1979a).

Aerosol haze can also degrade the view of the night sky. Light scattering and absorption diminish star brightness. Perception of stars is also reduced by an increase in the brightness of the night sky caused by scattering of available light. In or near urban areas, particle scattering of artificial light significantly increases night sky brightness. The combination of extinction of starlight and increased sky brightness markedly decreases the number of stars visible in the night sky at fine particle concentrations of 10 to 30 $\mu g/m^3$ (Leonard et al., 1977).

Thus, the overall impact of aerosol haze is to reduce visual range and contrast, and change color. Visually the objects are “flattened” and the aesthetic value of the vista is degraded even though the distances are small relative to the visual range. Much of the scenic value of a vista can be lost when the visual range is reduced to a distance that is several times greatest line-of-sight range in the scene.

2.5.2 Discolored Layers

Layers of colored haze can be caused by particles and nitrogen dioxide. The visual impact depends greatly on a number of factors such as sun angle, surrounding scenery, sky cover, viewing angle, perception parameters, and pollutant loading. Quantitative theoretical treatments of these effects, combining radiative transfer and human perception, are not fully developed. The following general observations can, however, be made (Charlson et al., 1978):

1. The relative importance of aerosol or NO_2 in determining the color and appearance of a plume or haze layer can be addressed, in part, in terms of the relative extinction as a function of wavelength.
2. Suspended particles generally scatter much more in the forward direction than in other directions. This fact means a plume or haze layer can appear bright in forward scatter (sun in front of observer) and dark in back scatter (sun in back of observer) because of the angular variation in scattered air light (Figure 2-24). This effect can vary with background sky and objects.
3. The added air light (see 2.3.1) is both angle and wavelength (color) dependent and the wavelength dependence can vary with illumination angle. Extinction is wavelength dependent but not angle dependent.
4. A visible aerosol layer will be brighter than an adjacent particle-free layer for sun angles (in front of observer) less than 30^o. At larger angles, the aerosols will usually be darker.
5. Aerosol optical effects alone are theoretically capable of imparting a reddish-brown color to a haze layer when viewed in backward scatter. NO_2 would increase the degree of coloration in such a situation. Specific circumstances of brown layers must be examined on a case-by-case basis.

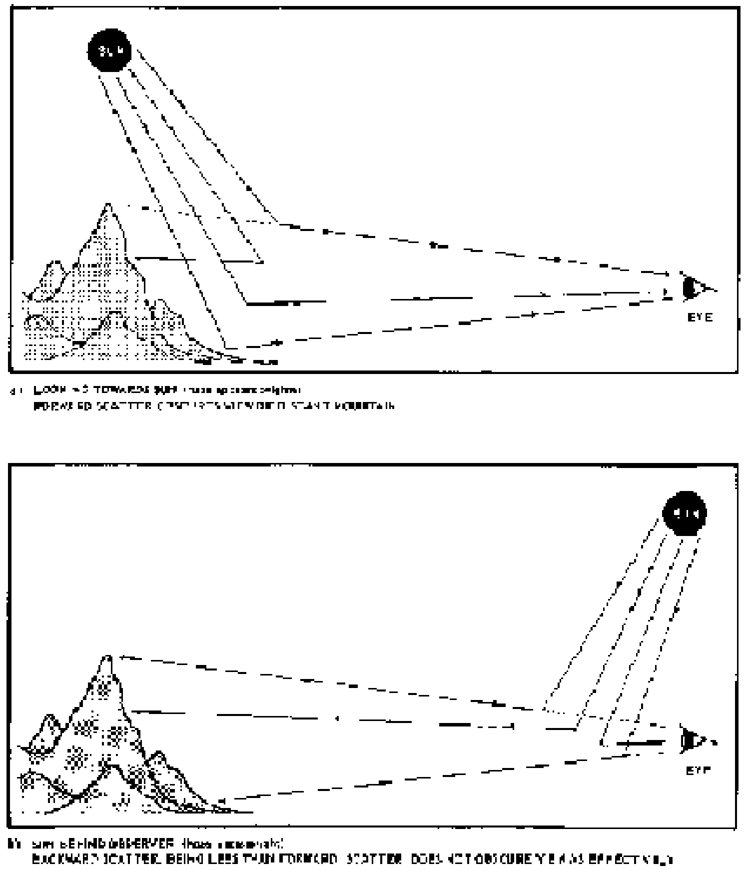

Figure 2-24. Effect of sun angle on visibility.

2.5.3 Plume Blight

The description of discolored layers in the previous section applies to plume blight. The significant factors affecting plume visibility are listed in Table 2-2 and Figure 2-25. The plume will have a brightness and color that is different from its background, and this difference can be approximated by simplifications to the radiative transfer operation for optically "thin" plumes; that is, plumes that transmit a large fraction of incident light (Latimer et al., 1978, Williams et al., 1979).

The plume air light is a strong function of scattering sun angle. A plume viewed in forward scatter will appear bright against the sky or background targets. The same plume can appear dark against the sky and bright against dark targets at scattering angles greater than 30^o. Detailed calculation for models requires particle concentration and size information for the plume and similar information or extinction measurements for the surrounding atmosphere. Increases in extinction resulting from plume absorption, from soot or NO_2, for example, will make the plume darker at all sun angles.

Because the line of demarcation between the plume and sky is "fuzzy," it has been argued (Latimer et al., 1978) that the threshold contrast for perception may be greater than that for dark targets with sharp boundaries (about 2 percent). Contrast enhancement* by the eye-brain system may, however, compensate for lost sharpness.

Additional experimental data are needed to define the threshold of perceptibility for plumes and haze layers.

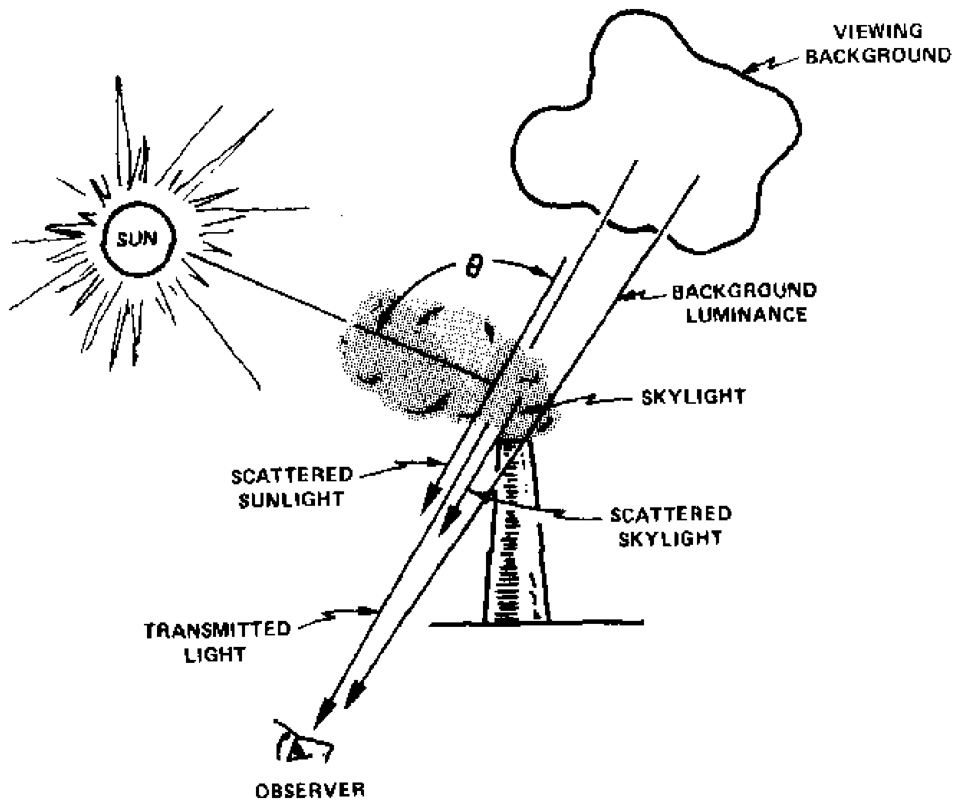

Figure 2-25. Appearance of a plume (Charlson et al., 1978).

Plume/source related factors	Environmental Factors
Particle size distribution	Sun position
Particle mass concentration	Time of day
Particle mass distribution (non-uniform mass distribution)	Day of year
Plume diameter	Longitude
Stack height	Latitude
Stack exit velocity	Cloud cover (sky color)
Particle density	Other light sources
Water vapor content	Ambient temperature
Particle complex index of refraction (plume color)	Relative humidity
NO_2 concentration in the plume	Wind velocity
	Wind direction
Observer related factors	Wind turbulence
Observer position	Terrain
Observer sensitivity	Background

Table 2-2. Factors affecting plume appearance (Charlson et al., 1978).

REFERENCES FOR CHAPTER 2

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PROTECTING VISIBILITY

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CHAPTER 3

3 METHODS FOR MEASURING ATMOSPHERIC VISIBILITY IMPAIRMENT

Measurements of visibility-related parameters in class I areas will be an important component of programs for making progress toward the national goal. Specifically, monitoring is necessary for:

1. Establishing a base line range of visibilities for a given area to be used in evaluating potential impacts of proposed sources;

2. Determining the extent to which man-made air pollution and natural sources cause or contribute to visibility impairment;

3. Identifying specific sources of air pollution that cause or contribute to visibility impairment; and

4. Monitoring the effectiveness of visibility protection programs over time.

Meeting these objectives will require measurement of optical parameters, pollutant levels, meteorological variables, and scenic characteristics. This chapter discusses the applicability of various visibility monitoring approaches and outlines current efforts to establish class I area visibility monitoring networks.

3.1 VISIBILITY-RELATED PARAMETERS

Because visibility involves human perception of the environment, no instrument truly measures visibility (Malm, 1979a). Thus it is essential to select appropriate measurable parameters, which can be related to both air quality of the environment and human visual perception. Important optical indices of visibility discussed in Chapter 2 include visual range, apparent contrast, extinction coefficient, and the variation of these parameters with wavelength (color) .The major categories of impairment (Chapter 1) to be dealt with include plume blight, general haze, and elevated layers of discoloration.

The most important indices for visibility measurements are apparent contrast and atmospheric extinction coefficient. In practice, the scattering component of the extinction coefficient, b_{scat}, is usually reported. Preliminary measurements in non-urban areas suggest that the scattering coefficient is 90 percent of the extinction coefficient (Charlson, 1979). Extinction coefficient is directly related to the visual air quality and represents the optical characteristics of the pollutants along an optical path that contribute to visibility impairment. The extinction coefficient, plus the optical effects of the target and illumination, determines the apparent contrast (visibility) of a target (such as plume or mountain) against a background (sky or other surroundings). Thus, extinction coefficient is the optical parameter related to air quality, and contrast is the optical parameter that describes visibility. Both extinction coefficient and apparent contrast are measurable at several wavelengths.

Contrast and light scattering measurements are directly applicable to visibility impairment caused by general haze. Plume blight and layers of discoloration might be assessed by employing contrast measurements and aircraft mounted extinction measurements. Direct observation of these kinds of impairment may, however, be the most practical approach for recording such conditions.

Measurement of aerosol parameters is a useful adjunct to optical measurements. Fine-particle concentrations, detailed size distributions, and chemical composition can be used to calculate extinction coefficient. More importantly, such data, when coupled with meteorological information, permit assessment of the contribution of anthropogenic and natural sources to visibility impairment.

3.2 MEASUREMENT METHODS

Regardless of the specific monitoring application, there are four components useful in characterizing visibility impairment and providing information that may link visual effects to their sources: human observations and measurements of optical, meteorological and pollutant parameters.

3.2.1 Human Observations

Since visibility is an interpretation of what is perceived by the human eye, it is essential that any monitoring effort have some relation to human observations. Human eye observation is the sole source of long-term visibility (visual range) data. Unfortunately, human eye observations depend not only on illumination, target characteristics, and air quality, but also include the effects of varying visual perception and subjective judgment. Nevertheless, with the development of observer-based visibility indices (Craik, 1979) and an adequate training program, human observations can provide useful information about visibility and can complement instrumental measurements.

The Federal Land Managers of parks and wilderness areas represent an important resource for human observation of visibility in class I areas. Although the traditional observation for visibility has been "visual range," i.e., the farthest point that can be seen, the U.S. Forest Service has incorporated more elaborate visual judgments into their Landscape Management System (USFS, 1973). The visual elements of a vista are described in terms of "form, line, color, and texture. " These elements represent subjective descriptions of contrast, the basic optical parameter. Meaningful judgments made by a trained observer about the contrast and coloration of a vista and about the presence of plume blight can be invaluable in assessing visibility impairment.

3.2.2. Optical Measurements

In order to quantify scenic contrast as perceived by the eye, optical measurements must be made. The visual air quality along the optical path must also be measured in order to determine the effect of atmospheric contaminants on the perceived scene.

A number of optical devices are available or under development that measure some property of visibility. The most obvious optical device is the standard photographic camera. Visibility monitoring should always include photography in some form, at least for documentation of existing good visibility conditions or impairment problems. The two general film formats are: negatives (from which prints may easily be made) and reversal film ("slides"). Both slides and negatives produce about equal color rendition. Prints made from negatives, however, are subject to quality control uncertainty during the additional laboratory printing process and are one more generation removed from the original image. Slides are more cumbersome to use but normally are more economical and more visually accurate than prints.

The chief use of photographs or slides is in preserving a scene in a form similar to the view as originally perceived. A secondary use is photogrammetry, the measurement of the density of color of individual sections of the picture to determine quantitative contrast values of different elements of the scene. The accuracy of this process, however, is sensitive to variations in film density and exposure and requires a densitometer closely matched to the response curve of the particular film being used.

Photometers measure light intensity and range in complexity from the photographer's light meter to a television camera. The principle of operation for each instrument is the same and is somewhat analogous to the human eye. The heart of a photometer is the photodetector, which converts brightness into representative electric signals. By the use of combinations of lenses and filters, different optical properties, such as color, may be determined.

Photometers designed specifically to measure properties of atmospheric visibility over an optical path to a target are *telephotometers*, so named because they resolve visual detail at a distance. Telephotometersprovide an output proportional to the absolute brightness of a target within the optical field of view. The human sensation of seeing, is however, produced not by absolute brightness levels of light, but by *contrast* in brightness or color between two objects. Therefore, the most practical application of a telephotometer is as a contrast measuring device-comparing the brightness of color of an object to a background. The visibility of a target can be quantified in terms of its contrast at a given distance from the observer and is dependent upon the inherent contrast of the target, uniformity of the atmosphere along the sight path, angle of observation, and illumination of the sight path. A disadvantage of using telephotometers is that it is difficult to separate the different effects from each other. This disadvantage is important if the goal is to isolate the contribution of anthropogenic air quality on visibility.

A transmissometer may be used to measure the optical characteristics over a given path. This instrument is comparable to an application of a telephotometer in which a known light source becomes the target. Transmission instruments measure the amount of light transmitted from a specified source to a receiver, allowing the direct calculation of the average extinction coefficient of the air along the instrument path. The light lost along the path is either scattered out of the path or absorbed by gas molecules and aerosol in the path. The path for transmission instruments is long compared to the small volume measured by scattering instruments and short compared with the 20 to 100 km paths used by telephotometers.

Transmissometers use artificial light sources; either the receiver or reflectors must be placed at one end of a base line and the transmitter at the other end. This fixed base line does not allow flexibility to measure visibility-related variables in different directions. When transmissometers are used in very clean atmospheres, such as class I areas in the Southwest, their critical sensitivity to atmospheric turbulence can introduce error. Additionally, these instruments are usually limited to a single wavelength and not very portable.

Scattering instruments are used to measure a basic optical property of the air sample: the volume scattering function. The measurement is independent of target properties, natural illumination of the atmosphere, and distance between the observer and the target. Scattering instruments include integrating nephelometers, back-scatter meters, forward-scatter meters, and polar nephelometers.

Integrating nephelometers perform a point measurement of the light scattered over a range of angles and permit determination of the scattering component of extinction, $b_{scat.}$ Since the contribution of air itself to b_{scat} is known, the b_{scat} measurement permits determination of light scattering by particles. In clean areas where light scattering dominates extinction, b_{scat} approximates the extinction coefficient, b_{ext}. Because b_{scat} is measured at a point, it can be directly related to simultaneous point measurements of aerosol properties. The air sampled by the integrating nephelometer is enclosed and illuminated indirectly by an artificial light source, allowing automated continuous day and night operation. Enclosed instruments also allow control of ambient air conditions; such control permits study of the influence of relative humidity. Nephelometers have been used in a variety of applications, including to a limited extent, applications in class I areas (Charlson et al., 1978). Models differing in wavelength response and sensitivity are available. Since nephelometers involve point measurements, care must be taken to minimize the influence from local sources, such as automobiles or cigarette smoke. Unless nephelometers are physically moved through a plume, inhomogeneous impairment, such as plume blight, cannot be detected. Nephelometers cannot be used to measure absorption and cannot detect discoloration caused by NO2.

3.2.3. Meteorological Variables

Meteorological conditions largely determine the extent and speed with which pollutants disperse, and thus have a major effect on visibility. Four specific meteorological parameters that strongly influence visibility include: wind speed and direction, mixing height, and relative humidity. Solar illumination and cloud cover affect atmospheric stability and are also important. Instrumentation for meteorology is standardized and will not be discussed here

3.2.4. Pollutant Measurements

A number of methods and instruments can be used to measure the size distribution, mass concentration or number concentration of the airborne particles that usually dominate the scattering of light. Nitrogen dioxide gas can also be measured. The Mie theory of light scattering allows measurement of the aerosol size distribution to be used to compute the scattering of light. These relationships allow a calculation of contrast, visual range and color change, but not as precisely as by more direct measurements. The most important advantage of measuring aerosol mass, size, and chemical properties is that when combined with meteorological data, such measurements aid in the identification of natural and anthropogenic aerosol sources in order to determine which are most important in affecting visibility.

The most useful particle monitoring instruments for visibility studies include those that permit analysis of chemical composition and particle size. Although multistage cascade impactors can be useful for detailed studies, samplers that permit separation of optically important fine (<2 *.5.um)* and coarse particles (>2 *.5.um)* are acceptable. These latter samplers, which are termed dichotomous samplers, have several arrangements for size separation, including direct and "virtual" impaction. (Stevens et al, 1978).

3.3 COMPARISONS AND RECOMMENDATIONS

Each of the visibility-related methods described above has inherent strengths and weaknesses, which limit its optimal application and utility. The characteristics and applicability of important methods are compared in Table 3-1. No single instrument or approach can provide sufficient information for meeting class I area visibility monitoring objectives. A significant limitation for most of the methods is securing locations in class I areas that are reasonably accessible and can accommodate instrument power requirements.

Recently, EPA sponsored a workshop on visibility monitoring to discuss alternate monitoring methods and make recommendations for further work (Malm, 1978). A number of technical experts and managers from industry, Federal and State agencies, and contractors participated in these discussions. As interim guidance for developing visibility monitoring programs in class I areas, this report adopts the recommendations of the workshop participants. Specifically:

1. Base line monitoring should be conducted for at least I year, preferably a meteorologically typical year;

2. Visibility measurements should include:

   a. Color photographs or slides and human observations of selected vistas,

   b. Multiwavelength telephotometer measurements of sky and target contrast of the selected vistas,

   c. Integrating nephelometer measurements of aerosol scattering;

3. Evaluation of source-receptor relationship requires:

a. A two-stage size-segregating particulate sampler compatible with gravimetric and chemical analyses techniques,

b. Sensors of wind speed and direction, representative of meteorological transport,

c. Relative humidity sensor,

d. An NO2 detector, if necessary.

TABLE 3-1. VISIBILITY MONITORING METHODS*

Method	Parameters Measured	Advantages	Limitations	Preferred Use
Human observer	Perceived visual quality Atmospheric Color Plume blight Visual range	Flexibility, judgment; large existing data base (airport visual range).	Labor intensive; variability in observer perception; suitable targets for visual range not generally available.	Complement to instrumental observations; areas with frequent plume blight, discoloration; visual ranges available target distances.
Integrating nephelometer	Scattering Coefficient (b_{scat}) at site	Continuous readings; unaffected by clouds, night; b_{scat} directly relatable to fine aerosol concentration at a point; semi-portable; used in a number of previous studies; sensitive models available; automated.	Point measurement, requires assumption of homogeneous distribution of particles; neglects extinction from absorption, coarse particles > 3 to 10 um; must consider humidity effects at high RH.	Areas experiencing periodic well mixed general haze; medium to short viewing distances; small absorption coefficient (babs); relating to point composition measurements.
Multiwavelength telephotometer	Sky and/or target radiance, contrast at various wavelengths	Measurement over long view path (up to 100 km) with suitable illumination and target, contrast transmittance, total extinction, and chromaticity over sight path can be determined; includes scattering and absorption from all sources; can detect plume blight; automated.	Sensitive to illumination conditions: useful only in daylight; relationship to extinction, aerosol relationship possible only under cloudless skys; requires large, uniform targets.	Areas experiencing mixed or inhomogeneous haze, significant fugitive dust; medium to long viewing distances (¼ of visual range); areas with frequent discoloration; horizontal sight path.
Transmissometer	Long path extinction coefficient (b_{ext})	Measurement over medium view path (10-25 km); measures total extinction, scattering and absorption; unaffected by clouds, night.	Calibration problems; single wavelength; equivalent to point measurement in areas with long view paths (50-100 km); limited applications to date still under development.	Areas experiencing periodic mixed general haze, medium to short viewing distance areas with significant absorption (babs).

TABLE 3-1. VISIBILITY MONITORING METHODS[a] (continued)

Photography	Visual quality Blume blight Color Contrast (limited)	Related to perception of visual quality; documentation of vista conditions.	Sensitive to lighting conditions; degradation in storage; contrast measurement from film subject to significant errors.	Complement to human observation, instrumental methods; areas with frequent plume blight, discoloration.
Particle samplers	Particles	Permit evaluation of causes of impairment.	Not always relatable to visual air quality; point measurement.	Complement to visibility measurements.
Hi Vol	TSP	Large data base, amenable to chemical analysis; coarse particle analysis.	Does not separate sizes; sampling artifacts for nitrate, sulfate; not automated.	Not useful for visibility sites.
Cascade impactor	Size segregated particles (> 2 stages)	Detailed chemical, size evaluation.	Particle bounce, wall losses; labor intensive.	Detailed studies of scattering by particles < 2 um.
Dichotomous and fine particle samplers (several fundamentally different types)	Fine particles (< 2.5 um) coarse particles (2.5 to 15 um) inhalable particles (0 to 15 um)	Size cut enhances resolution, optically important aerosol analysis, low artifact potential, particle bounce; amenable to automated compositional analysis; automated versions available; large networks under development.	Some large-particle penetration; 24 hour or longer sample required in clean areas for mass measurement; automated version relatively untested in remote locations.	Complement to visibility measurement, source assessment for general haze, ground level plumes.

[a](Charlson et al., 1978; Malm, 1978b, 1978c; Tombach, 1978).

Comprehensive monitoring of this kind will not be needed in all class I areas. Over the next several years, visibility monitoring in various regions of the country may indicate a smaller set of measurements, which can be used for most monitoring goals. In the interim, in programs with limited resources, the limitations and strengths outlined in Table 3-1 should be considered when choosing monitoring sites and methods. EPA is preparing detailed guidance on visibility monitoring.

3.4 VISIBILITY MONITORING PROGRAMS

The only substantial visibility monitoring program to date has been the National Weather Service hourly visual range observations. These observations have proven useful in identifying trends at particular locations but more accurate optical measurements and additional air quality parameters will be necessary for visibility modeling and source identification. Various optical qualities of the atmosphere have been studied in a number of short-term programs, generally with the use of turbidity and/or nephelometer measurements.

One of the first major instrumental monitoring programs designed to study visibility, air quality, and meteorological variables near class I areas was the Cedar Mountain, Utah visibility program which was begun in 1976 by NOAA and EPA (Allee, 1978). The site is north of several major class I areas in southeast Utah. Many measurements were taken with different instruments and much of the data is still being analyzed. The general conclusion thus far is that northerly air masses bring in substantially cleaner air than from other directions, causing base line visibility to vary dramatically. In addition, some information about the limitation of visibility monitors and spatial homogeneity of the surrounding atmosphere has been gathered.

The Cedar Mountain Study has been incorporated into EPA 's project VIEW (Visibility Investigative Experiment in the West), which is now is operation in the Southwest with 14 additional monitoring sites (Figure 3-1). The VIEW program is a prototype visibility-monitoring network that may be suitable for monitoring visibility in and near class I areas in the Southwest. At each site, a telephotometer records apparent contrast of different targets in different directions (denoted by the arrows at each location on the map in Figure 3.1). Where practical, sites are outfitted with additional visibility-related devices, such as nephelometers, particle samplers, photographic cameras, and meteorological instruments. Most of the sites are operated by personnel of the National Park Service, who also record visual observations.

Data from the VIEW network are currently being processed. Preliminary results appear similar to those reported at Cedar Mountain. The most obvious result so far is the strong correlation between observed visibility and air mass movement. Figure 3-2 is a sample plot of target contrast at Canyonlands National Park for September, 1978. Passages of weather systems from the Pacific Northwest, which generally bring in cleaner air, correlate closely with better visibility, measured as increasing target contrast. Further analysis of pollutant composition is needed to identify the causes of reduced visibility.

Visibility monitoring is also planned by the Electric Power Research Institute, the National Park Service, the Tennessee Valley Authority, and other groups. Most of these projects are now in the planning or initiation stage.

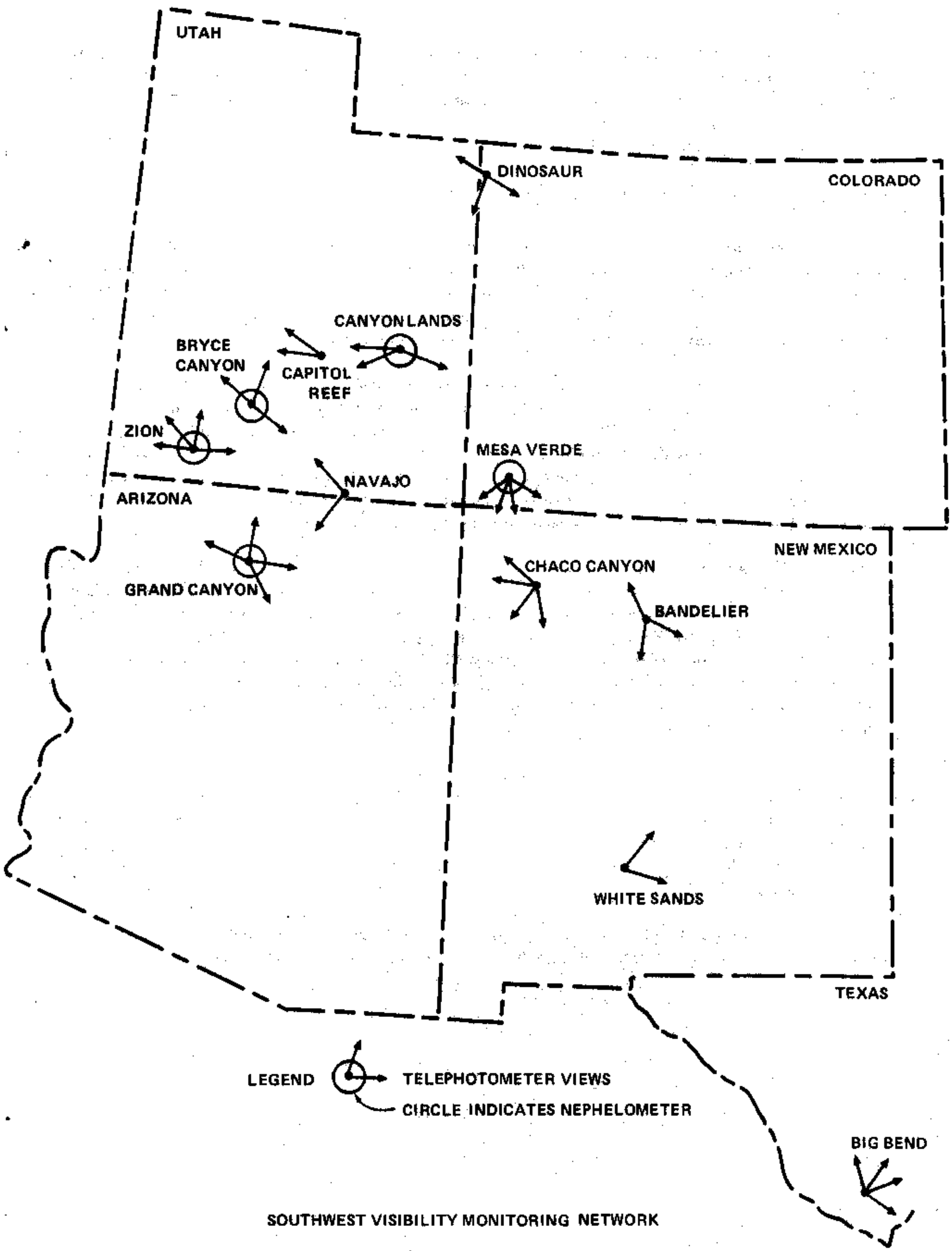

Figure 3-1. Project VIEW—EPA/NPS Southwest visibility monitoring network.

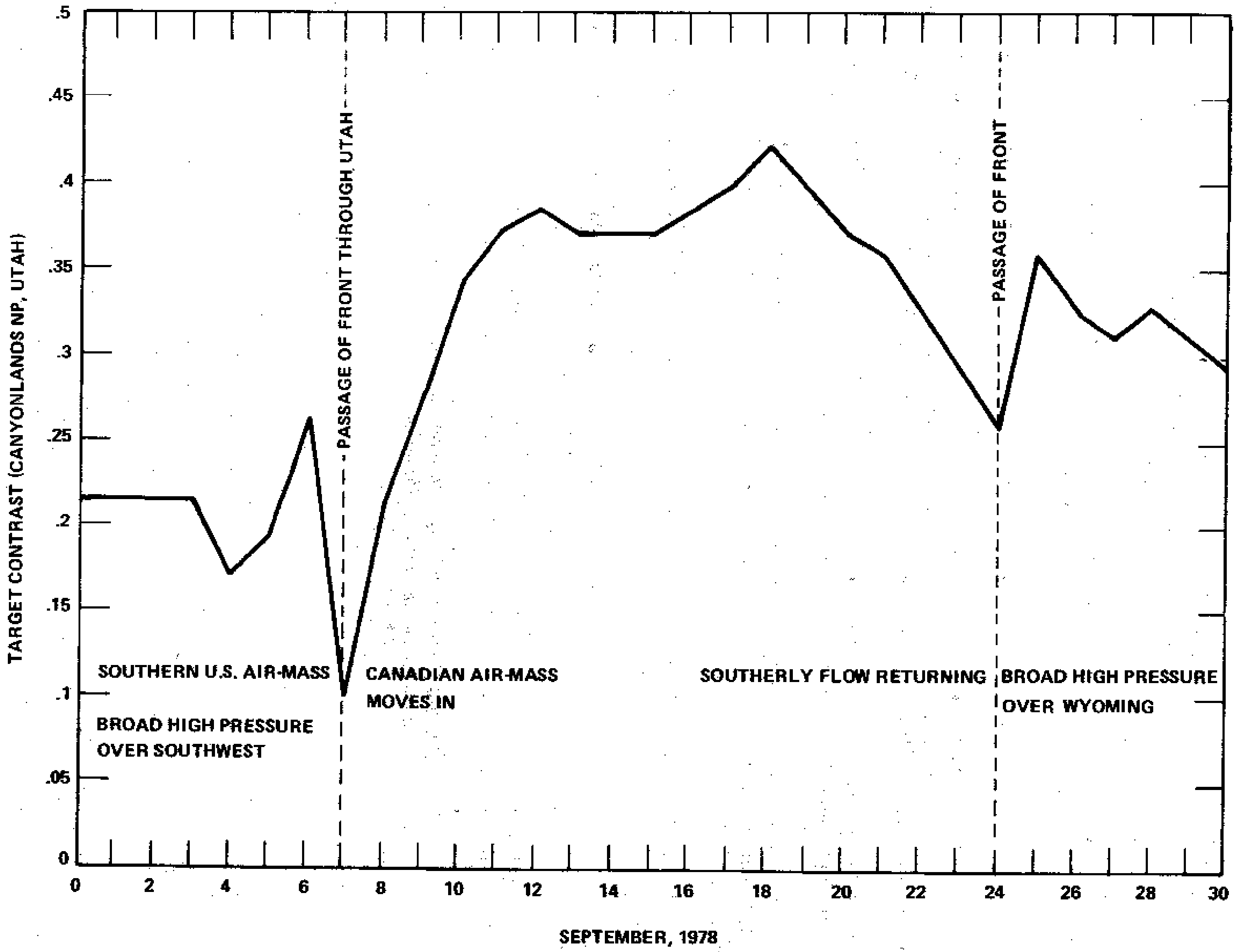

Figure 3-2. Target contrast at Canyonlands National Park, Utah, for September, 1978 (Malm, 1979b).

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CHAPTER 4

4 EMPIRICAL METHODS FOR ASSESSING POLLUTION DERIVED IMPAIRMENT

4.1 INTRODUCTION

Relating visibility impairment to emission sources is a central problem for developing visibility protection programs. Before discussing various approaches, it is worthwhile to summarize some important generalities regarding the current understanding of the relationship between anthropogenic air pollution and visibility impairment (Husar, et al., 1979):

1. The size distribution of atmospheric aerosol mass is generally bimodal. The distribution of fine particle or accumulation mode particles can vary, but most mass is concentrated in the 0.1 to 1 μm range.

2. Light scattering and particle related light absorption are usually dominated by fine mode aerosols.

3. The degree of haze is, thus, directly proportional to the aerosol mass (or volume) concentration in the fine particle mode. The identification and quantification of sources of haze in most areas reduced to the identification of the sources of fine particle mass.

4. Fine particle chemical composition can be used as a powerful tool for the identification of the source of the haze.

5. In some instances, particularly in combustion source plumes, atmospheric brown coloration may be caused by NO_2 absorption.

6. The relative humidity of ambient air influences the source/impairment relationship, and empirical humidity correction schemes have been developed.

7. Much of the fine particle mass is of secondary origin; fine particles are formed in the atmosphere from their precursor gases, sulfur dioxide, nitrogen oxides, and organics, and hence, their emission rate cannot be measured at the source. Furthermore, the gas-to-particle conversion process depends on factors such as solar radiation, the presence of other pollutants, and humidity. Thus, the amount of secondary material formed from a given emission rate of precursor gas is not constant but depends on the environment.

8. The residence time of fine particles in the atmosphere is estimated to be on the order of a week, and the transport distance can exceed 500 km. Within that distance, the contributions of many sources can be superimposed.

9. The long-range transport of the fine particle-precursor chemical complex results in the superposition and chemical interaction of different types of sources (e.g., power

plant and urban plumes). Many of these interactions currently cannot be predicted; hence, the quantitative evaluation of a source-receptor relationship requires collection and analysis of pollutant and visibility data. Properly calibrated theoretical models are necessary to predict the impact of controls on existing sources or the impact of new sources in a new physico-chemical environment.

10. Assessment of the nature of visibility impairment requires the monitoring of the pertinent aerosol parameters (e.g., size distribution, fine particle mass, chemical composition, optical parameters, (e.g., contrast, extinction coefficient)) and meteorological variables.

When a visible plume causes visibility impairment, the source can be identified by direct observation. Direct observation is an elementary example of an *empirical* approach to assessing the causes of impairment. Empirical approaches involve the collection and analysis of real-world data, ranging in complexity from simple observation to sophisticated aircraft sampling and satellite imagery. Identification and resolution of the sources of general haze or layers of discoloration is considerably more difficult than the case of a visible plume. Because of the complexity of the haze/source relationship, a number of markedly different approaches are currently being pursued.

In this chapter, applications of several empirical approaches to identifying sources and assessing their impacts are discussed. The first three approaches, which are receptor-oriented, utilize existing information on haze at various receptor sites in conjunction with other relevant data as clues for the probable origin of the haze. The relevant data include the haze chemical composition (Section 4.2), historical trends of emissions and haziness (4.3) or the direction from which the haze is coming (4.4). In the other methods discussed, the source is the starting point, and the pollutant transmission processes through the atmosphere to the impact at a receptor are examined. This can be done through field observations (4.5), and “diagnostic” modeling, i.e. simultaneous use of source data, ambient concentration data, and a model to decipher what is happening in between (4.6). Theoretical predictive modeling approaches are discussed in Chapter 5. Several of these methods can only provide circumstantial evidence for the source-receptor-effect relationships. Other approaches may provide direct evidence but impose heavy demands on environmental data that are currently sparse or non-existent. Hence, it is evident that assessing the impact of manmade pollution on visibility in various class I areas will require prudent use of all these available source resolution techniques, as well as new ones as they are developed.

4.2 CHEMICAL COMPOSITION OF LIGHT SCATTERING AEROSOLS

The knowledge of the chemical composition of light scattering aerosols is essential to understanding the cause of visibility impairment. The chemical composition of the aerosol can affect its optical properties (Barone, et al., 1978); more importantly, the chemical composition serves as a tracer of the probable origin of the light scattering aerosol. In fact, for atmospheric haze in general, the chemical composition is the most important available clue regarding its probable origin.

4.2.1 CHEMICAL-MASS BALANCE METHOD

The method by which the ambient aerosol chemical composition is sued as a tracer for origin of the aerosol was formulated and described by Friedlander (1973). Characteristic tracer elements such as vanadium (which comes primarily from fuel oil) and lead (emitted by the automobile) can be used as indicators of how much these sources contribute to the ambient aerosol. Application of this approach in various regions has indicated that the relative amounts of fine particle constituents vary in different regions.

The first comprehensive study of the size-chemical composition of a haze aerosol was conducted in the Los Angeles air basin as part of project ACHEX (Hidy et al., 1975). In their study of the nature and origins of visibility-reducing aerosols in Los Angeles, White and Roberts (1977) constructed a chemical mass balance for the measured aerosol at seven locations in the basin (Figure 4-1). The key contributing species to the total aerosol mass concentration were nitrates, sulfates, organics, and other unidentified substances. Based on a statistical analysis of light scattering (b_{scat}) and chemical composition data, the authors concluded that sulfates are the most efficient scatterers among the measured chemical species.

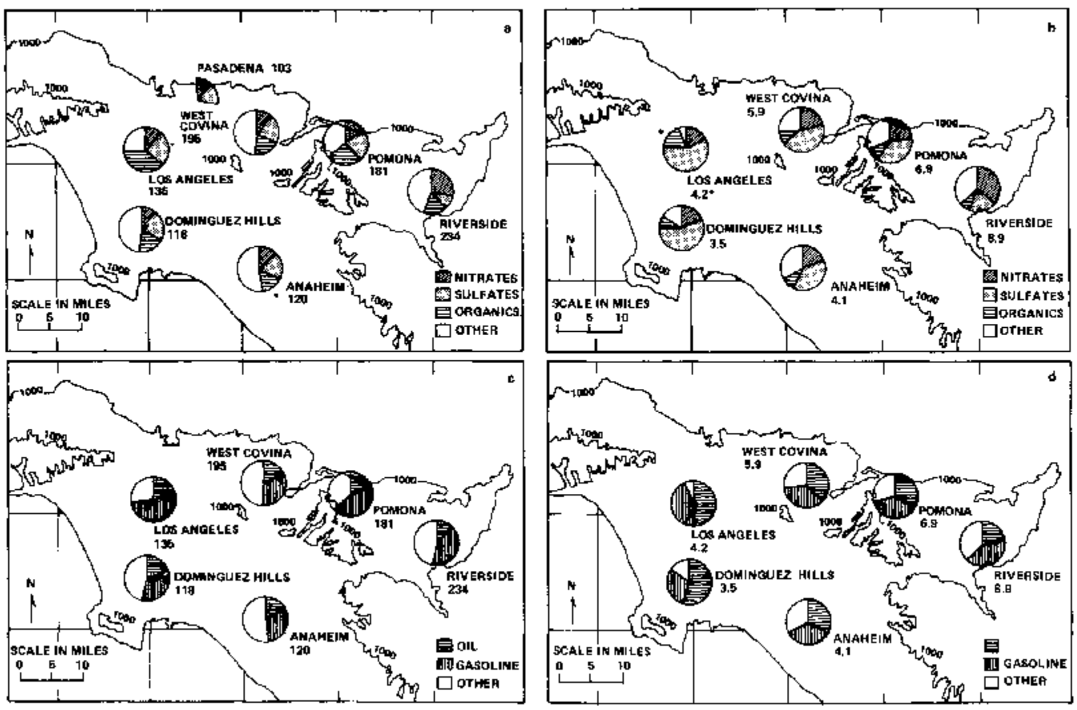

Figure 4-1. Geographical distribution of (a) particulate mass concentration and (b) light scattering coefficient in the Los Angeles basin. The pie diagrams show the relative contributions of nitrates, sulfates, organics, and other compounds. Sulfates evidently contribute only about 25 percent of the total mass but cause aobut half of the light scattering. The estimated contributions of source types (oil, gasoline, and other) to (c) mass concentrationo and (d) light scattering coefficient are also shown (White and Roberts, 1977).

The chemical mass balance approach is enhanced by use of size segregating particle samplers, which distinguish between fine (< 2.5 μm) and coarse (> 2.5 μm) mode particles. The composition of fine particles is important because this fraction contains the most efficient light-scattering aerosols by mass. The results for several locations are summarized in Figures 4-2 through 4-5. Urban data are presented to show the spectrum of applications and because urban sources can impact upon nearby class I areas. These and other data indicate that sulfur compounds constitute the most significant chemical component of fine particulate mass over the Eastern United States, including class I areas like the Smoky Mountains (Figure 4-3). As noted above, sulfates are also significant in Los Angeles. Pacific Northwest data (Figures 4-4, 4-5) suggest that various forms of vegetative burning (forest and field burning, space heating) are important sources of light scattering aerosols. In the Portland Aerosol Characterization Study (PACS), (Cooper and Watson, 1979) the chemical balance for organics was supplemented by use of carbon isotope analysis (Cooper et al., 1979). Because the distribution of the forms of carbon (C14, C12) varies for fossil fuels and modern vegetation, the origin of organic aerosols can be better specified. IN the Willamette Valley, Oregon study, a preliminary association between field burning and the presence of potassium in fine particles was used to “finger print” vegetative burning (Lyons et al., 1979).

Much of the current concern for visibility pertains to the origin of the haze in pristine areas of the Western and Southwestern U.S. where many of the class I areas are located. Reporting the results of the EPA VISTTA Program*, Macias et al. (1979) presented size-chemical composition data for size segregated aerosol collected in the Four Corners area of the Southwest during aircraft flights (Figure 4-61, b). The size distribution followed the typical bimodal p pattern (Figure 2-17). As anticipated, the coarse particle fraction could be accounted for by the crustal element contributions. In the fine particle mass balance, about 40 percent of the 5.3 $\mu g/m^3$ consisted of sulfate, another 10 percent of trace constituents, and 22 percent of other species such as ammonium and metal oxides. The have also reported a 29 percent contribution of silicon dioxide to the fine particle mass. This contribution is unusual because the crustal elements normally accompanying silicon were not present in the fine particle samples. Macias et al. argued, therefore, that the fine particle silicon may possibly be due to direct emissions from high temperature sources. However, the possibility of contamination of the sample (Macias, 1979) and limited data from other Western monitoring (Winchester et al., 1979) preclude definitive conclusions on the significance and source of fine silicon. Preliminary results from ore recent VISTTA regional flights suggest similar levels of fine mass, sulfate and silicon but also provide carbon and nitrate data. Carbon contributed roughly 10 percent of fine mass and nitrate only 2 percent (Wilson, 1979).

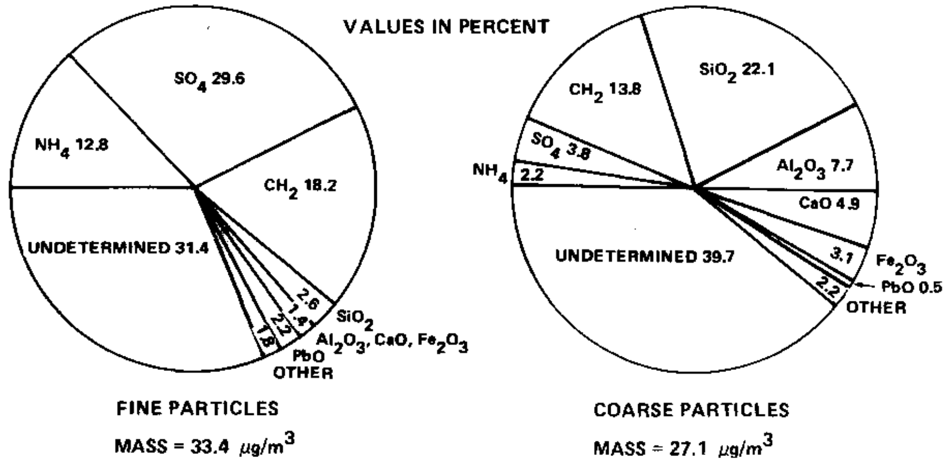

Figure 4-2. Chemical-mass balance for fine and coarse particles collected in Charleston, WV. The composition of the two modes is distinctly different. Ammonium sulfate accounts for about 40 percent of fine mass. A portion of the undetermined mass includes water associated with sulfates and other particles (Lewis and Macias, 1979).

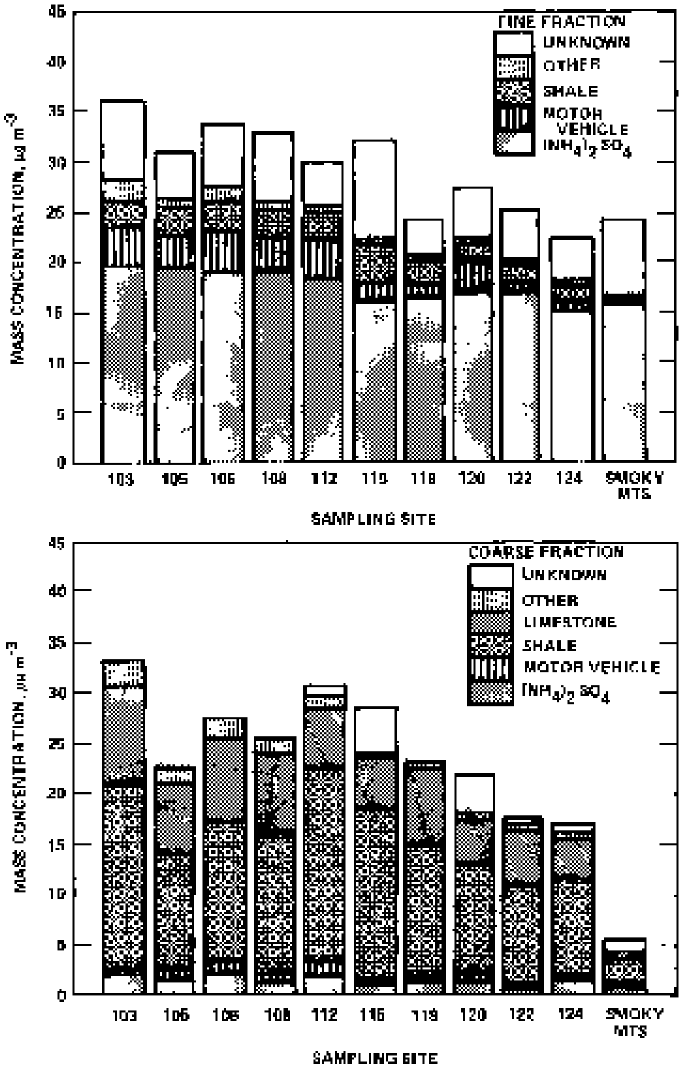

Figure 4-3. Source resolution of St. Louis aerosol compared with showrt term results from the Smoky Mountains in Tennessee. Rural sites near St. Louis (122, 124) and the Smoky Mountain site have similar sulfate levels, but significantly lower primary motor vehicle derived particles (<10 percent) than do urban sites in St. Louis. Significantly, about 60 percent of the fine mass in the Smokies is from sulfur oxide sources. The unknown fraction probably contains water, organics, and nitrates. Almost all of coarse particle mass at all sites is accounted for by dust from the earth's crust (Dzubay, 1979).

Macias et al. (1979) combined the results of the chemical elements balance with concomitant light scattering measurements to determine a visibility "budget" for the southwest aerosol. The measured scattering coefficient (b_{scat}) was within about 10 percent of that predicted from the size distribution. Visual range calculated from bscat (160 km or 96 miles) was consistent with observations and within the range of values typically reported for the Southwest. The estimated contribution of the aerosol components to light scattering (extinction) is shown in Table 4-1. On this typically clean day, Rayleigh (air) scattering contributes a significant amount, with fine particles contributing about 52 percent of the total extinction. Sulfates account for half of the scattering caused by particles.

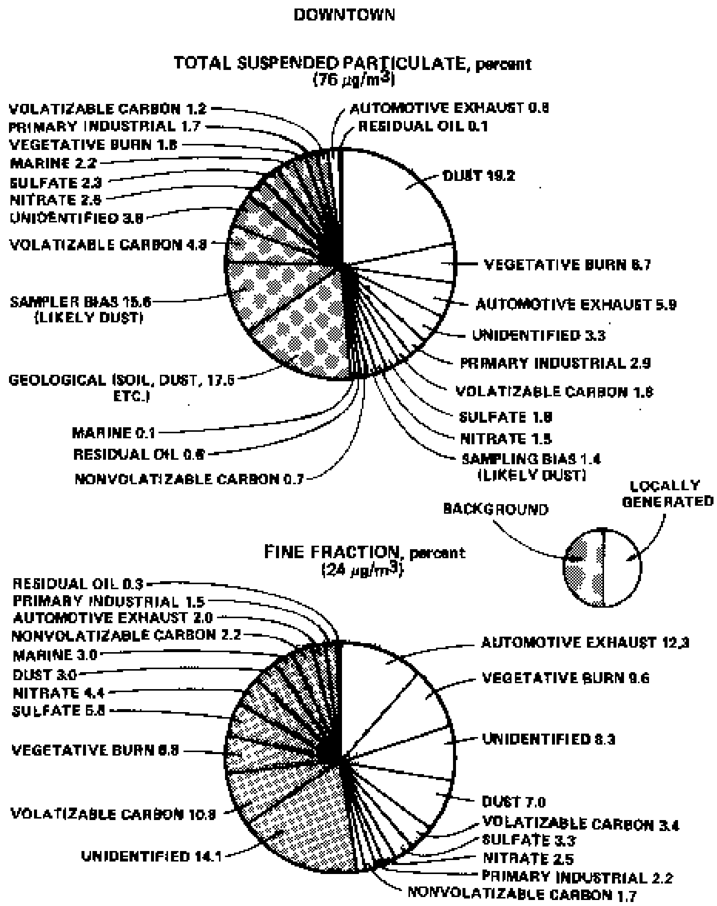

Figure 4-4. Source resolution of Portland, Oregon, aerosol indicates contributions of background air (shaded) and local sources. Carbonaceous (organics and elemental carbon) material from fireplaces and wood stoves, forest and field burning, automobiles, and other sources account for about 37 percent of the fine mass. Simultaneous light scattering measurements showed a 0.97 correlaton with fine particle mass (Cooper and Wilson, 1979).

In summary, the chemical composition of the light scattering aerosols provides a valuable, if not the most important, clue we currently have regarding their probable sources. Future applications of these techniques, combined with visibility measurements in class I areas, will add significantly to an understanding of the extent of manmade vs. natural visibility impairment. The approaches are, however, usually too coarse to provide resolution of specific source contributions or to enable prediction of the impact of control of single source emissions.

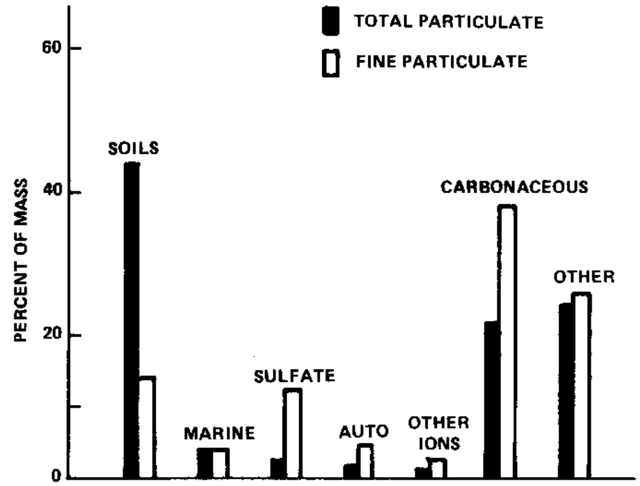

Figure 4-5. Relative Composition of Willamette Valley, Oregon, aerosol (June - Novemnber, 1978) from 11 rurual and urban sites. Carbonaceous material, partly from field and slash burning is the major fraction of fine particle mass. Burning impacts were dominant for ays on which burning occurred (Lyons et al., 1979).

4.2.2 Statistical Analysis of Visibility/Aerosol Relationships

As discussed above, detailed measurements of particle size distribution and chemical composition are useful in identifying the important components of urban and regional hazes. When large data sets are collected, statistical analysis can provide additional insights. The contribution o f certain components of total suspended particulate matter (TSP) to haze has been investigated through s statistical analyses relating routine Hi-Volume measurements to light-scattering (nephelometry data) or total extinction as determined from airport visual range data. This section describes these statistical studies and discusses conclusions and limitations.

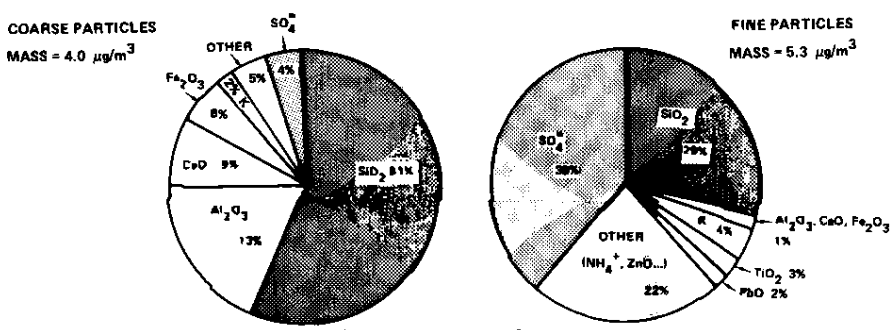

Figure 4-6a. Chemical-mass balance for fine and coarse particles collected during flights in the Four Corners region. The total aerosol mass was estimated from *in situ* size distribution measurements. In this data set SiO2 accounted for an estimated 29 percent of the fine particle mass (Macias et al., 1979). Preliminary results from more recent measurements suggest carbon contributes roughly 10 percent of fine mass and nitrates about 2 percent.

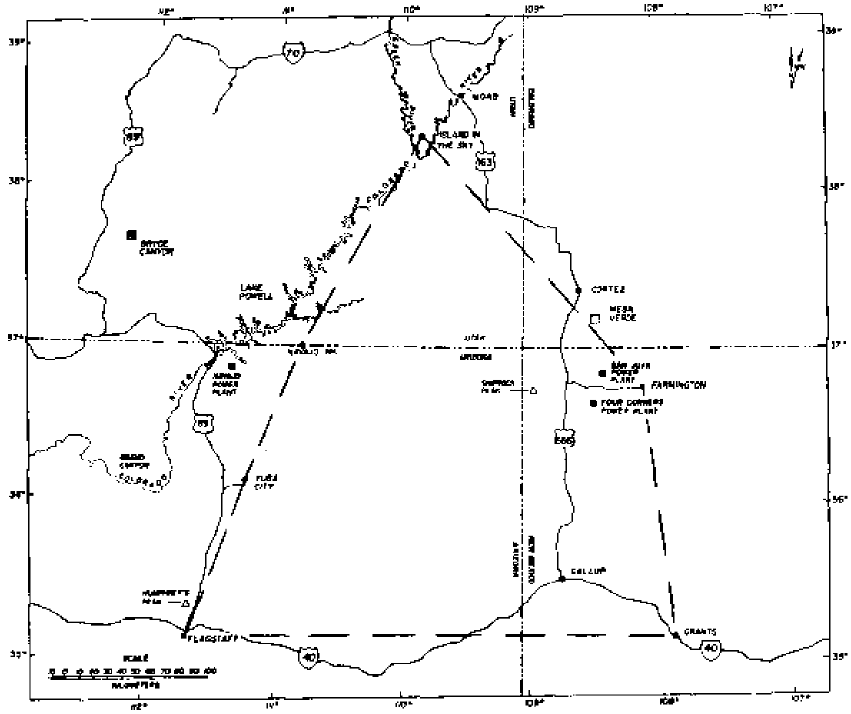

Figure 4-6b. Flight path of VISTTA regional flights on October 5 and 9, 1977. The entire flight path is about 1080 km (Macias et al., 1979).

Component	Particle Size (μm)	$b_{scat}(km^{-1})$	Contribution to Total b_{scat}	Contribution to Extra Extinction[c]
Air Molecules		0.011	44	
$(NH_4)_2SO_4$[a]	0.1 to 1.0	0.007	28	50
SiO_2[b]	0.1 to 1.0	0.004	16	29
Other compounds	0.1 to 1.0	0.002	8	14
Coarse Particles	1.0 to 20.0	0.001	4	7

Table 4-1. Light scattering budget for the Southwest Region, October 9, 1977 (Visual range approximately 160 km) (Macias et al., 1979). [a]Assumes all fine particle sulfate exists as ammonium sulfate. [b]Assumes that all fine particle silicon exists as SiO_2. [c]Extra Extinction is that fraction not including blue sky (Rayleigh) scattering. In this case, extra extinction is assumed to equal particle scattering (b_{scat}).

4.2.2.1 Multiple Regression Analysis—Several investigators have used multiple regression analysis to relate sulfates, nitrates, other particulate matter, and relative humidity to light-extinction, (Trijonis and Yuan, 1978a,b; Cass, 1976; Leaderer et al., 1979) or light–scattering (White and Roberts, 1977; Leaderer et al., 1978). The initial statistical analysis is often based on an equation such as the following:

$$B = b_o + \frac{b_1\,SULFATE + b_2\,NITRATE + b_3\,(TSP-SULFATE-NITRATE)}{(1-RH)^{\alpha}} \quad (4\text{-}1)$$

where B(km^{-1}) represents either the extinction coefficient (b_{ext}) (estimated from airport visibility data using the Koschmieder relationship) or light-scattering (b_{scat}) (based on nephelometry data); measured SULFATE ($\mu g/m^3$) and NITRATE ($\mu g/m^3$) levels are usually adjusted to account for associated ammonium; TSP-SULFATE-NITRATE ($\mu g/m^3$) represents the non-sulfate, non-nitrate fraction of TSP (including coarse and fine particles) and RH (no units) is relative humidity. The database usually consists of daily measurements for each parameter. Humidity is sometimes included in the regression equation as a separate linear term (RH) (Trijonis and Yuan, 1978a, b; Cass, 1976). The non-linear term $(1\text{-RH})^{\alpha}$ accounts for the increase in light scattering per unit mass observed for hygroscopic (water absorbing) aerosols like sulfates at higher humidities. Trijonis and Yuan (1978a, b) assumed an α of 1.0; Cass (1976) considered α of .67 to 1.0, while White and Roberts (1977) used other approaches to account for humidity. Multiple regression analysis selects the coefficients b_o through b_3 in the Equation 4-1 that produce the best straight line (linear) relationship between the "dependent" variable (B) and the "independent" variables (SULFATE, NITRATE, etc.).

Multivariate linear regression is an appropriate statistical tool for relating extinction to various aerosol components. Theoretically, extinction produced by various aerosols is additive, and the total extinction from a given aerosol component should be directly proportional to its mass concentration (assuming particle size is constant). Thus a *linear* relationship makes sense theoretically. Barone et al. (1978), however, report useful information from nonlinear regression approaches. *Multivariate* regression is designed to separate out the individual impact of each independent variable, accounting for the simultaneous effects of other independent variables. It is, therefore, preferable to analyses based on simple one-on-one relationships, because multivariate analyses have a better potential for avoiding some of the spurious relationships caused by intercorrelations among the independent variables.

4.2.2.2 Extinction Coefficients Per Unit Mass—Regression analysis is a purely statistical technique, and there is no guarantee that the observed relationships represent cause-and-effect. However, if, as in the above analysis, the regression is structured to reflect fundamental principles, the results may strongly suggest certain physical interpretations. In particular, the regression coefficients, $b_1/(1\text{-RH})^{\alpha}$ to $b_3/(1\text{-RH})^{\alpha}$ in Equation 4-1, are readily interpretable as extinction (or scattering) coefficients per unit mass for sulfates, nitrates, and other particles, respectively.

Table 4-2 lists extinction coefficients per unit mass for sulfates, nitrates, and the remainder of TSP obtained in various regression studies. There is general agreement that sulfates and, to a lesser extent, nitrates exhibit extinction coefficients per unit mass on the order of 0.004 to 0.011 [$km^{-1}/\mu g/m^3$], and that the extinction coefficient per unit mass for the remainder of TSP tends to be much lower. These results are quite consistent with Mie theory and experimentally derived fine-particle scattering efficiencies discussed in Section 2.4.3. Mie theory calculations indicate that fine particles like sulfates and nitrates should exhibit extinction coefficients per unit mass on the order of 0.003 to 0.009 [$km^{-1}/\mu g/m^3$], (Latimer et al., 1978; White and Roberts, 1977; Ursenbach et al., 1978). The remainder of TSP mass is usually dominated by the coarse particles (Diameter > 2.5 μm) (Bradway and Record, 1976; Whitby and Sverdrup, 1978). The coarse particle mode should exhibit an average extinction coefficient per unit mass on the order of 0.0002 to

0.0008 [$km^{-1}/\mu g/m^3$] (Latimer et al., 1978; White and Roberts, 1977; Ursenbach et al., 1978).

Location	Extinction coefficients per unit Aerosol mass (km^{-1})/μg/m3			Total correlation Coefficient(R) associated with the regression [a]
	Sulfates	Nitrates	Remainder of TSP	
Southwest (Trijonis and Yuan, 1978a)				
Phoenix: County Data	0.004	0.005	0.000	0.87
NASN Data	0.003	0.003	0.000	0.68
Salt Lake City	0.004	0.013	0.0004	0.72
	0.004[c]	0.010[c]	(0.0004[c])	0.81
Los Angeles (White and Roberts, 1977)	0.007	0.005	0.0015	0.60
Various Locations[b]	0.006[c]	0.004[c]	0.0020[c]	0.72
(Cass, 1976)				
Downtown Los Angeles	0.017	0.004[c]	0.0008	0.76
(Leaderer and Stolwijk, 1979)	0.009[c]	0.005[c]	0.0004[c]	0.76
Los Angeles Airport	0.016	0.003	0.0004	0.91
Northeast (Trijonis and Yuan, 1978b)				
Chicago	0.004	(NP[d])	(NP)	0.48
	0.003[c]	(NP[c])	(NP[c])	0.52
Newark	0.002	(NP)	0.0026	0.67
	0.006[c]	(0.000[c])	0.0014[c]	0.71
Cleveland	0.008	(NP)	(NP)	0.70
	0.007[c]	(NP[c])	(NP[c])	0.72
Lexington	0.006	(NP)	(0.0001)	0.68
	0.006[c]	(0.004[c])	0.0019[c]	0.72
Charlotte	0.011	(NP)	(0.0001)	0.67
	0.011[c]	(NP[c])	(0.0000)	0.73
Columbus	0.012	0.009	(0.0004)	0.81
	0.013[c]	0.006	(0.00019[c])	0.90
(Leaderer and Stolwijk, 1979)				
New York [b]	0.007	0.005	(NP)	0.88
New York	0.010	(0.006)	(0.0001)	0.76
New Haven	0.016	(NP)	(0.000)	0.90
St. Louis	0.008	(NP)	(NP)	0.83

Table 4-2. Extinction Coefficients per unit mass. ( ) Not significant at 95 percent confidence level. [a] Only those variables that are statistically significant at the 95 percent confidence level are included in determining the total correlation (R). Note that the square of the correlation coefficient represents the percent of variance

explained by the regression; thus, a correlation of 1.0 indicates a perfect statistical fit. [b] Based on light-scattering (nephelometry data) rather that total extinction (airport visibility data). [C] Based on nonlinear RH regression model, with insertion of average RH. [d] NP Not positive.

As shown in Figure 4-7, Latimer et al., (1978) found that the regression analysis by Trijonis and Yuan (1978a) for the Southwest also tends to be consistent with theoretical calculations in regard to the relative humidity dependence of light scattering by sulfates. The regression results obtained by Trijonis and Yuan (1978b) for three locations in the Northwest (Newark, Cleveland, and Lexington) are in equal agreement with the theoretical predictions in Figure 4-7. The empirical extinction coefficients at two other Northeast sites (Charlotte and Columbus) are, however, nearly twice the theoretical values, while the empirical extinction coefficient at another site (Chicago) is almost half the theoretical value.

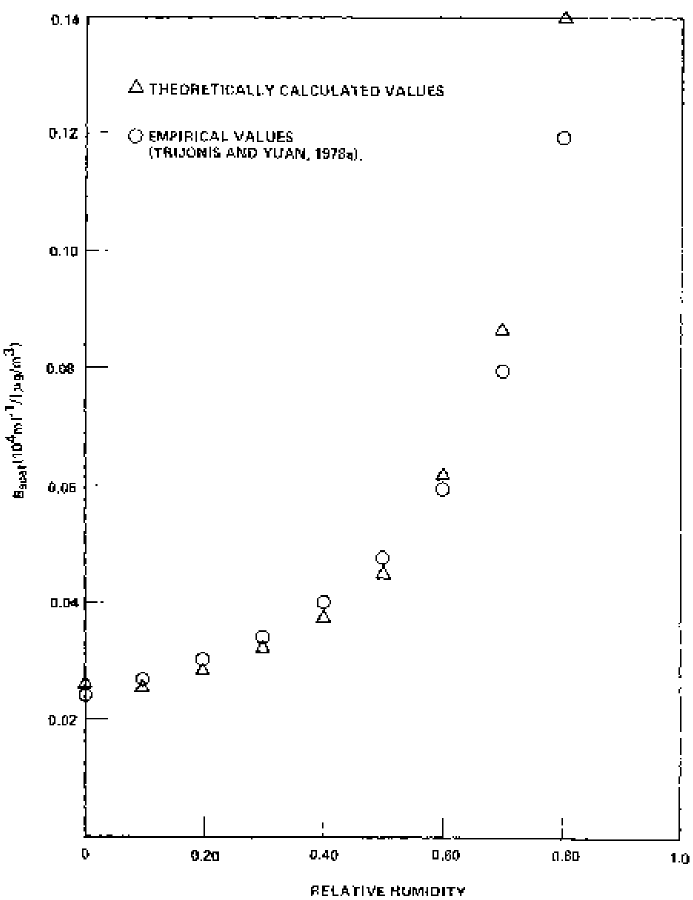

Figure 4-7. Light-scattering per unit mass of sulfate aerosol as a function of relative humidity (Latimer et al., 1978).

4.2.2.3 Extinction Budgets—By entering average values for each of the variables in the regression equations, the average fraction of extinction attributable to each aerosol component can be estimated. For example, the term "b_1 (average SULFATE) $/(1\text{-RH})^{\alpha}$" in Equation 4-1 would indicate the average contribution of sulfate aerosols to extinction.

The term "b_o" is assumed to represent Rayleigh scatter plus contributions to extinction that are unaccounted for by the regression.

	Average percent contributions to extra extinction [a] (%)			
Location	Sulfates	Nitrates	Remainder of TSP	Unaccounted for
Southwest				
(Trijonis and Yuan, 1978a)				
Phoenix	53	37	0	10
Salt Lake City	34	31	35	0
Los Angeles				
(White and Roberts, 1977)				
Various Locations [b]	31	27	42	0
(Cass, 1976)				
Downtown Los Angeles	46	0	15	39
(Leaderer and Stolwijk, 1979)				
Los Angeles Airport	30	11	0	9
Northeast				
(Trijonis and Yuan, 1978b)				
Chicago	27	0	0	73
Newark	42	0	38	20
Cleveland	55	0	0	45
Lexington	32	0	44	24
Charlotte	59	0	0	41
Columbus	68	8	0	24
(Leaderer and Stolwijk, 1979)				
New York [b]	67	14	0	19
New York	74	0	0	26
New Haven	81	0	0	19
St. Louis	51	0	0	49
Average [c]	53	8	12	27

Table 4-3. Extinction Budgets based on the regression studies. [a] Extra extinction is defined to be the fraction of extinction above-and-beyond the contribution from Rayleigh scatter. For each location, the extinction budget is based on the regression equation that achieved the best statistical fit (see Table 4-2 for correlation coefficients). Variables are included only if they are statistically significant at 95-percent confidence level. [b] Budget for light-scattering rather than for extinction. [c] The average is only for the sites presented and is not intended to represent an average of national conditions.

Table 4-3 presents extinction budgets for the various study locations. The budgets are given for *extra* extinction; the portion of extinction above-and-beyond the contributions from Rayleigh scatter by air molecules. The regression studies indicate that, in each of the three areas studied, sulfates tend to be the most important single component of the aerosol with respect to visibility degradation. The contribution of sulfates to extra extinction ranges from approximately 30 to 80 percent and averages 53 percent among the study locations. The contribution of sulfates in the Southwest agrees well with preliminary VISTTA visibility budget (Table 4-1), in which sulfates contribute 50 percent of extra extinction. The special importance of sulfates to visibility in California cities has also been suggested by strong statistical relationships observed in other recent studies (Barone et al., 1978; Grosjean et al., 1976). Barone et al., included detailed size and composition data in four California cities (Los Angeles, Los Alimitos, Bakersfield, Oakland). They found visibility reduction to be dependent on elemental content as well as particle size and that each area exhibited some site-specific (local) variables that affected visibility. Sulfur (compounds) in the 0.65 to 3.6 μm size range was the only variable significantly related to visibility at all sites.

The estimated contributions of nitrates and remainder of TSP to extra extinction in Table 4-3 vary greatly among locations and are often zero. The estimates of zero contribution imply only that a statistically significant relationship was not observed and do not necessarily mean that the actual contributions are really zero. Problems in estimating the effects of nitrates and remainder TSP are included in the discussion of limitations below.

4.2.2.4 Limitations of the Regression Studies—There are several limitations in the above regression studies. One limitation involves random errors in the data base produced by imprecision in the measurement techniques (for airport visibility, light-scattering, or aerosol concentrations) and, in the case of studies using airport visibility data, by the fact that the airport and Hi-Vol site are often located several miles apart. Random errors in the data tend to weaken the statistical relationships, leading to lower correlation coefficients and lower regression coefficients. This results in an underestimate of the extinction coefficients per unit mass and an underestimate of the contribution of the aerosol species to the total extinction budget. The overall effect of random errors in the database should not be excessive, however, because good correlations (typically 0.7 to 0.8, as may be seen in Table 4-2) are usually obtained in the analysis.

For the studies using airport visibility data (as opposed to nephelometry data), at least two types of systematic bias are possible. The aerosol concentrations measured at the downtown Hi-Vol locations may be systematically higher than the aerosol concentrations averaged over the visual range surrounding the airport. The bias caused by relatively high aerosol measurements would result in an underestimate of extinction coefficients per unit mass for the aerosol species. A reverse type of bias (e.g. an overestimate of extinction coefficients per unit mass) would result if daytime aerosol levels (corresponding to the time period of the visibility measurements) were higher than the 24-hour average aerosol levels measured by the Hi-Vol. Although these systematic errors could bias the extinction coefficients per unit mass (Table 4-2), they should not bias the extinction budgets, which are based on a multiplication of extinction coefficients per unit mass times the measured mass of the aerosol (Table 4-3).

Another limitation is that the regression analysis may overstate the importance of the aerosol variables if these variables are correlated with other visibility-related pollutants omitted from the analysis. In particular, sulfates and nitrates may act, in part, as surrogates for related pollutants, such as total fine particle mass, organic and primary carbon aerosols, and nitrogen dioxide, not measured or included in the regression.

Potential errors in Hi-Vol measurements of sulfate and nitrate are another important problem. “Artifact” sulfate (formed by SO_2 conversion on the measurement filter) may cause a slight underestimation in the extinction coefficient per unit mass for sulfates. The greatest measurement concern, however, involves nitrates (Spicer and Schumacher, 1977). Nitrate data may represent gaseous compounds (NO_2 and especially nitric acid), as well as nitrate aerosols. Also, high sulfate concentrations may negatively interfere with nitrate measurements (Harker et al., 1977). Because of potentially severe measurement errors, the visibility/nitrate relationships are especially uncertain.

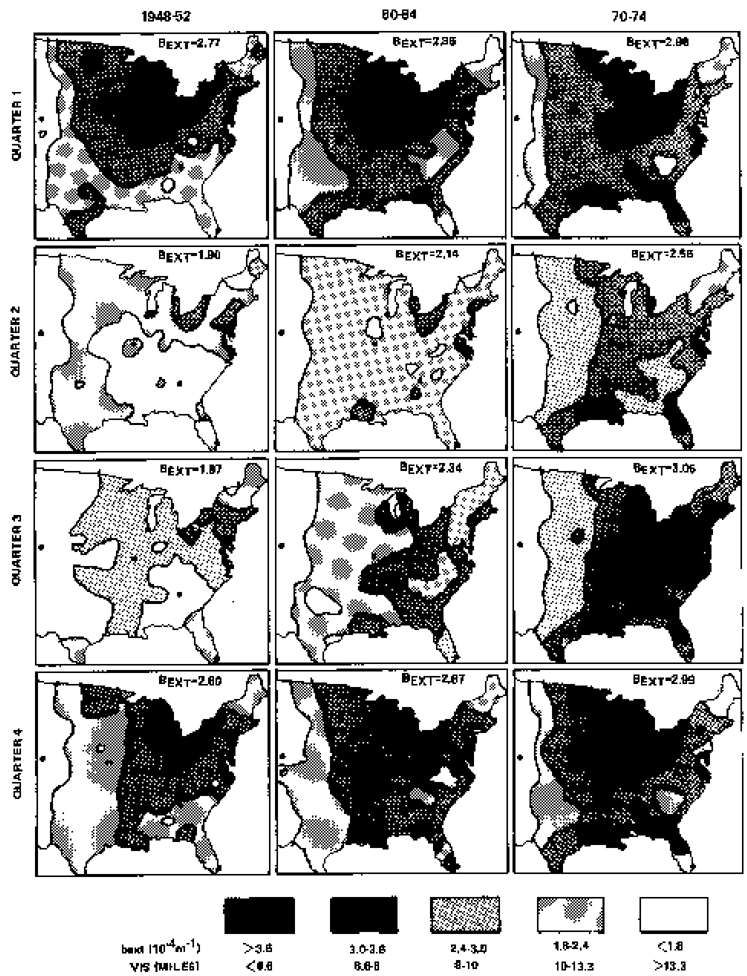

Figure 4-8. Seasonal and spatial distribution of long-term trends in average airport visiblities for the eastern United States. Note marked decline in summertime (third quarter) visual range throughout the East (Husar et al., 1979).

A final difficulty in the regression analysis is the problem of colinearity; i.e. the intercorrelation among the “independent” variables (sulfates, nitrates, remainder of TSP, and relative humidity). Although the intercorrelation among these variables is not extremely high, they usually are significant (correlations on the order of 0.2 to 0.6). Multiple regression is designed to estimate the individual effect of each variable, discounting for the simultaneous effects of other variables, but he colinearity problem can still lead to distortions in the results. In particular, the effect of nitrates and the remainder of TSP may be lost in the analysis because these variables are colinear with sulfate, which tends to be the predominant aerosol variable related to extinction.

Although the regression models are subject to several limitations, the conclusions resulting from these models have proven to be very reasonable. The extinction coefficients per unit mass estimated for sulfates, nitrates, and the remainder of TSP are consistent with the Mie theory of light scattering by aerosols, and the extinction budgets agree (at least qualitatively) with the conclusions of special field studies conducted in corresponding areas of the country.

4.3 ANALYSES OF HISTORICAL VISIBILITY/POLLUTANT TRENDS

Several investigators have used historical airport visibility data (observer-determined visual range) to examine long-term changes in haze. These studies have generally focused either on the Northeast, where the lowest rural visibilities in the United States occur, or on the Southwest, where the highest rural visibilities in the United States occur (Figure 1-10). Some of the studies have also examined the relationship of visibility trends to emission and ambient aerosol trends. Although these historical trend analyses basically provide only circumstantial evidence concerning the relationship between visibility and man-made emissions, the results are nevertheless very consistent with the conclusion of other studies. This section discusses these studies in some detail because of the relevance of the results and usefulness of the analytical approaches. Until adequate visibility monitoring data for class I areas in these and other regions are available, analysis of airport visibility data can provide useful information for preliminary assessments.

4.3.1 VISIBILITY/POLLUTANT TRENDS IN THE EAST

In comparison studies, Husar et al. (1979) and Trijonis and Yuan (1978b) investigated historical trends in airport visibility data for the East and Northeast, respectively. Husar et al. took a large-scale regional view by preparing visibility maps based on 70 locations (representing varied degrees of urbanization, from rural to metropolitan), partially accounted for meteorological variations by eliminating days with precipitation, and converted the visibility data to extinction by using the Koschmieder relationship. Their study examined the period 1948 to 1974.

The findings of Husar et al. with respect to the spatial and seasonal aspects of historical extinction trends from 1948-1952 to 1970-1974 are summarized in Figure 4-8. During the winter (first) quarter, the northern half of the East underwent little change (or a slight decrease) in haziness from 1948-1952 to 1970-1974, while the southern half experienced a moderate rise (~20%) in extinction. A slight to moderate increase in extinction (averaging about 18%) occurred throughout the East during the fall quarter with a moderate to strong increase (averaging about 35%) during the spring quarter. A dramatic growth in haze occurred during the summer quarter. This growth was distributed through the region as follows: a more than 100 percent increase in extinction for the central/eastern states (Kentucky, Tennessee, West Virginia, Virginia, and North Carolina); an increase on the order of 50-70 percent for the Midwest (Missouri, Illinois, Indiana, Michigan, and Ohio) and for the Eastern Sunbelt (Arkansas, Louisiana, Mississippi, Alabama, Georgia, and South Carolina); and an increase on the order of 10-20 percent for the far Northeast (the Northeast Megalopolis area and New England). The summer quarter, which had been nearly the best season for visibility in the East during the early 1950s, became the worst season by the early 1970s.

	Parallel between visibility and sulfate trends		Potential explanation in terms of SO_X emission trends (early 1950s - early 1970s)
Trend Feature	(Early 1950s - early 1970s)	(Early/mid 1960's - early 1970s)	
Suburban/nonurban areas	Visibility decreased substantially at suburban/nonurban locations	Sulfates increased substantially at suburban/nonurban locations	An increase in total SO_X emissions occurred in the Northeast; in particular, there was a very great rise in SO_X emissions from nonurban, tallstack sources (power plants). This may have increased large-scale background levels of sulfates.
Metropolitan areas	Visibility changed very little at metropolitan locations.	Sulfates changed very little at metropolitan locations	SO_X emissions were reduced within metropolitan areas by control of residential, commercial, and some industrial sources. This may have locally offset the increase in large-scale background levels of sulfates.
Summer (third quarter)	Visibility decreased dramatically during the summer. By the early 1970s, the third quarter became the worst season for visibility.	Sulfates rose dramatically during the summer. By early 1970s, the third quarter became the worst season for sulfates.	The summer exhibited the greatest increase in total SO_X emissions because of rapid growth of power plant emissions was offset only by small summertime reductions in emissions from other sulfates.
Winter (first quarter)	Visibility changed little during the winter.	Sulfates changed little during the winter.	Total SO_X emissions changed little during the winter because a large increase in power plant emissions was offset by a nearly as large decrease in wintertime emissions from other sources.
Best-case Areas	The only region of the east exhibiting an improvement was the Northeast Megapolis Area surrounding New York City.	The only region of the east exhibiting a decline in sulfates was the Northeast Megapolis Area surrounding New York City.	The only region showing a significant decline in SO_X emissions was the far Northeast (the Northeast Megapolis Area and New England).
Worst-case Area	The greatest decline in visibility occurred in the central/eastern states.	The central/eastern region was one of the areas showing the largest increase in sulfates.	The largest rise in SO_X emissions occurred in the central/eastern states (particularly Kentucky, Tennessee, West Virginia, and North Carolina.)

Table 4-4. Parallels among historical trends for visibility, ambient sulfates, and SO_X emissions in the Northeast.

Trijonis and Yuan (1978b) examined differences in airport visibility trends between large metropolitan areas (New York, Chicago, Cleveland, and Washington, D.C.) and suburban/rural areas of the Northeast. They found that, from the middle 1950s to the early 1970s, visibility did not change much in large metropolitan areas. Outside the large metropolitan centers, however, visibility decreased on the order of 10 to 40 percent over the same period with the largest declines occurring in the central/eastern region (at Lexington, KY, and Charlotte, NC). The 10-40 percent decrease in visibility at suburban/rural locations corresponded to an increase in extra extinction (extinction above-and-beyond Rayleigh scatter) of 10 to 80 percent. Seasonally, the constant yearly visibility trends at metropolitan locations were actually composed of moderate (~20%) declines in summertime visibility, which cancelled moderate increases in wintertime visibility. The 10-40 percent decrease in yearly visibility at non-urban locations was composed of strong (~25-60%) declines during the summer and moderate declines during the spring and fall, with little change during the winter.

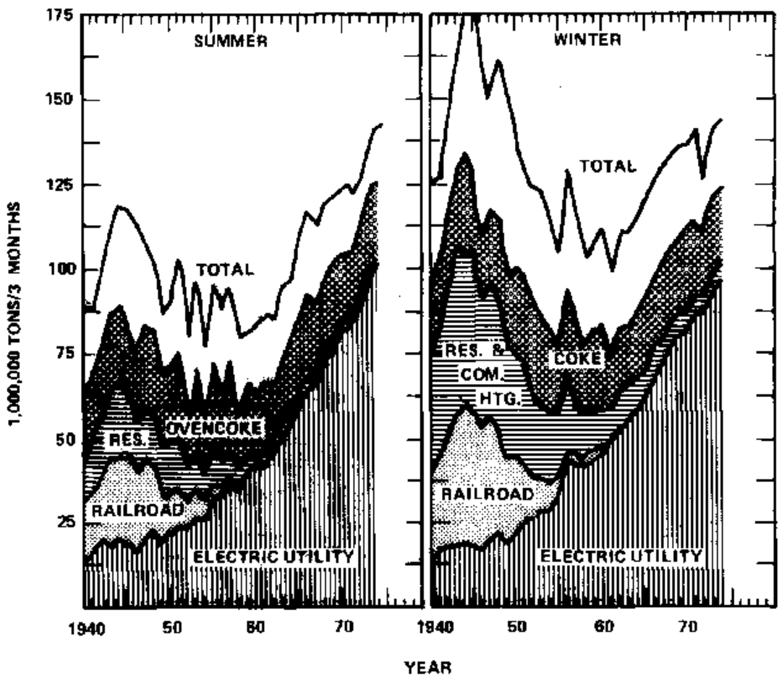

Figure 4-9a. Seasonal trends in U.S. coal consumption. A. In 1974, the U.S. winter coal consumption was well below, while the summer consumption was above, the 1943 peak. Since 1960, the average growth rate of summer consumption was 5.8 percent per year while the winter consumption increased only at 2,8 percent per year (Data from the U.S. Bureau of Mines, Minerals Yearbooks 1933-1974) (Husar et al, 1979).

The above conclusions concerning visibility trends in the Northeast are supported by the results of several other trend studies. Miller et al. (1972) reported substantial declines in airport visibilities during the 1960s for the summer season at three nonurban airports in Ohio, Kentucky, and Tennessee. From the middle 1950s to the early 1970s, airport observations of haze increased significantly in eastern Canada, especially during the summer at nonurban locations (Munn, 1973; Inhaber, 1976). Sun-photometry data from the middle 1960s to the middle 1970s indicate that turbidity increased at nonurban locations in the East, especially during the summer, and that turbidity at urban locations decreased (Peterson and Flowers, 1977). Also, the acidity of rainfall (presumably related to sulfate and nitrate concentrations) increased substantially in the East from 1955-1956 to 1972-1973 (Likens, 1976).

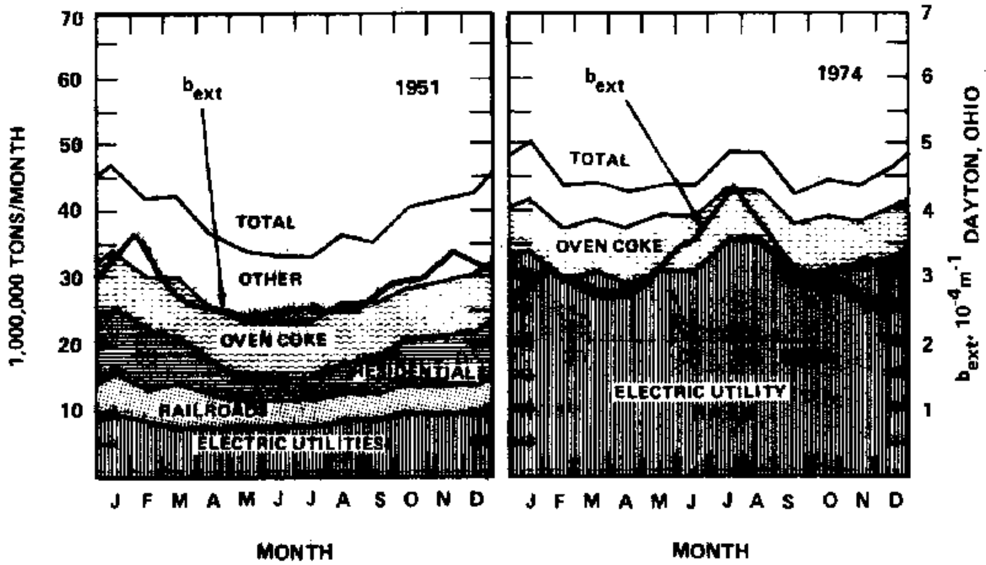

Figure 4-9b. In the 1950s, the seasonal U.S. coal consumption peaked int the winter primarily because of the incresed residential and railroad use. By 1974, the seasoal pattern of coal usage was determined by winter and summer peak of utility coal usage. The shift away from a winter peak toward a summer peak of coal consumption is consistent with the shift in haziness from a winter peak to a summer peak at Dayton, Ohio for 1948-52 and 1970-74. (Data form U.S. Bureau of Mines, Minerals Yearbooks 1933-1974) (Husar et al., 1979).

Because several studies have indicated that sulfates are the single most important component of the visibility-reducing aerosol in the Northeast (Trijonis and Yuan, 1978b; Leaderer et al., 1978, 1979; Weiss et al., 1977; Charlson et al., 1974), it is of interest to compare historical visibility trends in the Northeast with corresponding trends in ambient sulfate concentrations and sulfur oxide (SO_x) emissions. Ambient sulfate concentration and sulfur oxides emission trends from the early/middle 1960s to the early 1970s have been analyzed by Altshuller (1976), Frank and Posseil (1976), Trijonis (1975), and EPA (1975). Trijonis and Yuan (1978b) and Husar et al. (1979) noted very close parallels between the spatial/seasonal features of visibility trends and the spatial/seasonal features of ambient sulfate and SO_x emission trends. These parallels, summarized in Table 4-4, provide strong circumstantial evidence that the historical visibility changes in the Northeast were caused, at least in part, by trends in sulfate concentrations and SO_x emissions.

Trends in coal usage, the dominant factor affecting sulfur oxide emission trends, have been documented from the early 1950s to the early 1970s and have been related to airport visibility trends by Husar et al. (1979). Shifts in seasonal patterns for coal usage and visibility are shown in Figure 4-9a and 4-9b. Consistency of long-term or seasonal trends of coal consumption and haziness can hint at, but not substantiate, a cause and effect relationship. It is instructive, however, to examine the state-by-state spatial trend of yearly coal consumption data (Figure 4-10) available since 1957.

The comparison of the Eastern U.S. summer coal consumption and summer average extinction over the entire Eastern United States is shown in Figure 4-11. While a high statistical correlation could be established between the trends in coal consumption and haze, a cause-effect relationship cannot be established from trends analysis alone. Trends in other fuel use and in emissions of various pollutants from a number of source categories must also be examined.

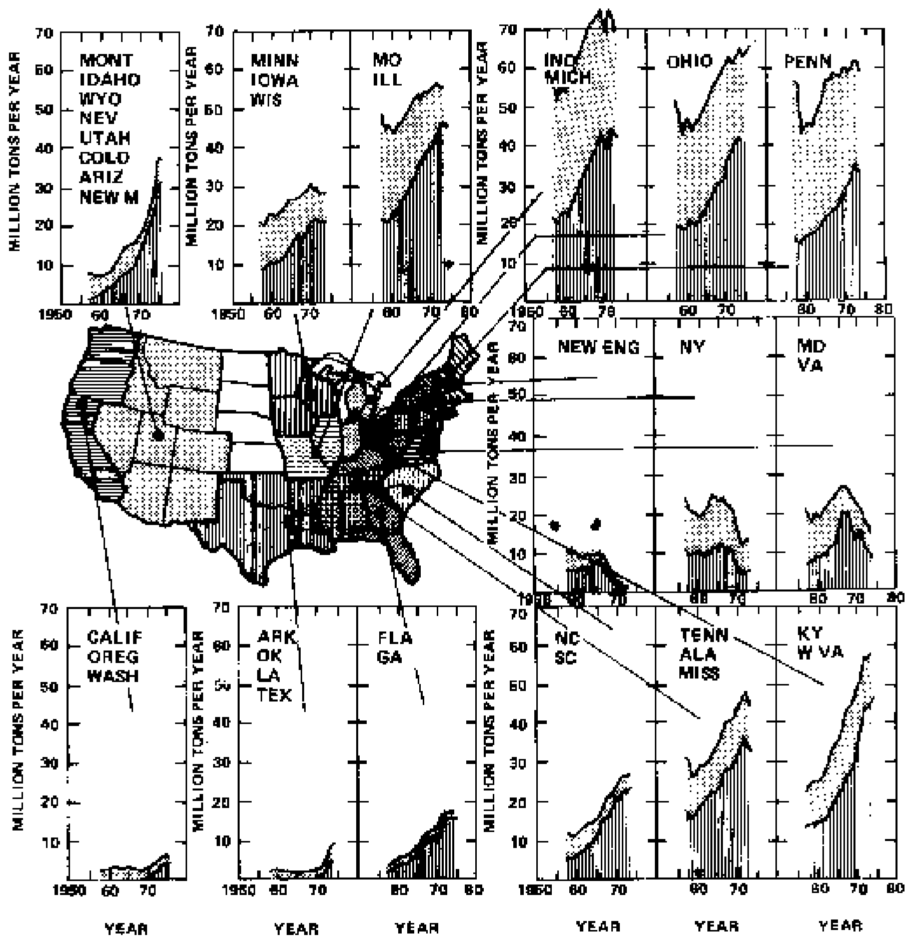

Figure 4-10. Regional trends of coal consumption in the continental United States. Dark shading is electric utility coal. The greatest increases in haziness occurred in the east central United States (Kentucky, West Virginia, North and South Carolina, and Tennessee). Sulfur oxides emissions in these regions are not completely dependent on coal use because of toher SOX sources (oil in the east, smelter in west, oil and gas in the south) and differences in coal sulfur content (lower in the west) (Husar et al., 1979).

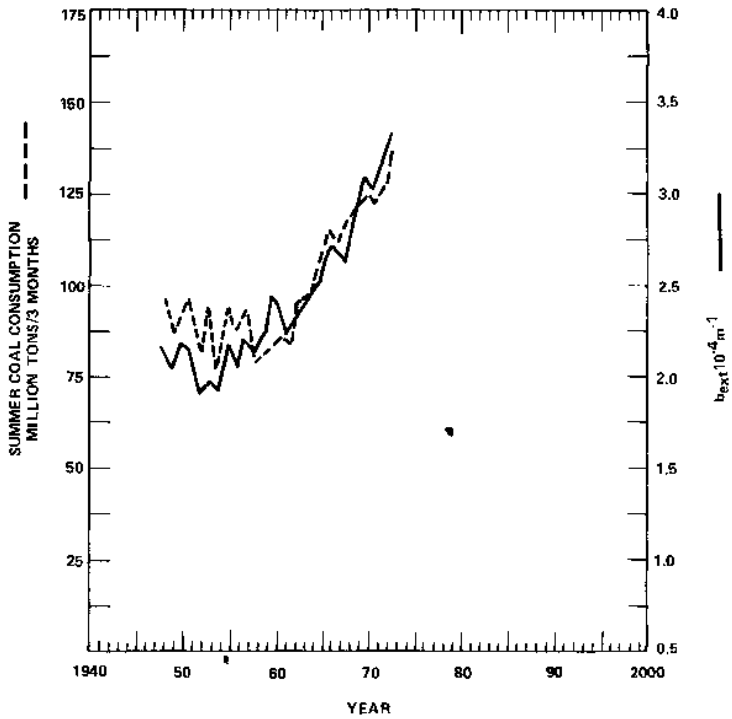

Figure 4-11. Summer trends of U.S. coal consumption (dashed line) and Eastern U.S. average extinction coefficient, or haziness (solid line). Adapted from Husar et al., 1979.

4.3.2 Visibility/Pollutant Trends in the Southwest

4.3.2.1 Visibility Trends—Recent studies have investigated airport visibility data for the Rocky Mountain Southwest, a region containing numerous class I areas, for the period 1948 to 1976. Trijonis and co-workers (Trijonis and Yuan, 1978a; Trijonis, 1979; Marians and Trijonis, 1979) examined historical visibility trends at 12 locations: 4 urban airports and 8 suburban/nonurban airports. After reviewing data quality with individual airport observers, the investigators restricted their analysis to daytime visibility data, to locations with farthest markers at distances exceeding 40 miles (typically at 60 to 90 miles), and to time periods with constant observation location, inexcessive turnover of personnel, and consistent reporting practices.

Visibility data were expressed as percentiles, such as median. Visibility trends in the Southwest were summarized according to three time periods within the 1948 to 1976 time span. From the late 1940s to the early/mid 1950s, visibility trends were mixed, with some sites showing a slight improvement and a lesser number of sites showing a slight deterioration. From the early/mid 1950s (1953-1955) to the early 1970s (1970-1972), 11 of the 12 trend sites indicated a drop in visibility of approximately 10 to 30 percent. From the early 1970s (1970-1972) to the middle 1970s (1974-1976), visibility generally tended to increase by about 5-10 percent, especially at those sites in or near Arizona.

Latimer et al. (1978) examined visibility trends from 19448 to 1976 at 16 airports; 14 sites in the Rocky Mountain Southwest, and 2 sites in the Northern Great Plains. They reported visibility trends in terms of the percent of time visibility exceeded various thresholds on days without fog or precipitation. Although Latimer et al. included several more locations, used a different type of visibility trend index, and subdivided the 1948-1976 time period differently than Trijonis and co-workers, the conclusions reached by both groups were qualitatively consistent. Latimer et al. found a tendency toward declining visibility from 1948 to 1970; they concluded that, during this period, visibility decreased at seven sites, remained relatively constant at eight sites, and improved at one site. From 1970 to 1976, Latimer et al. found that visibility improved at 12 sites, remained relatively constant at 3 sites, and declined at one site.

4.3.2.2 Historical Emission Trends—In order to help explain visibility trends in the Southwest, Marians and Trijonis (1979) documented historical emission trends for precursors of secondary aerosols: sulfur oxides (SO_x), nitrogen oxides (NO_x), and organics (non-methane carbons, NMHC). Primary (directly emitted) fine particle emissions data were not available. Emissions for the 10 dominant source categories were determined on a year-by-year basis from 1948 to 1975. The emission trends were compiled individually for four states (Arizona, Colorado, Nevada, and Utah) and for certain air basins within those states.

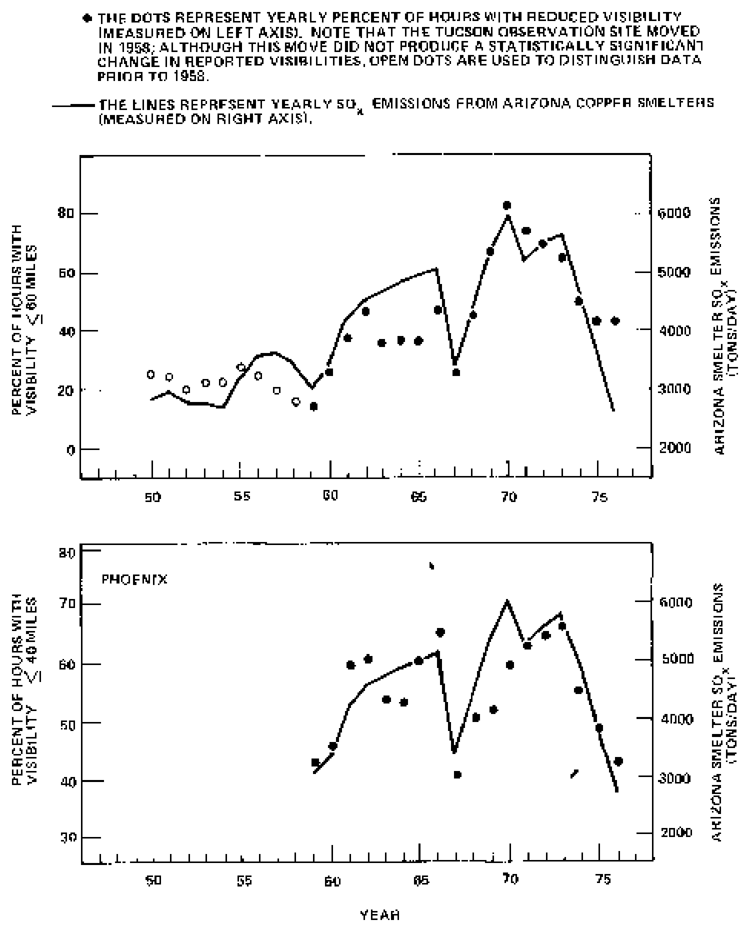

Figure 4-12. Historical trends in hours of reduced visibility at Pheonix and Tucson compared to trends in SO_X emissions from Arizona copper smelters (Marians and Trijonis, 1979).

The historical emission trends agreed qualitatively with the overall visibility trends noted in the previous section. Specifically, the slight and varied visibility trends from the late 1940s to the early/mid 1950s occurred while the principal emission changes were as follows: moderate decreases in Utah smelter SO_x and in region-wide railroad SO_x, moderate increases in Nevada smelter SO_x and in region-wide sources of NO_x and NMHC, and constant levels of Arizona smelter SO_x (the single predominant source, on a tonnage basis, of aerosol precursor emissions in the Southwest). The 10 to 30 percent decrease in visibility (20 to 70 percent increase in extra extinction) form the early/mid 1950s to the early 1970s was accompanied by a 70 percent increase in regional SO_x emissions (almost all due to a doubling of SO_x from Arizona copper smelters), a three and one-half fold increase in regional NO_x (almost all due to power plants and motor vehicles and a doubling of regional NMHC emissions (almost all due to gasoline vehicles)). The 5-10 percent improvement in visibility from the early to middle 1970s occurred as regional SO_x emissions dropped 25 percent, regional NO_x emissions increased 25 percent, and regional NMHC emissions decreased 5 percent.

Marians and Trijonis used multiple regression techniques to derive quantitative relationships between yearly extinction levels (for six Arizona airport visibility data sets) and yearly Arizona emissions of smelter SOx, non-smelter SOx, NOx, and NMHC. The multiple regressions selected Arizona smelter SOx as, by far, the most significant variable for each of the data sets and as the only significant variable for five of the data sets. The particularly close relationships between Arizona smelter SO_x and visibility at Tucson and Phoenix are illustrated in Figure 4-12.

The significant relationship between extinction in Arizona and copper smelter SO_x emissions is not surprising in light of the extremely large emissions arising from the smelters. For example, during the late 1960s and early 1970s, Arizona NMHC and NO_x emissions constituted about ¾ percent of the nationwide total NHMC and NOx, but Arizona SO_x emissions (96 percent of which cam from the smelters) constituted over 6 percent of the nationwide total SO_x. Also, the Arizona smelters emitted over ten times as much SO_x as the Los Angeles basin and over four times as much SO_x as the state of California (Marians and Trijonis, 1979).

Data Set	Correlation Coefficient	Regression Coefficient extinction/emissions km^{-1}/(1000 TPD)	t-Statistic (t > 1.7 for 95% confidence) (t 2.5 for 99% confidence
Tucson (1950-1975)	0.91	0.0035	11.1
Tucson (1959-1975)	0.88	0.0038	7.2
Phoenix (1959-1975)	0.81	0.0041	5.4
Winslow (1948-1973)	0.68	0.0047	4.5
Prescott (1948-1975)	0.70	0.0031	5.0
Prescott (1949-1969)	0.70	0.0039	4.4

Table 4-5. Correlation/regression analysis between airport extinction and copper smelter SO_X emissions (Marians and Trijonis, 1979).

Table 4-5 summarizes the results of the correlation/regression analysis between yearly airport extinction (visibility) data and Arizona smelter SO_x emissions. The correlation coefficients and t-statistics indicate significant statistical relationships at high confidence levels. The regression (extinction/emission) coefficients are remarkably consistent from site to site and represent the change in yearly median extinction associated with a given change in SO_x emissions; i.e., adding 1000 tons/day of SO_x tended to increase yearly median extinction by approximately 0.004 km-1. Considering the placement of the airports and smelters, these extinction/emission estimates might pertain to distances of approximately 50 to 200 miles (80 to 320 km) from the source (Marians and Trijonis, 1979).

Because of the limited number of data points (at most 28 yearly values) and because of problems introduced by intercorrelations among the emission variables, Marians and Trijonis could not isolate the effects of NO_x and NMHC emissions on extinction trends in Arizona. They found several indications, however, that the effects of NO_x and NMHC were probably significant, although secondary to the effects of the large SO_x emissions in Arizona. Moreover, estimates of the extinction/emission coefficient for SO_x could be inflated because of concurrent changes in NO_x, NMHC, and primary particulate emissions.

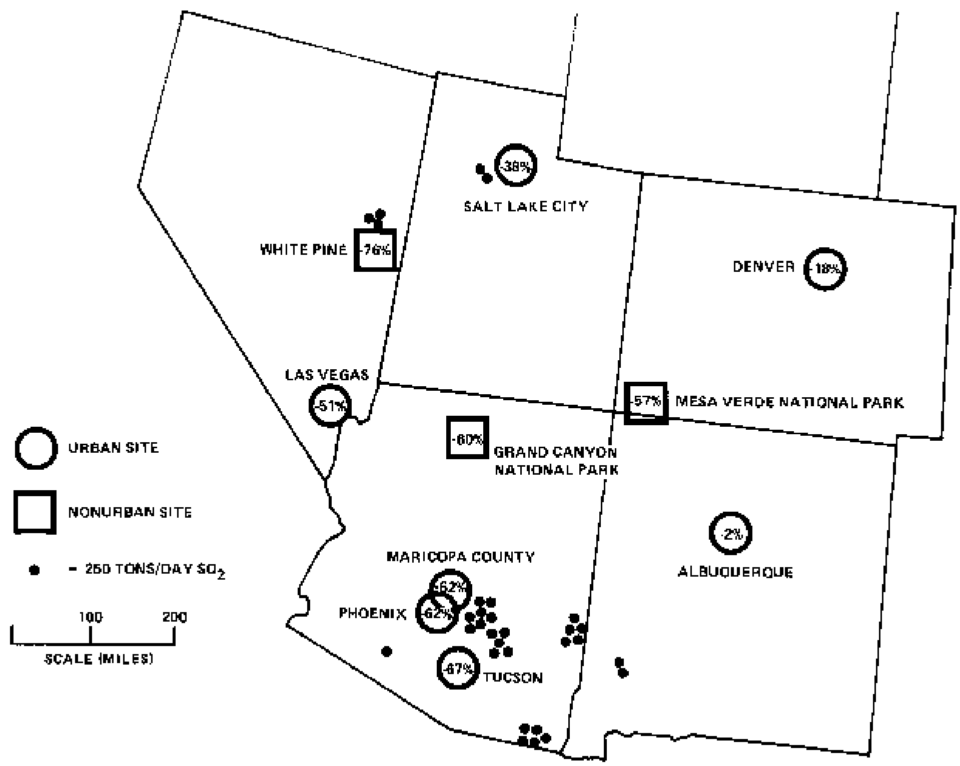

Figure 4-13. Seasonally adjusted changes in sulfate during the copper strike of 1967-68 compared to the geographical distribution of smelter SO_X emissions (Trijonis and Yuan, 1978a).

Regression studies relating extinction trends to historical emissions were also performed for four other sites: Salt Lake City, Denver, Grand Junction (Colorado), and Ely (Nevada). Possibly because of the lack of a predominating emission type (such as SO_x in Arizona), the regressions tended to have lower statistical significance than in

Arizona, and the extinction/emission coefficients lacked consistency from site to site. Although the results were somewhat uncertain, the analysis did suggest that growth in urban emissions of photochemical precursors (NO_x and NMHC) was the key factor related to visibility changes in Salt Lake City and Denver, and that a measurable impact for the Arizona smelters may have extended well north of Arizona.

4.3.2.3 The 1967-1968 Copper Strike—In the late 1960s, copper smelters accounted for approximately 90 percent of the sulfur oxide emissions in the Rocky Mountain Southwest (Marians and Trijonis). The nine month industry-wide shutdown of the smelters during a labor strike (July 1967-March 1968) provided a unique opportunity to investigate the relationship between SO_x emissions and regional visual air quality.

Trijonis and co-workers examined regional changes in sulfate concentrations and visibility during the strike. As shown in Figure 4-13, substantial decreases in sulfate occurred at five locations (Tucson, Phoenix, Maricopa County, White Pine, and Salt Lake City) that are within 12 to 70 miles of copper smelters. More notably, sulfates evidently dropped by about 60 percent at Grand Canyon and Mesa Verde; these class I areas are located 200-300 miles from the main smelter area in Southeast Arizona.

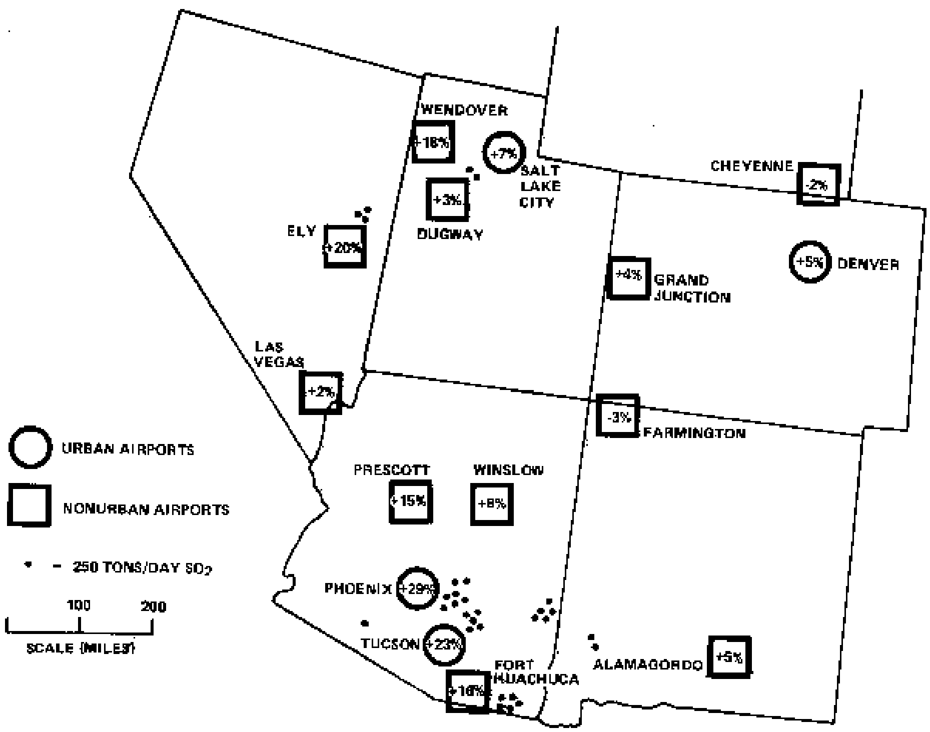

Figure 4-14. Seasonally adjsted percent changes in visibility during the copper strike compared to the geographcal distribution of smelter SO_X emissions (Trijonis and Yuan, 1978a).

As shown in Figure 4-14, Trijonis and co-workers found that visibility improved at almost all locations during the strike, with the largest improvements occurring near and downwind (north) of the copper smelters in southeast Arizona and near the copper smelters in Nevada and Utah. The nine locations showing statistically significant improvements are all within 150 miles of a copper smelter.

Many of the sulfate and visibility changes during the copper strike are statistically significant at extremely high confidence levels (Trijonis, 1979). The statistical significance of the changes is also illustrated by step functions in the time series data (Figure 4-15) and by major differences in frequency distributions (Figure 4-16). Preliminary analyses of meteorological data indicated that unusual weather did not contribute significantly to the observed air quality changes during the strike (Trijonis and Yuan, 1978a).

The reductions in sulfate and extinction during the copper strike tend to confirm the results of the multiple regression models for Phoenix and Salt Lake City (See 4.2.2.2). For example, the regression model for Phoenix indicated that sulfates account for 53 percent of extra extinction. Since sulfates decreased by 62 percent in Phoenix during the strike, one would predict that extra extinction should decrease by 33 Percent (0.53x62%). The actual decrease in extra extinction, computed from the visibility increase, was 29 percent, quite good agreement. Similar agreement was found in Salt Lake City.

There is one paradox concerning the air quality changes during the copper strike. The spatial scale of the visibility impact during the strike (apparently on the order of 150 miles from the smelters) seems to differ from the spatial scale of the sulfate changes (apparently on the order of 300 miles away from the smelters). In particular, as shown in Figures 4-13 and 4-14, significant improvements in visibility did not occur in Farmington, NM, and Las Vegas, NV, although these sites experiences pronounced drops in sulfates. Several potential explanations for this discrepancy are discussed in Trijonis and Yuan (1978a), but the basic cause of the discrepancy remains unresolved. Latimer et al. (1978), however, found statistically significant improvements in visibility at Farmington (as well as other locations) during the strike by stratifying the data according to wind direction and/or relative humidity.

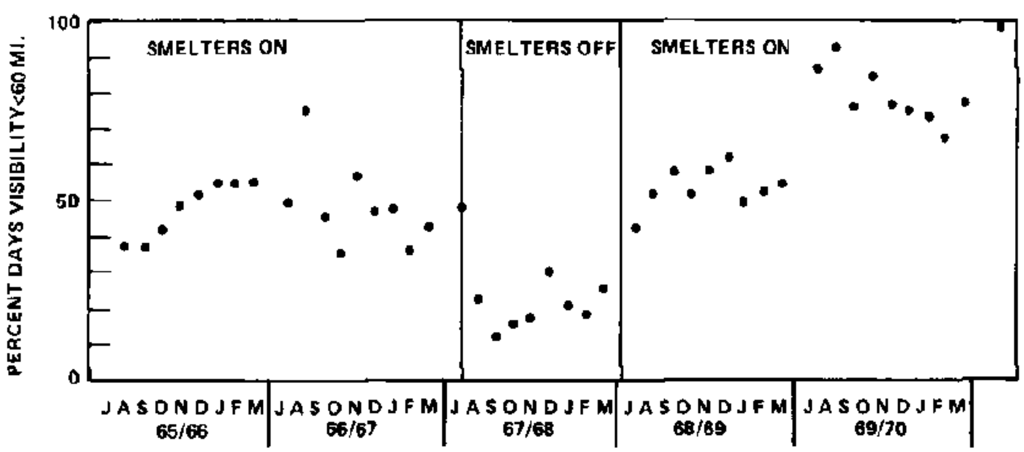

Figure 4-15. Changes in number of hazy days at Tucson during the 1967-68 copper strike. The number of hazy days before the strike (aobut 50%) fell to about 20 percent during the strike and rose to about 80 percent during the following year when copper production expnded substtantially (Hartmann, 1972).

Marians and Trijonis (1979) used the air quality changes during the copper strike to estimate regional extinction/emission coefficients for SO_x. They found that both the visibility data and sulfate data implied an extinction/emission coefficient of 0.001 to 0.003 km^{-1}/(1000 tons per day SOx) for the mesoscale region (50 to 200 miles from the source). This estimate for the mesoscale extinction/emission coefficient is somewhat lower than the one derived by the historical regression analysis (See 4.3.2.2). Marians and Trijonis also found some evidence of the following: (1) average regional extinction produced by an SO_x emission source in the Southwest *may* tend to be inversely proportional to distance from the source; (2) at distances of 250-375 miles from the source, the extinction/emission coefficient *may* be approximately 0.001 km^{-1}/(1000 tons per day SO_x); and (3) at distances within 10 to 15 miles from the source (within the air basin scale), the extinction/emission coefficient *may* be as high as 0.01 to 0.025 km^{-1}/(1000 tons per day SO_x). AS indicated by the qualified wording, however, these latter three conclusions are regarded as tenuous.

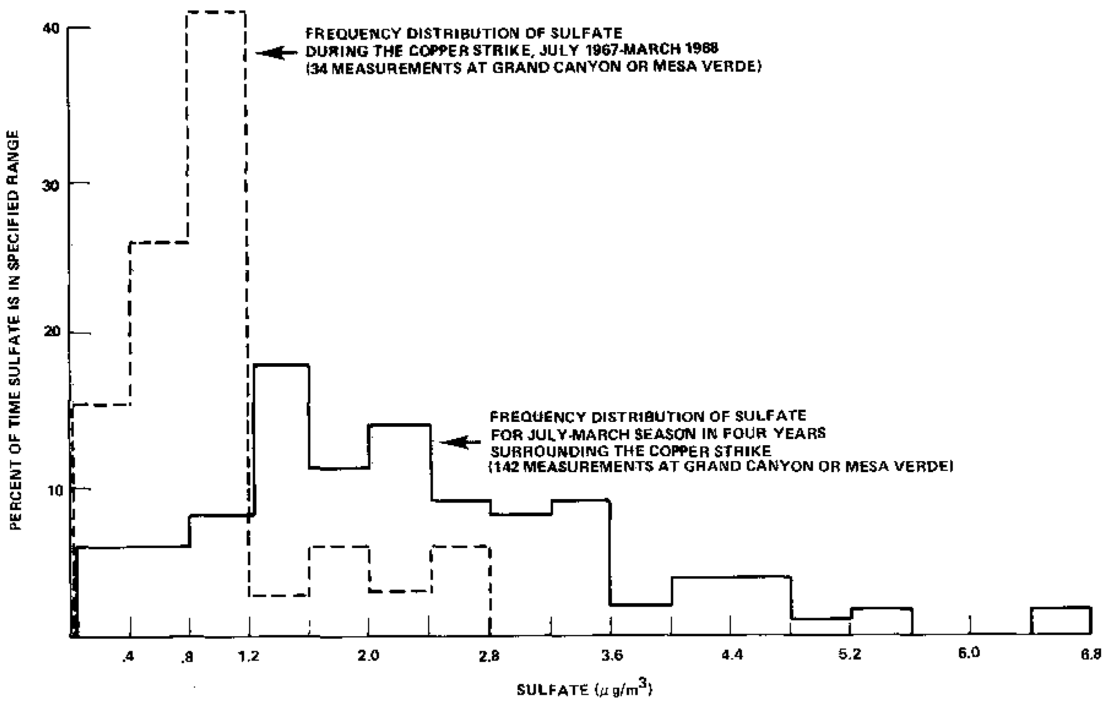

Figure 4-16. Frequency distribution of sulfate concentrations during te copper strike compared to seasonal average distriution for Grand Canyon and Mesa Verde data combined. Most sulfate measurements fell below 1.2 $\mu g/m^3$ during the strike (Trijonis and Yuan, 1978a).

4.3.3 Limitations of the Historical Trend Studies

The greatest drawback in the visibility trend analysis is the possibility that the trends may be distorted by changes in visibility observation procedures or that airport visibility does not adequately represent regional conditions. Of particular concern are relocations of the observation sites, excessive turnover of personnel on the observation teams, and changes in reporting practices (i.e., the set of visual ranges that are routinely reported). Husar et al. (1979) attempted to minimize the overall effect of such changes by using data from a large number of airports (70 locations in the East). Trijonis and co-workers performed data quality checks and restricted their analysis to sites and time periods of constant observation location, stable personnel, and consistent reporting practices.

Because changes in visibility observation procedures—even very subtle changes—can distort visibility trends at individual airports, it is important to examine trends at *numerous* locations to see if a consistent pattern emerges. Su h consistency has been found both in the Northeast and in the Southwest. For example, Figure 4-17 superimposes third quarter extinction trends for about 15 stations, each in the central-eastern states and the Northeast Megapolis Area.

Several other factors add confidence to the conclusions reached concerning East and Southwest visibility trends:

1. The visibility trend pattern for the East is supported by very similar patterns in trend data for SO_x emissions, ambient sulfates, photometric turbidity, and acid rain (see 4.3.1).

2. One of the most significant features of the Northeast trends, the deterioration in summer visibility relative to winter visibility, is independent of changes in visibility reporting procedures.

3. In the Southwest, qualitative agreement (and in some cases very high quantitative correlation) exists between visibility trends and emission trends.

4. These factors and the site-to-site consistencies significantly lessen the uncertainty associated with the trends. Confidence in the conclusions should be especially high for the Northeast where there is a multitude of visibility stations and where independent data sets (e.g., for sulfates and turbidity) confirm the results.

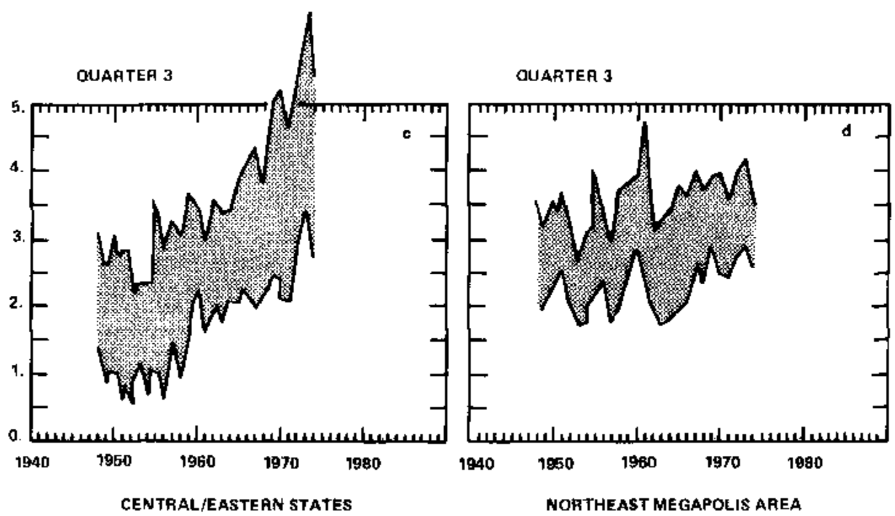

Figure 4-17. Third-quarter extinction trends at various locations in the central/eastern States and the Northeast Megapolis area (Husar et al., 1979).

For studies that have related visibility trends to historical changes in emissions, a basic limitation is the intercorrelation among trends in various types of emissions (e.g., SO_x,

NO_x, NMHC, and primary particles). This drawback may be less severe in cases such as central/southern Arizona, where emissions of a single pollutant (e.g., SO_x) appear dominant. In many other cases, however, the effect of intercorrelated emission variables may be important. For example, although the patterns of sulfate increases and visibility decreases in the Northeast seem to be consistent with the patterns in SO_x emission changes, one cannot rule out significant contributions from NO_x and/or NMHC emissions in the production of the observed air quality changes. Disentangling the individual impact of each emission variable cannot be accomplished by historical trend analysis alone. Moreover, potentially important emissions of primary particles (dust storms, fires, and stack emissions) were not included in the analysis.

Another problem of emission-visibility trend analysis is that of choosing the proper spatial scale in a region such as the Eastern United States. If the scale of trend analysis is chosen to be, say a 700-km sized region, then long-range transport from neighboring sources may obscure the cause-effect relationship. If on the other hand, the scale is too large, say the entire Eastern United States, then the trends within interdivided sub-regions (e.g., states) are masked by the overall averages.

4.4 WIND DIRECTION ANALYSES

The estimation of source-receptor relationships via "pollution roses" has been used successfully for decades in the case of primary pollutants, such as sulfur dioxide. In its simplest form, the method consists of classifying each pollutant measurement according to the corresponding wind direction and computing the average pollutant concentration for each wind direction class. The plot of average concentration versus wind direction is referred to as a pollutant rose; with careful selection of the wind direction classes, it is possible to infer the individual effect of local sources. The major assumption required in such analysis is that the plume must arrive at the receptor from the same direction in which the source lies.

A similar technique has been applied by Latimer et al. (1978) to historical visibility data from Farmington, NM (Figure 4-18). The percentage of daylight observations for which RH < 60 percent and visual range > 121 km was chosen rather than the mean. The visual range was significantly improved for the South-Southeast (SSE) to West (W) wind direction classes during the shutdown of copper smelters, lying in the same directions at distances of more than 400 km. Thus it might be inferred, for example, that the smelters cause a major portion of the reduction of visual range below 121 km associated with SSE winds.

Most cases of general haze/source location are not as clear as the smelter strike. During long-range transport, the plume may meander and arrive at the receptor from almost any direction. In these situations, the traditional pollution rose may be inadequate for determining the sources of regional haze.

The utility of wind directional analysis determining the source-receptor relationship may be improved by the more sophisticated approach of trajectory sector analysis. Backward air-parcel trajectories are performed to determine the source region that contributes most strongly to the measured concentration. The direction from the receptor to the source may then be used in place of the local wind direction in construction of the pollution rose (Figure 4-19). Samson (1978) and Niemann et al. (1978) have used this approach to establish the importance of Ohio River Valley sources of sulfate concentrations at non-urban sites Pennsylvania and NY State. Chung (1978) used trajectory analysis to implicate the same region as an important source of sulfate in southwestern Canada. Rodhe et al. (1972), Brosset et al. (1975), and others established the importance of continental European sources via this technique. The Organization for Economic Cooperation and Development (OECD) Program on the Long-Range Transport of Air Pollutants (LRTAP) included trajectory sector analysis of sites across Europe.

The more elaborate trajectory analysis techniques are easily adapted to include simple gas-particle conversion and removal kinetics along the trajectory. Such models are used to extract the regional average rate constants from source emissions and measured concentrations, as in the OECD project. Such empirical approaches to data analysis, which are known diagnostic models, are discussed further in (4.6).

In summary, observed measurements of aerosols wand visibility parameters such as contrast (b_{scat}) or visual range can be attributed to sources or source regions when the meteorological transport between source and receptor is known. For conditions where long-range transport and unsteady winds are significant, the utility of pollution roses may be increased by receptor-back-to-source trajectory computations.

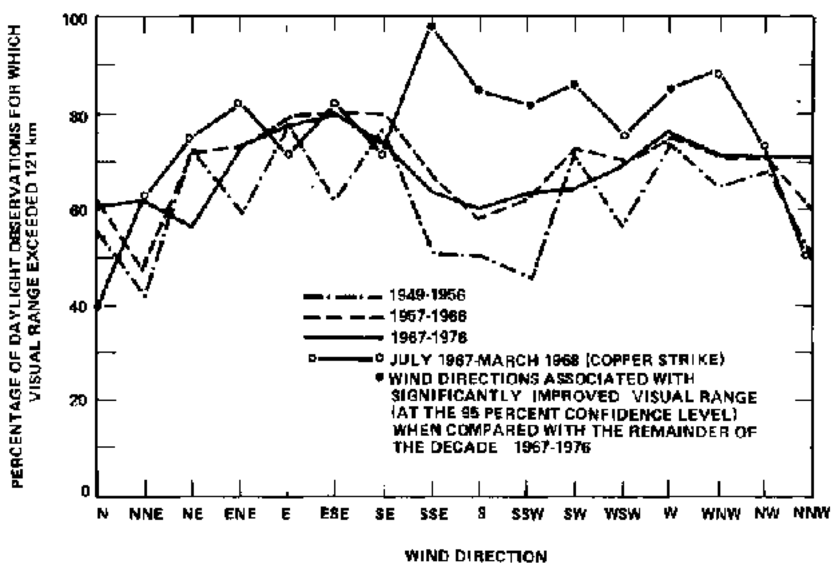

Figure 4-18. Percentage of daylight observations with RH < 60% for which visual range was > 121 km as a function of wind direction at Farmingotn, NM. The period of the copper strike sows significant improvement of visual range from the direction of copper smelters, SSE to W implicating the contribution of these SO_X sources (Latimer et al., 1978).

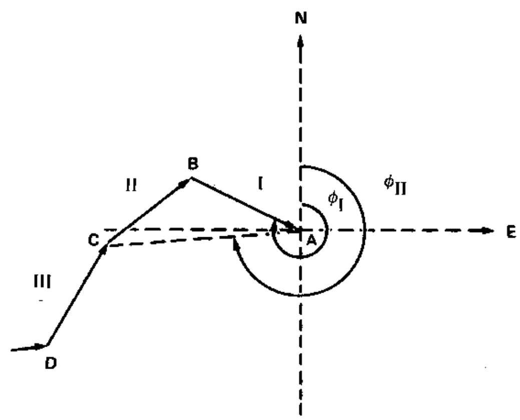

Figure 4-19. Hypothetical backward trajectory illustrating the curved transport path of a plume arriving at receptor point A. If the emissions originated at source D, the direction of the source-receptor sector is defined by the line from D to A and not the local wind direction (Samson, 1978).

4.5 DIRECT OBSERVATIONS OF SOURCE IMPACTS: PLUMES AND REGIONAL HAZES

In the previous three sections, the source-receptor relationships were examined from the point of view of the receptor; i.e., what source types contribute how much to the total burden at that site. An alternative approach, discussed in this section, is that of starting at the source and following the transmission of the air pollutants through the atmosphere until they are ultimately removed. Studies of this kind permit identification of the specific roles of transport, transformation and removal processes, which facilitates consideration of these transmission processes in the appropriate control strategies.

4.5.1 Power Plant and Smelter Plume Studies

Since the late 1960s and increasing fraction of the national sulfur oxide emissions to the atmosphere have been released from tall stacks, of 150-300 meters height. The visible impact of these emissions begins in the near stack region, where primary particles can make the plume itself visible against the background sky and where fumigation can occur. The impact of such stacks may extend large distances downwind, where the secondary products (sulfates and NO_2) can cause layers of discoloration and general haze.

The atmospheric transmission of tall stack effluent has been studied extensively during the past decade, by EPA, DOE, the Electric Power Research Institute (EPRI), and others. In these studies, the transport, chemical transformations, removal, and the interaction of these processes in determining the sulfur budget of large plumes have been assessed. One set of results and conclusions of these studies is given in Figure 4-20.

Instrumented aircraft have been used to track and characterize plumes from large sources. A number of these studies have included visibility (light scattering) measurements. EPA's MISTTT* project tracked the plume from the Labadie power plant near St. Louis. Figure 4-21 illustrates the plume geometry and the measured sulfur dioxide concentrations attributed to the Labadie plume for two long-range sampling days, July 9 and July 18, 1976. On both days, the plumes were tracked to about 300 km from the source.

The average light scattering coefficient imposed on the background by the Labadie power plant plume is shown in Figure 4-22. Near the source, over the first 50 km, the excess light-scattering coefficient was quite variable (between 0.01 to 0.10 km^{-1}). At distances of between 50 and 200 km, however, the MISTT data indicate a rather uniform light-scattering coefficient of 0.05 km^{-1} plume excess b_{scat}, averaged over the plume width. This observation indicates that the horizontal and vertical dispersion of the plume material is generally balanced by the formation of secondary aerosols. Neglecting background, at that b_{scat} level, the visual range would be approximately 60 km, which is typically the width of the plume at 100 or 200 km from the source when dispersed by daytime convection.

Light scattering measurements for the Four Corners power plant in New Mexico have been reported by EPRI. These measurements, extending to 50 km from the source are compared to the Labadie plant in Figure 4-22. Plume excess b_{scat} near the Four Corners plant (less than 20 km) is higher or equal to comparable measurements at Labadie. Where, however, excess bscat for Labadie tends to remain constant at greater distances, the Four Corners generally show a decrease with distance. In this regard it should be noted that annual SO_x emissions from Four Corners are roughly 1/3 that of Labadie but primary particulate emissions from Four Corners are as much as ten time higher (FPC, 1976). Primary particulate impacts are greater near the source (See Figure 1-5) and tend to decrease with distance. Secondary particulate sulfates (related to SO_x emissions) that form during transport are probably responsible for maintaining b_{scat} levels in the Labadie plume.

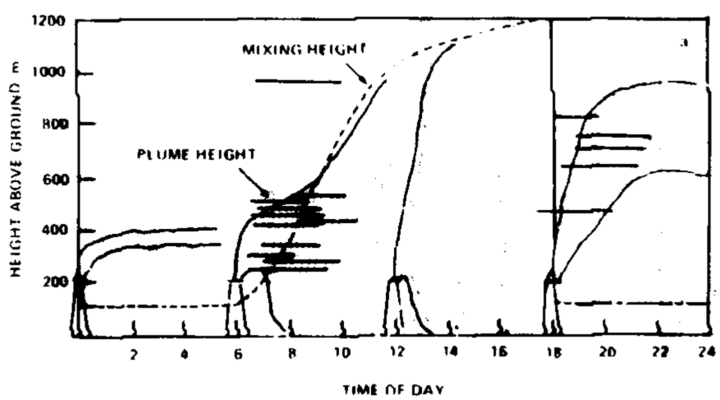

Figure 4-20. Results of plume studies (Husar et al., 1979).

Figure 4-20a. Diurnal pattern of plume dispersion. The vertical plume dispersion is limited at night by the stability of the planetary boudary layer, resulting in narrow ribbon-like plumes at night and in the early morning. Daytime dispersion increases as the "mixing" layer height increses to about 1 km, diluting the plume and decreasing near source visual impact. Late afternoon atmospheric instability and plume buoyancy results in elevation of tall stack plumes to 1-2 km heights. Such a plume may appear as a visible, elevated ribbon.

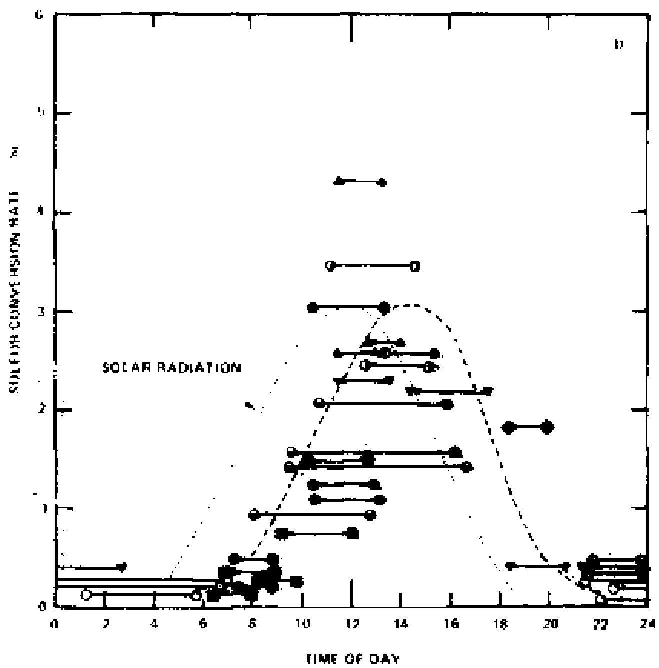

Figure 4-20b. Diurnal sulfate formation rate. The daytime conversion rate of SO2 to light scattering sulfates in the MISTT study was quite variable, between 1 to 4%/hr, whereas nightime values were consistently below 0.5%/hr. Either photochemical conversion or liquid-phase oxidatio in daytime cumulus clouds are consistent with the daytime peak of conversion rate.

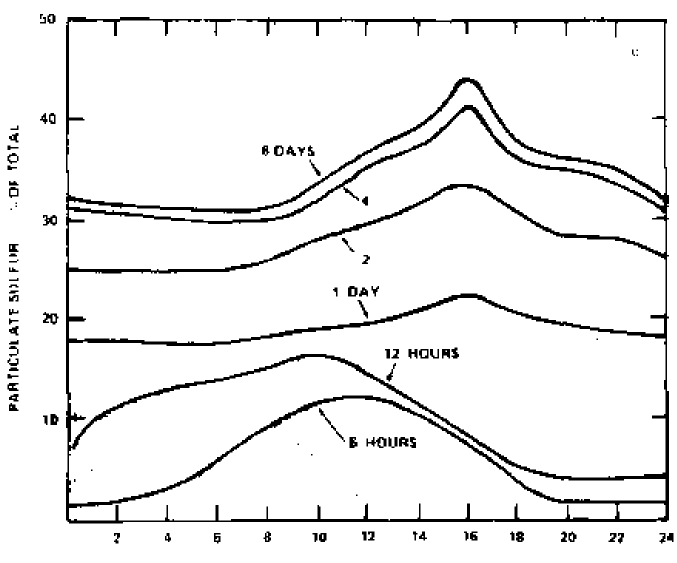

Figure 4-20c. Diurnal frction of SO_2 conversion to aerosol. The amount of particulate sulfur formed increases when the plume is removed from the surface by dilution or by decoupling from the surface layer. Hency daytime emissions into deeply mixed layers or elevated stable layers are expected to produce more sulfate than nighttime emissions.

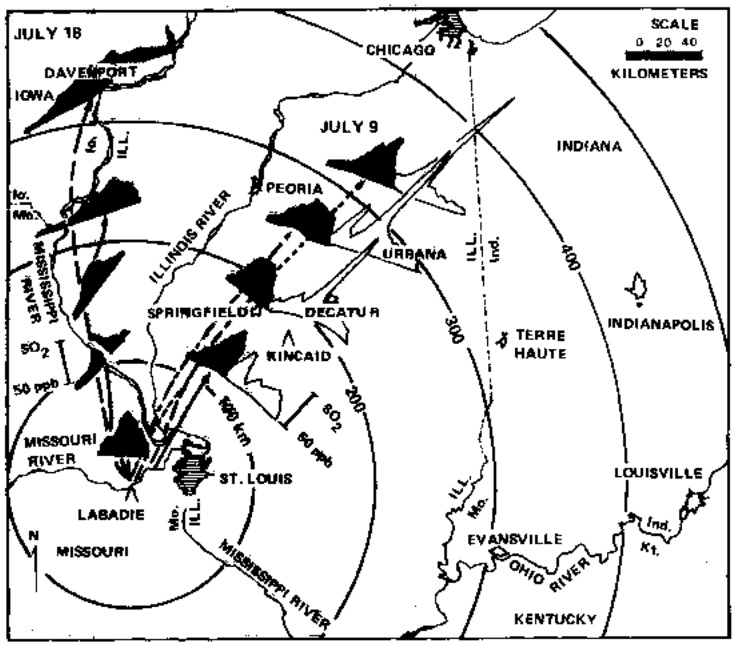

Figure 4-21. Horizontal profiles of SO_2 during selected constant altitude aircraft flights on July 9 and July 18, 1976. July 9 traverses are at about 450 m above ground, and July 18 traverses are at about 750 m. The Labadie plume sections are shaded. Also shown are backward trajectories for the Labadie plume. The plume was tracked to distances of over 300 km from the plant (Gillani, 1978).

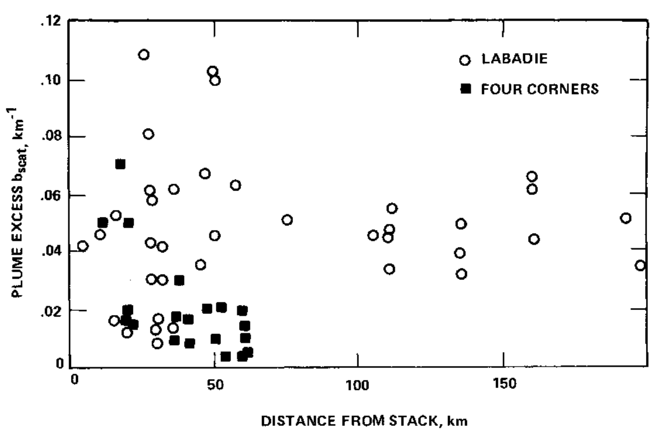

Figure 4-22. Average plume excess bscat measured during flights through the Labadie and Four Corners power plant plumes (MRI, 1976; EPRI, 1977).

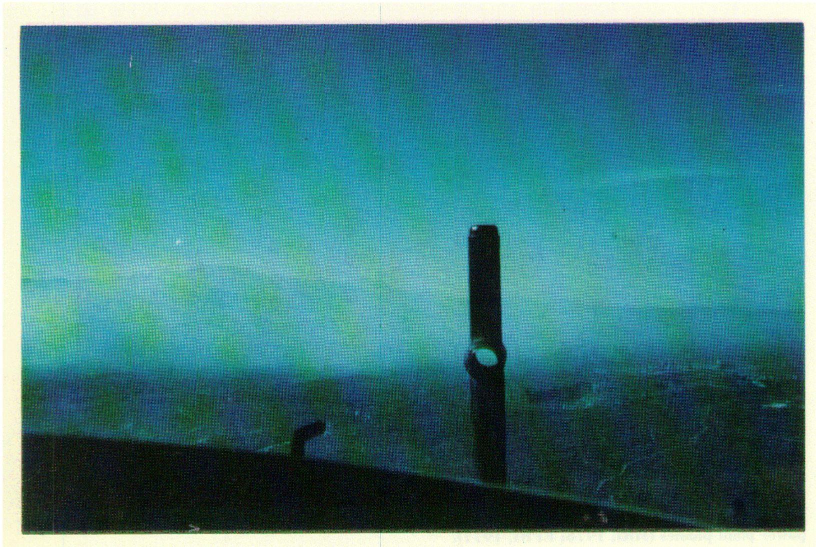

Figure 4-23. San Manuel smelter plume viewed from VISTTA aircraft. View is approximately eight km downwind of the smelter.

In the VISTTA program, plume visibility parameters have been measured in the San Manual Smelter (Figure 4-23) (Arizona) and the Mohave Power Plant (California) (Macias, et al., 1979). An indication of sulfate formation at distances greater than 30 km was reported. The SO_2 transformation rate in the smelter plume was estimated to be 0.7%/hr, or comparable to rates measured for Labadie and other sources. An excess plume visibility budget for these sources is presented in Table 4-6. Sulfates account for 43 percent of plume light scattering in the smelter plume (at 60 km), the balance being made up of primary coarse and fine particles. These results suggest that the statistically derived smelter extinction/SO_x emissions estimates reported in Section 4.3 may be somewhat high. The Mohave data are not representative of a typical power plant plume because wind blown dust from agricultural activities were mixed into the plume during the sampling period.

The visibility impacts of the plume measurements discussed above are compared in Table 4-7. Visual range (Vr) is calculated for an observer standing at the edge of the plume, viewing a hypothetical black target. Visual range and plume impacts for the measured background conditions during the studies are given. To enhance the comparison among sources, the impacts of the plumes on visual range for relatively clean background conditions (Vr = 195 km) are given in the last column. The plume impacts are marked and in some cases are dramatic. Visually, the plumes would cause the whitening of the horizon sky and reduction in general contrast associated with haze. If the plumes were elevated from the surface, they could appear as definable haze layers.

4.5.2 Urban Plumes

Urban plumes constitute an aggregate plume from various sources originating within a metropolitan area. The best-studied urban plume is that of the metropolitan St. Louis area, a major industrial center, encompassing coal-fired power plant with a combined capacity of 4600 MW, oil refineries with a combined capacity of 4.4×10^5 barrels per day, various other industries and a population of about 2 million (White et al., 1976). Because St. Louis is remote from other major metropolitan areas, its impact on the surrounding ambient air quality is relatively easy to identify; air that has been modified by the aggregate emissions of the metropolitan area form an "urban plume" downwind. The Fate of Atmospheric Pollutants Study (FAPS) (e.g. Hagenson and Morris, 1974) has shown that this plume is often identifiable at distances of 80 to 120 km from the city.

Component	Particle Size (μm)	b_{scat}^{c} (km^{-1})	Contribution to total particle scattering (%)
San Manuel Smelter	(62 km downwind)	10/4/77	
$(NH_4)_2SO_4^{a}$	0.1 to 1.0	0.041	43
SiO_2^{b}	0.1 to 1.0	0.0095	10
Other compounds	0.1 to 1.0	0.0055	6
Coarse particles	1.0 to 20.0	0.039	41
		0.095	**100**
Mohave Power Plant	(32 km downwind)	10/8/77	
$(NH_4)_2SO_4^{a}$	0.1 to 1.0	0.003	11
SiO_2^{b}	0.1 to 1.0	0.002	7
Other compounds	0.1 to 1.0	0.001	4
Coarse particles	1.0 to 20.0	0.021	78
		0.027	**100**

Table 4-6. Plume excess visibility budget. [a]Assumes that all fine particle sulfate exists as ammonium sulfate. [b]Assumes that all fine particle silicon exists as SiO_2. [c]Determined from b_{scat} (total) – b_{scat} (fine particles).

As a part of project MISTT (Wilson, 1978), the three-dimensional flow of aerosols and trace gases in the St. Louis urban plume was studied. The plume was successfully tracked up to 240 km, and it was mapped quantitatively up to 160 km (Figure 4-24). At these distances, the plume was still well defined and on the order of 50 km wide.

An increased concentration of light-scattering aerosols was a key characteristic of the St. Louis urban plume. The primary contribution of project MISTT was to quantify the flow of material at increasing downwind distances so as to study the transformations that pollutants undergo in the atmosphere.

The flow rate of ozone light scattering (b_{scat}) and particulate sulfur (S_p) all increased with distance downwind of St. Louis on July 18, 1975, reflecting the secondary origin of ozone and most of the light scattering aerosols (White et al., 1976). Most of the increase in the b_{scat} flow rate was observed downwind of the major increase in ozone flow rate; this is consistent with the finding of laboratory studies that aerosol production lags behind ozone production in a photochemical system (Wilson et al., 1973). The ratio of the flow rate of $_{bscat}$ to the flow rate of particulate sulfur (S_p) indicates that sulfate compounds accounted for most of the newly formed light scattering aerosol in the urban plume. This case study illustrates that emissions from a metropolitan area such as St. Louis can cause reduced visibility and elevated ozone concentration in urban plumes, long after their primary gas phase precursors have been diluted to low concentrations.

Source	SO_X emission (tons/day)	Down wind distance (km)	Plume width (km)	Plume excess light scattering (km^{-1})	Visibility perpendicular to plume (through plume)					
					(From experimental data)			(Normalized to "clean" background)		
					Visual Range		Visual range reduction due to plume (%)	Visual Range		Visual Range reduction due to plume (%)
					With Plume (km)	Backgr ound (km)		With plume	Backgr ound	
Labadie Power Plant[a] (St. Louis)	880[d]	40-60	20	0.030	28	30	7	165	195	15
		150-200	60	0.050	23	30	23	56	195	70
Four Corners[b] Power Plant (New Mexico)	250[d]	50	25	0.020	50	55	10	170	195	13
San Manuel[c] Smelter (Arizona)	557	8	16	0.283	12	85	86	12	195	94
		32	20	0.092	45	85	47	103	195	47
		60	25	0.095	46	120	62	76	195	61
		127	54	0.050	36	120	70	80	195	69
	66	32	8	0.018	104	110	5	191	195	2
Mohave[c] Power Plant, (+ wind blown dust)		60	27	0.033	84	110	24	150	195	23

Table 4-7. Aircraft measurements of plume visibility impacts. [a]Typical values for July 9, 11, 1979; see Figure 4-2 (MRI, 1976). [b]Typical values for July 10, 1976; see Figure 4-2 (EPRI, 1976). [c]Excess bscat from Table 9; Plume width, Table 10 (Macias et al., 1979). [d]Based on annual (1976) emissions (FPC, 1976).

The visibility reduction in the St. Louis urban plume was also studied as part of project METROMEX. Komp and Auer (1978) have reported actual observations of visual range from aircraft downwind of St. Louis and presented those as contour maps, Figure 4-25. Their observations show that, within about two hours of aging in the urban plumes, the visual range was reduced by a factor of two.

4.5.3 Regional Scale Episodes of Haziness

Episodes of regional-scale haziness have been observed in the Eastern United States. While the class I areas east of the Mississippi account only for about 20 percent of the class I area acreage, their proximity to population centers results in high visitor attendance. For example, the Shenandoah National Park in Virginia has been among the most frequently visited class I areas in the United States (Bammel and Bammel, 1978).

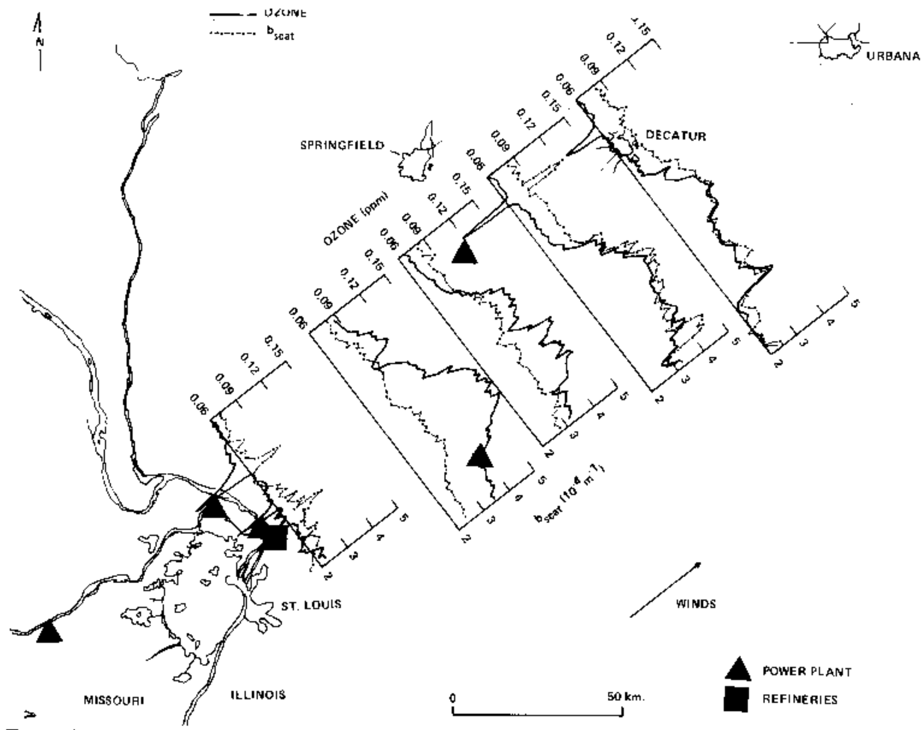

Figure 4-24a. Ozone and light scattering (b_{scat}) measurements downwind of St. Louis on 18 july, 1975. Data are taken from horizontal traverses by instrumented aircraft, at altitudes indicated in figure 4-24b. Graph base lines show sampling paths; base-line concentrations are not zero.

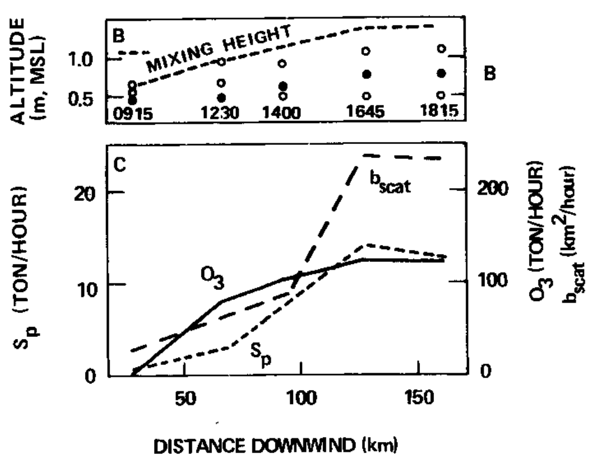

Figure 4-24b. Traverse altitudes and pollutant flow rates in the St. Louis urban plume on 18 July, 1975. Data are plotted against distance downwind of the St. Louis Gateway Arch. Closed circles correspond to traverse shown in 4-24a. Mixing heights were determined from aircraft surroundings. Approximate time (C.D.T.) of sampling is shown at the bottom.

Figure 4-24c. Flow rates (in excess of background) of ozone (O_3), bscat, and particulate sulfur (S_p). The total loading across the plume for all these increases, indicating that these pollutants are being produced in the plume.

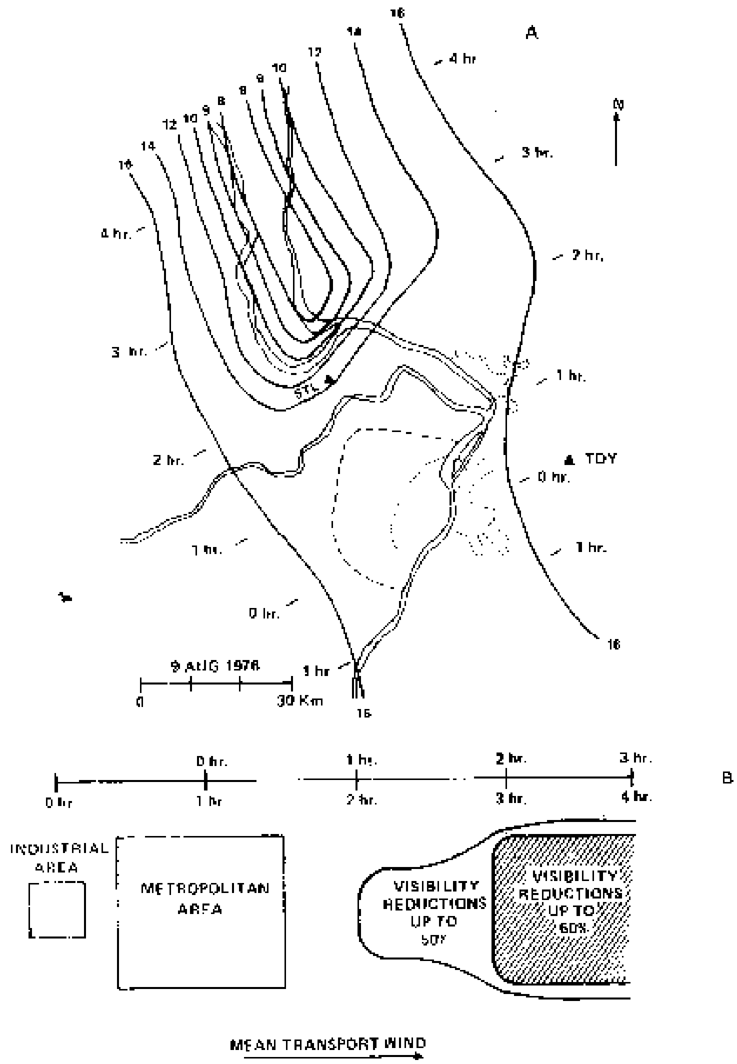

Figure 4-25. Visual range contours (statute miles) downwind of St. Louis for 9 August, 1976 between 1400-1800 CDT. Outline of city limits and surrounding communities is represented by short-dashed lines and the metropolitan area by long-dashed lines.

Large-scale episodes of reduced visibility in the West have not yet been documented. The meteorological conditions, which lead to regional episodes also occur in the West, but, because of the low density of air pollution sources, Western episodes would be much less intense than in the East. Efforts to detail Western haze episodes are now under way (Niemann, 1979).

One of the earliest case studies of transport of large-scale hazy air masses was that of Hall et al. (1973). Since about 1975, the evolution and transport of regional-scale hazy air masses have received increasing attention by numerous research groups. Detailed case studies of such episodes have been reported by Tong et al. (1976), Husar et al. (1976), Lyons and Husar (1976), Wolff et al. (1977), Samson and Ragland (1977), Vukovich et al. (1977), Galvin et al. (1978), and Hidy et al. (1978), among others. A common finding among recent studies is that formation of regional-scale haziness is usually associated with the presence of slow moving high-pressure systems. Since precipitation is relatively infrequent in anticyclonic systems, the residence time of fine aerosol may be increased to a week or more.

An example of one such episode over a two-week period I June-July, 1975, is presented in Figure 4-26 (Husar et al., 1976). The sequence of contour maps reveals that multistate regions are covered by a haze layer in which noon visibility is less than 10 km (b_{ext} = 0.4 km^{-1}, outer contours).

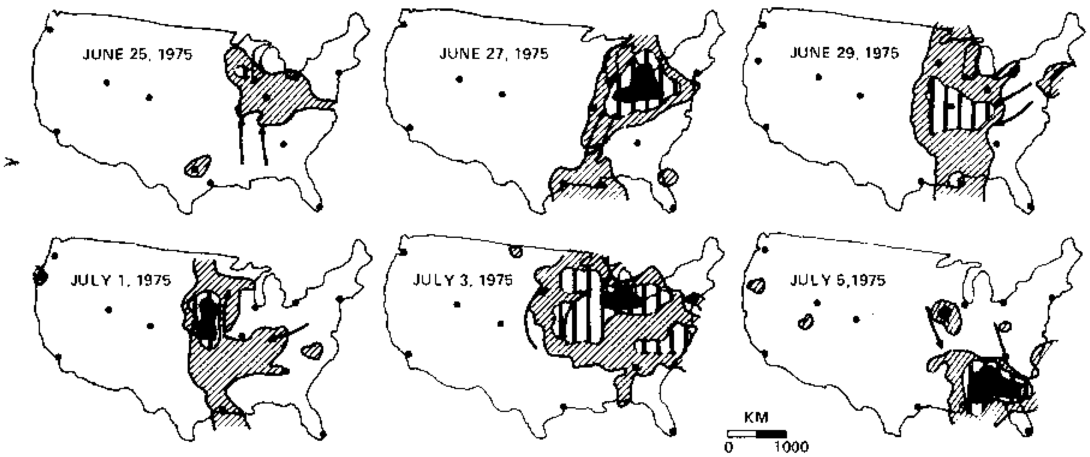

Figure 4-26. Sequential contour maps of noon isibility for June 25-July 5, 1975 illustrate the evolution and transport of a large-scale hazy airmass. Contours correspond to visual range 6.5-10 km (light shade), 5-6.5 km (medium shade), and <5 km (black) (Husar et al., 1976).

The regions of haziness in these and other such episodes are clearly visible in satellite photography (Figure 4-27) (Lyons and Husar, 1976). Sequential photographs confirm the motion of the haze. Figure 4-28 shows the impacts of regional haze at ground level.

Two passages of the June-July, 1975, hazy air mass over St. Louis resulted I sharp increases of bscat over the entire metropolitan region. Sulfate concentration also increased during the haze episode, from about 9 to 33 $\mu g/m^3$. Figure 4-29 indicates substantial correspondence of the regions of highest sulfate and lowest visibility for two days during the episode period. During this period, the visual air quality was beyond the control of any local jurisdiction. The Alabama Air Pollution Control Commission reported the following (Bulletin of the AAPCC, 1975):

"During the weekend of July 5, 1975, a heavy haze layer enveloped the State of Alabama and much of the Southeastern United States. At that time, the AAPCC technical staff received may comments from the public concerning the origin and composition of the haze. The National Weather Service in Birmingham did issue an air stagnation advisory (ASA) for Alabama for this same time period; however, the traditional pollutant measurements made by the AAPCC and local programs did not show excessive levels. In fact, the measured local levels were lower than had been measured under previous ASAs, making the dramatic decrease in visibility more intriguing."

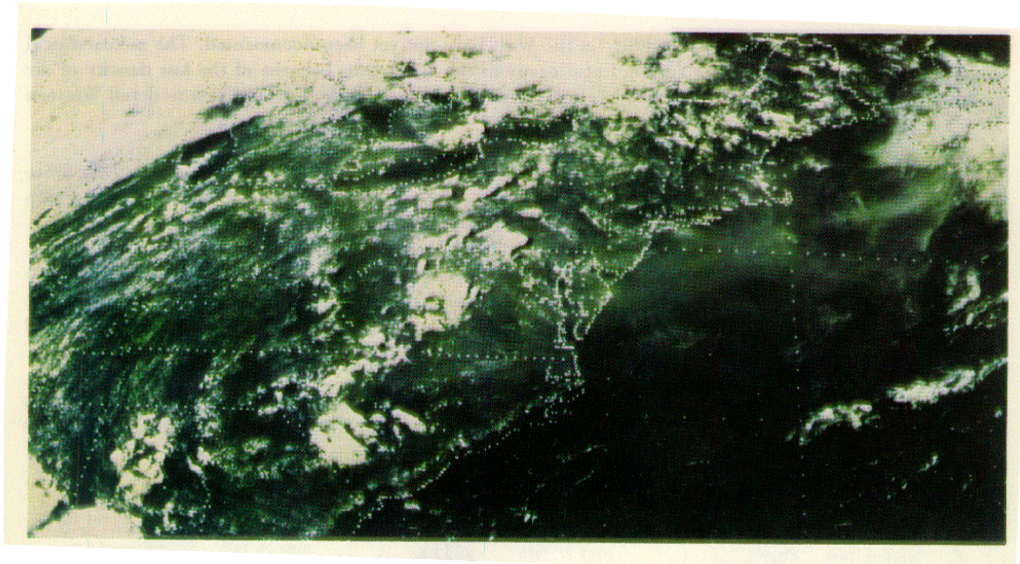

Figure 4-27. Satellite photograph of hazy air transport. Haze appears over parts of Ohio, West Virginia, Eastern seaboard states and stretches several hundred miles into the Atlantic (Lyons, 1979).

Figure 4-28. Eastern Regional Haze, (a) clear vista in White Mountains, New Hampshire (b) Effect of episodic haze intrusion.

Husar et al. (1976) reported that in June-August 1975, there were at least six episodes similar to that discussed above. Other investigators confirm that episodes of regional scale hazy air masses are not rare in the Eastern United States. Yet, at present, only the qualitative features of such episodes are understood; the observed effect on visibility, the composition in terms of secondary sulfate and ozone, and the apparent motion of the haze.

Important questions remain to be answered about regional scale episodes of haziness, including the following:

1. Do the hazy air mass and the meteorologically defined anticyclone completely coincide?

2. How may the effects of superimposing multiple SO_2 plumes and urban reactive plumes be quantified?

3. What are the effects of high pollutant concentration on rainfall, temperature, and cloudiness?

4. What is the actual residence time of fine particulates in the atmosphere during such episodes; it may be, for example, that lack of precipitation leads to extremely long sulfate lifetime.

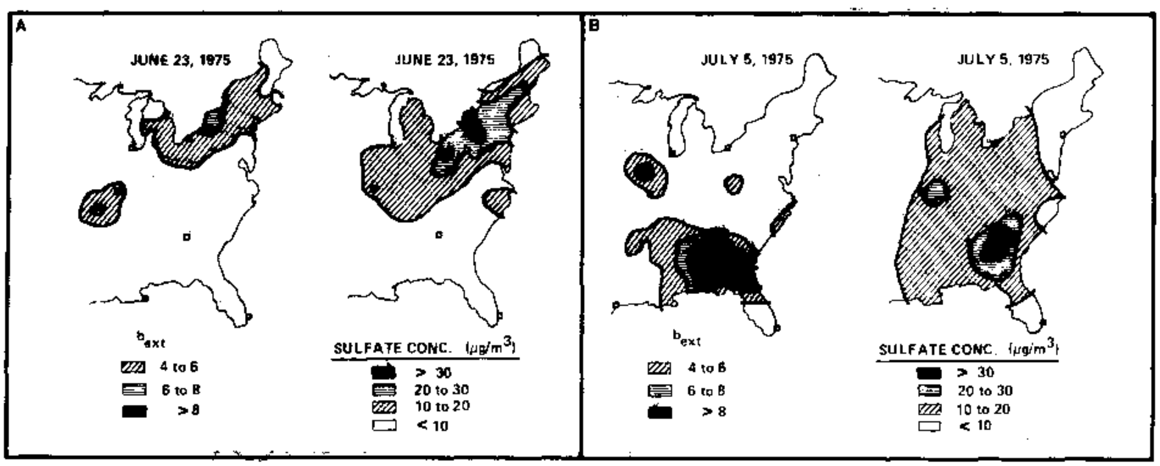

Figure 4-29. Comparison of noon extinction coefficient and daiy mean sulfate concentration on June 23 and July 5, 1975. The regions of ighest sulfate concentratios coincide with area of lowest visibility (Husar et al., 1976).

The current Sulfate Regional Experiment (SURE) program, sponsored by the Electric Power Research Institute, is yielding valuable information about sulfur transmission in the eastern United States. The Environmental Protection Agency's Transformation and Transport in the Environment (STATE) program is directed toward expanded knowledge of the complicated source receptor relationship. The upcoming Prolonged Elevated Pollution Episode (PEPE) project of STATE is specifically designed to sample such regional scale episodes of haziness from their inception throughout their residence over the eastern United States.

The East has experienced the most severe episodes of manmade haziness to date, because the sources of precursor gases are concentrated in that area. As noted in 4.3, empirical evidence indicates that anthropogenic sulfates are important factors in the visual air quality of the West and Southwest as well. Figure 4-30 from Holzworth (1972) reveals that the meteorological potential for air pollution/haziness in the West may be as high or higher than the Eastern U.S. potential.

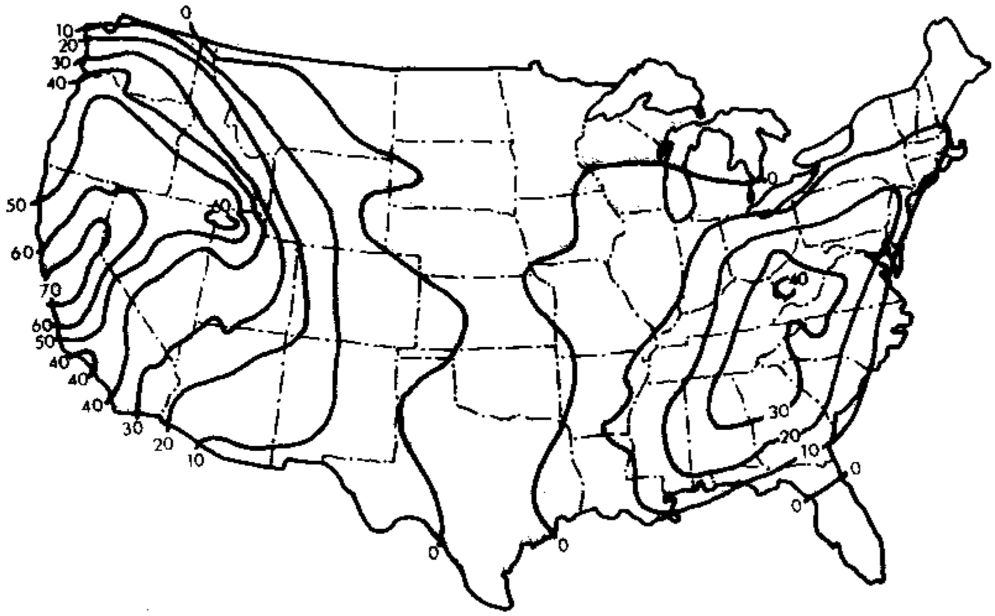

Figure 4-30. Isoleths of total number of forecast-days of high meteorological potential for air pollution in a 5-year period (Holzworth, 1972). Evidently the potential for regional scale anthropogenic haziness is at least as high in the West as in the East.

4.6 DIAGNOSTIC MODELS

When adequate information is available about both the source distribution and the total impact at a receptor, knowledge of the transmission from source to receptor completes the picture and permits quantification of the source-receptor relationship. The transmission of the most important pollutants that cause deterioration of visual air quality is more complex than simple dilution of the emissions by meteorological action; both NO_2 and atmospheric aerosols undergo the additional processes of formation and removal during transport. These key processes are currently the least well-documented aspects of the visibility problem; particularly, for the *secondary* fine particulate species (e.g. sulfate, nitrate, and organics), these processes entirely determine the impact of a source.

Since atmospheric kinetics cannot be measured directly, available emissions, trajectories, and resulting concentrations must be filtered through some mathematical formulation of the key processes to extract the rates of creation and depletion within the atmosphere. The mathematical formulation used for this purpose is referred to as a diagnostic model.

One of the best-known applications of a diagnostic model was for the analysis of the OECD monitoring data (OECD, 1977). An emission inventory and transport conditions for the European region were input to the model. The rates of gas to particle conversion and removal were then extracted by tuning these parameters until the best fit between calculated and observed concentrations was achieved. The resulting parameters for sulfur transmission from the OECD study are listed in Table 4-8.

The year-round average conversion rate of 1-2 percent per hour and the overall average dry removal rate of 3-4 percent per hour were major new results. Studies being conducted in the United States, with similar scope and objectives as the OECD study include the Multistate Atmospheric Power Production Pollutant Study (MAP3S) of the Department of Energy and EPA (MacCracken, 1978), and the aforementioned EPRI SURE program (Perhac, 1978), and the STATE project of EPA. Similar models have been deve4loped by Eliassen and Saltbones (1975), Fisher (1978), and Johnson et al. (1978).

Characteristic	Value
Fraction of emitted sulfur deposited locally	00.15
Fraction of emitted sulfur transformed directly to sulfate	00.05
Decay rate of sulfur dioxide	
Rain	14.4%/hour
Dry	03.6%/hour
Transformation rate of SO_2 to sulfate	01.26%/hour
Loss rate of sulfate	01.44%/hour
Mixing height	1000m

Table 4-8. Empirically derived atmospheric conversion and removal paramters for European region (OECD, 1977).

The main utility of the regional approach is that the obtained rate constants are inherently averaged over all sources and spatial-temporal scales of interest. The suitably tuned model may then be used to separate the impact of an individual source.

On a smaller scale, White and Husar (1976) estimated the aerosol size distribution dynamics contributing to visibility reductions at Pasadena, CA. Their study used emission grids of gases and particulates, solar radiation intensity, an initial marine background aerosol size distribution, and backwards trajectories at 1-hour intervals as inputs to the diagnostic model. The conversion rate was tuned to match the observed daily mean fine mass; thus, the output included hourly estimates of total fine mass and aerosol size distribution, as shown in Figure 4-31. Diagnostic models have also been developed for the urban plume of St. Louis (Isakson et al., 1978) and Power Plant Plumes (Gillani, 1978).

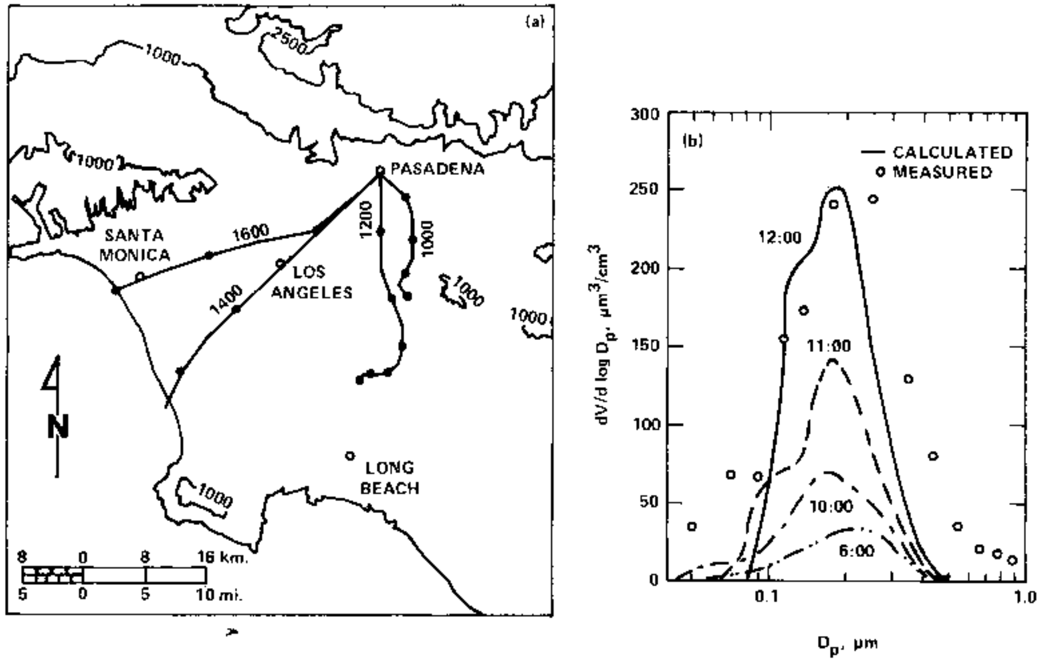

Figure 4-31. (a) Calculated air trajectories arriving in Pasadena on 3 September 1969; (b) Development of the calculated aerosol volume distribution (White and Husar, 1976).

In summary, the determination of the source-effect relationship of secondary fine particulates on a regional scale requires the filtering of measurable data (emissions, transport path, and concentrations) through a diagnostic model. The impact of major source regions can be roughly estimated once the model is properly tuned. Also, with care, the tuned diagnostic model may be used to investigate the effect of altering source characteristics.

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PROTECTING VISIBILITY

AN EPA REPORT TO CONGRESS

CHAPTER 5

5 MODELING VISIBILITY IMPAIRMENT

5.1 INTRODUCTION

While the empirical approaches of Chapter 4 are useful for identification or confirmation of source impacts on visibility, "prognostic " mathematical approaches are needed to predict the visibility improvement associated with retrofit controls or the incremental effect of proposed new sources. Thus, visibility models predict, for a given set of environmental conditions, the visual effects resulting from air pollution loadings of the atmosphere. The general flow of a visibility model is shown in Figure 5-1. Visibility models adapt the atmospheric dispersion and transformation features of other air pollution models to predict fine particle and nitrogen dioxide concentrations across a sight path. The modeling procedure must relate changes in light scattering and absorption, resulting from those atmospheric constituents, to changes in contrast, which will be perceived as changes in visibility.

Visibility models require information about the dispersion, transport, transformation, and removal of the pollutants, as well as the optical characteristics of the pollutants, the background air, and the environment (illumination, target properties). These factors must be further related to human visual perception to evaluate possible visibility impairment. Although there are uncertainties in all of these areas, ongoing research should result in significant refinements over the next several years.

5.2 REGIMES OF VISIBILITY IMPAIRMENT

Visibility models must address the major categories of impairment: "plume blight,” layers of discoloration, and general haze. As a preface for constructing predictive models, it is helpful to consider the processes that lead to these types of impairment. To simplify discussion, they are considered here as two separate regimes, depicted in Figure 5-2.

Plume blight may be defined as a coherent, identifiable plume, which can be seen as an optical entity against the background sky or distant object. Implicit in this definition is the assumption that a single source produces light-affecting pollutants that are not widely dispersed. Thus, plume blight is considered "local" and can be treated with traditional Gaussian dispersion modeling.

As the plume travels downwind, it diffuses throughout the mixing layer and becomes identified less as a "plume, " but more as a general haze, which obscures the view of distant objects. Not only are targets on the horizon masked, but also the contrast of nearby objects is reduced. In some cases, the haze may be elevated and appear as layers of discoloration. Multiple sources may combine over many days to produce haze, which may be regional in scale. The summertime haze in the Eastern United States is a prominent example of a very large-scale haze. Because of these different visual impairment regimes, separate modeling approaches must be used: short-term dispersion from a single source to model plume blight, and regional transport and climatic models to accommodate single or multiple sources on a larger meteorological scale. Scales of time and distance, which provide the dimensional framework for modeling, are graphically depicted in Figure 5-3. It is logical first to consider local short-term dispersion, which results in plume blight and haze layers from single sources.

5.3 SINGLE-SOURCE GAUSSIAN MODELS

Gaussian dispersion modeling, long used for estimating single-source pollution concentrations, is a reasonable concept for developing a local, single-source visibility model. With appropriate geometry, chemistry, and optical considerations, the visual effect of a plume against the background sky may be characterized.

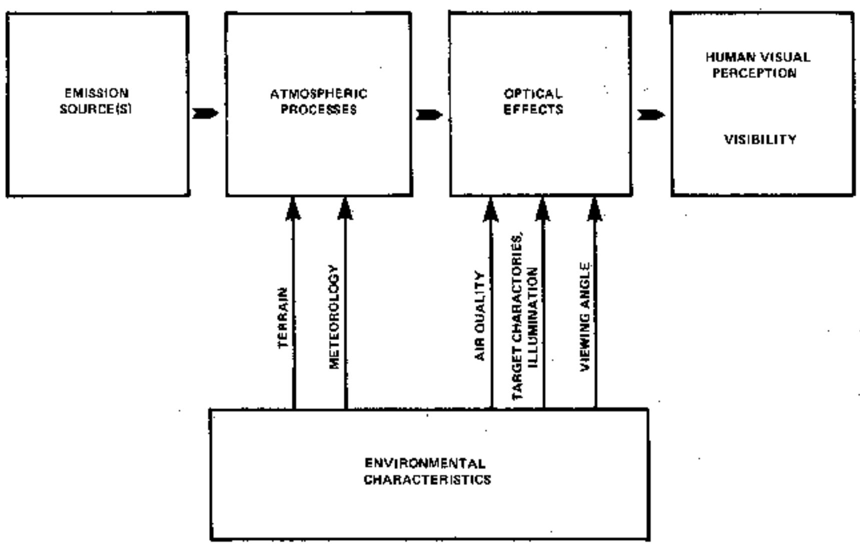


Figure 5-1. General visibility model.

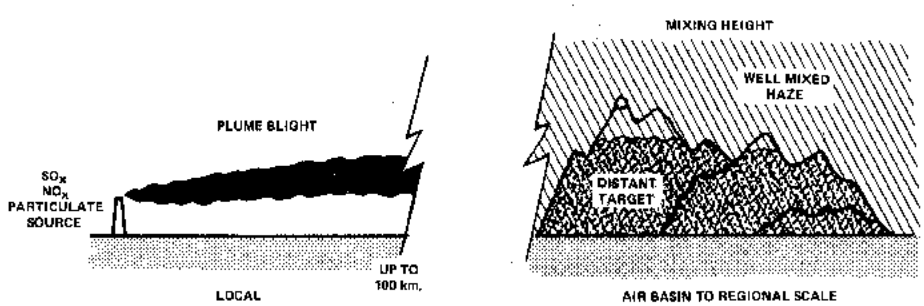


Figure 5-2. Visibility impairment regimes.

Several Gaussian based mathematical models have been developed that predict the optical effects of a coherent plume (Latimer et al., 1978; ERT, 1978; Williams et al., 1979). These visibility models are oriented toward emissions from individual point sources, such as smelters and coal-fired power plants, and compute the optical effects of primary fine particles, sulfate from sulfur dioxide emissions and nitrogen dioxide from nitrogen oxide emissions.

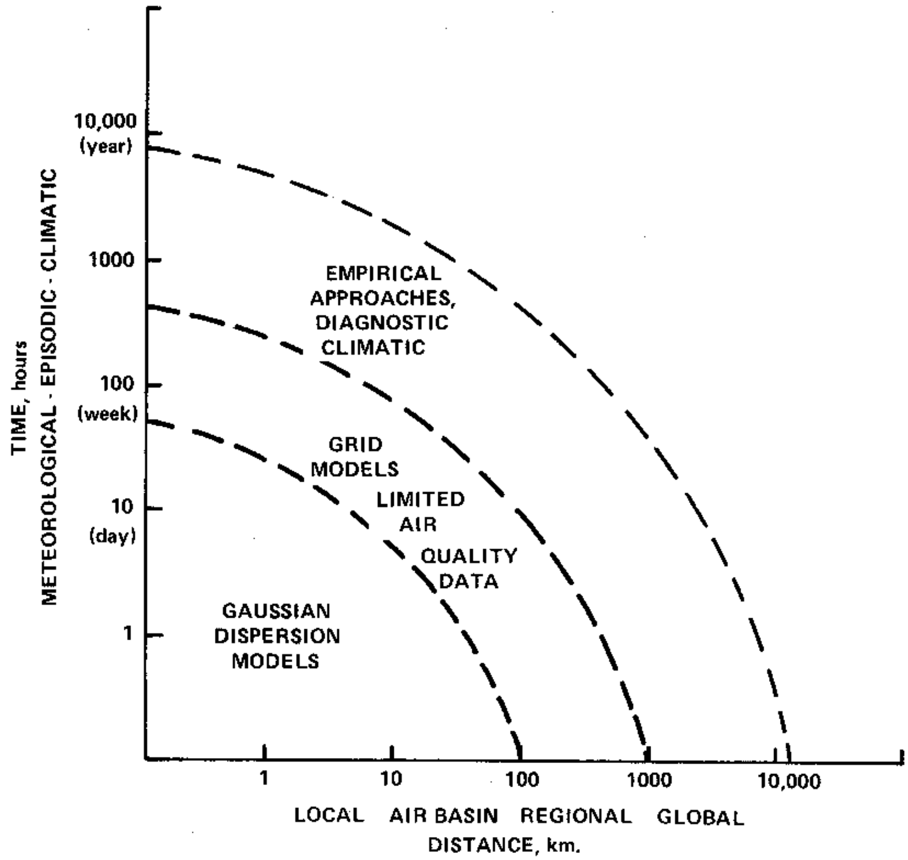


Figure 5-3. Scales of time and distance. Approximate dimensions for applicable models.

Figure 5-4 illustrates the major components of visibility models, in this case the model developed for EPA. The input requirements for these models include standard stack emission and meteorological data, plus additional data for computation of the optical effects of the particles and nitrogen dioxide gas. The models use Gaussian diffusion parameters for dispersion and empirical estimates or chemical reaction simulations to compute the transformation of sulfur oxides and nitrogen oxides to pollutants that affect visibility. The direction and amount of light scattered and absorbed by the particles and gases are calculated through approximations of the radiative transfer equation (Section 2.3). The output of the models is a set of wavelength-dependent light fluxes, which are then used for computation of more easily understood parameters representing the reduction of visual range and discoloration of the sky through the plume, contrast of the plume (against the sky), and overall perception of the plume.

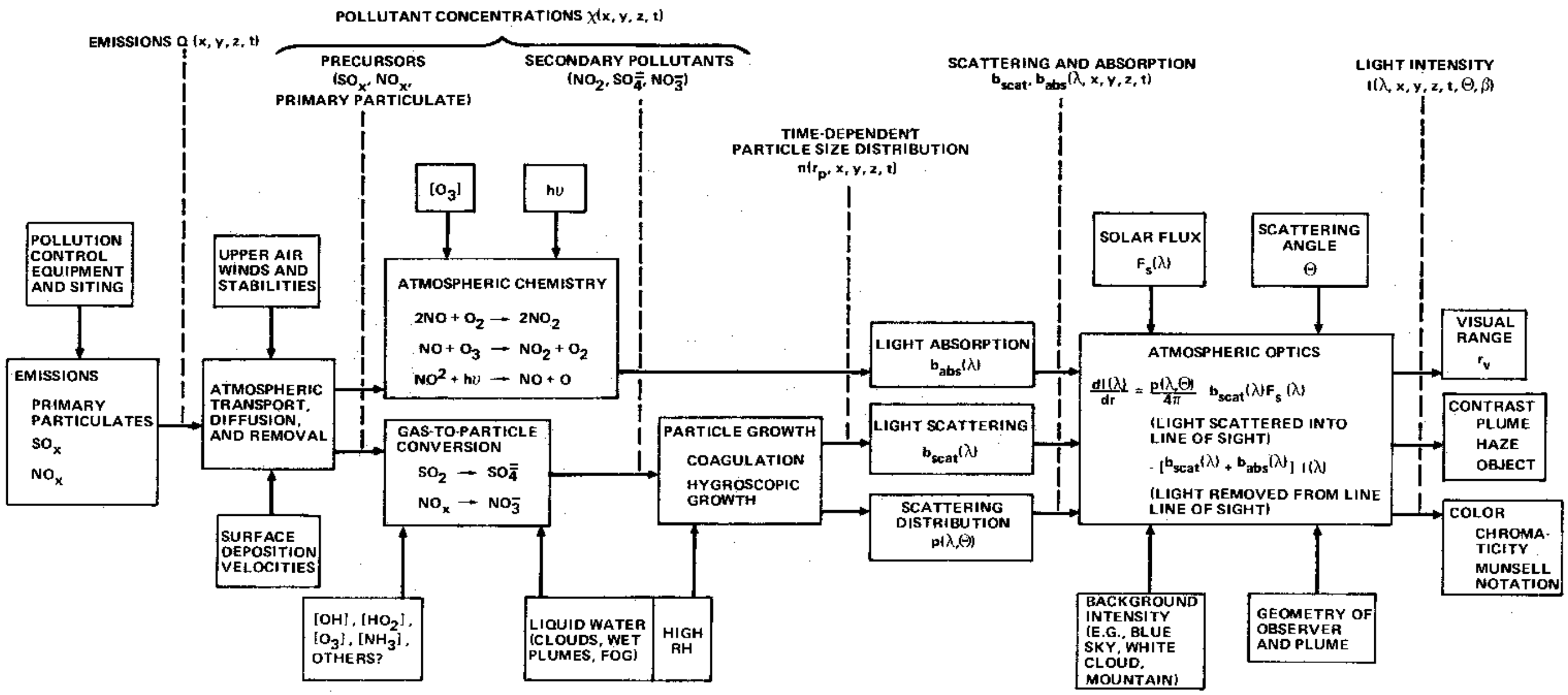


Figure 5-4. Flow of single-source Gaussian Visibility Model (Latimer, et al., 1978).

5.3.1 Display Formats

Two general kinds of formats have been developed for displaying the output of visibility models. The most commonly used format is a graphical plot of an optical parameter (such as discoloration) versus downwind distance for a set of given atmospheric and emission conditions. This format is useful for estimating distances where maximum visual impacts could occur and for quantifying parameters related to visibility. Figure 5-5 shows the graphical format used in displaying the EPA model.

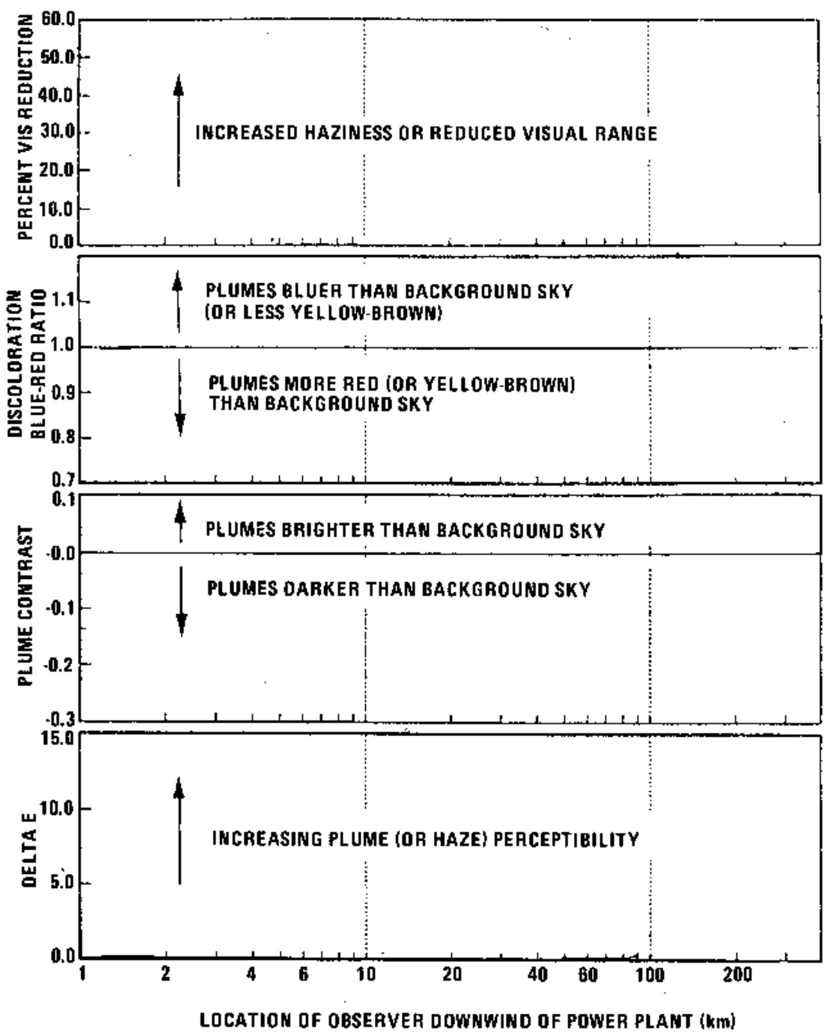


Figure 5-5. Example graphical format of single source-visibility model output (Latimer, et al., 1978).

A more dramatic format for displaying the output of visibility models has been developed by Los Alamos Scientific Laboratory for the Department of Energy (Williams et al., 1979). This technique creates a computer-generated simulation of a plume on a color television screen. To accomplish this simulation, a photograph of a "clean" background vista (Figure 5-6a) is digitized according to color and brightness of different elements in the picture (Figure 5-6b). Then, the effects of the plume, as predicted by the visibility model, are introduced into the clean picture by a digital computer, and the result is displayed on a color TV screen. Figures 5-6c and d show the model prediction for fine particle additions of 5 $\mu g/m^3$ and 26 $\mu g/m^3$, respectively, throughout the background scene. The resulting haze and reductions in visual range and contrast are apparent.

a. Original slide, "clean" scene visual range 250 km.

b. "Clean" scene digitized through computer.

c. Simulated pollution: Effect of addition at $5 \mu g/m^3$ of sulfate to (b). Visual range 80 km.

d. Simulated pollution: Effect of addition of $26\ \mu g/m^3$ of sulfate to (b). Visual range 20 km.

Figure 5-6. Clean, digitized clean, and simulated haze photographs (Williams et al., 1979).

The computer simulated plume or haze picture is more readily useful for illustrating impacts than are graphical outputs. Only one location can be depicted at a time, however, and the extensive and sophisticated hardware requirements are presently too costly to allow for routine simulation of many views and conditions. Additional uncertainty is introduced in this technique because the elements of the original picture must be digitized, modified according to the model, and converted back into a color television representation. Moreover, no visibility model can currently predict human color perception. As such, photographic representations may be misleading. Nevertheless, this promising display technique should be developed for more routine use as visibility models are improved and our understanding of color perception increases.

5.3.2 Applications of Single Source Visibility Models

The single-source Gaussian plume visibility models developed for EPA and DOE (LASL) have been applied to a variety of conditions for different sizes and emission levels of hypothetical coal-fired power plants. The complete description of the EPA model, the assumptions under which it is run, and output scenarios are described in detail elsewhere (Latimer et al., 1978). The LASL model scenarios are also detailed elsewhere (Williams et al., 1979).

The sample applications assume flat terrain, constant dispersion conditions and fixed transformation ratios. At sulfur oxide emission levels comparable to the ceiling for the recently promulgated new source performance standard (NSPS) for power plants, the model predicts relatively little sulfate haze at distances up to 100 km from a single 2000-MW facility. Limited mixing conditions, longer downwind transport, and multiple sources-even widely separated-could intensify the impact significantly, however, since fine- particulate sulfates have long-residence times in the atmosphere and may accumulate under such conditions. The Gaussian models do not adequately address cumulative pollution intensification from separated emission sources.

The potential for discoloration from nitrogen dioxide (NO_2) may be significant at distances up to 80 km even for a plant meeting the NSPS for nitrogen oxides (NO_χ). The models also show that primary particles, controlled at NSPS levels, contribute little to visibility impairment. Therefore, discoloration from NO_2 might be the most troublesome cause of local plume blight for new power plants.

Figure 5-7 is an example of the EPA model's output for a 2250-MW coal-fired power plant under neutral (D) atmospheric stability. In this example, SO_2 emissions are the maximum ceiling allowed by the current NSPS (1.2 Ib/106Btu). Four optical parameters are computed and plotted as a function of downwind distance from the source. Visual range reduction (top graph) results mostly from the sulfate formed from SO_2. The second graph shows discoloration effects plotted as blue red ratio. Under the indicated conditions, the plume would appear the most discolored-a reddish brown-about 25 km downwind. This predicted effect is almost entirely due to NO_2 formed from NO_χ emissions. Plume contrast (third graph) is an indication of the brightness of the plume relative to the background sky. The negative number indicates that, for these viewing and sun angles, the plume would appear darker than the sky. The same plume could appear brighter than the background under different illumination conditions. Delta E (bottom graph) is a parameter synthesized from color and brightness contrasts between sky and plume and represents a relative plume "perceptibility" term (see Section 2.2). According to the model, the plume would be most perceptible about 25 km downwind, owing mostly to NO_2 discoloration. Similar visual effects are indicated from the Gaussian model developed by LASL for DOE (Williams et al., 1979).

These models suggest two visibility impacts:

1. NO_χ emissions resulting in NO_2 formation may cause perceptible discoloration of a plume up to 80 km downwind, particularly during atmospheric conditions of poor dispersion. The perceptibility of the predicted impacts, however, must be empirically verified.

2. Sulfate formed from SO_2 emitted from poorly controlled large sources could cause perceptible haze for very long downwind distances. The effect from an individual well-controlled plant is small, but the cumulative effect of many sources may be large. These predictions agree qualitatively with aircraft plume studies summarized in Section 4.5.

It must be emphasized that no visibility model has yet been fully tested and validated.

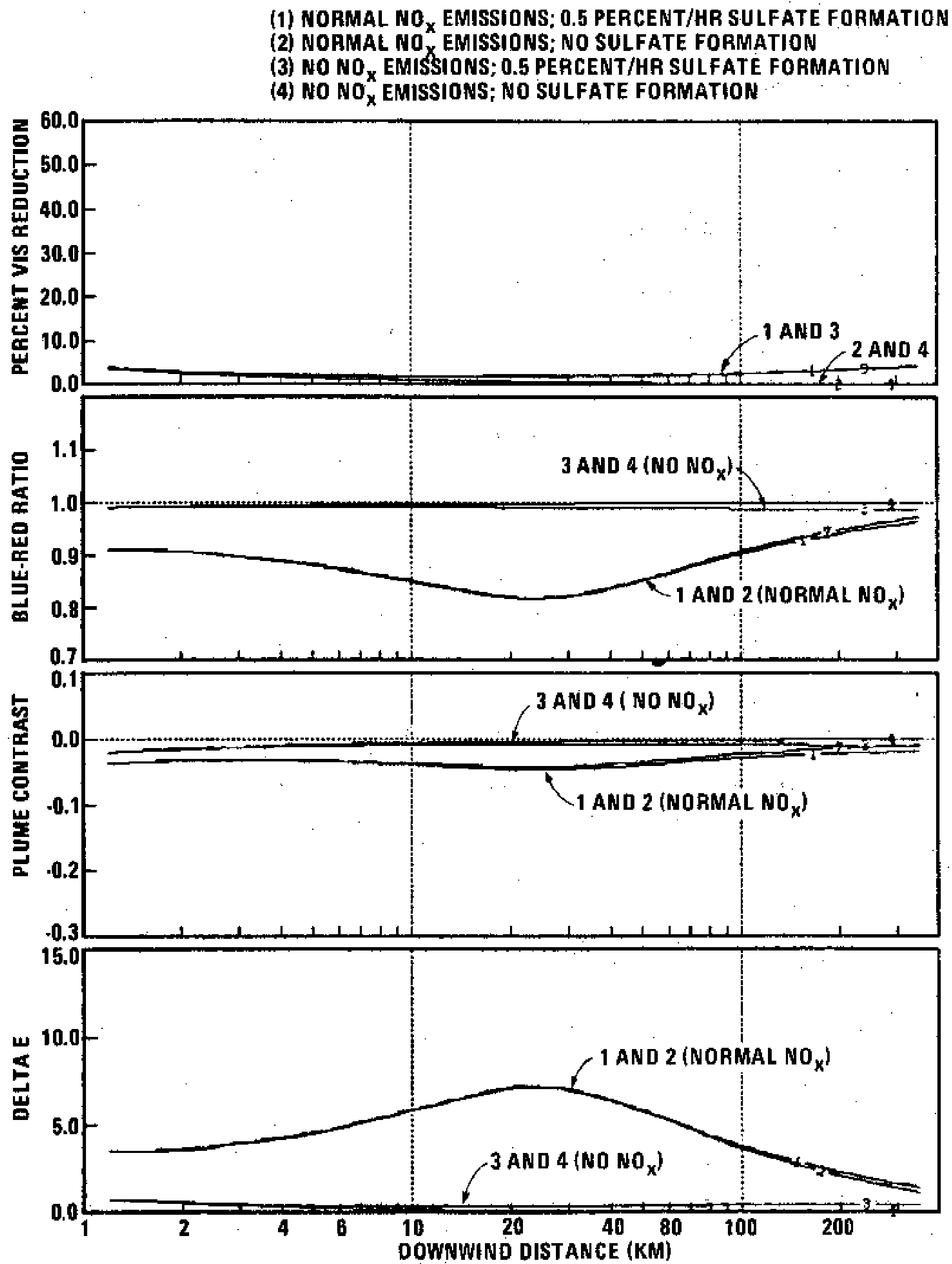


Figure 5-7. Visual effects predicted for a 2250 MW hypothetical power plant with stability D. View is perpendicular to the plume with sun overhead (90° light scatter).

5.3.3 Sensitivity Analysis for Single-Source Models

Sensitivity analyses provide insights into the potential uncertainties that may limit model application; that is, what input information needs to be known to what precision. Sensitivity analyses also can aid in identifying which variables may be the most important in controlling visibility impairment.

For a 2000-MW or smaller power plant operating at or below the current NSPS, single source visibility models are more sensitive to background pollutants and meteorological conditions than to SO_χ and particulate emission rates at distances up to 100 km from the source. The principle implication that could be drawn is that, for a well-controlled emission source, siting may be the key factor in protecting visibility in a class I area. Even if a validated single-source visibility model existed, there would likely remain enough inherent modeling uncertainty to preclude meaningful analysis of the incremental visibility improvement from particulate and SO_χ controls beyond those required for new source performance standards.

Visibility models are very sensitive to:

1. Background visibility input to the model, which is used as the base line. The aerosol loading of the background atmosphere is especially important because it determines the coloration of the background sky. In Figure 5-8, atmospheric discoloration from pollution in clean Western air is predicted to m significant while, under Eastern conditions, the effect should be masked.

2. Atmospheric conditions. Atmospheric stability can inhibit or promote dispersion of pollutants. Figure 5-9 and 5-10 a,b show the effect of atmospheric stability on visual effects. Dispersion decreases as stability goes from "C" to "F". Under stable conditions (such as E or F), mixing is limited and plume concentrations are greater with corresponding increased visual effects. As the mixing height increases, pollutants become more dilute and visibility effects are smaller.

3. Chemical conversion of SO_2 to sulfate and NO_χ to NO_2 and particulate nitrate. Figures 5-11 and 5-12 show the effects on visual range on varying the rate of sulfate formation from 0 to 5 percent per hour, and the effect on discoloration resulting from NO_2 formation from different levels of ozone. The effect of increased NO_χ emissions is shown in Figure 5-10c. The impacts of particulate nitrate formation (if any) cannot yet be estimated because of a lack of empirical data. The initial and ultimate particle size of secondary (and primary) particles is also important. Particles may be below, in, or above the optimal size range for light scattering during the course of transport and transformation.

4. Removal processes for SO_2 sulfate, and NO_2. Deposition mechanisms must be incorporated into visibility models to account for removal of pollutants from the atmosphere. Deposition on ground surfaces is increased by good mixing, lower stack heights, and certain surface characteristics of the terrain. The conversion-

removal processes determine the amount of secondary pollutants available for transport and dispersion.

5. Viewing angles relative to the sun and plume. These angles are important in determining the optical effect of the plume. Different viewing geometries result in different optical effects, e.g. Figure 5-10d.

5.3.4 Uncertainties and Limitations of Single Source Models

There are substantial uncertainties common to all visibility models that, unfortunately, affect the most sensitive input parameters described above. While different models use different algorithms in their dispersion and optical calculations, they are all sensitive to the same factors and share similar uncertainties. Limitations of visibility modeling can be categorized as follows.

1. Uncertainties inherent in dispersion modeling. Since the mathematical visibility model relies on some type of dispersion model, many of the uncertainties of air quality modeling will be inherent in visibility modeling. These uncertainties in modeling over flat terrain (such as assumed by EPA's and LASL's visibility models) are compounded greatly in complex terrain. Figure 5-13 is a physiographic diagram, which illustrates the mountainous terrain in the West. This terrain can channel pollution and create "corridors of pollution" which are very difficult to model. Visibility modeling is, however, primarily concerned with visual effects of a pollutant integrated through an entire plume. Questions of ground level concentrations at a point and horizontal dispersion are not as important as is the case for conventional air pollution modeling.

2. Optical and chemical characteristics of the pollutant. Research is underway to develop more information about the physical properties of pollutants which impair visibility and their formation mechanisms. Reasonable assumptions, however, may be made on the basis of empirical data.

3. Base-line visibility. There are very limited data available on base-line visibility. Airport visual range observations are of some use in determining historical trends but are often inadequate for modeling purposes. Because the determination of visual impact rests on base-line visibility, this is an important limitation.

4. Human visual perception. As discussed in Section 2.2, perception of color and contrast is based on psychophysical mechanisms, which are not completely understood. There are little data available to define threshold values of color perceptibility under actual atmospheric conditions.

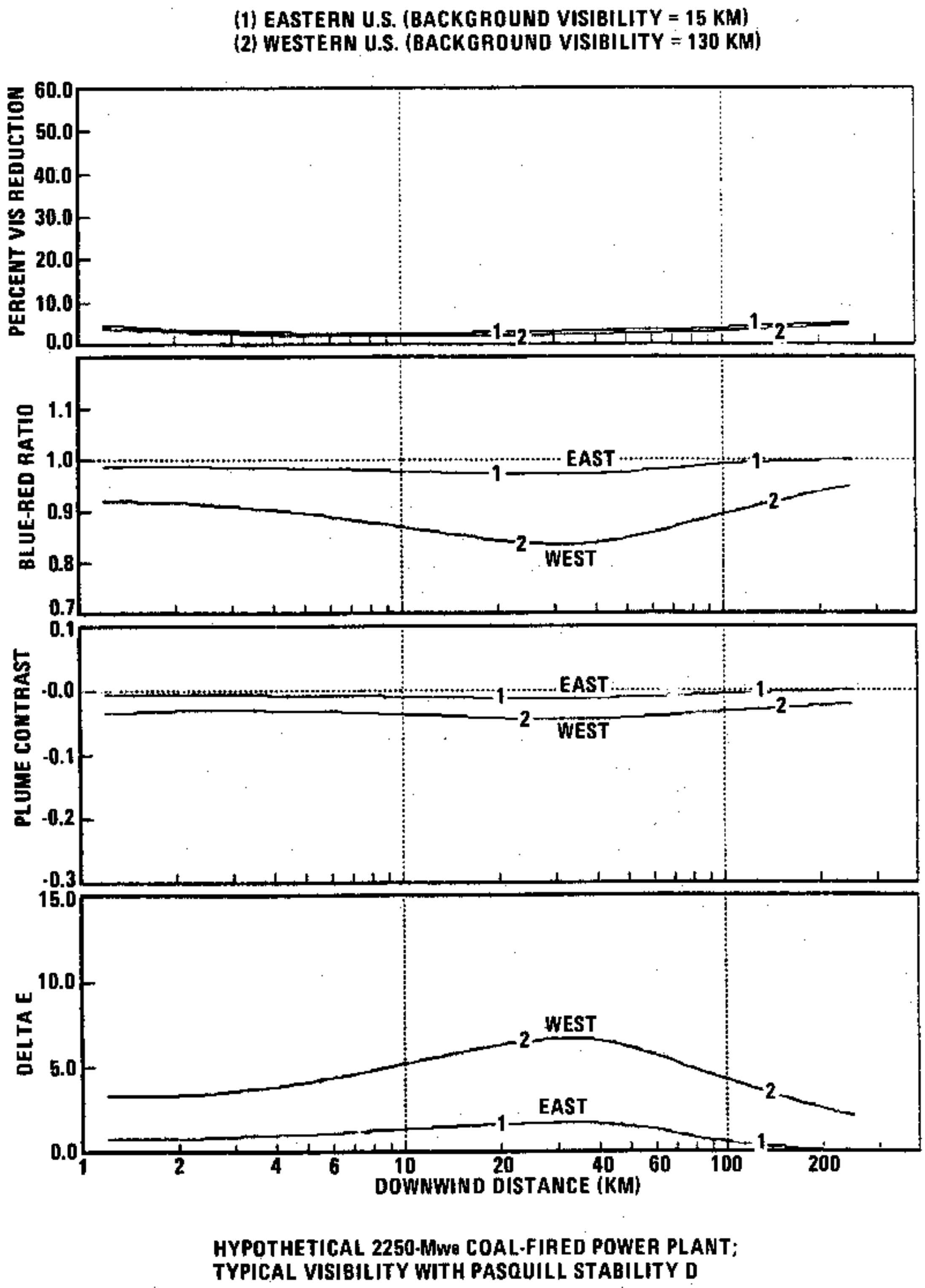
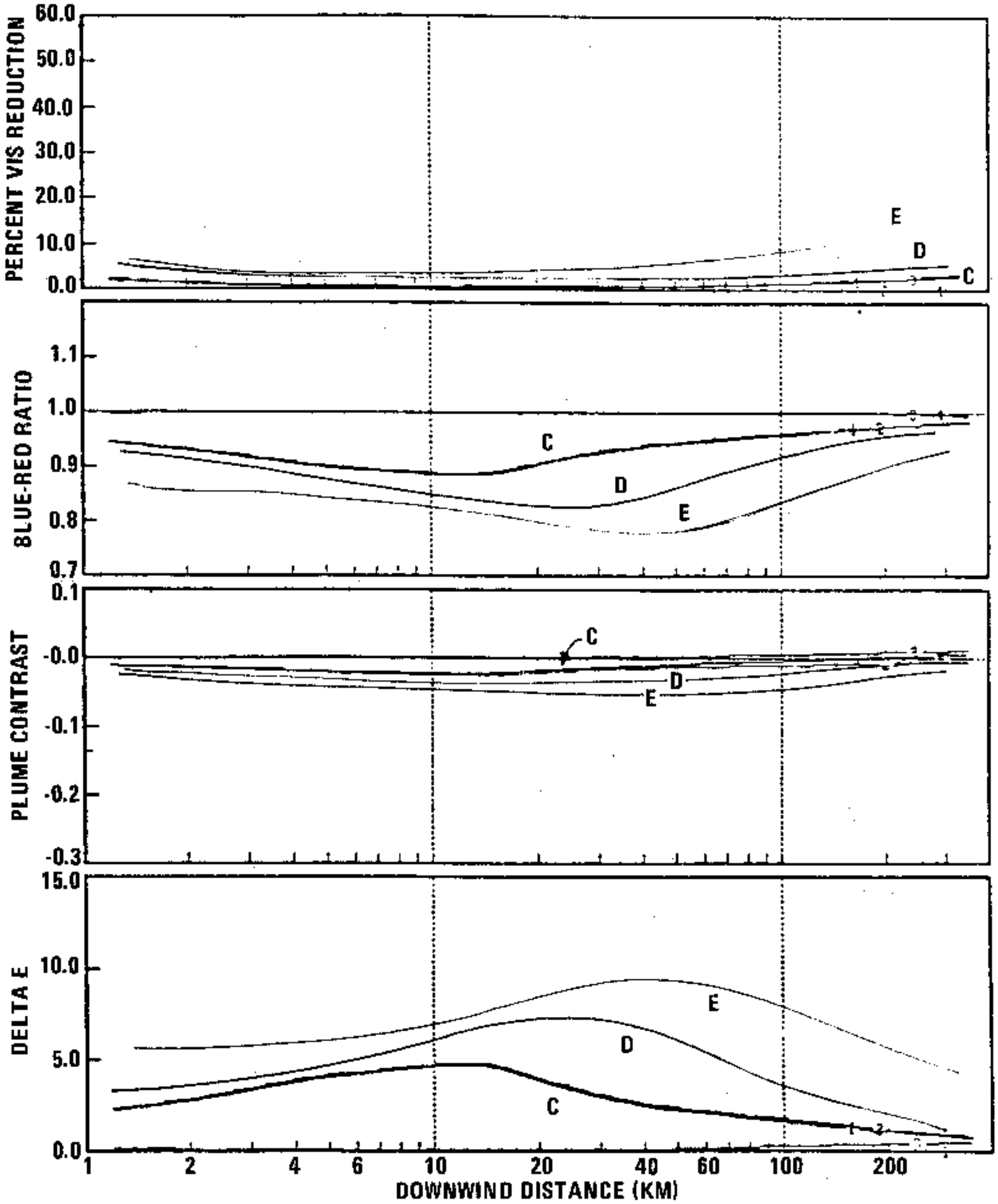


Figure 5-8. Comparison of predicted plume visibility in the eastern and western United States. Higher background particulate loadings mask NO_2 related discoloration.



HYPOTHETICAL 2250-Mwe COAL-FIRED POWER PLANT WITH LIGHT SCATTERING ANGLE OF 45°

Figure 5-9. Comparison of predicted visibility impairment for stabilities C, D, and E (slightly unstable, neutral, slightly stable). A single stability would rarely occur over the entire transport time and distance.

a. Base case, stable atmospheric conditons (F). Coloration due to NO_2.

b. Same as (a) except neutral stability (D). NO_2 plume less visible.

c. Effect of increase in NO_x emissions to 0.7 lb/MMBTU. Base case (a) equals 0.5 lb/MMBTU

d. Same as (a) except observer is closer to plume (3 km instead of 10 km) and plume normal (90°) line of sight (orientation angle for base case is

Figure 5-10. Comparison of simulated plume impacts for different atmospheric stabilities, NO_x emissions, and observer location. Hypothetical 2000 MW power plant viewed 30 km. downwind, low SO_x, particle emissions; other assumptions in Williams et al., (1979).

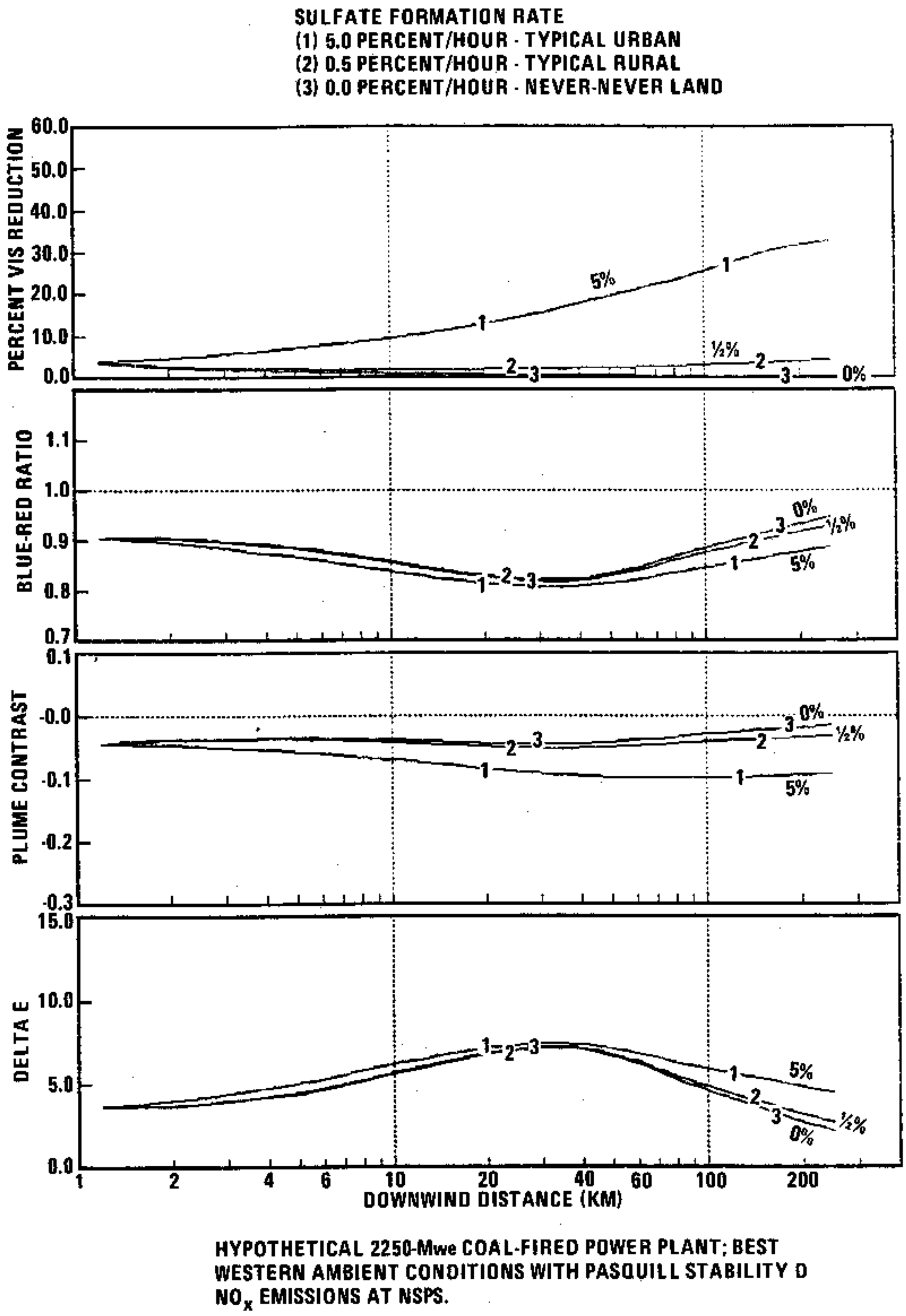


Figure 5-11. Comparison of effects of different sulfate formation rates. A marked increase in predicted haze occurs at rapid sulfate formation rates (5% per hour). Based on limited plume studies, overall Western conditions average about 0.5% per hour and range from 0 to 2% per hour (Wilson, 1979).

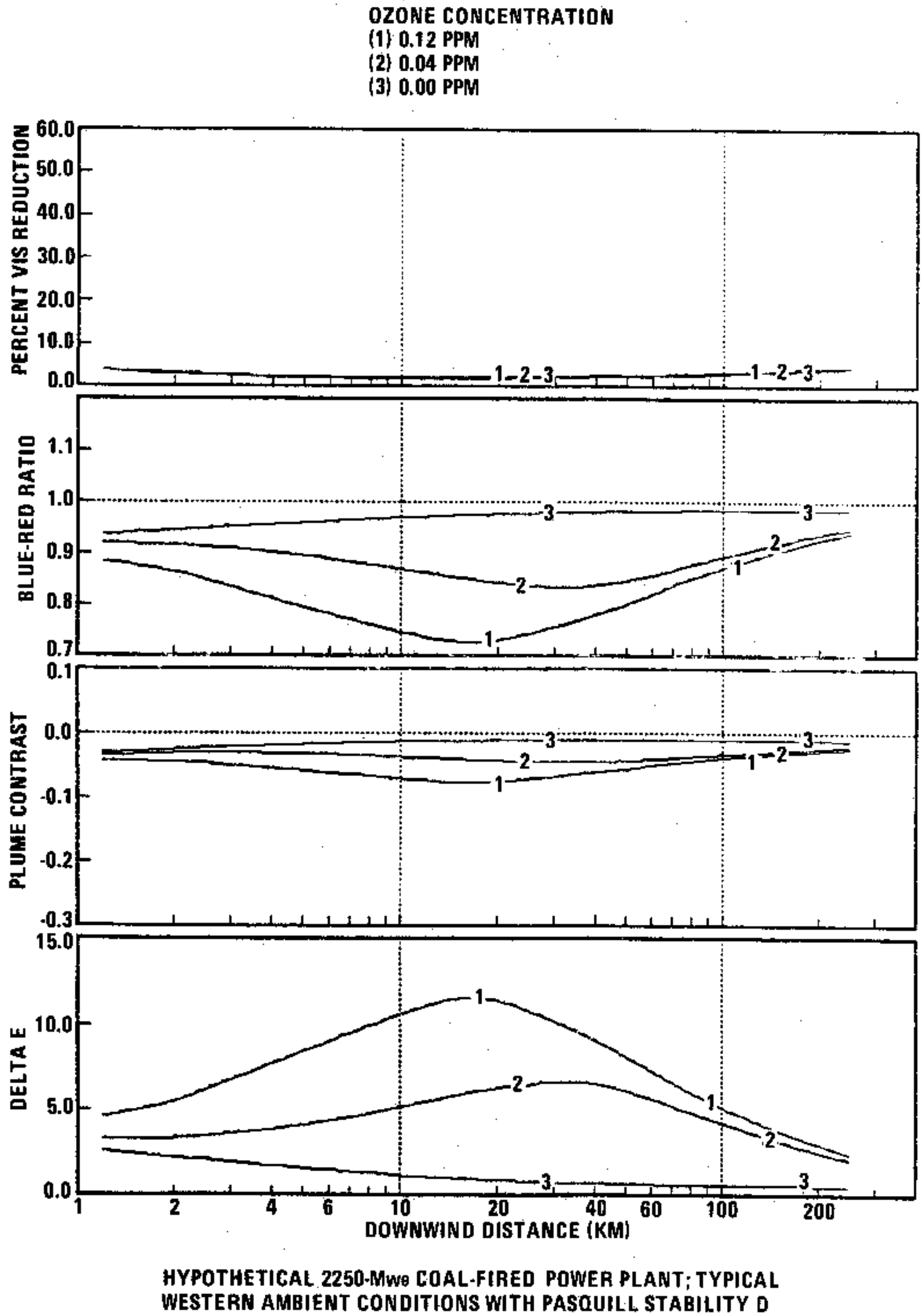


Figure 5-12. Comparison of effect of available ambient ozone on predicted visibility impairment from NO_2. Higher background ozone results in more rapid NO_2 conversion and greater discoloration from NO_2. In the West levels of 0 to 0.06 ppm ozone are typical.

5.4 REGIONAL MODELING

As a plume travels downwind and becomes uniformly vertically mixed (as illustrated in Figure 5-2), it may combine with pollution from other sources, both natural and anthropogenic. The resulting haze cannot readily be linked to a specific source, or perhaps not even to an area. The fate of this haze is now a function of meteorological processes that occur concurrently on larger scales of time and distance. Visibility modeling can be no more accurate than regional-scale transport models. Until the meteorological processes are better under- stood, regional visibility modeling, like other regional dispersion modeling, will be subject to significant uncertainties.

In Figure 5-3, the dotted lines separate the time and distance scales into different regimes for modeling applicability. Local short-term dispersion is handled through Gaussian modeling. As the time and distance increase, Gaussian modeling becomes less and less reliable and numerical grid schemes must be used. Most of the unknowns of Gaussian modeling remain, however, as well as a number of additional uncertainties, which arise because most of the simplifications, assumptions, and boundary conditions used in Gaussian modeling are no longer valid. Data are limited and computer numerical computations must be iterated many times over very large databases.

There is a certain balance between time steps and distance points, which is required in order to maintain computational stability in a numerical model. As time and distance dimensions increase, a point is eventually reached where numerical modeling is no longer practical. Diagnostic and other approaches based on empirical and statistical relationships (see Chapter 4) may then be used to suggest large-scale effects.

5.4.1 Applications of Regional Models

Various numerical regional models have been developed which attempt to predict the fate of pollutants over a wide area (Nuber et al., 1977; Lui and Durran, 1977). Generally speaking, on a regional scale, the transport of pollutants is controlled by air mass movement, which is dependent upon the wind field. Thus, most regional air quality models rely on some type of scheme to compute the changing wind field, which varies with time and in both horizontal and vertical dimensions and which transports the pollutant of concern.

To date, the application of these models to visibility consists mostly of computing isopleths of sulfate from SO_2 sources via chemical transformation, and then calculating increases in general extinction coefficient resulting from light scattering by fine-particulate sulfate. Obviously, many simplifying assumptions must be made, including assumptions regarding meteorology, transformations, and removal processes. Variations in terrain are reflected only in the changing wind field as it moves around and over mountains.

Figure 5-13. Physiographic Map of the United States. The uneven terrain of the West can channel pollution into "corridors" and is extremely difficult to model.

At this time, no validated regional air quality models are available for assessing the visibility impacts of many sources on a large scale. Latimer et al. (1978), however, have used regional models to estimate the potential spatial impact of multiple sources on regional visibility during short-term episodes. Qualitatively, the results of such preliminary predictions agree with empirical studies.

5.4.2 Sensitivity and Uncertainties of Regional Models

Regional visibility models are extremely sensitive to the rate of conversion of SO_2 to sulfate and to the wind field, both of which are uncertain and must be assumed or interpolated from limited data.

Among the additional limitations of regional models are:

1. Lack of adequate inventory of emission sources and base-line visibility. The visual impact of any source at any location is a function of existing visibility. Any model must be able to handle multiple sources. Urban areas in particular are difficult to characterize.

2. Incomplete knowledge of large-scale meteorological processes and uncertainties about boundary conditions. Chemical transformations apparently vary greatly and are largely unknown on regional scales.

3. The existing visibility database is insufficient for input to a model and too imprecise for validation of output.

4. Statistical and empirical methods such as those discussed in the previous chapter do not necessarily specify source and effect relationships and do not permit strategy analysis because of the independent variables.

5.5 SUMMARY AND RECOMMENDATIONS

Development of visibility models is just beginning. No model has been validated at this time, although the optical principles used are sound and theoretical concepts have been established. The primary modeling questions concern optical and chemical properties of the integrated cross section of the plume and not individual concentrations at specific points. The sensitivities of the models can be used to advantage in identifying critical variables in consideration of visibility impairment, given visibility model input parameters.

Despite the inherent uncertainties, visibility models can and should, within certain limits, be used to evaluate source impacts. Single-source models can estimate the expected visual effects of primary particle emissions at distances of up to 50 to 100 km from the source. These models can also be used to provide rough estimates of the impacts of sulfur and nitrogen oxide emissions at similar distances for relatively isolated sources located in clean environments. Thus, the degree of visibility improvement resulting from controls on major, obvious sources of plume blight can be predicted, and potential visibility impairment by proposed major facilities can be addressed. In the case of new sources proposed to be located within 100 to 150 km of class I areas, an analysis of prevailing meteorological conditions, background visibility, and application of available single-source plume models can provide an improved basis for siting decisions. Preliminary model applications suggest that, with careful siting, power plants meeting the recently promulgated NSPS can be constructed without serious impairment in class I areas.

Models for evaluating the effectiveness of controls on existing or proposed new sources on a regional scale require further refinement and validation before they can be used in regulatory applications. Empirical data analyses, coupled with mathematical modeling exercises, are a useful tool in identifying at least the scales of time and distance upon which visibility impairment may occur. On the basis of empirical evidence and modeling exercises, it is reasonable to expect that changes in the regional emissions of fine particles and sulfur oxides will produce changes in regional visibility levels, although the extent, duration, and location of these changes as a function of emissions can not be adequately predicted at this time.

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PROTECTING VISIBILITY

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CHAPTER 6

6 SIGNIFICANT SOURCES OF VISIBILITY IMPAIRMENT

6.1 NATURAL SOURCES

Vision in the natural, unpolluted atmosphere is restricted by blue-sky scattering (Air molecule light scattering is often termed Rayleigh scattering), by curvature of the earth's surface, and by suspended liquid or solid natural aerosols. Important sources of natural aerosols include water (fog, rain, snow), wind-blown dust, forest fires, volcanoes, sea spray, vegetative emissions, and decomposition processes. Although these sources are not generally amenable to control, they contribute to the natural "baseline" visibility in class I areas. As such, their impacts must be considered in evaluating anthropogenic visibility impairment.

6.1.1 Visibility Effects of Particle-Free Air

The particle-free atmosphere scatters light and limits visual range to about 200 miles at sea level. Although no class I area enjoys such perfectly clean air all year, Charlson et al. (1978) and Malm (1979) have measured light scattering coefficients within a few percent of the particle-free limit on a number of occasions in Southwestern class I areas. Since light scattering by air molecules is proportional to the air density, it decreases with altitude as shown in Table 6-1.

Class I Area	Altitude (m)	Rayleigh Scatter[a] (km^{-1})	Potential Visual Range (km)	Contrast[b]
Acadia	Sea Level	0.012	337	-0.49
Big Bend (1200m)	1000	0.011	371	-0.51
Grand Canyon (2100m)	2000	0.010	410	-0.54
Bryce Canyon (2500m)	3000	0.009	453	-0.56
Mt. McKinley (6000m)	4000	0.008	503	-0.59

Table 6-1. Rayleigh Scattering by clean air. [a]Rayleigh scattering coefficient for 0.55μm light (roughly green). Scattering for 0.400μm (blue)) at sea level is 0.042 km^{-1}. Scatttering at longer wave lengths is much smaller. [b]Apparent contrast between the sky and a dark tree covered mountain 50 km away. Initial contrast is –0.87.

Dark objects, such as distant mountains, when viewed in daytime through a particle-free atmosphere, appear bluish because blue light is scattered preferentially into the line of sight. Bright snow-covered mountain tops or clouds on the horizon can appear yellow to pink because the atmosphere scatters more of the blue light from bright "targets" out of the line of sight, leaving the longer wavelength colors.

The actual visual range in the particle-free atmosphere is also limited by the earth's curvature. Few class I areas have any vistas in excess of 200 km (120 miles). Thus, Rayleigh scattering is seldom the limiting factor in the detection of the most distant objects, i.e. the visual range. Rayleigh scattering is, however, important in reduction of visual texture and in bluish coloration of distant dark visual targets. Moreover, air scattering is solely responsible for the blue color of the non-horizon sky.

6.1.2 Visual Impairment by Condensed Water

Atmospheric water vapor is transparent for visible radiation. Deposition of water vapor onto condensation droplets (producing fog, clouds, or snow) or absorption of the vapor by suspended particles can drastically change the optical properties of water. White convective cumulus clouds may appear "from out of the blue" simply by a change of phase from transparent gas to light-scattering droplets. Such natural visibility-impairing water condensates include clouds, rain, hail, snow, and fog.

Relative humidity is a measure of the amount of water vapor in the atmosphere and as such, is an index of the potential for condensation of water onto small particles from natural or manmade sources. At relative humidities greater than 70 percent, the condensation of water vapor onto hygroscopic particles (e.g., sulfates) significantly increases light scattering and visibility reduction (Charlson, et al., 1978). Figure 6-1 illustrates average U.S. humidity levels. Humidities higher than 70 percent are common in the East and in the Pacific Northwest.

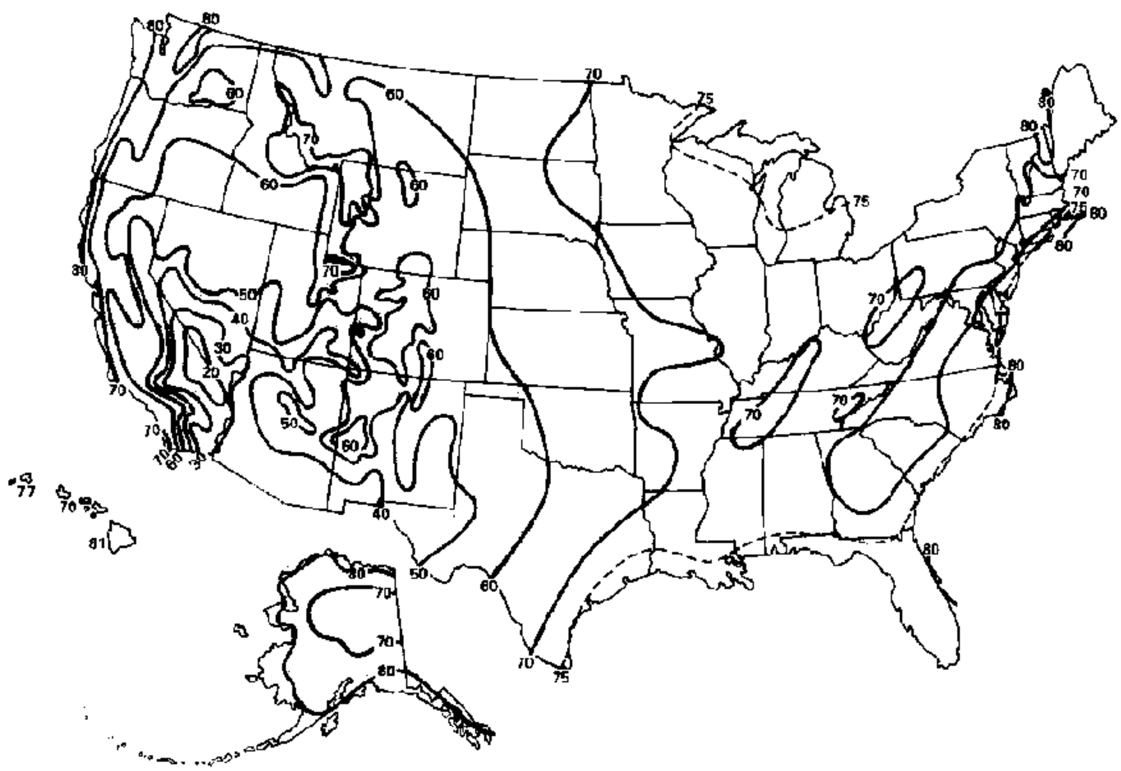

Figure 6-1. Annual mean relative humidity (5) (NOAA, 1978).

Fog is a naturally occurring phenomenon, which can reduce the visual range to nearly zero. It is characterized by high liquid water content, typically over 1000 $\mu g/m^3$, dispersed in droplets with a mean diameter of several micrometers or more. In "natural" fogs all colors are scattered and absorbed about equally, so the atmosphere appears white (Husar, et al., 1979).

The historical frequency of occurrences of fogs in the continental United States reveals considerable geographic variability (Figure 6-2). Coastal areas experience the highest frequency. Most inland portions of the United States west of the Appalachians can expect fewer than 20 days of fog per year, with less than five days of fog annually in the arid west.

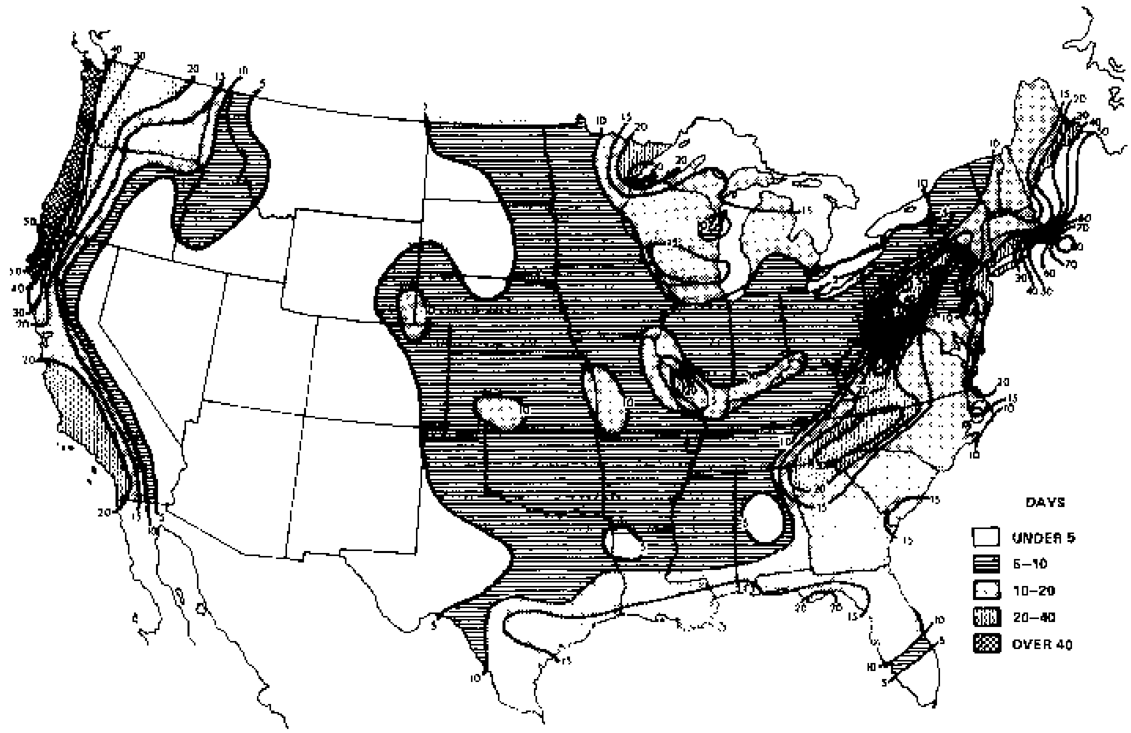

Figure 6-2. Average annual number of days with occurrence of dense fog (Conway, 1963). Coastal and mountainous regions are most susceptible to fog.

With the exception of coastal and mountainous regions, fogs are rare during the summer months. Fogs tend to be localized events of, at most, a few hours duration, commonly during the early morning hours. On an hourly basis, fogs exist less than one percent of the time (Conway, 1963). Thus, the overall contribution of fog to the degradation of visual air quality is small, and it is an insignificant cause of reduced visibility during the daylight hours.

Thunderstorms and other rainfall can also reduce visibility. East of Nevada, most of the U.S. experiences from 30-50 days each year with thunderstorm activity. Such storms are most common on summer afternoons. Since thunderstorms are usually intense but brief, they also contribute to visibility reduction less than one percent of the time on an annual basis.

Snow is another major natural cause of degradation of visual air quality. It is an important factor in many regions of the North and in some mountainous areas, where blowing snow occurs from 1 to 12 percent of winter hours (Conway, 1963). During the winter months, snowstorms may account for most of the hours of reduced visibility, and certainly may dominate the episodes of extremely low visibility in winter months.

The natural contribution of fog, thunderstorms, snow, and other forms of precipitation can thus cause severe degradation of visual air quality. With few exceptions, however, these intense but infrequent events do not dominate the average visual range within the continental U.S.; typically only a small percentage of the hours involve storms or fog. Such effects are currently beyond human control and are seldom viewed as an aesthetic degradation of visual air quality. It is also worth noting that the removal of manmade aerosols by precipitation often leads to a relatively clearer atmosphere.

6.1.3 Visual Impairment by Wind-blown Dust

In the arid West, where many class I areas are located; the contribution of wind-blown dust to degradation of visual air quality is an important problem. Because human activities that disturb natural soil surfaces add significantly to wind-blown dust, dust storms are only partially natural (see Section 6.2.4). Quantification of these effects is important for visibility protection programs.

Cohesiveness of the particles to the underlying material, the force of the surface wind, and the topography of the surface layer determine the suspension of particles from the surface. The ideal situation leading to suspension of surface material is a dry, crumpling, or disturbed crust in flat terrain without vegetation. Agitation of such surfaces by strong winds and turbulence can transform a pristine arid atmosphere into a dust storm with severely reduced visibility.

Suspended crustal material in a dust storm usually consists of coarse solid particles with volume mean diameters of tens of micrometers (μm) or more. Figure 6-3 displays measured particle volume size distributions in a major Texas dust storm. Most of the particulate mass is of diameter much greater than 2 μm. As discussed in Chapter 2, the light scattering efficiency per unit mass of coarse particles is very low relative to that for fine particles; however, the mass of coarse particles in a severe dust storm is on the order of several thousand $\mu g/m^3$, so that total light extinction is pronounced. Pattterson et al. (1976) found that the optically important fugitive dust particles include those up to 40 μm in diameter.

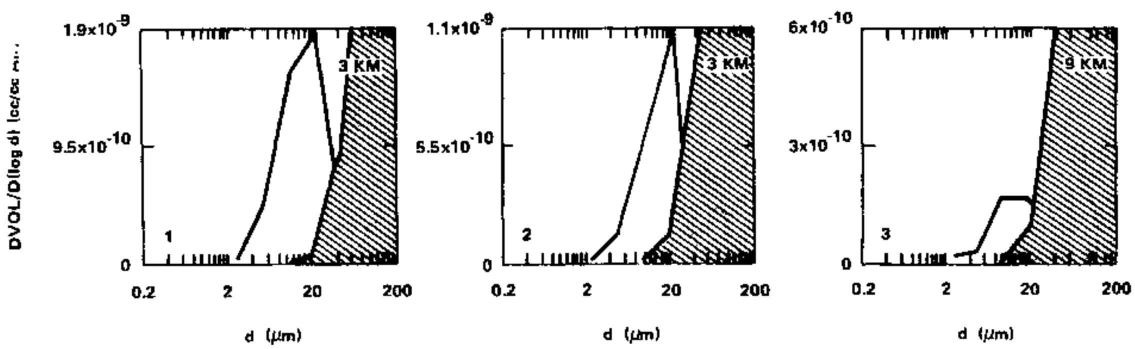

Figure 6-3. Aerosol volume size distributions of dust collectedin a major dust storm in NW Texas on 18 April 1975 (Gillette et al., 1978). The optically important dust mode peaks at about 20 μm diameter.

Orgill and Sehmel (1976) have analyzed the frequency of occurrence of dust storms in the continental United States in great detail, based on National Weather Service observations of wind-blown dust and sand associated with visibility of seven miles or less. The peak hours for dust are noon to eight p.m., during the period of maximum thermal turbulence. Forested, coastal, and mountainous regions have few, if any, episodes. The Pacific coast has high (>0.1%) incidence of dust only in the San Joaquin Valley and the Los Angeles Basin. Western desert areas in Eastern Washington, Western Nevada, Utah, New Mexico, and Arizona are also prone to dust. The highest dust frequency is in the Southern Great Plains, where wind-blown dust is a serious problem up to 3% of the time (Figure 6-4).

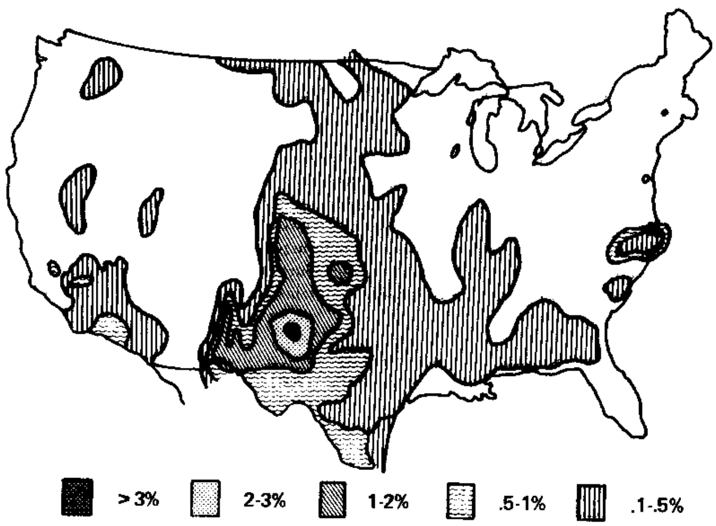

Figure 6-4. Annual percent frequency of occurrence of wind-blown dust when prevailing visibility was 7 miles or less, 1940-1970 (adapted from Orgill and Sehmel, 1976). Dust is a visibility problem in the Souther Great Plains and Western desert regions.

The monthly dust frequencies for seven regions covering the contiguous United States show a consistent summer maximum (Figure 6-5). The spring and fall peaks are partially due to agricultural activity in most sections of the country.

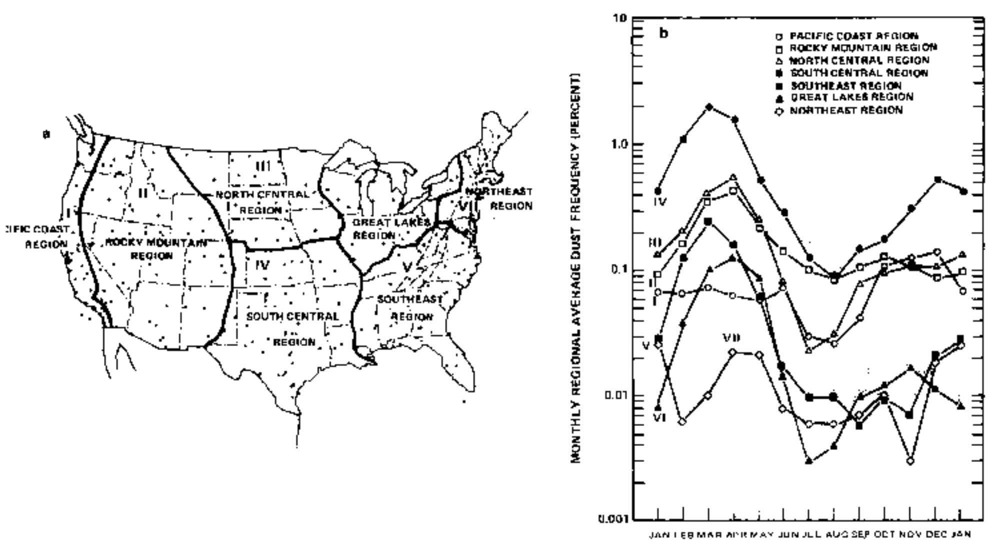

Figure 6-5 (a) Seven defined dust regions; (b) Monthly regional average frequencies for seven regions of the U.S. (Orgill and Sehmel, 1976). Dust is most common in the South Central region, and least common in the industrialized Northeast.

Visual Impairment by Forest Fires

Since many class I areas are located in or near forested areas, wildfires can be a significant source of natural visibility impairment. Controlled burning of forested areas by human intervention is, however, increasingly replacing the natural process of uncontrolled wildfires. Such managed burning is discussed in Section 6.2.4.

Forest fires impair visibility by producing massive visible smoke plumes and by causing general haze and reduced visibility over broad regions. Studies of the burning process (Sandberg and Martin, 1975) and measurements made in forest fire plumes (Radke et al., 1978) indicate that approximately 80 percent of the mass of smoke particles is less that 1 μm in diameter. Figure 6.6a shows light scattering coefficients measured in the plume of a managed burning of logging debris. The width of the visible plume is sketched in Figure 6.6b. Similar measurements made in other fires indicate that visual range in smoke plumes can be reduced to one mile or less (Eccleston et al., 1971; Packham and Vines, 1978).

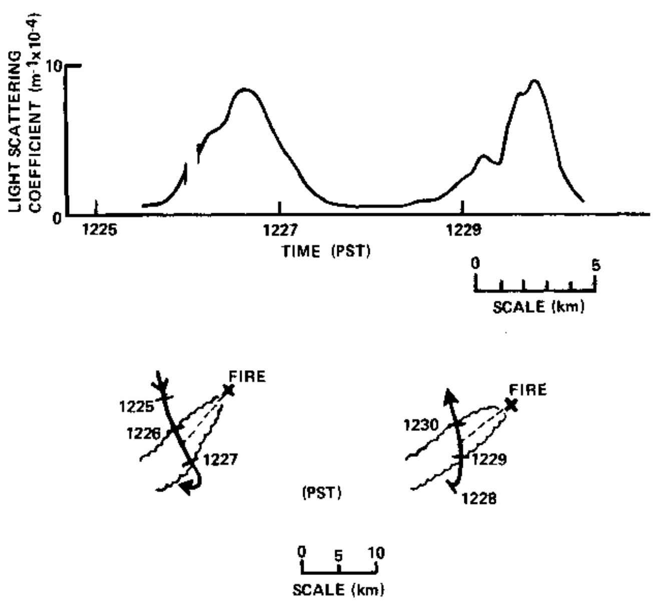

Figure 6-6. (a) Measurements of light scattering coefficient for forest burning plume. Thepeak in scattering occurred when the plume was intercepted. The broken segment was due to instrument adjustment. (b) Flight path of the aircraft. The broken line indicates theThke plume centerline. Thke first pass was made at an altitude of 520 m, and the second pass was made at an altitude of 580 m (Radke et al., 1978).

Wildfires burn approximately 1.8 million acres per year in the United States and emit an estimated 2 million tons per year of particulate matter. The regional breakdown of wildfires for 1975 is presented in Figure 6-7 (U.S. Forest Service, 1976). Although a large number of fires are reported, most of these are extremely small. Large fires constituting less than one percent of the total number of occurrences consume about two-thirds of the total acreage burned.

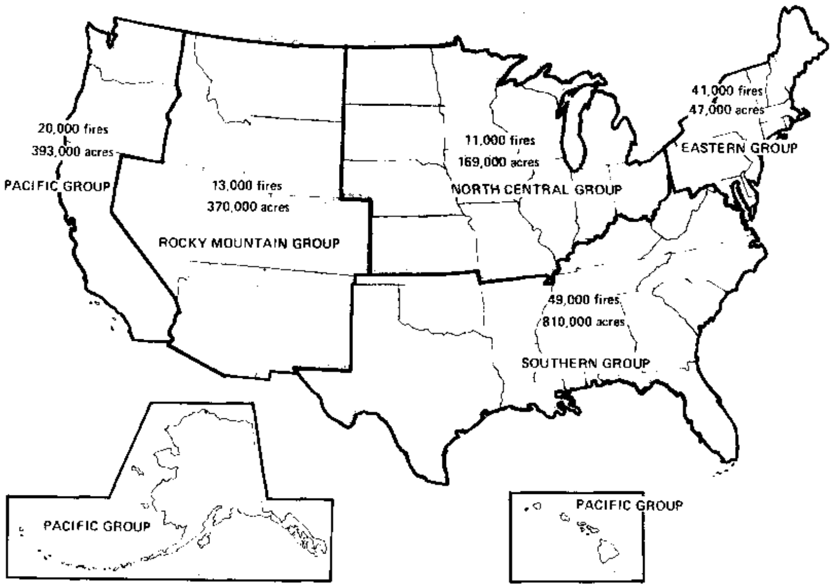

Figure 6-7. National wildfire statistics, 1975 (USFS, 1976).

6.1.5 Visual Impairment by Natural Sources of Secondary Aerosols

Secondary aerosols are those formed by atmospheric reaction of gaseous "precursor" emissions. Important natural sources of secondary aerosols include biogenic emissions of hydrocarbons and various sulfur species and volcanic emissions of sulfur dioxide (SO_2). These emissions can, under varying conditions, be transformed into fine particles and impair visibility.

Plants release a number of volatile organic substances comprised primarily of ethylene, isoprene, and a variety of terpenes. Although all of these substances are photochemically reactive, the terpenes can be transformed from the vapor state into particulate matter. Smog chamber studies demonstrated that terpenes from pine needles react rapidly with ozone to produce a blue haze (Rasmussen and Went, 1965; Jeffries and White, 1967). The blue color indicates that the gaseous terpenes react to form particles with the diameter of less than 0.1 μm. Particles of this very fine size preferentially scatter blue light (Chapter 2). Similar bluish hazes have long been noted in heavily forested areas. The Blue Ridge Mountains and the Great Smokies may owe their names to terpene-derived particles.

An initial attempt at a natural hydrocarbon emissions inventory for vegetation has been reported by Zimmerman (1978). Figure 6-8 indicates the major biotic regions of the United States. Table 6-2 lists regional vegetative emission factors derived from direct measurements of emissions from trees and forest litter and estimates of the distribution of species in the major regions. It should be noted that oak emissions consist primarily of isoprene, which does not form particles, while conifer emissions are principally terpenes, which do. Terpene emissions tend to be greatest at higher temperatures, at lower elevations, and in the spring of the year. Due to uncertainties in sampling procedures, biomass estimates, and insufficient data for various times of year, latitude, temperature, and sun conditions, these vegetative emissions estimates should be considered only as rough approximations.

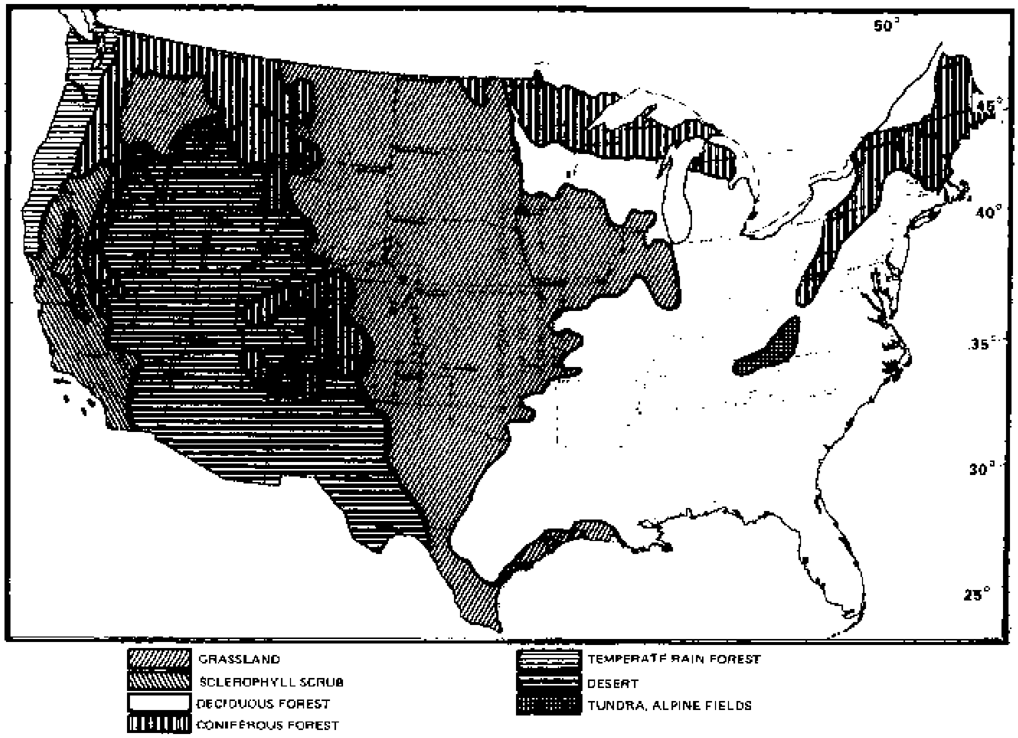

Figure 6-8. Major biotic regions of the United States (Zimmerman, 1978).

Because adequate measurements of ambient concentrations of terpene derived particulate matter in rural areas are not available, it is difficult to estimate the extent of their visual impacts. Based on the emissions estimates in Table 6-2, the temperate rain and conifer forest regions of the Pacific Northwest should have among the highest natural terpene emission densities. Since visual ranges reported in the region (25 to 35 miles) are three to four times higher than those of the Southeast, factor other than terpene emissions must dominate haze in Southeastern class I areas. This is supported by limited air sampling in the Smoky Mountains (Dzubay, 1978). Non-sulfated particles amount to about one-third of fine particulate mass in the Smokies (less than 8 $\mu m/m^3$). Only a portion of this non-sulfate fraction could have been derived form terpenes. Because terpene particles cause blue haze, their size is probably less than the optimal light scattering range (0.1 to 1 μm). This reduces their potential effect on contrast and visual range. Eventually, however, such particles may undergo further transformation and growth into the optimal scattering range. Additional information is needed on the impacts of terpenes in specific class I areas.

Biotic Region	Vegetation type	Leaf biomass, g/m^2	Emission factors, $\mu g/m^2 - hr^a$		
			Day	Night	Winter
Grassland	Conifers	5	44.5	44.5	17.5
	Oaks	2.5	61.75	11.75	0
	NC-NI[b]	3.75	16.13	16.13	0
	NO-I[c]	3.75	38.6	9.00	0
	LL[d]		162	162	0
Total		250	322.98	243.38	17.5
Schlerophyll Scrub	Conifers	15	133.5	133.5	52.5
	Oaks	30	141	141	0
	NC-NI	210	903	903	0
	NO-I	45	463	24.72	0
	LL		162	162	0
Total		300	2402.50	1364.22	52.5
Temperate Rain forest	Conifers	990	8811	8811	3465
	Oaks	55	1385	258.50	0
	NC-NI	22	94.6	94.6	0
	NO-I	22	226.6	226.6	0
	LL		162	162	0
Total		1100	10679.20	9552.70	3465
Deciduous forest	Conifers	135	1201.5	1201.5	473
	Oaks	180	4446.0	4446.0	0
	NC-NI	90	387	387	0
	NO-I	45	463.5	108	0
	LL		162	162	0
Total		450	6660	2704.5	473
Coniferous forest	Conifers	559	4975.10	4975.10	1957
	Oaks	39	963.30	183.30	0
	NC-NI	26	111.80	111.80	0
	NO-I	26	267.80	62.40	0
	LL		162	162	0
Total		650	6480.00	5494.60	1957
Desert	Conifers	25	222.5	222.5	88
	Oaks	25	617.5	117.5	0
	NC-NI	40	172.0	172.0	0
	NO-I	10	103.0	24	0
	LL		162	162	0
Total		100	1277	698	88
Tundra, alpine field	Conifers	18	160.2	160.2	63
	Oaks	0	0	0	0
	NC-NI	9	38.7	38.7	0
	NO-I	9	92.7	21.60	0
	LL		162	162	0
Total		180	453.6	384.3	63

Table 6-2. Vegetative volatile organic emission activities (Zimmerman, 1978). [a]Standardized to 30°C; [b]NC-NI = non-conifer, non-isoprene emitters; [c]NO-I = non-oak isoprene emitters; [d]LL = leaf litter/soil, pasture.

Natural sulfur sources include sea spray, volcanic activity, decay of animal and plant tissue, green algae, microbiological activity along shores of lakes, rivers, marshes, and oceans, and inland soil processes. Sea spray generally consists of large particles and effects on visibility are limited to the near shore area. Volcanic emissions are of significance on a global scale, but the small number of volcanoes located in or near class I areas are often considered part of the visual resource, such as in Hawaii Volcano Park. The natural source of sulfur nearest most class I areas is therefore biological (biogenic) processes.

Various attempts at deriving a global sulfur budget suggest significant quantities of biogenic sulfur emissions. However, all available estimates are subject to considerable uncertainty and controversy (McClenny et al. 1979). Recent measurements of natural sulfur emissions from various soil types suggest that swamp and marsh regions produce the largest emissions. Measurements of emissions from inland soils in Indiana, Ohio and Arkansas suggest an emission rate of 0.002 to 0.02 grams of sulfur per square meter per year (Adams et al., 1979). Emissions from marsh areas indicate average rates of 0.02 grams of sulfur per square meter per year (McClenny et al., 1979). One apparently unique marsh site emitted over 100 grams per square meter per year.

Further work must be undertaken before more reliable natural sulfur emissions estimates are possible. However, assuming an inland soil emission rate of 0.02 grams of sulfur per square meter per year, natural sources in the entire Eastern United States (approximately 3 million km^2), emit an SO_2 equivalent of 120,000 metric tons per year, or about as much as a single 800 megawatt power plant burning 2 percent sulfur coal. Emissions form marsh area alone might be equivalent to the inland soil contribution. These relatively small emissions estimates together with measurements made in remote locations suggest that biogenic contributions to secondary sulfate levels should be less than 1 $\mu m/m^3$ in most class I areas.

6.1.6 Example of Natural Effects in the Southwest

The association between visibility and some natural phenomena in the arid Southwestern United States is illustrated in Figure 6-9 (Latimer et al., 1978). In this "Venn" diagram the outer box represents the fraction of the time (about 20%) when visibility was below 80 km. Similarly, the area of the right-most circle represents frequency of occurrence of sky cover greater than 90 percent.

Overlapping areas of two or more circles represent the fraction of the time when each phenomenon occurs simultaneously. Visibility below 80 km always occurs when fog is present, and reduced visibility usually accompanies precipitation. The coincident occurrence of reduced visibility wit sky cover greater than 90 percent; relative humidity grater than 90 percent and wind speed greater than 10 meters per second is also more frequent than would be expected by chance. With the exception of fog, however, none of the natural parameters is necessarily a cause of reduced visibility greater than 80 km.

The diagonally shaded portion of the visibility less than 80-km circle represents the fraction of the time when reduced visibility cannot be attributed to the natural phenomena shown. This suggest that over half of the occasions of reduced visibility may be due to other causes, such as other natural sources and anthropogenic aerosols.

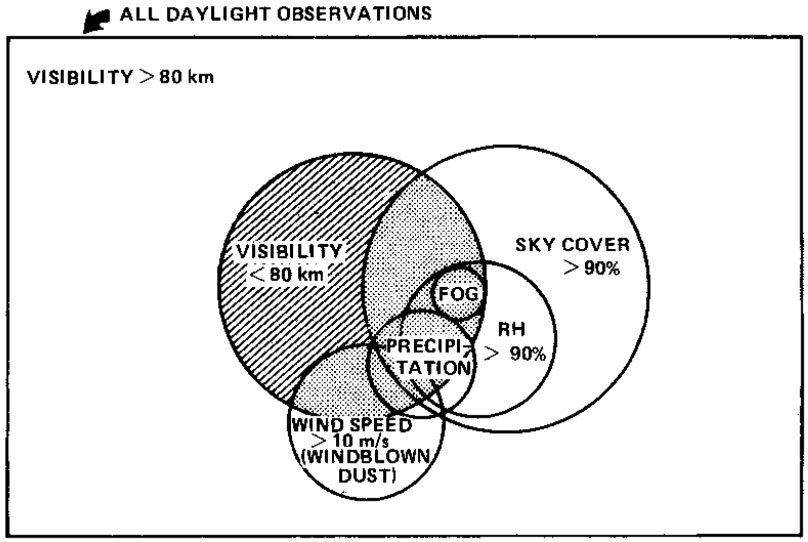

Figure 6-9. Venn diagram of the association of some naturla phenomena with visibility in the Southwestern U.S. Over half of the hours of daylight visibility below 800 km remain unexplained by these natural phenomena (Latimer et al., 1978)

6.2 ANTHROPOGENIC SOURCES AND CONTROL TECHNOLOGY

This section discusses anthropogenic sources of air pollution, which may potentially impair visibility. An overview of national emission densities and major source categories is presented, followed by summary information on the characteristics, location, growth potential, and applicability of control to several important source categories that may impair visibility in class I areas. This information is intended to provide some idea of the spatial distribution of current and future emission sources in relation to class I areas, the general effectiveness of the available control technology and a rough estimate of the economic costs of installing such technology on certain source categories. No attempt is made to provide a definition of "best available retrofit control technology" for specific source categories or to provide and economic impact analysis. A regulatory impact analysis is, however, being prepared in support of the forthcoming EPA proposal of visibility regulations and guidance to the States.

6.2.1 Overview

The principal air pollutants that directly impair visibility are fine particles (aerosols) and NO_2. Sulfur oxides emissions contribute to visibility impairment because they are transformed into sulfates, which, in some areas, can dominate the fine particulate mass loading. Volatile organic compounds (VOC) can contribute to visibility impairment by increasing photochemical formation of sulfates, nitrates, and NO_2 and by conversion into organic aerosols. Nitrogen oxides also participate in photochemical reactions. Therefore, the emissions of particulate matter sulfur oxides, nitrogen oxides, and volatile organics are of significance to visibility impairment.

Table 6-3 summarizes national emission estimates for these pollutants by major source category for 1977 (EPA, 1978a). These rough estimates were based on published data on fuel use and industrial production and on other EPA data describing emission factors and the extent of air pollution controls employed. Figures 6-10 through 6-13 are shaded maps that display emission density estimates by county for these same pollutants. These maps are derived from data obtained from the National Emissions Data System and represent 1975 data. As might be expected, emission densities are usually low in counties, which contain class I areas. In general, emission density increases with higher population density for each of the four pollutants, with highly urbanized areas having high emission densities. This relationship is strongest for nitrogen oxide and hydrocarbons, the principal pollutants generated by automobiles.

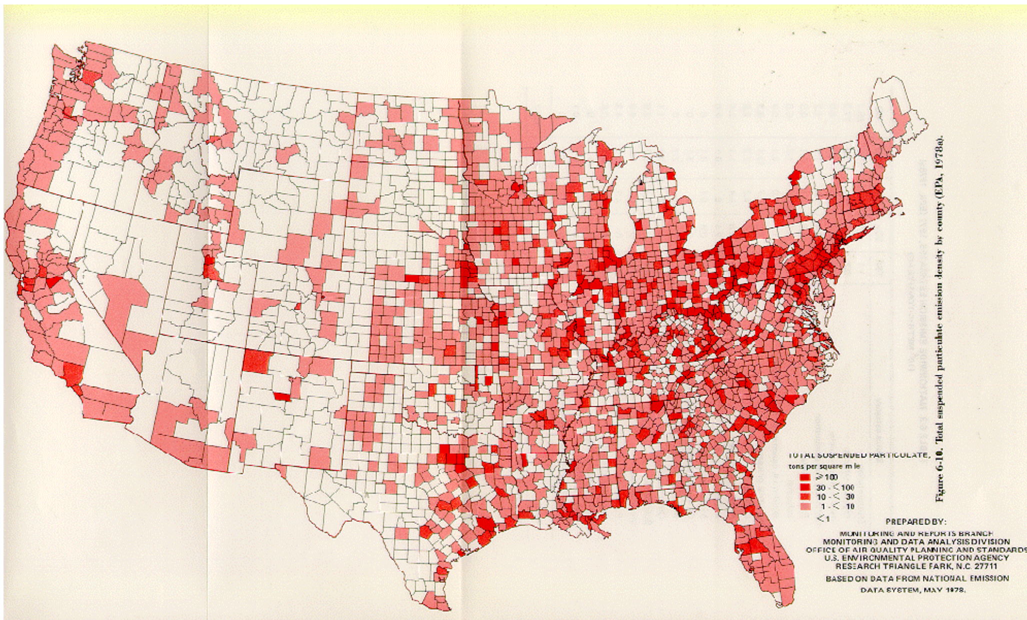

Figure 6-10. Total suspended particulate emission density by county (EPA, 1978a).

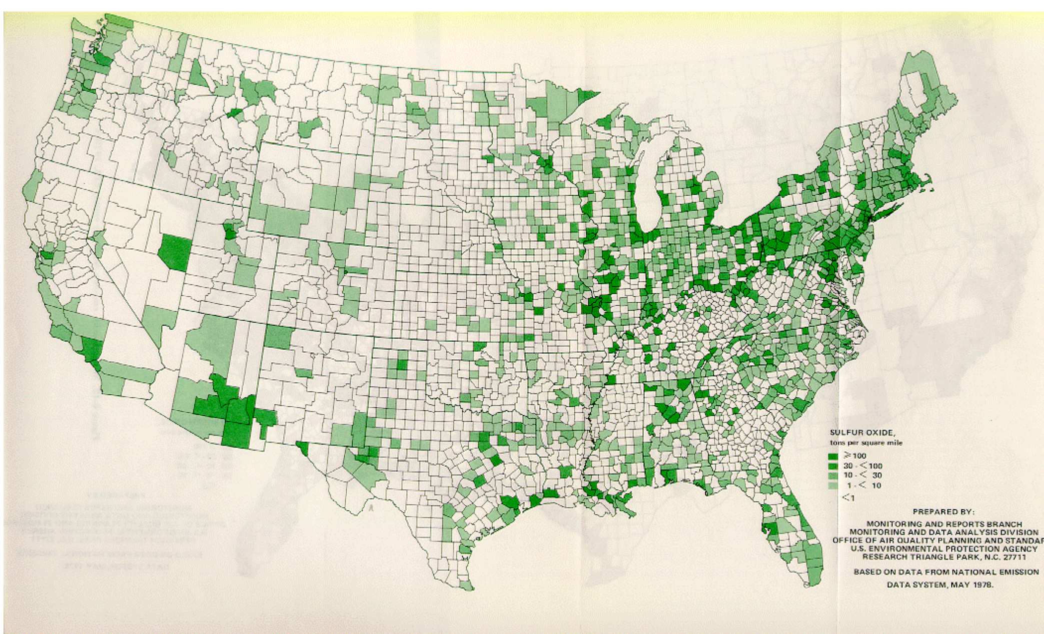

Figure 6-11. Sulfur oxide emission density by county (EPA, 1978a).

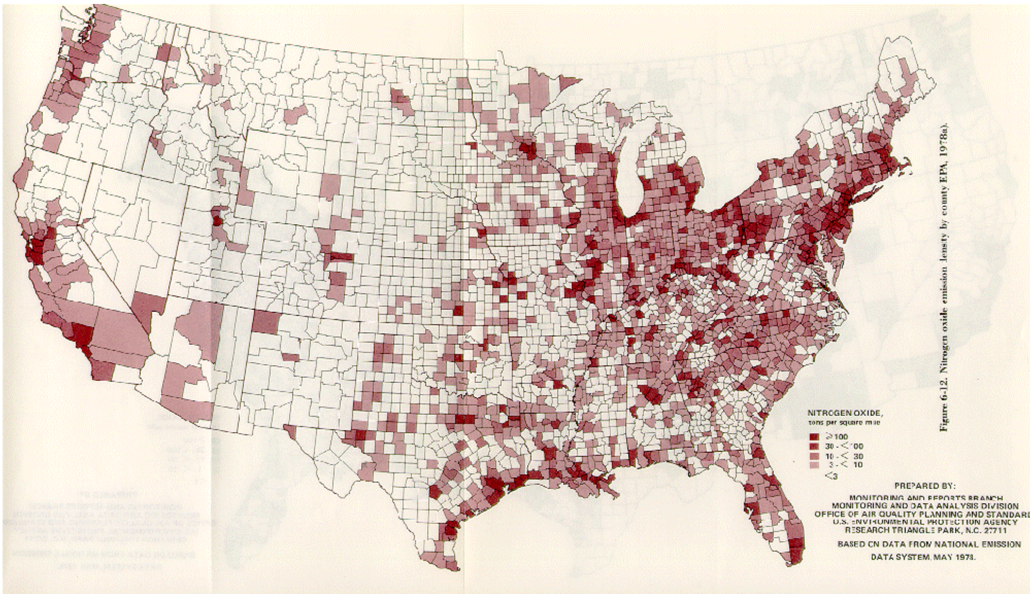

Figure 6-12. Nitrogen oxide emission density by county (EPA, 1978a).

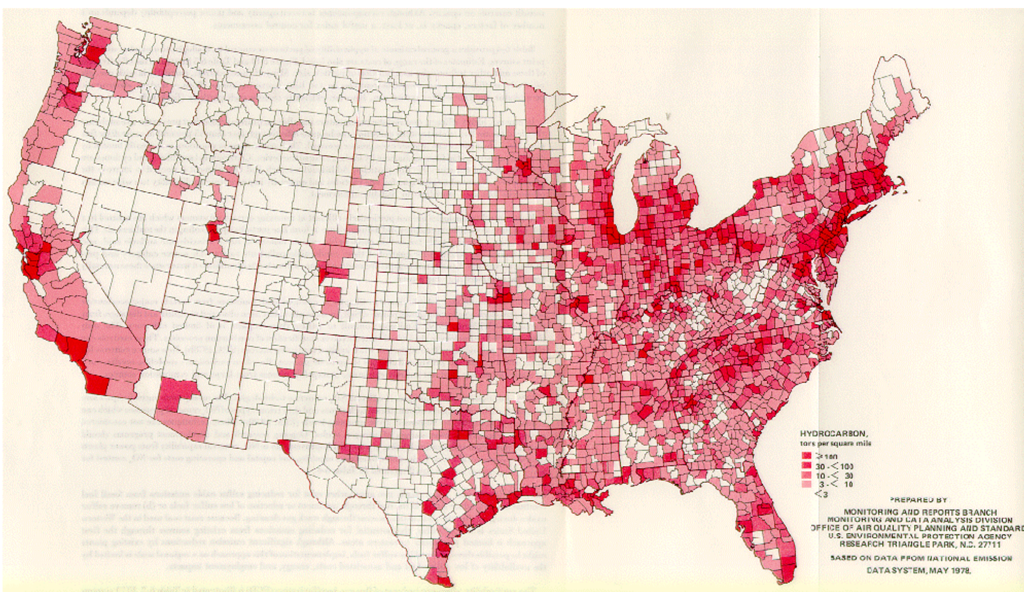

Figure 6-13. Hydrocarbonemission density by county (EPA, 1978a).

Source Category	TSP	SO_X	NO_X	VOC	CO
Transportation	1.1	0.8	9.2	11.5	85.7
Highway vehicles	0.8	0.4	6.7	9.9	77.2
Non-highway vehicles	0.3	0.4	2.5	1.6	8.5
Stationary fuel combustion	4.8	22.4	13.0	1.5	1.2
Electric utilities	3.4	17.6	7.1	0.1	0.3
Industrial	1.2	3.2	5.0	1.3	0.6
Residential, commmercial, and institutional	0.2	1.6	0.9	0.1	0.3
Industrial processes	5.4	4.2	0.7	10.1	8.3
Chemicals	0.2	0.2	0.2	2.7	2.8
Petroleum refining	0.1	0.8	0.4	1.1	2.4
Metals	1.3	2.4	0	0.1	2.0
Mineral products	2.7	0.6	0.1	0.1	0
Oil and gas production and marketing	0	0.1	0	3.1	0
Industrial organic solvent use	0	0	0	2.7	0
Other processes	1.1	0.1	0	0.3	1.1
Solid waste	0.4	0	0.1	0.7	2.6
Miscellaneous	0.7	0	0.1	4.5	4.9
Forest wildfires and managed burning	0.5	0	0.1	0.7	4.3
Agricultural burning	0.1	0	0	0.1	0.5
Coal refuse burning	0	0	0	0	0
Structural fires	0.1	0	0	0	0.1
Mescellaneous organic solvent use	0	0	0	3.7	0
Total	12.4	27.4	23.1	28.3	102.7

Table 6-3. Nationwide emission estimates, 1977 (EPA, 1978a) (106 metric tons/year). Note: A zero indicatres emissions of less than 50,000 metric tons per year.

These maps are only imperfect indicators of potential impairment. For example, TSP emissions are not a uniformly good surrogate for primary fine particle emissions. Furthermore, in areas of apparently low emission density, single point sources located in close proximity to class I area may produce significant local plume impacts. Regions containing several counties of high TSP emission densities are, however, at least indicative of regional primary fine particulate impacts. High sulfur oxide emission densities indicate potential regional sulfate impacts. As noted in Chapter 4, strong geographical similarities exist between high sulfur oxide emission density and low regional median visibility levels. The nitrogen oxide map is a less useful visibility indicator. Discoloration of visibility in class I areas by nitrogen oxide emissions is probably only significant near (within 80 km of) large power plants in clean areas and for class I areas immediately adjacent to urban areas of the highest nitrogen oxides emission density. The significance of VOC (hydrocarbon) emission density for visibility impairment is not well understood. However, the VOC emission density map is a good surrogate for population centers and possible impacts of general urban development.

6.2.2 Control Technology for Potentially Important Point Sources

This section discusses general kinds of control technologies and the effectiveness of each as applied to major point sources of particulate matter, sulfur oxides, and nitrogen oxides. Significant variations in the application, effectiveness, and cost of these technologies will occur among source categories and between sources of the same category. In particular, control technologies for point sources are generally more effective and less expensive when applied to new sources than when applied to existing sources. Detailed information on control technology can be obtained form a number of sources listed as references. A comprehensive control techniques document for nitrogen oxides has been published (EPA 1978b), and similar documents will be available for sulfur oxides and particulate matter in Spring, 1980. In addition, detailed information on available control technology for specific source categories has been published as support documents for the new source performance standard for utility boilers, kraft pulp mills, aluminum smelters, and other sources categories. (EPA, 1979a; EPA, 1976; EPA, 1974).

6.2.2.1 Particulate Matter -- Although primary fine particulate emissions from point sources can contribute to region-wide haze conditions, the principle concern with these emissions over the next several years is likely to be intrusion of perceptible plumes or haze layers into important vistas. As noted in Chapter 4, such plumes have been observed in the Southwest to extend for over 50 km from large, inadequately controlled sources. Visible primary particle plumes from smaller industrial or well-controlled larger sources are normally limited to the near source environment, at distances of less than 20 km from the facility. Historically, the public has complained about the presence of visible plumes even in urban settings; therefore, reduction in visible plumes has long been a concern of air pollution regulations. Traditionally, agencies have enforced such regulations by setting limits on plume opacity, or optical "thickness." Many state regulations call for restriction of opacity to no more than 20 percent. This level is generally achievable by most sources of particulate matter. Some localities have adopted regulations calling for no visible emissions. Such restrictions are more difficult to meet on a continuous basis, but, using available control technologies, many source types can meet a no visible emission standards most of the time.

The effectiveness of any control device in reducing near source particulate plume blight is limited by the control efficiency for fine particles. Although fine particulate removal efficiency is known form many control technologies, the lack of adequate emissions estimates and particle size distributions will limit the accuracy of visibility models in assessing control alternatives for some source categories. Previous experience and experimentation in reducing opacity can, however, enable sources or control agencies to assess the effectiveness of possible retrofit controls on opacity. Although correspondence between opacity and plume perceptibility depends on a number of factor, opacity is, at least, a useful index for control assessments.

Table 6-4 provides a general estimate of applicability of particulate control technologies to a number of major point sources. Estimates of the range of costs are also listed. Figure 6-14 and Table 6-5 illustrates the effectiveness of these and other technologies as a function of particle size. Many of these controls, currently in wide use, are relatively inefficient at removing fine particles in the light scattering range. Both a modern electrostatic precipitator and fabric filter system can, however, efficiently remove such particles (Table 6-5).

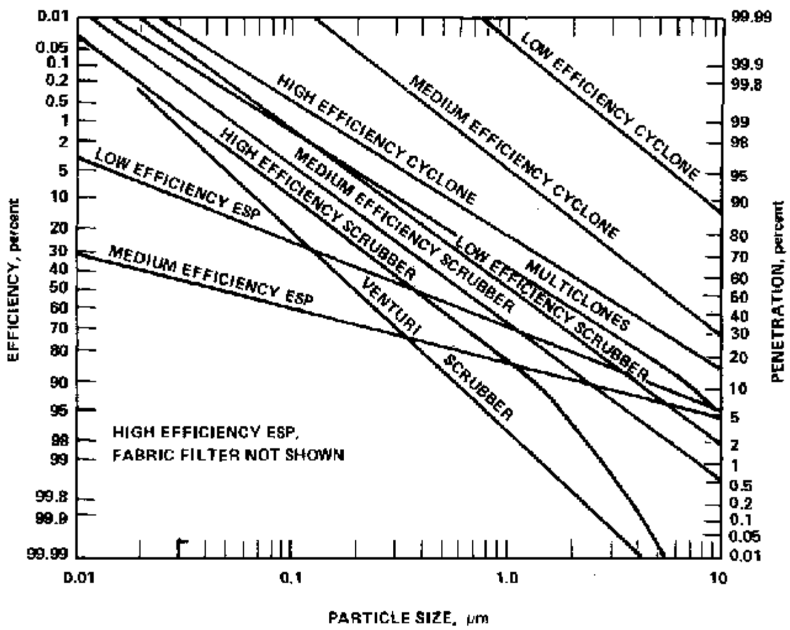

Figure 6-14. Comparison of Control Device fractional efficiency (Weast, 1974).

Source type	Size	Control	Costs (10^6 dollars) a		
			Capital	O & M	Annual
Utility boilers[b,c]	250 MW	Fabric filter	16.1	0.3	3.0
	500 MW		28.3	0.6	5.0
	1000 MW		51.0	1.2	9.7
Copper smelters	73,000-160,000 metric tons/year	ESP	2.7-23.6	NR	0.5-4.6
Industrial boilers[b,e]					
Coal	150 x 10^6 BTU/hr	Fabric filter	0.9	0.03	0.171
	200 x 10^6 BTU/hr		1.19	0.03	0.210
Oil	150 x 10^6 BTU/hr	ESP	1.04	0.01	0.160
Kraft pulp mill[f,g]	1000 TPD				
	ADP[h]				
Power boiler[e]	20 MW	Fabric filter	1.19	0.03	0.20
Recover furnace[f]		ESP	6.1	0.25	1.2

Table 6-4. Summary of particulate matter ocntrol costs for selected sources. [a]Costs do not include any costs for compliance with state and local regulations. [b]Costs based on 6,000 hr/yr. [c]Capital costs increased 25 percent to account for retrofit (EPA, 1978c). [d](Weisenbery, 1979). [e](Roeck et al., 1979). [f]Costs (EPA, 1976) updated to 1978 dollars using the Marshall and Swift Plant Index. Operating costs were updated using the consumer price index. [g]Costs based on 8,000 hr/yr of operation. [h]ADP = Air Dried Pulp.

Most control technologies are not particularly efficient at removing certain substances, which are emitted in a gaseous state at stack temperatures and then condense to form fine particles upon cooling in the ambient air. This effect is particularly notable for certain condensable organic materials, sulfur trioxide and sulfuric acid, and water vapor. The potential for control of these condensable pollutants varies with source category and pre-existing technology. Usually no attempts are made to reduce white clouds of condensed water since these normally vaporize relatively near the source.

Device	Application	Total	% Efficiencies Fine Particles (0.1 to 1 mm)
Electrostatic Precipitator	Coal Fired Boiler, High Sulfur Coal	99.8	99-99.6
	Coal Fired Boiler, Medium Sulfur Coal		95-98.9
	Coal Fired Boiler, Low Sulfur Coal	98.3	90-99..3
Fabric Filters	Coal Fired Boiler	—	94.5-99.7

Table 6-5. Particle collection efficiency of controls (Abbott and Drehmel, 1976).

6.2.2.2 Nitrogen Oxides -- As discussed in Chapter 5, nitrogen oxide emissions from certain major combustion sources produce a yellowish-brown plume, which, in some cases, has been observed at significant distances from the source (Williams, 1979). Emission controls to reduce these impacts are of limited efficiency. The only demonstrated technology in the United States involves modifications of combustion processes. These controls can reduce NO_x emissions by 30 to 50 percent when applied to existing sources (EPA, 1978b). New source controls for large power plants can provide efficiencies of up to 80 percent. Based on preliminary modeling results, such controls can reduce, but not entirely eliminate, perceptible plumes from large coal combustion sources.

EPA and others are developing more efficient NO_x reduction technologies. The most promising techniques are: (a) additional improvements of combustion techniques (b) various types of NO_x removal processes which can reduce NO_x emissions by 90 percent form incoming levels (EPA, 1978b). These techniques are not considered generally available to most sources of nitrogen oxides. Ongoing research and development programs should provide significant information leading to potential improvements in NO_x removal capability from power plants over the next several years. Estimated efficiencies, capacity, and capital and operating costs for NO_x control for major combustion sources are illustrated in Table 6-6.

Source Type	Size	Control[b] (% reduction)[a]	COST		
			Capital[c,d]	Annual[e] (¢ 10^6 BTU) (without fuel cost)	Annual (¢ 10^6 BTU) (with fuel cost)
Coal fired utility boiler	250 MW	LEA (11)	3×10^6	0.2	-0.35
		SCR (90)	30×10^6	26.0	36.4
	500 MW	LEA (11)	6×10^6	0.2	-0.35
		SCR (90)	60×10^6	26.0	36.4
	1000 MW	LEA (11)	12×10^6	0.2	-0.35
		SCR (90)	120×10^6	26.0	36.4
Coal fired industrial boiler	200×10^6 BTU/hr	LEA (11)	14×10^3	0.3	-1.8
		SCR (90)	1×10^6	23.0	32.6
	150×10^6 BTU/hr	LEA (11)	10.5×10^3	0.3	-1.8
		SCR (90)	0.75×10^6	23.0	32.6
Oil fired industrial boiler	150×10^6 BTU/hr	LEA (11)	14×10^3	0.26	-1.67
		SCR (90)	1×10^6	23.0	35.0

Table 6-6. Summary of NO_X control costs for selected sources. [a]Percent reduction over uncotrolled emission rate given in NO_X Control Technique Document (EPA, 1978b). [b]LEA = Low Excess Air. SCR = Selective Catalytic Reduction. [c]Capital cost is 1978 estimated retrofit cost (EPA, 1978b). Includes equipment installation . [d]Costs do not include any costs fro compliance with state and local regulations. [e]Annual costs include O & M and annual capital recovery factor based on 6,000 hr/yr.

6.2.2.3 Sulfur Oxides -- Essentially two approaches exist for reducing sulfur oxide emissions form fossil fuel combustion: (a) reduce sulfur in the fuel through treatment or selection of low sulfur fuels or (b) remove sulfur oxides during or after the combustion process through stack gas cleaning. Because most coal used in the Western United States is low in sulfur, the potential for reducing emission from existing sources through the first approach is limited principally to eastern areas. Although significant emission reductions by existing plants might be possible through use of low sulfur fuels, implementation of this approach on a regional scale is limited by the availability of low sulfur fuel and associated costs, energy and employment impacts.

The applicability, efficiency and cost of flue gas desulfurization (FGD) are illustrated in Table 6-7. FGD systems and/or coal cleaning are mandated for all new utilities by the recently promulgated new source performance standard (Costle, 1979). Emissions reductions of up to 90 percent are required. Applicability of FGD systems to existing sources can be constrained by a number of factors including remaining useful life, cost, available space for the controls, and degree of improvement expected. A number of improvements in FGD control systems are expected to be demonstrated over the next several years which will improve sulfur removal capabilities and in some cases achieve emission reductions at lower costs.

Visibility improvements associated with controlling SO_x emissions from isolated, major point sources can be estimated by use of the visibility models discussed in Chapter 5. The limitations of available models, discussed in the chapter, should be noted. It is currently not possible to estimate the scale and degree of visibility improvements associated with control of any *single* SO_x source in a region of high SO_x emissions. Historical trends and other empirical and analysis provide strong support for a proportional relationship between regional SO_x emissions and sulfate/visibility impacts, but additional validation work is needed before more quantitative estimates are possible.

Source type	Size	Control		Costs (10^6 1978 dollars) [a,b]		
			SO_2 removed	Capital	O & M	Annual
Utility Boiler[c]	250 MW	Lime	1-5 lb/10^6 BTU	38.4-40.8	3.6-4.6	12.7-14.2
	500 MW	FGD		66.5-71.3	5.04-7.56	20.8-24.4
	1000 MW			115.2-124.6	7.06-12.42	34.1-41.6
Industrial boilers	200 x 10^6 BTU/hr	Lime	90% removal	1.9	0.77	1.21
Coal[d]		FGD	3.5% sulfur coal			
	150 x 10^6 BTU/hr			1.75	0.65	1.05
Non-ferrous smelters [e,f]						
Copper	73,000-160,000 metric tons/yr.	Double contact acid plant + MgO FGD system	95	14.4-99.1	NR[g]	5.36-38.43

Table 6-7. Summary of SO_X control costs for selected sources. [a]Costs based on 6,000. [b]Costs do not include any costs for compliance with state and local regulations. [c]Costs from (EPA, 1979b) adjusted for size. Capital costs were increased by 25 percent to account for retrofit. [d]Costs from (Dickerman

et al., 1979). Costs were increased by 25 percent to account for retrofit. [e]Costs from (Weisenbery, 1979). [f]Costs based on 8,000 hours per year of operation. [g]NR = not reported.

6.2.3 Potentially Important Point Sources

Utilities -- The geographical locations of existing coal and oil fired power plant boilers are presented in Figure 6-15. The circles are proportional to generating capacity in megawatts. For purposes of comparison, regions within 100 km of class I areas are shown in Figure 6-16. Although single source visibility impacts may occur at these and perhaps larger distances, the range of influence will vary with emission strength, meteorology, terrain and other factors. Planned utility sites through 1990 are shown in Figure 6-17.

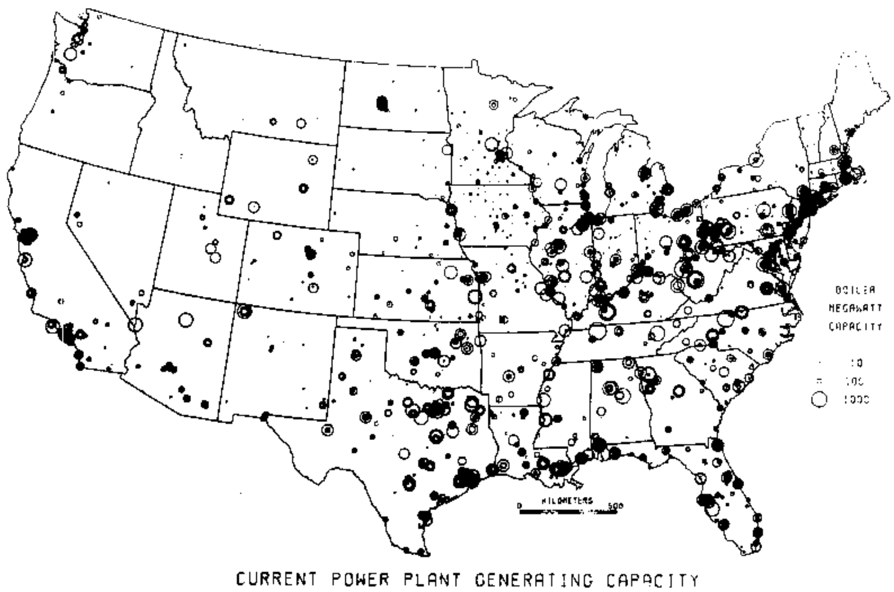

Figure 6-15. Current power plant generating capacity (EPA, 1979c).

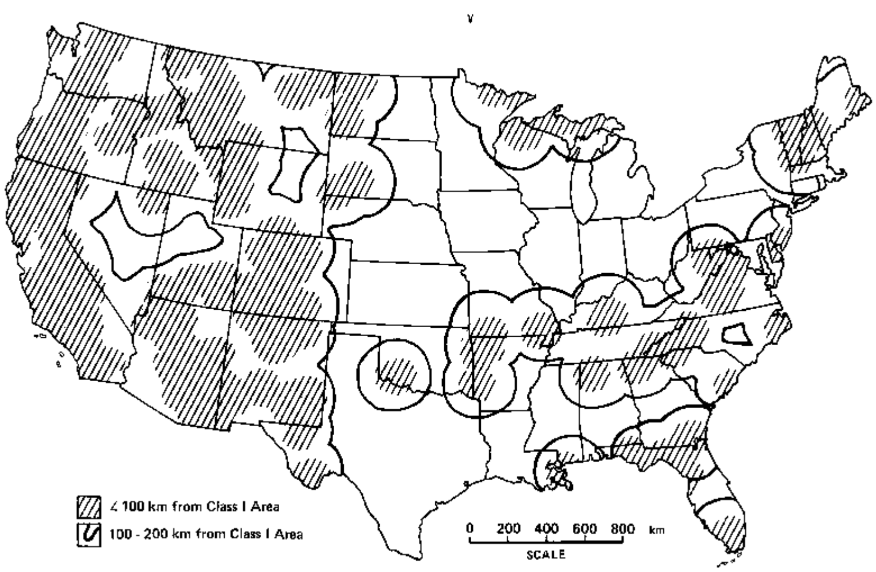

Figure 6-16. Areas within approximately 100 km (60 miles) of class I areas.

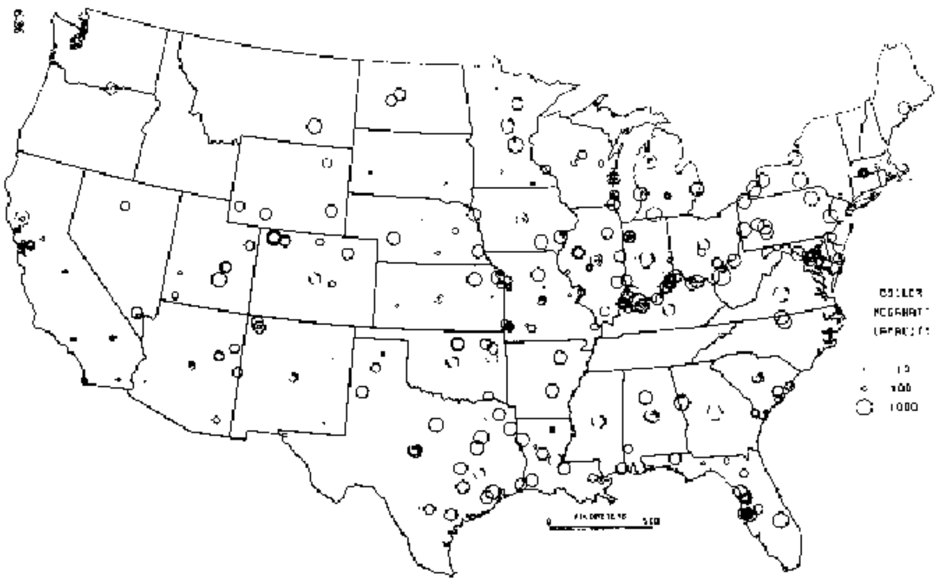

Figure 6-17. Future power plant generating capacity (EPA, 1979c).

Potential future regional visibility impacts of utilities can be estimated form projected regional sulfur oxide emissions trends. Comprehensive projections have already been made as part of the analysis accompanying the recently announced new source performance standards for power plants. Projected regional sulfur oxide emissions through 2010 are presented in Figure 6-18. The underlying assumptions, uncertainties and models used in these projections are detailed elsewhere (ICF, 1979). This timing and extent of projected emissions reductions after 1995 are very sensitive to assumptions concerning the rate of retirement of existing, less well controlled plants, growth n nuclear capacity, and energy conservation actions. These projections must therefore be viewed with caution. As shown in the figure, significant decreases in utility sulfur oxide emissions are expected after 1995 in regions of current high utility emission density. Although modest increases in emissions are expected in the West, utilities are not currently the dominant source of regional sulfur oxide in this region.

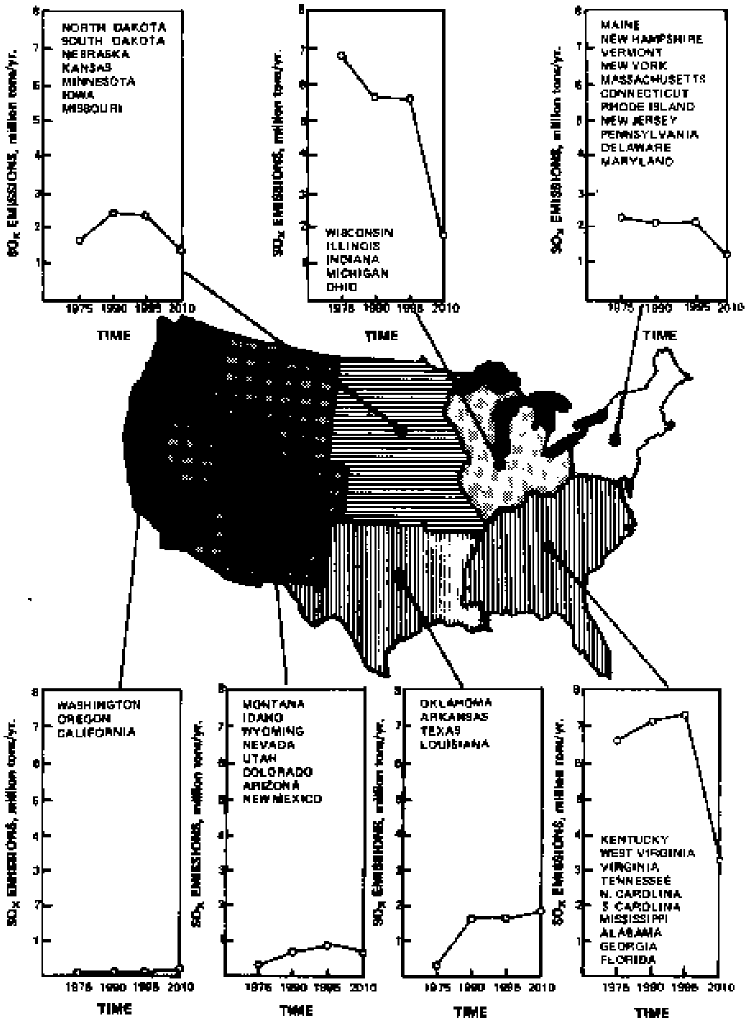

Figure 6-18. Projected utility sulfur oxide emissions by geographic region (ICF, 1979). Note added in proof: Continuing analysis of potential utility emissions growth using differing assumptions on plant retirement, existing control requirements, and energy mix suggest that the timing and extent of emissions reductions shown here may be optimistic.

Industrial Fuel Consumption -- Industrial boilers are dispersed throughout the country. Because they are generally concentrated in industrialized urban areas, these sources can contribute to visibility impairment associated with urban plumes. Figure 6-19 shows counties containing industrial boilers. Most growth in industrial coal use is expected to occur in these same counties (DOE, 1979). Current and projected sulfur oxide emissions form industrial facilities by region are shown in Figure 6-20. The basis for the projections are detailed elsewhere (DOE, 1979). The projections assume installation of emission controls on major industrial fuel users and also assume that growth in coal use will follow the national energy plan. According to DOE these assumptions may tend to overstate projected industrial emissions growth.

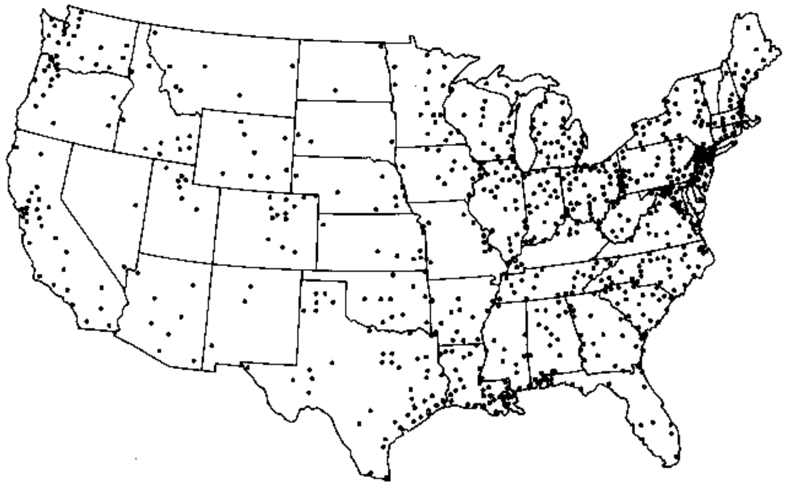

Figure 6-19. Counties containing industrial coal boilers. Most growth in industrial coal use is expected ino r near these same counties (DOE, 1979).

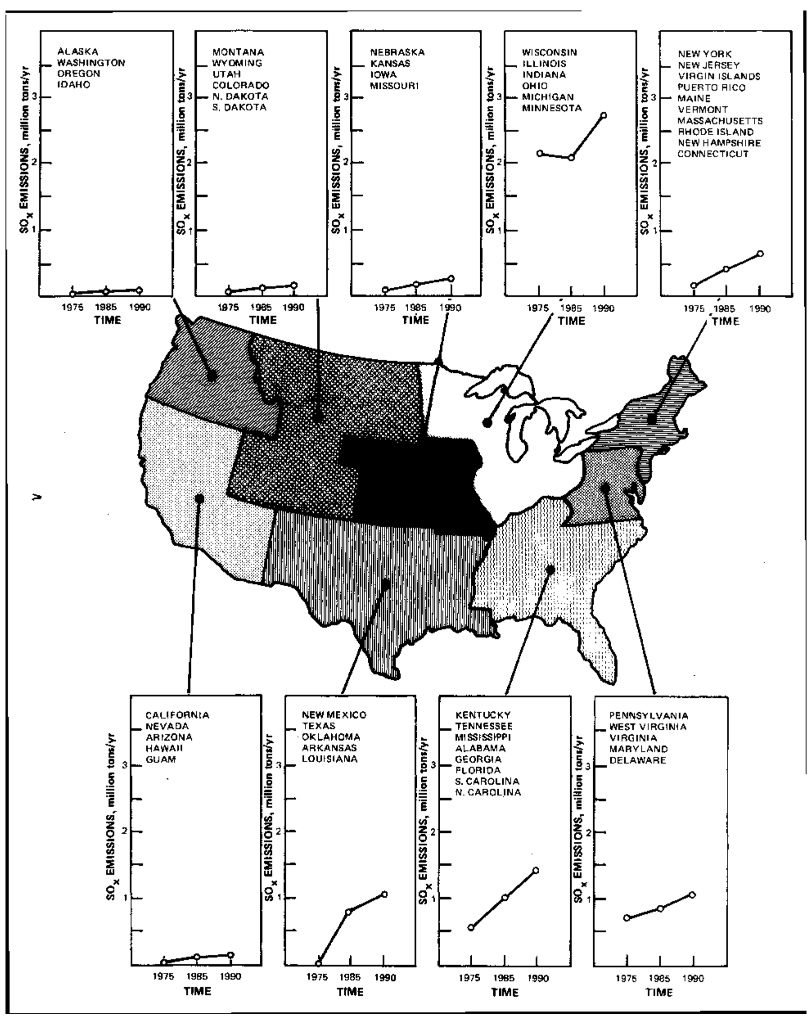

Figure 6-20. Projected regional sulfur oxide emissions from industrial coal use (DOE, 1979).

6.2.3.3 Smelters -- Studies summarized in Chapter 4 have implicated copper smelter particulate and sulfur oxide emissions (Figure 6-21) as one of the principal causes of reduced visibility in the Western United States. Historical and projected emissions are illustrated in Figure 6-22. During the past ten years, significant reductions in sulfur oxide emissions have been made in copper smelters (Marians and Trijonis, 1979). As noted previously, these reductions may have already produced improvement in southwestern visibility. These reductions have resulted from smelter retirement, decreased copper production, and improved emission controls. Further improvements in emissions are anticipated as smelters comply with air quality standards. Although some growth in copper production is contemplated, no additional smelter sites are currently planned.

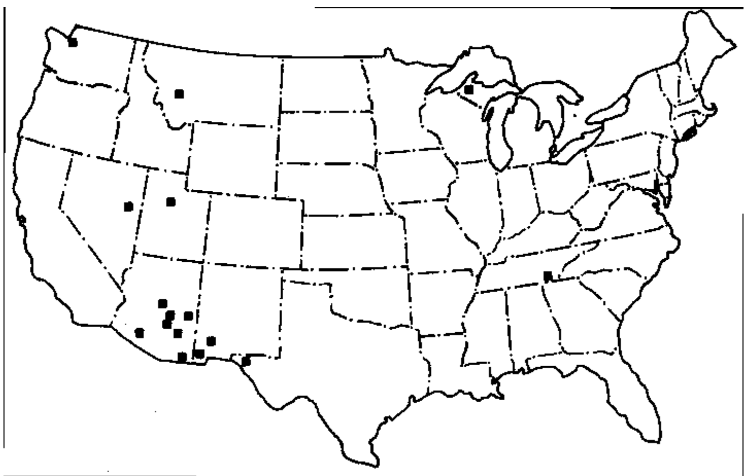

Figure 6-21. Existing primary copper smelters.

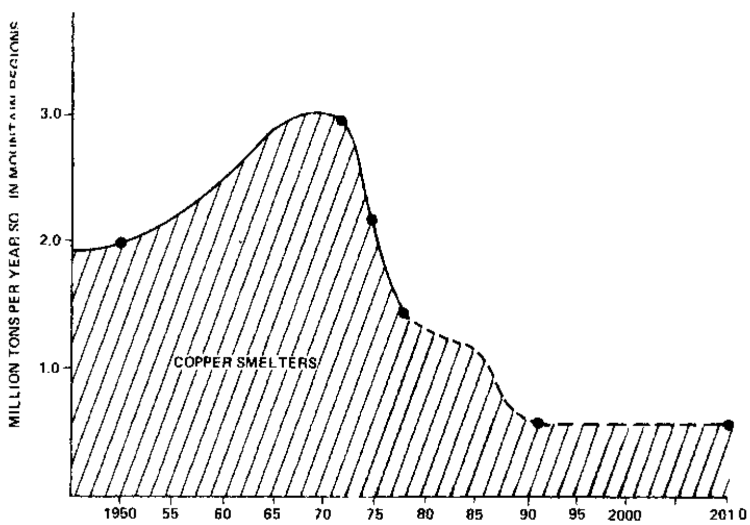

Figure 6-22. Historical and projected trends in Western copper smelter emissions (Mariano and Trijonis, 1979). On a regional basis, the reductions from 1978 to 19900 could offset projected utility increases (see Figure 6-18).

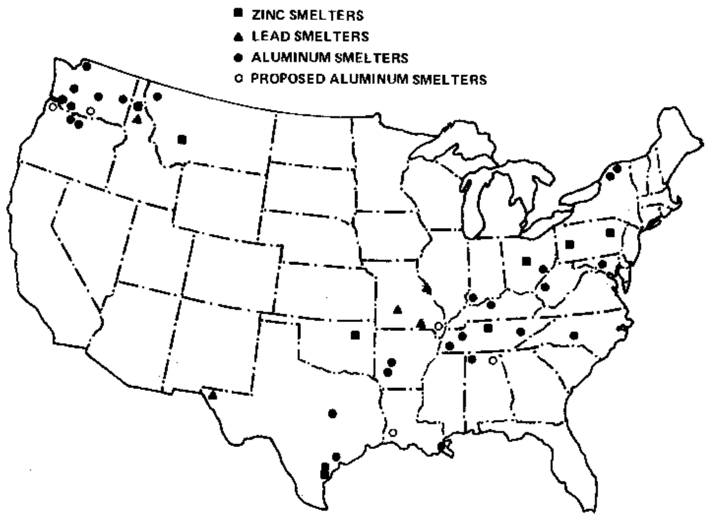

Figure 6-23. Aluminum, lead, and zinc smelters.

Figure 6-23 gives the location of existing aluminum, lead, and zinc, smelters. These sources emit particles and sulfur oxides. As a class, these sources are most likely to effect class I area visibility through visible plumes or other near source impacts. Many of these smelters have already or are expected to install particulate and sulfur oxide controls. Only a few new smelters are expected over the next 15 years.

6.2.3.4 Kraft Pulp Mills -- Pulp and paper manufacturing operations are often located near forest production sites and wilderness areas, including some class I areas (Figure 6-24). Visible particulate plumes form these sources may, in some cases, impair visibility in some class I areas. Kraft pulp mills account for about 85 percent of total pulp production. Most existing mills have already installed particulate control devices of varying effectiveness at removing fine particles (Goldberg, 1975), while new kraft pulp mill emissions are regulated under a new source performance standard (EPA, 1976). Pulp production is expected to increase by about 3 percent annually through 1985 (DOC, 1977a).

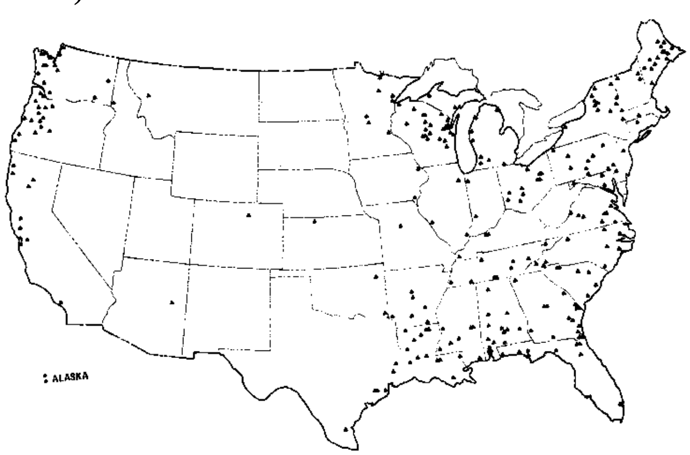

Figure 6-24. Existing pulp mills (Post, 1975).

6.2.4 Area Sources

Area sources include groupings of smaller point sources, e.g. home heating and automobiles, and large-scale emission sources such as field burning. The impact of these sources on visibility can in some cases equal or exceed that of major point sources. Because of their number and/or spatial characteristics, however, area sources are that of major point sources. Because of their number and/or spatial characteristics, however, area sources are generally difficult to control. The best control approach may be to limit the growth of area sources that significantly impair visibility in the vicinity of class I areas and to limit certain intermittent area source operations to prescribed times of the year or day. This section discusses three major categories of area sources which have been observed to impair visibility in class I areas; urban plumes, fugitive dust, and fire.

6.2.4.1 Urban Plumes -- Urban plumes result from the combination of the many point and area emissions sources located in urban areas. The combined grouping can be considered as an area source. Visual impacts of urban plumes have been tracked at distances of over 100 km from their origin (Chapter 4). These plumes may blanket a class I area or be visible as a distinct haze layer or area of discoloration. The Los Angeles urban plume (Figure 6-25) frequently extends into the southern California desert area, a region which contains several class I areas. The Los Angeles plume may also be transported into the southwestern states. The Phoenix urban plume (Figure 6-26) combines with smelter emissions and can affect class I areas in southern Arizona. The Denver brown plume (Figure 6-27) is visible from the Rockies.

Figure 6-25. The Los Angeles urban plume appears as a visible smog font as it moves into the southern California desert near Victorville (Niemann, 1979).

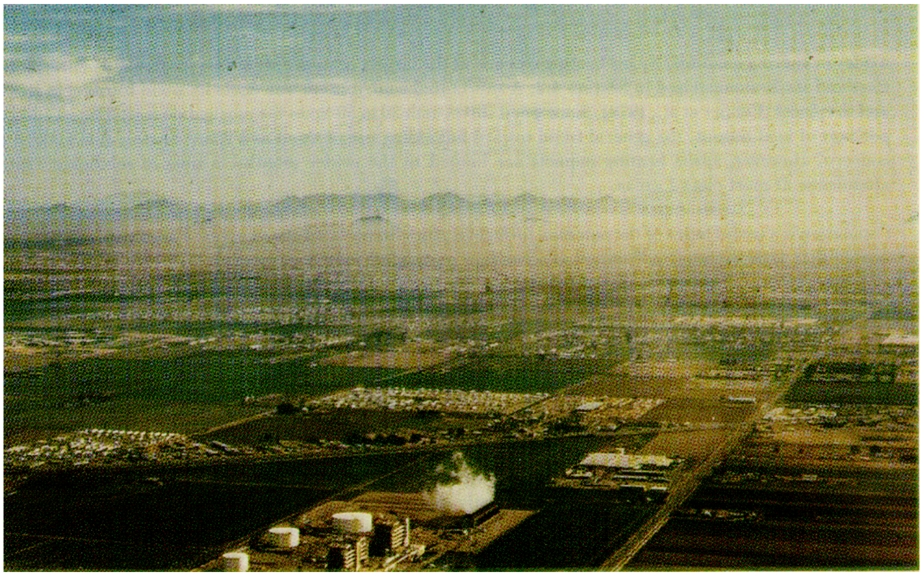

Figure 6-26. Phoenix urban plume derived from smelters and area sources (Niemann, 1979).

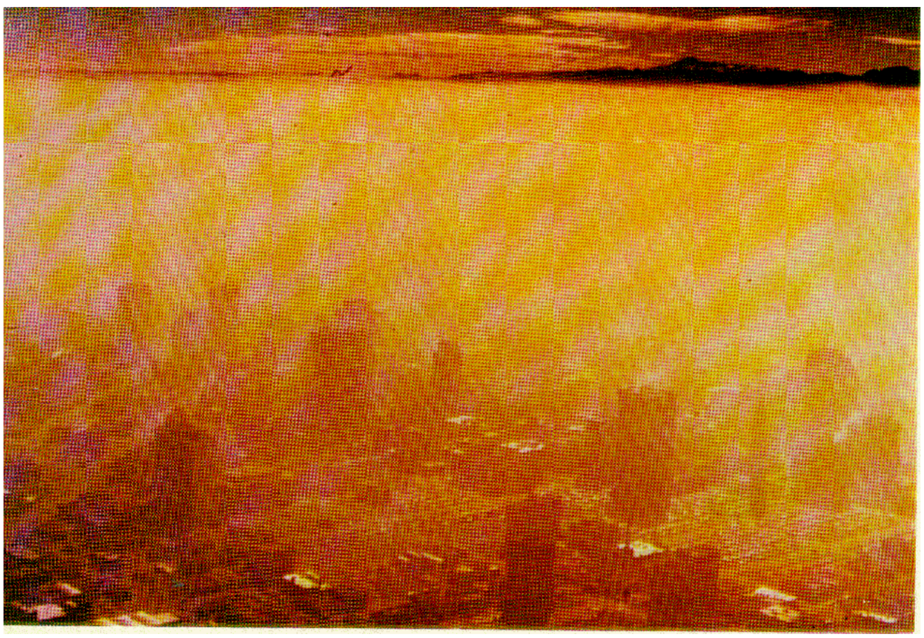

Figure 6-27. Denver brown cloud (Niemann, 1979). Particles and NO_2 contribute to this discoloration.

The visibility impact of urban plumes varies with source composition, meteorology, location, and season. The principal sources of primary and secondary fine aerosols in urban plumes include 1) major stationary source emissions of sulfur oxides, organics, and primary particulate matter, 2) mobile source emissions, and 3) space heating. Many of these sources also emit nitrogen oxides. Each of these categories is briefly discussed below.

Point Source Emissions -- In areas with significant sulfur oxide emissions such as St. Louis, southern Arizona, and Los Angeles, secondarily formed sulfates are a major component of light scattering in the urban plume. Primary emissions of unburned carbonaceous material and metallic oxides form major fuel combustion and industrial process point sources are usually of lesser importance in the downwind plume. Control of these point source categories is discussed in Section 6.2.2 In addition, large and small point source emissions of volatile organic chemicals and nitrogen oxides can accelerate the formation of both organic and inorganic secondary aerosols.

Mobile Sources—The principle primary particulate emissions from mobile sources have been associated with lead. These emissions can account for ten to twenty percent of fine particulate mass within urban areas. Although automotive lead emissions are expected to decrease with increased use of catalytic converters, the replacement of conventional gasoline engines with diesels suggests a possible increase in fine particulate replacement of conventional gasoline engines with diesels suggest a possible increase in fine particulate mass emissions from mobile sources. Studies in Denver suggest that light absorption by carbonaceous particulates, such as those emitted by diesels, account for up to 30 percent of the fine particulate visibility reduction in the city (Waggoner, 1979). Mobile source emissions of nitrogen oxides and unburned hydrocarbons also contribute to photochemical smog formation and are themselves transformed into secondary particulates (organics, nitrates) and nitrogen dioxide.

Space Heating—Homes, apartment houses, commercial dwellings, and the like are often heated by combustion of oil, gas or wood fuels. These sources emit primary particulate matter, nitrogen oxides, and sulfur oxides in varying amounts. Space heating was one of the largest components of fine particulate matter in the Portland study summarized in Section 4.2. A substantial contribution was made by wood burning in stoves and fireplaces (Cooper et al., 1979). Since wood stoves emit 20 to 50 times the particulate matter as oil and gas per unit of heat output, the general trend toward increasing use of wood as a space heating fuel may be of concern. However, space-heating impacts are limited to the colder months, a time of minimum visitor attendance at most class I areas.

Population is a useful index of the potential for urban plume impacts on class I areas. For example, is has been estimated that approximately one pound of secondary particulate matter per person is formed in the St. Louis urban plume, and overall emissions rate of 1000 tones of fine particles per day. This per-capita emissions rate will of course vary greatly with time and city. The distribution of major United States population centers, their relationship to call I areas and anticipated state population growth rates are shown in Figures 6-28 and 6-29. A number of states containing class I areas are expected to grow rapidly over the next twenty years. The observed effects of populated areas on surrounding rural visibility suggest that care must be taken to prevent aggravation of existing impacts or creation of new urban plume visibility problems, particularly in regions sensitive to small emission changes.

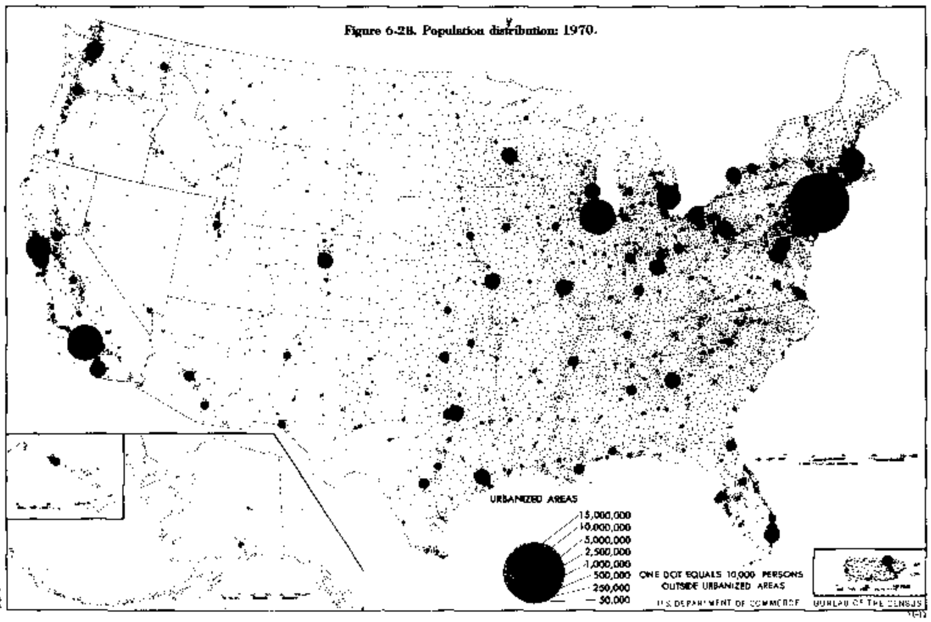

Figure 6-28. Population distribution, 1970.

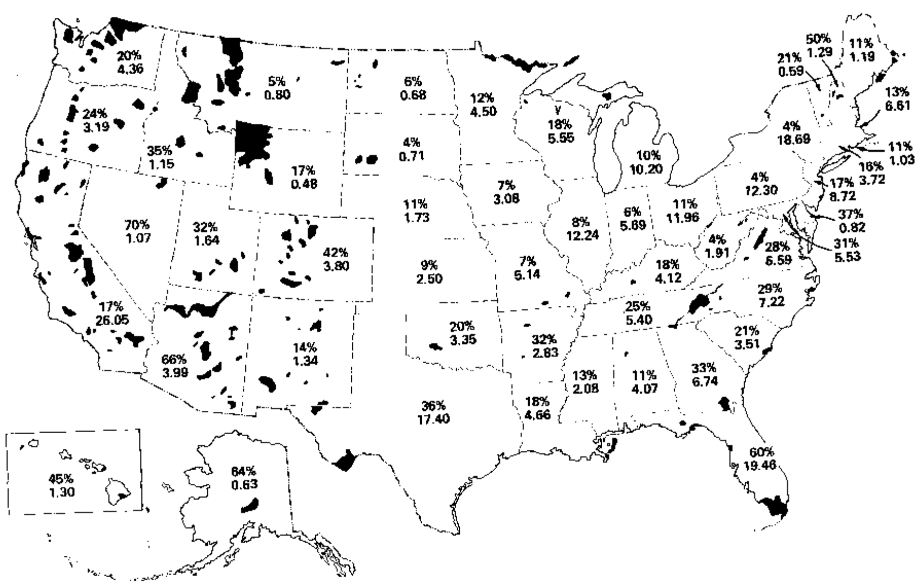

Figure 6-29. Projected population growth by State, 1978-2000 (DOC, 1977b).

6.2.4.2 Fugitive Dust—Recent studies indicate that while some fugitive dust emissions result from the natural phenomena discussed in Section 6.1, most frequently fugitive dust sources result directly form previous or ongoing human activity (EPA, 1977a). Direct man-caused fugitive dust sources include unpaved roads, agricultural tilling, construction or mining activity, off road motor vehicles and inactive tailing piles. These and other processes that generally disturb natural soil surfaces can also make large areas more susceptible to dust emissions form wind erosion. Figure 6-30 presents typical particle size characteristics of fugitive dust sources.

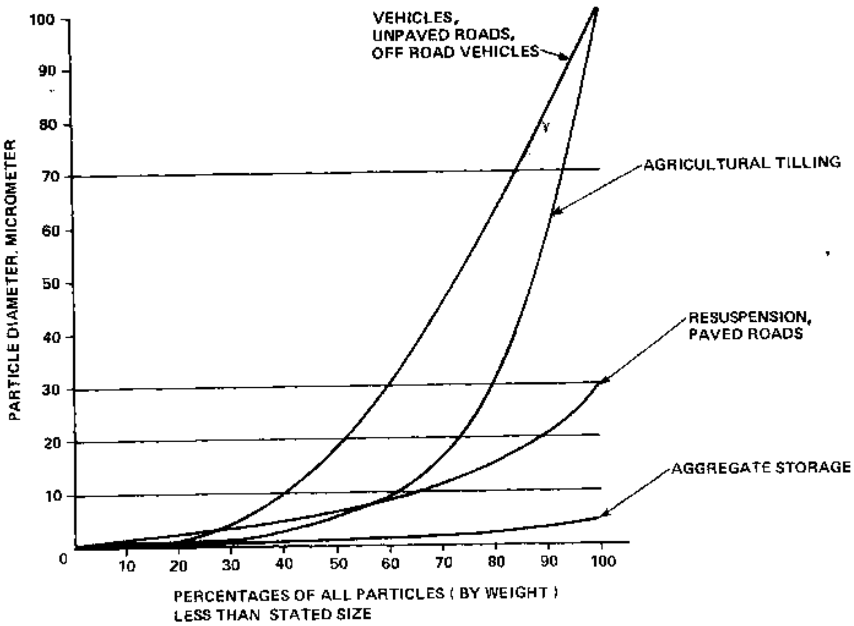

Figure 6-30. Particle size distribution for fugitive dust emissions (EPA, 1977a).

Fugitive dust sources are not normally a major component of visibility reduction in urban plumes, but when such sources are located relatively near class I areas, they may adversely affect visibility. Control approaches include: Paving or use of chemical stabilizers on unpaved roads; increasing overall vegetative cover, modified tilling operations, irrigation, and stabilizers on agricultural fields; physical controls (covering), application of water, and vegetative cover for construction and storage piles.

The effectiveness and cost of controlling these sources vary widely. In many cases significant reduction of fugitive emissions may impose unreasonable demands. For example, paving roads may reduce fugitive dust emissions by up to100 percent but cost $100,000 per mile. More detailed information on these control approaches, their efficiencies, and costs is available (EPA, 1977a,b; Richard et al., 1977). The impacts of mining emissions (Figure 6-31) on visibility in class I areas are likely to increase because of the increasing need to develop the major energy resources located in pristine Western areas. Table 6-8 presents a summary of control efficiencies and costs for major sources of fugitive particulates form mining operations (EPA, 1977b).

Given the difficulty of controlling existing sources of fugitive dust, it is important to consider the growth of activities which produce fugitive dust emissions near class I areas. Particularly important are those activities, which can disturb large areas of soil, increasing the potential for wind derived dust emissions. Even activities which themselves generate dust for only a short time period for example, agricultural tilling and recreational vehicles, can cause changes in soils leading to increased emissions over much longer time periods (EPA, 1977a).

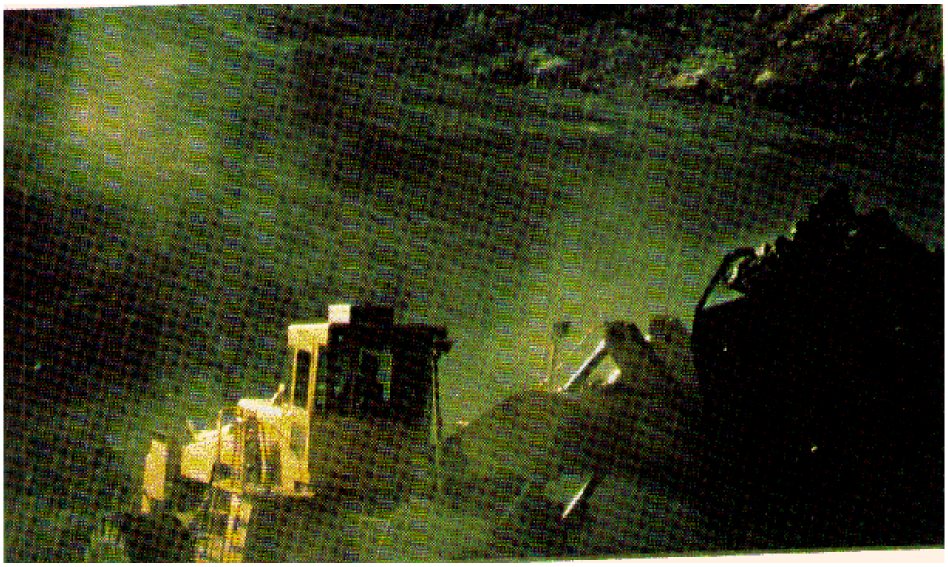

Figure 6-31. Fugitive dust emissions from strip mining.

Source	Control		Control Cost	
	Applicate control method/comments	Estimated efficiency	Unit cost per application, $	Units
Overburden removal	Watering/rarely practiced	50% [a]	No data	
Drilling/Blasting	Watering, cyclones, or fabric filters for drilling/Employment of control equipment increasing; Mats for blasting/very rarely employed	No data	No data	
Shovels/Truck ore loading	Watering/rarely practiced	50% [a]	No data	
Haul road truck transport	Watering/by far the most widely practiced of all mining fugitive dust control methods	50% [b]	No data	
	Surface treatment with penetration chemicals/employment of this method increasing	50% [b]	600-1800 [f] (1000-3000)	Kilometer (mile)
	Paving/Limited practice	90-95% [a]	2390-6860 [j,k] (2220-6370)	1,000 m^2 (10,000 ft2)
Truck dumping	Watering/rarely practiced	50% [a]	No data	
	Ventilated enclosure to control device/Rarely employed	85-90% [a]	No data	
Crushing	Adding water or dust suppressants to material to be crushed and venting to baghouse/Fairly commonly practiced	95% [a]		
Transfer/ Conveying	Enclosed conveyors/Commonly employed	90-99% [a]	100-360 [l,m] (90-330)	Mg/hr capacity (ton/hr capacity)

	Enclosure and exhausting of transfer points to fabric filter/Limited employment	85-99% (depends on control devices)		
Cleaning	Very little control needed since basically a wet process			
Storage	Continuous spray of chemical on material going to storage piles/Rarely practiced	90% [c]	0.5-1.50 [f] (.10-3.25)	Kilogram of chemical (pound)
	Watering (sprinklers or trucks)/Rarely practiced	50% [a]	No data	
Waste disposal/Tailing piles	Chemical stabilization/Limited practice	80% [d]	40-100 (160-400) [g]; 65-150 (250-600)	1000 m^2 (acre)
	Vegetation/Commonly practiced	65% [e]	50-115 (200-450) [h] (hydroseeding)	1000 m^2
	Combined chemical-vegetative stabilization/Rarely employed	90% [a]	25-40 (100-160) [i]	1000 m^2
	Slag cover/Limited practice	90-99% [a]	90-115 (350-450) [g]	1000 m^2

Table 6-8. Summary of control efficiencies and costs for mininng fugitive particulate emission sources (EPA, 1977b). a-m References in EPA, 1977b.

6.2.4.3 Managed Fires—The three major sources of large-scale fires that can impair class I area visibilities include: (1) wildfires, (2) prescription fires in natural areas and (3) agricultural burning. The nature of visibility impairment caused by the dense smoke accompanying wild fires is discussed in section 6-1. The latter tow categories can produce impacts similar in character to wildfires. Because the burning process is manageable in space and time, the impacts are usually lower on a unit basis than form wildfires.

6.2.4.3.1 *Prescription Fires*—Prescription Fires, also know as prescribed burning, are those fires that are burning under predetermined conditions of weather, fuel moisture, soil moisture and other factors that will produce the intensity of heat and rate-of-spread required to accomplish certain planned benefits to one or more land management objectives such as silviculture, wildlife management, grazing and hazard reduction. These fires may result form either planned or unplanned ignitions. Private, State and Federal land managers throughout the United States use prescription fires. The amount of use attributable to each varies by State. Prescription fire is most widely used in timber producing areas under supervision of the U.S. Forest Service. Figure 6-32 lists national prescription fire statistics by category. Federal land managers use prescription fires in class I areas primarily to maintain natural ecosystems. This practice is increasing in the National Parks and Fish and Wildlife Service and National Forest Wilderness. A primary difference between these fires and those outside the class I areas is the method of ignition. Within wilderness, natural sources of ignition (primarily lightning) are relied upon while outside these areas people ignite the prescription fire. If a fire is naturally ignited within a wilderness or park under conditions outside the prescription, the fire is suppressed. Outside these areas, fires are not ignited unless prescribed conditions exist.

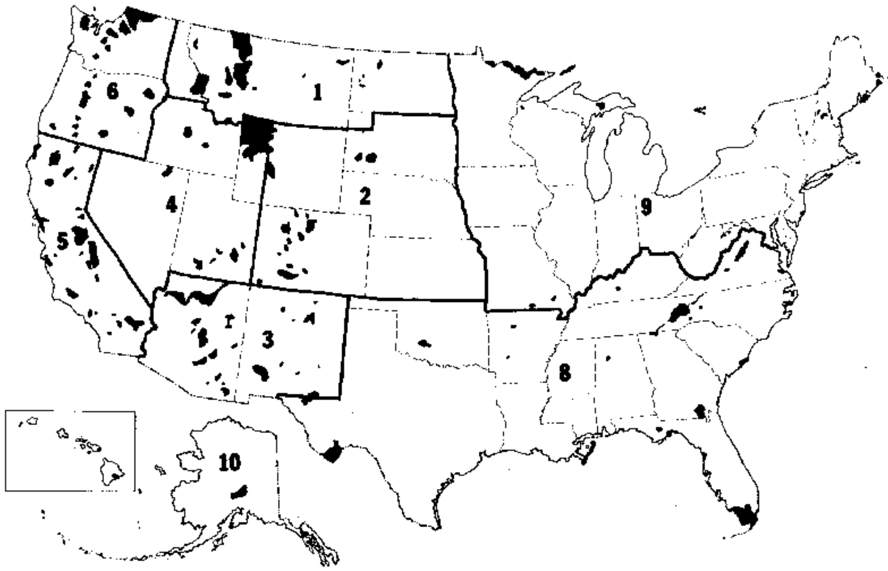

Figure 6-32. U.S. Forest Service regions.

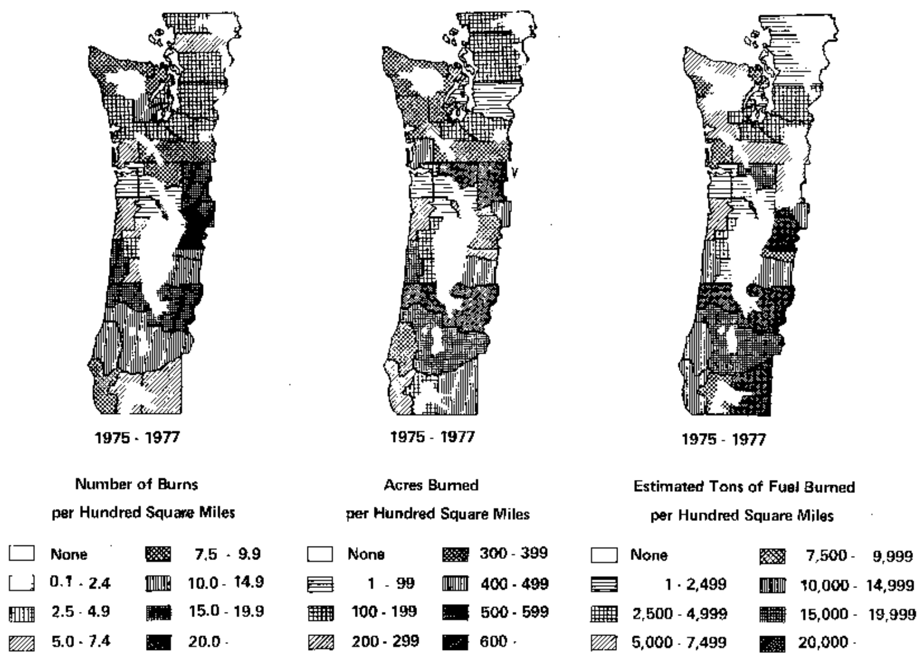

Figure 6-33. Geographic dsistributions off prescribed burns in Washinton and Oregon, 19975-77 (Geomet, 1978).

In the Pacific-Northwest, prescription fires for silviculture and hazard reduction purposes have been the source of political controversy where prescription fires apparently affect urban as well as class I area air quality (Cooper et al., 1979). In Washington and Oregon, particulate emissions from these fires are estimated at 50-200,000 tons per year (Figure 6-33). Currently, the principal means for reducing the air quality impact of these emissions is through use of smoke management programs designed to keep the smoke out of designated populated areas. The programs have been effective in minimizing smoke in designated areas, but because of the geographic and meteorological relationships between populated regions and class I areas, the programs tend at times to encourage burning during periods when winds carry the smoke toward class I areas. A general view of the impact of forestry burning on air quality in Washington and Oregon is available (Geomet, 1978).

Although a number of means for reducing impacts of prescription fires on class I areas visibility exist, they will be difficult to implement. The least costly method is to restrict burning to periods of minimum impact on class I areas or limit such impacts to times of low visitor utilization. In the Oregon/Washington area this approach may conflict with existing health protection goals or at best significantly reduce the frequency of allowable burning conditions. Reduction of burns might have adverse impacts on the silvicultural and hazard reduction objectives of forestry practices. Smoke from burning can also be reduced by improved burning practices and technology. A number of possible alternatives to forestry burning are listed in Table 6-10. The feasibility, effectiveness and environmental impacts of these approaches vary with site. Most of these alternative methods are useful for disposal of accumulated slash material. However, practical alternatives to the use of fire for improving wildlife habitat and reducing fire hazard in non-harvested areas have not been documented.

Forest Service Region (See Figure 6.32)	Burns of Timber Harvesting and Land Clearing Residues (slash) (million tons/yr)	Burns of Naturally Occurring Forest Residues (million tons/yr)	Total Material Burned (million tons/yr)
1	9.81	--	9.81
2	0.65	0.02	0.67
3	2.28	0.03	2.31
4	0.84	--	0.84
5	3.13	0.05	3.18
6	9.64	--	9.64
8	1.19	12.59	13.78
9	0.04	0.01	0.05
10	0.05		0.05
Total	27.60 (69%)	12.70 (31%)	40.33 (100%)

Table 6-9. National Prescribed Burning Statistics (Pierovitch, 1979).

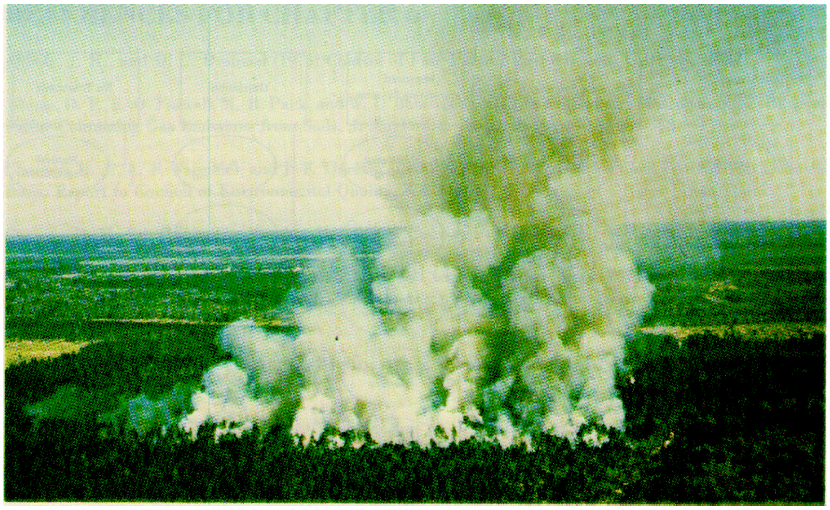

Figure 6-34. Prescription fire in forested area (Pierovitch, 1979).

6.2.4.3.2 *Agricultural Burning*--Managed fire is used in agriculture to dispose of unwanted vegetative residue to reduce the possibility of disease and to prepare fields for future planting. Agricultural burning can be an important source of particulate matter in a number of the Western states. Although emissions and visibility impacts are probably less than those from forestry burning, significant impacts can occur where such burning takes place near class I areas.

Field burning is particularly important in the Pacific Northwest. In the Willamette Valley of Northwestern Oregon, approximately 140,000 acres of grass seed stubble were burned in 1978 during the months of July through October including 51,000 acres on a single day (Figure 6-35)(Lyons et al., 1979). In the Northwest, agricultural burning is controlled under a smoke management plan similar to the plan discussed above for prescribed burning in forests. The state of Oregon is encouraging the development of reasonable and economically feasible alternatives to the practice of open field burning. These alternatives are generally similar to those outlined for control of forestry debris disposal.

Figure 6-35. Agricultural (grass seed production) burning in Willamette Valley, Oregon.

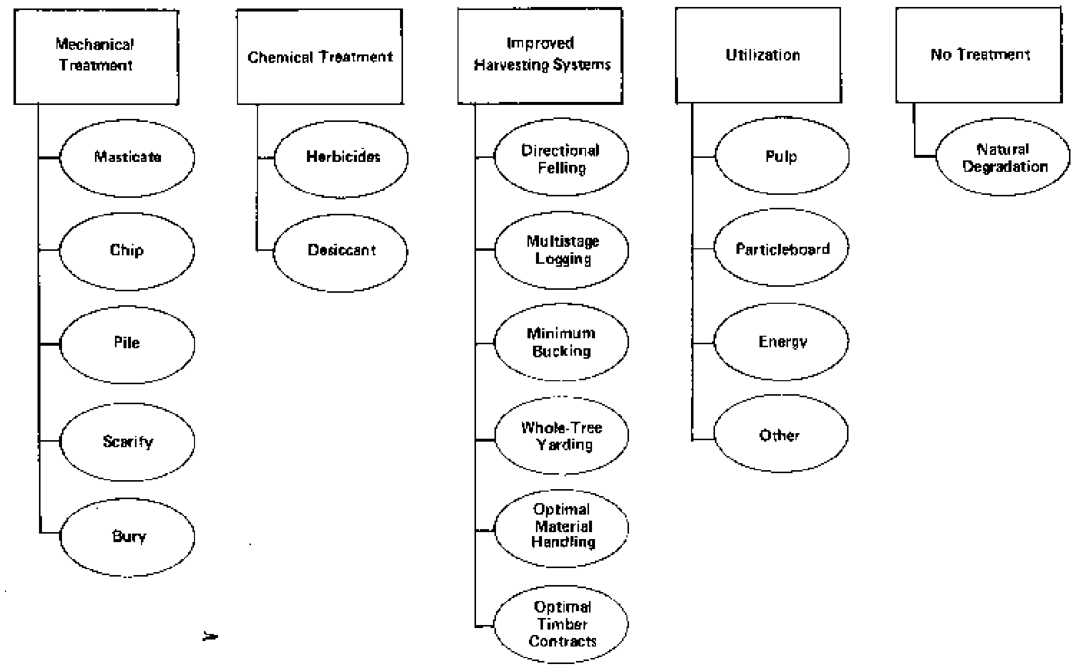

Table 6-10. Major alternatives to prescribed burning.

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PROTECTING VISIBILITY

AN EPA REPORT TO CONGRESS

CHAPTER 7

7 PROGRESS TOWARDS THE NATIONAL VISIBILITY GOAL: CONTROL STRATEGIES PERSPECTIVES

Drawing from information and discussion in previous Chapters of this report, and from a preliminary analysis of class I area visibility conducted by the Federal Land Managers, this chapter provides some initial perspectives on technological and regulatory control strategies for making progress toward the national visibility goal. The chapter summarizes the preliminary class I area visibility assessment, discusses important implications of the assessment, and outlines key components of visibility protection programs, together with alternative control approaches.

7.1 PRELIMINARY ASSESSMENT OF VISIBILITY IN CLASS I AREAS

7.1.1 Nature of the Preliminary Analysis

A fundamental process in conducting programs for protecting class I areas visibility is to evaluate existing visibility, to identify sources of perceptible impairment, and to establish visibility management objectives on a national, regional, or area specific basis. (Such objectives could take the form of criteria for incorporating visibility value judgments in case-by-case control decisions. See 7.2.3) A comprehensive evaluation might involve a year or more of monitoring, source identification and modeling, and judgments on the nature, frequency, and extent of significant or adverse visibility impacts. Clearly, it will be some time before complete assessments are available for the 156 class I areas.

Therefore, in order to develop guidance in the interim for control programs, EPA requested that the Federal Land Managers (National Park Service, Fish and Wildlife Service, Forest Service) perform a preliminary national assessment of visibility values in their respective class I areas. In conducting their assessments, the Land Managers relied on the collective expertise of individual park managers and field and regional office personnel. Visibility analysis "workbooks " were developed and distributed for completion by managers representing each of the 156 areas. Although the format developed by the three land management agencies differed in specifics, each requested the same basic information. An example of one of the workbooks is included as Appendix B.

The workbooks generally called for the following kinds of information:

1. General information on the current status of visibility, including:

    a) Man-made sources of air pollution which may significantly affect visibility,

    b) Sources and significance of natural visibility degradation (e.g., fog, dust),

    c) Impact of area management practices which may significantly affect visibility (e.g., prescribed burning, campfires, traffic),

2. An assessment of the individual scenic resources in the area, including:

a) Identification of the important vistas in the area,

b) An assessment of current visibility conditions specifying degree and extent of impairment,

c) A judgment as to whether or not the view at each vista represents desirable or undesirable visibility;

3. Formulation of visibility management objectives for each area, considering both the national visibility goal and the management responsibilities assigned to the Federal land managing agencies by enabling legislation;

4. Photographic documentation; to supplement the written analysis and to provide a baseline for further assessments, each of the land managing agencies instituted a program to photograph the most critical vistas and document desirable visibility conditions for important vistas.

The visibility workbooks were completed by field personnel for 150 of the 156 areas during the summer and fall of 1978 and transmitted to their respective headquarters for summary and analysis (NPS, 1979; USFS, 1979; FWS, 1979). The information contained in these workbooks is, in effect, as assessment of visibility in class I areas based on human observations made over a period of one to many years. Evaluation of the sources of impairment, the desirability of current conditions, and articulation of visibility management objectives represent the subjective judgment of the individual Land Managers. Because factors such as the time of service, understanding of pollutant/visibility relationships, and criteria for specifying "desirable " visibility all may be expected to vary among these managers, the results of the preliminary analysis for any individual class I area must be evaluated with caution. Nevertheless, as long as these limitations are understood, the personal observations, experiences, and judgments of the individuals managing the class I areas in question can be extremely valuable.

All 150 workbooks have been reviewed and summarized for this report. When viewed in the context of information available from other sources on regional visibility patterns (Chapters 1,4) and location of existing and projected major sources of visibility-impairing pollutants (Chapter 6), the Land Managers' assessments provide important perspectives for developing visibility control strategies. A preliminary synthesis of the workbook summary with this additional information is presented in Figure 7-1 and Table 7-1. For convenience, the airport visibility isopleth map for the summer months is reproduced as Figure 7-2. To avoid placing undue significance on the results of any single workbook, the class I areas are grouped into regions according to similarities in both the nature of visibility impairment reported and regional visual range patterns. For each region, Table 7-1, summarizes 1) subjective judgments on the status of visibility impairment as reported in the workbooks, 2) observed phenomena affecting visibility, 3) a listing of potential manmade and natural sources reported in the workbooks and, in some cases from other studies, and 4) an indication of the potential for future impairment within each general region.

7.1.2 Implications of the Preliminary Analysis

The preliminary analysis suggests a number of implications for developing control strategies and for approaching some of the major issues, which have arisen in structuring visibility regulations. Some of these implications are summarized below.

7.1.2.1 Definition of Visibility Impairment - Approximately one-third of the individual class I area managers reported "undesirable" visibility conditions and/or the need to evaluate suspected anthropogenic impacts. The remaining two-thirds of the areas were reported as having "desirable " or "acceptable " visibility conditions for all or most of their vista. Although more detailed analyses and later judgments by Land Managers and other interested parties might alter this estimate, the preliminary results suggest that, for a fair percentage of the class I areas, anthropogenic pollution is not currently causing frequent significant or adverse influences on visitor enjoyment of the area. On the other hand the analysis suggests that virtually none of the class I areas are free from at least some measurable or potentially observable anthropogenic visibility influence.

These findings indicate that, if impairment is defined as any perceptible difference from natural visibility conditions, it appears likely that few, if any, of the class I areas will be able to achieve the national goal in the foreseeable future. Moreover, little impetus may exist for improving current visibility in areas that have "desirable " visibility, but perceptible impairment.

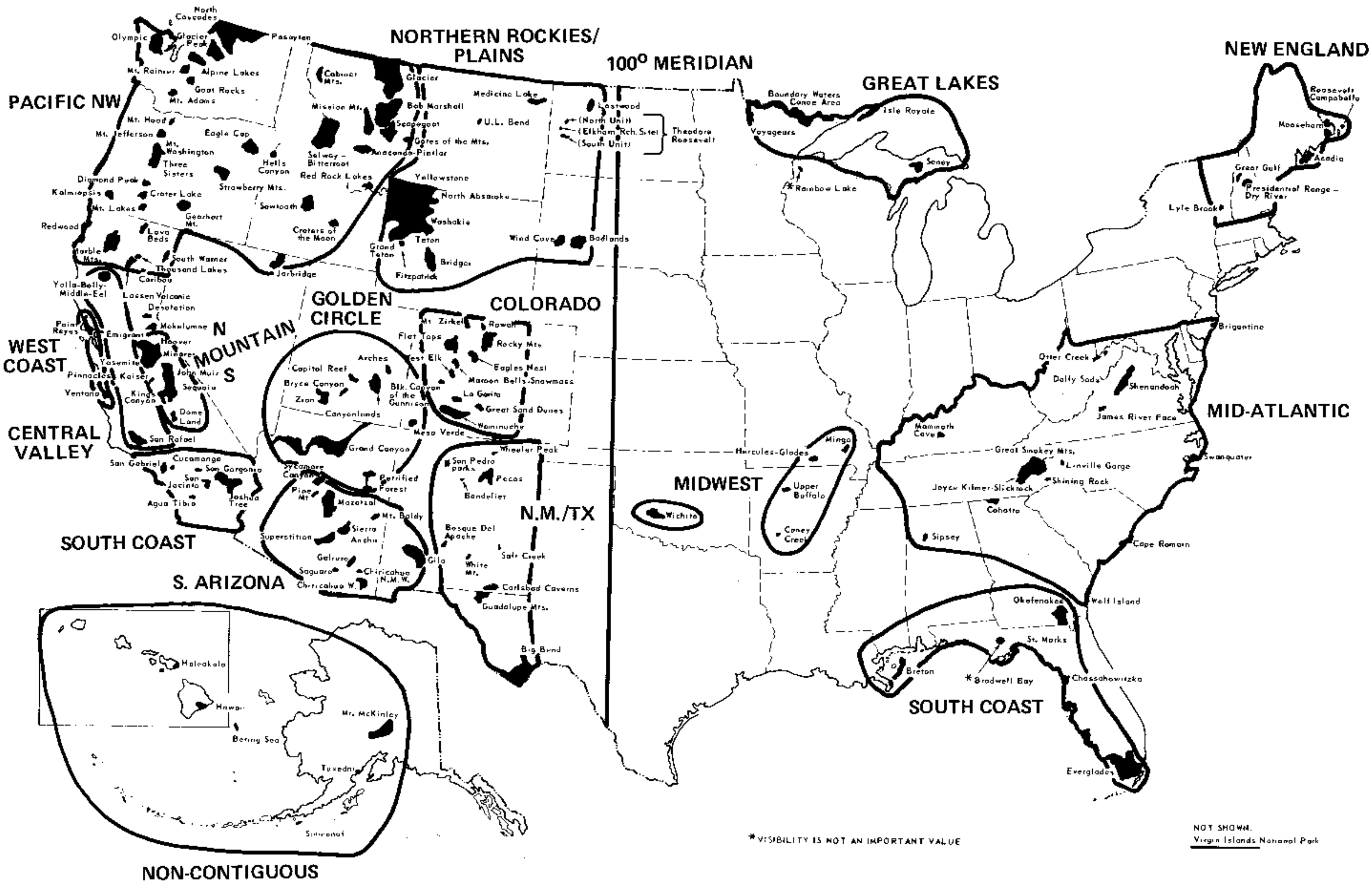

Figure 7-1. Class I area regions.

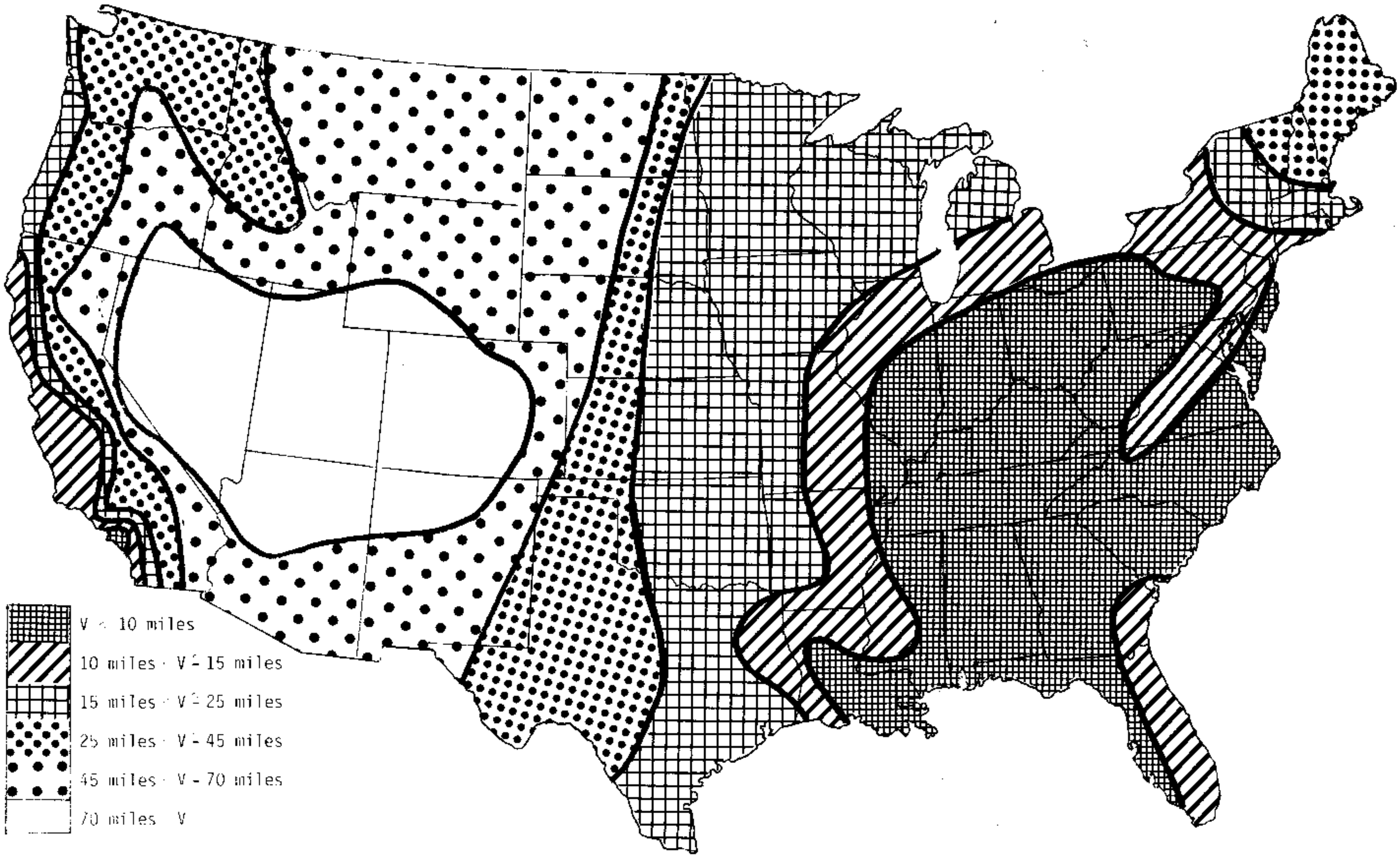

Figure 7-2. Visual Range Isopleths—Summer 1974-76 (Trijonis and Shapland, 1978).

TABLE 7-1. STATUS OF CLASS I AREA VISIBILITY IMPAIRMENT[a]

Region (see map)	Number of class I areas	Reported visibility status[a]	Observed visibility[a] phenomena	Potential sources[a]		Potential for future impairment[a-e]
				Man-made	Natural	
West of 100° Meridian						
Pacific Northwest	39	Generally desirable visibility, intermittent undesirable conditions	1. Smoke, haze 2. Visible plumes	1,2. Agricultural burning; slash burning; forest products industry; pulp, paper mills; saw mills; Al, Cu smelters; urban plumes; prescribed burning	1,2. Wildfires; fog	Small increase in utility, industrial coal use;[b,c] population growth[d]
California (excluding North): West Coast Central Valley	7	Generally impaired outside areas, some impairment in areas	1. Haze 2. Smoke 3. Dust	1,2,3. Agricultural activity, burning; urban plumes; prescribed burning	1,2. Wildfires 3. Windblown dust	Small increase in utility, industrial coal use;[b,c]
East Mountain	2 North	Impairment outside areas, intermittent in areas	1. Haze 2. Smoke	1. Lake Tahoe, urban plume 2. Prescribed burning	2. Wildfires	Some improvement, with progress toward meeting air quality standards
	7 South	Generally desirable visibility, some impairment out in areas	1. Haze 2. Smoke	1. Agricultural activity, San Joquin Valley sources	2. Wildfires	
South Coast (W)	6	Generally impaired	1. Haze, smog	1. Los Angeles; other urban plume intrusions; some prescribed burning		
Northern Rockies/Plains	12	Generally desirable visibility Some impairment outside areas	1. Smoke 2. Visible plumes 3. Dust	1,2. Slash, agricultural burning; prescribed burning	1,2. Wildfires 3. Windblown dust; fog	Increased utility coal use;[b] increased industrial coal use;[c] possible decrease in smelter emissions in attaining air quality standards;[e] Increased mining energy production activities;[c] associated population growth.[c,d]
Colorado	11	Generally desirable visibility	1. Smoke	1. Agricultural burning; saw mills; prescribed burning 2. Urban plumes	1. Wildfires 2. Windblown dust 3. Fog	Significant population growth in CO, UT;[d] associated urban, other development.
"Golden Circle"	9	Some impairment; need to assess noted	1. Haze (intermittent) 2. Visible plumes 3. Discoloration (brown, yellow bands)	1. Power plants; smelters; urban plumes 2. Power plants; miscellaneous small sources	1. Natural haze 2. Wildfires	Possible decrease in smelter impacts from air quality standard attainment[e]
Southern Arizona	11	Generally impaired	1. Regional haze 2. Dust 3. Smoke 4. Discoloration	1. Smelters; urban plumes (Phoenix, Tucson) 2. Agricultural activities; burning 3. Prescribed burning	1. Natural haze 2. Windblown dust	Possible further decrease in smelters emissions to attain air quality standards;[e] major population growth;[d] increased general development
New Mexico/Texas	10	Generally desirable visibility Need to assess noted	1. Haze 2. Dust 3. Smoke	1. Smelters 2. Agricultural activities 3. Prescribed burning	1. Natural haze 2. Windblown dust	Possible decrease in smelter impacts;[e] increased general development[a]

TABLE 7-1. (continued) STATUS OF CLASS I AREA VISIBILITY IMPAIRMENT[a]

Region (see map)	Number of class I areas	Reported visibility status[a]	Observed visibility[a] phenomena	Potential sources[a] Man-made	Potential sources[a] Natural	Potential for future impairment[a-e]
East of 100° Meridian						
New England	6	Generally desirable visibility	1. Episodic regional haze 2. Visible plumes outside some areas	1. Regional sulfur oxide; fine particle emissions 2. Pulp mills; open dump	1. Fog; Natural haze	Anticipated growth in regional coal use;[c] planned utility growth;[a] oil refinery;[a] significant population growth[d]
Mid-Atlantic	15	Some impairment, need to assess visibility noted	1. Regional haze, more intense in summer 2. Visible plumes 3. Discoloration (grey haze, brown plumes)	1. Regional sulfur oxide; fine particle emissions; urban plumes 2,3. Miscellaneous industrial sources; prescribed burning	1. Fog; natural haze 2. Wildfire	Some decrease in regional SO_x emissions through air quality Standards, NSPS replacement of older power plants;[b] significant population growth[d]
South Coast (E)	6	Generally desirable visibility	1. Regional haze, more intensive in summer	1. Regional sulfur oxide; fine particle emissions	1. Fog; natural haze 2. Wildfire; prescribed burning	Planned utility growth;[a] increase in utility coal use;[b] significant population growth[d]
Great Lakes	4	Generally desirable visibility	1. Fog 2. Smoke, visible plume	2. Pulp mills (1 area)	1. Fog 2. Wildfire; prescribed burning	Planned Canadian power plant;[a] increased regional utility coal use[b,c]
Midwest	5	Generally desirable visibility	1. Smoke, visible plume 2. Dust	1. Charcoal kiln (1 area)	1. Prescribed burning; wildfires 2. Fugitive dust	Significant increase in utility, industrial coal use, SO_x emissions[b,c]
Noncontiguous U.S.						
Alaska/Hawaii	7	Generally desirable visibility	1. Fog 2. Smoke	2. Agricultural burning[a]	1. Fog 2. Volcanic emissions	Planned power plant siting[a]

[a]Federal Land Manager Workbooks (NPS, 1979; USFS, 1979a; USFWS, 1979).
[b]Utility Emission Projections (ICF, 1979); see Figure 6-18.
[c]Industrial Coal Use Projections (DOE, 1979); see Figure 6-19.
[d]Population Projections (DOC, 1977); see Figure 6-29.
[e]Smelter Emission Projections (Trijonis, 1979); see Figure 6-22.

As a practical matter, it may not make much difference whether impairment is defined as a measurable, perceptible, or undesirable visibility impact. Given competing demands on available resources and lack of adequate information on impairment in most areas, the areas with current or projected undesirable visibility impacts should, in any case, receive highest priority in control programs. Section 169A of the Clean Air Act provides for consideration of the degree or significance of visibility improvement, costs, energy, and other factors in applying retrofit controls to major sources and in making "reasonable " progress toward the national goal. These provisions indicate that some flexibility can be allowed in implementing control programs for remedying existing impairment and that priorities can be established. Similarly, under Section 165 (PSD), the Federal Land Manager must determine whether construction of a major new source would result in "no *adverse* impact on the air quality related values (including visibility)" of an impacted class I area (emphasis added). This provision suggests that in making progress towards the national goal, priority is to be given to situations where impairment by a new source is projected to be perceptible *and* undesirable or adverse. Defining visibility impairment in the literal sense, (as a perceptible impact) and permitting flexibility in implementation appears to be consistent with Congressional intent.

7.1.2.2 Need for Protecting Vistas Extending Out of Class I Areas -The preliminary analysis confirms the notion that it is important to consider the impact of air pollution on visibility for vistas that extend beyond class I boundaries. Land Managers in over 90 percent of the class I areas, who provided detailed information on vistas, reported that one or more views from within the area looking outside the area may be, to some extent, important. Moreover, in some areas, these external views appear to be an integral part of the visibility experience in the area. For example, the view from Mesa Verde of Shiprock (New Mexico), a unique natural feature, is reportedly impaired regularly by power plant plumes. To exclude consideration of visibility impairment of this kind of vista appears contrary to the national goal.

Nevertheless, it may not be practical or necessary to require protection for all vistas extending outside of class I areas. A number of class I area managers reported that large urban areas are visible from some vantage points within the areas. In some cases, visibility impairment and discoloration within the urban or developed areas were reported. It is not clear that Congress intended to remedy this kind of visibility impairment. It is, therefore, important to develop criteria for determining which views outside class I areas constitute an integral part of the class I area experience.

7.1.2.3 Variety of Sources and Control Approaches Needed - The preliminary analysis indicates that the mix of sources that tend to dominate visibility impairment varies greatly throughout the country. The most frequent sources of impairment named by the Land Managers include (in alphabetical order):

1. Agricultural activities-burning, fugitive dust

2. Forest product development-prescription fires, pulp and paper mills, saw mills

3. Miscellaneous point sources-usually in connection with visible plumes

4. Natural sources-fog, natural haze, wind-blown dust, smoke from vegetation burning (wildfires)

5. Power plants-as single point sources and contributions through regional emissions

6. Prescription fires-supervised by Land Managers for hazard reduction, ecosystem management, etc

7. Smelters-copper and, to a lesser extent, aluminum

8. Urban pollution-mix of industrial activities, motor vehicles, space heating

The feasibility and effectiveness of remedying existing impairment from these sources vary with both the source category and the regional setting in which they are located. For example, the empirical evidence discussed in 7-7 previous chapters suggests that power plants make a significant contribution to the general regional haze, which impairs visibility throughout much of the Eastern United States. Because of the large number of power plants and the presence of significant contributions from other manmade and natural sources, however, it appears unlikely that control of any single power plant in the East will perceptibly improve visibility. On the other hand, in the Golden Circle region of the West, the Land Managers reported that the impacts of single power plants are quite noticeable; hence, control in this region could conceivably provide substantial improvements.

A totally different control approach will be needed in the Pacific Northwest and much of California to deal with the intermittent impairment caused by prescription fires and agricultural activities. Such sources are clearly not amenable to control through mechanisms requiring best available retrofit technology. Technically and economically feasible controls for these sources may, at least for the time being, be confined to attempts to minimize impacts during peak visitor periods or on days when meteorology ensures visibility impacts will be minimal. As noted in Chapter 6, prescription fires are often used in or near class I areas to protect natural ecosystems from eventual catastrophic natural wildfires.

Guidelines for the states in developing visibility regulations must recognize and take into account the diverse nature of the sources of visibility impairment.

7.1.2.4 Relative Importance of Enhancement and Protection - As discussed above, approximately one-third of the areas reported undesirable visibility conditions and/or a need to assess current visibility to determine the impact of anthropogenic pollution. Pinpointing the causes of these conditions and effecting improvements where possible are clearly important needs. Nevertheless, nearly all of the class I areas indicated the need to prevent existing conditions from deteriorating as a result of new source impacts. As Table 7 -1 indicates, many of the class I areas are likely to be influenced by increased energy development and utilization, population, and urban growth, and associated emissions increases. Once such sources are constructed, it is very difficult to mitigate their impacts. It, thus, appears that a high priority for visibility protection programs is to incorporate visibility objectives in prevention of significant deterioration (PSD) programs and to develop long-term strategies in the state implementation plans for ensuring that increased development does not adversely affect visibility in class I areas.

EPA is developing guidance for dealing with the impacts on visibility of major emitting facilities and associated development through the preconstruction review procedures required under PSD. The PSD requirements, however, do not adequately address increases in emissions associated with population growth, such as increased urbanization, automotive emissions, and space heating. PSD also may not adequately cover the impact of activities such as agricultural growth and highway construction. Additional studies to quantify the influence of such activities on visibility are needed before adequate guidance for states can be developed.

7.2 COMPONENTS OF VISIBILITY PROTECTION STRATEGIES

A number of important activities are involved in developing programs for making progress towards the national visibility goal. A conceptual framework for this process is outlined in Figure 7-3. The remainder of this chapter focuses on the most important components illustrated in this figure and highlights significant considerations and alternative regulatory approaches for these components.

7.2.1 Regulation and Guidance

As indicated earlier, EPA must promulgate visibility regulations and guidelines under Section 169A and 165 of the Clean Air Act. These regulations will establish minimum requirements for States to follow in ensuring reasonable progress towards the national goal. In order to ensure effectiveness and coordination of regulations, the Clean Air Act requirements for State implementation plan (SIP) guidance and preconstruction review of new sources under PSD will be integrated. The regulations must also specify the roles and responsibilities of the Federal Land Managers in this process.

In promulgating these regulations, EPA must consider the issues outlined in the previous section and acknowledge the limitations in current scientific and technical knowledge. For this reason, EPA recommends a phased approach to visibility programs. Although regulations and guidelines for the State must encompass the full range of Clean Air Act requirements, they should, to the extent possible: 1) permit State control programs to focus initially on the most clearly defined cases of existing impairment and on strategies to prevent future impairment and 2) allow for the evolution of guidelines and control strategies with expected improvements in scientific understanding of source/visibility/observer relationships.

Available technical information does not permit the development of control strategies for ultimate attainment of the national goal, but enough is known to develop a series of corrective and preventive actions. An evolutionary or phased regulatory approach permits these steps to be taken while delaying actions for which the technical basis is less clear. Moreover, such an approach will allow for more effective use of the limited resources available to States, Federal Land Managers, and EPA for developing visibility control programs. In the discussion of the remaining components of Figure 7-3, the need and potential for phasing of activities are identified.

7.2.2 Assessment of Class I Area Visibility

An essential initial step in developing visibility control strategies is an assessment of existing visibility conditions in class I areas and the identification of sources of perceptible impairment. Preliminary assessments such as Federal Land Manager workbook analyses summarized in Section 7.1 can identify significant sources of impairment, indicate the sensitivity of the area to future impairment, and form the basis for establishing priorities for control strategy development and conducting detailed visibility assessments. These detailed assessments will be necessary to provide an improved basis for control strategy decisions, especially where the impact of existing or proposed man-made sources is less obvious.

Figure 7-3 lists the essential components of an assessment of class I area visibility:

1. Review of Available Data-Airport data, preliminary Land Manager analysis, and other information should be obtained to support preliminary analyses and establish priorities.

2. Monitoring - As discussed in Chapter 3, determining the current or "baseline" visibility characteristics in a class I area will require a minimum of a year of monitoring involving human observations and several types of visibility pollutant and meteorological monitoring devices.

3. Source Identification - Sources that might impair visibility can be identified by direct observation of impacts of a visible source (empirical evidence), review of existing data bases containing emission source information, and analysis of the nature of the air pollutants detected in the monitoring program.

4. Evaluation of Source Impacts - The relative impacts of man-made and natural sources on visibility can be estimated by empirical analyses of available visibility, pollutant, meteorological monitoring data, and mathematical modeling of the impacts of various man-made sources that have been identified. Empirical assessments of visibility impairment can range from simple observations of plume blight from visible sources to the more complex data analyses summarized in Chapter 4. The resolution of empirical techniques is, however, often inadequate for evaluating the effect of control strategies. The contribution of individual major point sources can also be estimated through the use of mathematical models such as those described in Chapter 5. Such models can, within certain limits, be used to evaluate the effectiveness of controls. At the current stage of development, it is important, where possible, to supplement the results of mathematical models with empirical evidence.

5. Estimation of Natural Baseline - Ideally, a comprehensive assessment of visibility in a class I area would permit estimation of the distribution of visual parameters expected over the course of a meteorologically typical year in the absence of any anthropogenic air pollution impacts. Although this

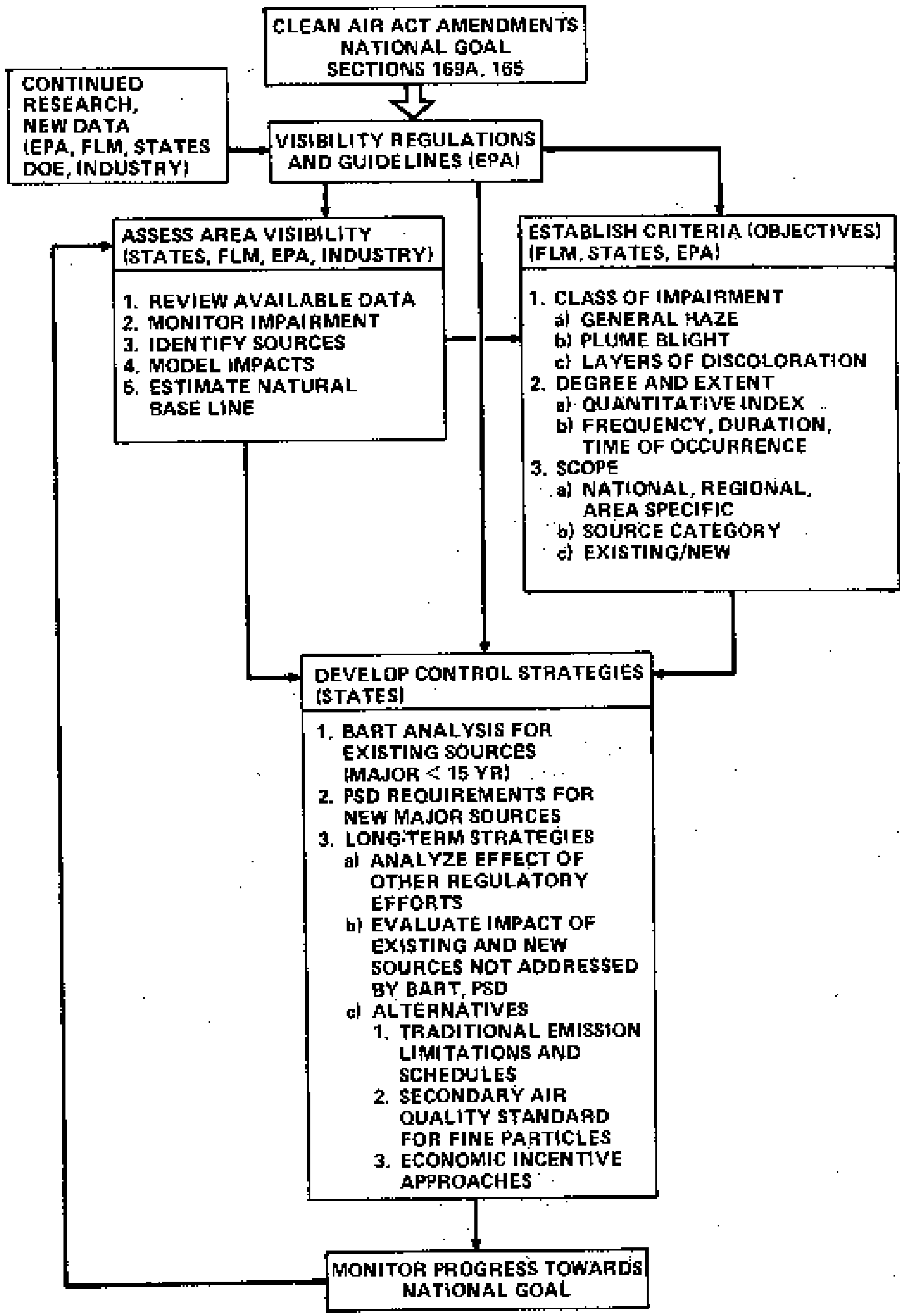

Figure 7-3. Conceptual framework for visibility protection programs.

> objective is a desirable one, even with years of monitoring, the precision of available visibility assessment tools and the variability of natural impacts will probably preclude anything more than a very rough approximation of natural visibility conditions.

The principal purpose of assessing visibility in class I areas is to assist the States and Federal Land Managers in implementing Clean Air Act requirements. Therefore, the primary responsibility for assuring that these assessments are conducted must lie with the States and Land Managers. As indicated above, however, these assessments can be costly and time-consuming. Since visibility protection represents a major new regulatory program, it is unlikely that the States and Federal Land Managers possess sufficient funding, manpower, or expertise to conduct the full range of activities needed for comprehensive assessments. Although the Land Managers and EPA are acquiring additional funding for support of such assessments, it would be neither wise nor cost-effective to attempt detailed assessments and analyses of visibility in all 156 class I areas at once. Federal and State programs should attempt to establish priorities for conducting assessments in areas already reporting significant anthropogenic visibility impairment or in those areas where construction of new sources poses the greatest threat to future visibility. Where available resources are inadequate, EPA or the states might require proposed sources to conduct visibility assessments in class I areas as part of the preconstruction review process.

7.2.3 Establishing Visibility Objectives

Development of control strategies for meeting the national goal will require a number of judgments concerning priorities for assessments and controls, the meaning of "perceptible," "adverse," and "significant" impairment, and criteria for measuring "reasonable" progress. Such judgments will involve coordination among the Federal Land Managing, Agencies, States, EPA, and the public. Although many such judgments must be made on a case-by-base basis, it is desirable to establish, where possible, a consensus among interested parties in advance of control strategy decisions. For this purpose, it may be useful to establish series of visibility objectives as general guidelines for control strategy development. The term "objective," is used here to distinguish desirable/acceptable visibility conditions or control strategies, which may vary for class I areas, from the national goal, which is, in principle, the same for all class I areas where visibility is an important value. These objectives would represent the visibility characteristics and values, which are to be restored and protected, or, in some cases, tolerated on a temporary basis. Although ultimate visibility objectives must be consistent with the national goal, interim or preliminary objectives reflecting the range of judgments noted above will be useful in making reasonable progress towards the goal.

Visibility objectives should, where possible, be articulated in such a form as to permit eventual measurement or estimation by models. The objectives also must take into account the various kinds of visibility impairment and incorporate the results of studies of human perception and visibility values. Significant aspects to be considered are outlined in Figure 7-3. The objectives should express qualitative judgments concerning desired visibility in quantifiable terms, which can be related to source emissions. For example, the general objective "maintain good visibility" might be expressed in several ways: a) maintain a median visual range ofx kilometers, b) ensure no new source emissions result in a change of contrast of greater than y percent on any day at the most sensitive viewing distance, or c) limit total anthropogenic fine particulate concentration at any point in the area to z$\mu g/m^3$ annual average.

There has been some debate over what single indicator might best be used to characterize visibility objectives. Prominent examples include extinction coefficient, contrast (between sky and target plume and background), visual range, fine particulate concentration, and chromaticity. As discussed in Chapter 3, the basic visibility indices are contrast and extinction. With the exception of chromaticity, however, all of these indices of visibility can be directly monitored or estimated from monitoring data, although simplifying assumptions and approximations are often necessary. No single indicator will be clearly useful for characterizing general haze, plume blight, and discoloration in all areas. It is, however, advisable to tie visibility objectives to indices that are directly measured in class I areas.

Frequency, duration, and time of occurrence should be taken into account in establishing visibility objectives. These factors are important because meteorological conditions can cause natural and anthropogenic visibility impacts to vary widely throughout the course of a year. Moreover, all else being equal, impairment from anthropogenic sources is considerably more objectionable during times of the year with greatest visitor attendance (e.g., summer). Visibility objectives might, therefore, be stated in terms of acceptable frequency distributions of visibility (e.g., contrast) over the course of a year. A comprehensive visibility assessment would be necessary before such an objective could be articulated. Frequency might also be considered by expressing the visibility objective as an allowable increment (e.g., an x percent increase in contrast) over an estimated or assumed baseline for any day in the year.

Conceptually, the scope of visibility objectives might be national, regional, or area-specific and might distinguish among source categories and existing and new sources. National objectives must be articulated in such a way as to account for prevailing differences in regional visibility. A national visual range objective would have no meaning. A hypothetical visual range within x percent of natural background might, however, be a useful long-term objective. Several qualitative examples of interim visibility objectives include:

1. National or regional objectives regarding the seasonality, frequency, and intensity of prescribed burning activities.

2. A national objective with respect to visible coherent plumes.

3. Area-specific objectives with respect to vistas extending outside class I areas.

4. National or regional objectives concerning allowable increments from new sources.

5. Regional or area-specific objectives calling for maintenance of current visibility or improvement to specific levels.

Providing a mechanism for the development and articulation of visibility objectives is a key problem. The process must include affected States and Land Managers and opportunity must be provided for direct public comment. EPA could call for formal procedures in guidelines for implementing Section 169A or allow individual states and Land Managers to develop ad hoc mechanisms. The Forest Service has recently proposed regulations that incorporate air quality considerations (including visibility) in their overall land management planning process (USFS, 1979b).

7.2.4 Development of Control Strategies

The development of control strategies is guided and limited by the regulations, assessments, and judgments discussed above. The essential control programs required by the Clean Air Act are outlined in Figure 7-3. Each of these components is discussed below.

7.2.4.1 Best Available Retrofit Technology (BART) Analysis -State visibility strategies must require that certain major stationary sources install and operate BART. These requirements apply to major stationary sources that (a) may reasonably be anticipated to impair visibility in a class I area, (b) began operation during the period from August 1962 to August 1977, (c) are not exempted from BART requirements by the Administrator of EPA. The Administrator can exempt on a case-by-case basis major sources that do not by themselves, or in combination with other sources, cause or contribute to significant impairment of visibility in a class I area. Furthermore, in determining BART, the State must evaluate the degree of improvement in visibility, economics, energy, and other factors, as well as availability of controls.

In essence then, application of BART will be restricted to those major sources a) for which the preliminary or detailed visibility assessment provide reasonably good evidence for noticeable visibility impacts, b) which meet the age requirements and c) the control of which can be expected to result in a perceptible improvement in visibility. The applicability of BART to those 28 source categories named in Section 169 will depend upon such factors as the type and amount of emissions and the location of each individual source. The potential applicability of the BART mechanism to man-made visibility impairment identified by the Land Managers, workbooks is summarized in Table 7-2.

It appears likely that in the early stages of visibility protection programs, application of BART will be quite limited. Improvements in understanding source/visibility relationships and developments in control technology could expand, to some extent, the application of BART.

The preliminary Land Manager analysis indicates that a number of significant sources of visibility impairment identified in the preliminary analysis will not be covered under BART requirements. However, states must ultimately consider such sources in developing long-term strategies for making progress toward the national goal. This requirement is discussed in 7.3.

7.2.4.2 Prevention of Significant Deterioration - Issues in making progress towards the national visibility goal with respect to new major emitting facilities must be resolved within the procedures established for the prevention of significant deterioration (PSD). Therefore, the preconstruction review procedures established by the state under PSD must incorporate mechanisms for a) evaluating visibility impacts, and b) involving Federal Land Managers in judgments as to whether permitting construction of a proposed new source would adversely affect current visibility or be inconsistent with long-term programs for making reasonable progress toward the national goal. As discussed in the previous section, one mechanism for formalizing such value judgments is the establishment of regional or area-specific visibility objectives to guide the implementation of procedures for granting new source permits.

A visibility analysis for a proposed new source must consider whether the new source impact is consistent with applicable visibility objectives with respect to general haze conditions, perceptible plumes, and atmospheric discoloration. The analysis must rely heavily on predictive models as supported by empirical data. As discussed in previous chapters, there are a number of uncertainties, which must be recognized in applying these procedures. Areas of important uncertainty include the difficulty in predicting the formation of secondary aerosols (sulfates) under varying meteorological conditions, estimation of transport and dispersion parameters in areas of complex terrain, predictions of the impact of single or multiple sources on a regional (200 to 500 kilometer) scale, and theoretical limitations in predicting whether incremental changes in contrast or color will be perceptible. Although major efforts to reduce these uncertainties are of high priority, the available tools can, and must, be used in evaluating new source impacts. The alternative, allowing construction of new sources as long as prescribed class I increments are met, is not acceptable. Analyses of available scientific information by Charlson et al. (1978), Latimer et al. (1978), and others support the contention of the House Commerce Committee that "mandatory class I increments do not protect adequately visibility in class I areas" in all cases.

These preliminary analyses also suggest that the areas most sensitive to these effects lie in or near the "Golden Circle " region of the Southwest, the region with the best visual range and a number of heavily visited class I areas. Initial modeling of alternative power-plant configurations suggests that potential problems in this region include plume bright from NO2 and sulfate-derived haze. As discussed in Chapter 5, brown NO_2 plumes might occur at distances of up to 80 km from the source and be perceptible for plants larger than a capacity of 500 megawatts. Under most meteorological conditions, maximum impacts of sulfate haze derived from SO_2 emissions would be expected at distances from 100 to 200 km from the source. Preliminary analyses suggest these impacts will likely not be significant for single well-controlled plants of less than 2000 MW capacity, although the cumulative effect of several sources may be of concern.

If preconstruction analysis for a proposed new source suggests an unacceptable visibility effect, the available options for the sources include reduced emissions through improved controls or "downscaling" of the project and alternative siting in locations where meteorology and/or the terrain reduce or eliminate the expected impacts. Specification of visibility objectives and detailed analyses of visual air quality will be needed to determine the extent to which such alternative sites can accommodate regional power-plant growth

TABLE 7-2. POTENTIAL APPLICABILITY OF BART MECHANISM TO PRINCIPAL SOURCE CATEGORIES NAMED BY FLM

Source category	BART applicability
Agricultural activities	
Burning	Not applicable
Fugitive dust	Not applicable
Forest product development	
Slash burning	Not applicable
Pulp and paper mills	Varies with age, controls, impairment
Saw mills	Not applicable
Miscellaneous point sources	Varies with age, controls, impairment
Prescription fires	Not applicable
Power plants	
Single identifiable sources	Varies with age, controls, impairment
Regional emissions	Probably not applicable (evaluation of improvement not possible)
Smelters	
Copper	Not applicable to most (too old)
Aluminum	Varies with age, controls, impairment
Urban pollution	
Industrial activities	Varies with age, controls, impairment (probably limited)
Motor vehicles	Not applicable
Space heating	Not applicable

in the Southwest. Initial analyses, however, suggest that, with proper siting, application of NSPS controls, and expected reductions in smelter emissions, planned growth in Southwestern utility generation through the year 2000 should not be unduly constrained by visibility requirements (Latimer, 1979).

The analysis of the impact of proposed new sources also encompasses the impacts of other growth associated with the proposed facility. The Federal Land Managers' workbooks underscore a need for evaluating the impacts of general urban development, since these impacts are often reported to be substantial. As noted earlier, PSD mechanisms do not provide for an explicit analysis of visibility impacts for growth in smaller or urban scale source emissions not associated with a major facility. Moreover, PSD guidance to date does not provide for assessing the cumulative impact of issuing permits for a large number of new sources on a regional scale. Again, such issues must eventually be considered by the States in developing long-term strategies.

7.3 LONG-TERM STRATEGIES

As indicated in the previous discussion, development and implementation of long-term strategies are central to making progress towards the national visibility goal. These strategies should provide for integration of visibility objectives into ongoing air management efforts, to take into account sources not adequately covered by other mechanisms and to explore innovative approaches for making cost-effective progress toward visibility protection. Important considerations and alternatives are outlined below.

7.3.1 Analysis of the Effect of Other Regulatory Efforts

An essential starting point in developing long-range strategies for visibility protection is to assess the impact of other air pollution related control programs. These control programs include: 1) State implementation plan emission limits and compliance schedules for attainment and maintenance of the ambient air quality standards, 2) new source performance emission standards for power plants, industrial boilers, and other major sources of visibility impairing pollutants, 3) motor vehicle emission standards, and 4) PSD increments for class II, as well as class I areas. These regulatory programs can be expected to provide significant benefits in meeting interim objectives and making progress toward the national visibility goal.

The potential impact of existing programs on some of the more difficult visibility-impairment problems identified in the workbook analysis is outlined below.

1. Southwestern regional impairment from smelters -The Southwestern smelters have significantly reduced emissions in response to state programs for attaining the national ambient air quality standards and because of reduced production. The smelters are under compliance schedules that should provide further significant reductions in emissions by 1990 (see Figure 6-22). Preliminary analyses (Marians and Trijonis, 1979; Latimer et al., 1978), suggest that the reductions in smelter emissions to date have resulted in improved regional visibility in the Southwest

since 1972. Therefore, the exemption of most smelters from BART requirements (due to their age) will not materially affect progress toward the visibility goal.

2. Regional visibility impairment in the East - As discussed in Chapters 4 and 5, regional trends in visibility are strongly associated with regional sulfur oxide emissions, especially from power plants. Additional contributions come from direct fine particulate emissions and photochemically produced organic particles. Strategies for attaining the air quality standards for particulate matter, sulfur oxides, and ozone in the East have already stopped the general trend toward increased emissions of these pollutants. In addition, the recently announced new source performance standard for power plants represents an important long-term strategy that will ultimately reduce Eastern sulfur oxides emission levels, because the eventual replacement of older, poorly controlled power plants will be with cleaner new plants. This strategy however, will not begin to significantly reduce emissions until after 1995 (see Figure 6-18).

3. Impairment from urban plumes -A number of the class I areas are impaired by urban plumes from cities where one or more of the current ambient air quality standards are not met; for example, the South Coast Air Basin of California. Such urban areas are already moving as rapidly as practical towards meeting the air quality standards.

These efforts should, at least, limit any increased impairment and in some cases improve visibility conditions.

Once the impact of other regulatory programs is evaluated, the need for additional control approaches for meeting the national goal can be assessed. For example, in the cases of impairment caused by smelters or the South Coast Air Basin urban plume, it does not appear reasonable or necessary to develop major new strategies for visibility improvement at this time. Such strategies would not significantly affect the rate, or extent, of control application. Long-term strategies must focus on those situations and source categories that can not meet interim visibility objectives or make reasonable progress toward the national goal.

7.3.2 Analysis of Existing Sources not Covered by BART

As discussed above, long-term strategies must consider the problem of existing sources of visibility impairment that are not covered by BART requirements and that are inadequately handled by other programs. Significant examples are sources that began operations after August 1977 or before August 1962, certain non-major point source categories, such as agricultural and other prescribed burning, and area wide emissions from populated areas. In many cases, the age of the source and existing controls may preclude any action for major stationary sources. Control of many categories of area sources for visibility protection will be difficult to justify and defend. However, the preliminary workbook results indicate a significant need to consider the impact of prescription fires in a manner that minimizes visibility impacts. This task will not be an easy one. In the area with the most significant problem (the Pacific Northwest), current fire management practices are designed to avoid effects on populated areas. Because of geography, this practice often results in increased burning impacts on class I areas. Clearly, in such situations public health protection must be paramount. However, it is likely that current programs have not attempted to deal with the question of minimizing visibility impacts.

7.3.3 Growth of Sources not Adequately Considered by PSD

As indicated above, general urban development and increased dispersion of smaller population centers in the vicinity of class I areas pose a significant threat to visibility in these areas. Long-term strategies must give some consideration to the impact on class I areas of new population growth, residential development, and increased agricultural activities. Historically, efforts to control the impact of generalized small sources have been controversial. Nevertheless, without some consideration of these sources, generalized growth could thwart attempts at preserving and attaining pristine conditions in class I areas.

7.3.4 Innovative or Supplemental Long-Term Strategies

Over the next several years, State visibility control programs will focus on controlling existing sources that have a demonstrable impact on visibility, evaluating visibility impacts of major new point sources located within about 150 kilometers of class I areas, and assessing the impact of other regulatory programs on improving and maintaining visibility in class I areas. Continued study of the various aspects of the visibility problem will permit evaluation of the effectiveness and necessity of additional control approaches for making progress toward the national goal. Examples of visibility problems that must ultimately be faced when improved technical information is available are given in Table 7-3. Potentially desirable technical control approaches are also listed. Although traditional emission limitations and control strategies may be useful, implementation of these and other necessary long-term technical control approaches may also require the use of innovative or supplemental regulatory strategies. Technical control approaches include applying control technology, conservation or other actions, which reduce emissions. Regulatory strategies include means of implementing desirable technical controls.

TABLE 7-3. EXAMPLES OF POTENTIAL LONG-TERM STRATEGIES

Visibility problem	Major sources	Desirable technical control approach
Reduce regional haze in East (more rapidly than NSPS approach)	Regional sulfur oxide emissions/power plants, other fossil fuel combustion	Reduce regional sulfur oxide emissions/emphasis on reduction during summer months of peak sulfate levels
Maintain regional visibility in Southwest	Regional sulfur oxide emissions/smelters, power plants, urban plumes	Maintain or reduce current regional sulfur oxides emissions - regional "offset" approach
Reduce smoke impacts from burning in Northwest	Prescribed burning to maintain ecosystem, slash burning of forestry, agricultural wastes	Limit times of necessary burning to minimize impacts/ encourage alternative disposal, energy recovery of slash

Several alternative regulatory approaches that may prove useful are outlined below, with some discussed in greater detail elsewhere (Fiorino, 1979). Because of the regional character of the visibility problems and the nature of the approaches, some of the alternatives discussed below are beyond the capability of individual States without further guidance from EPA and, in some cases, are not without additional legislative mandates. Considerable analysis of the feasibility, effectiveness, and desirability of these and other approaches is needed before they can be seriously considered.

7.3.4.1 Secondary Air Quality Standard for Fine Particles - Current understanding of the regional visibility problem in the Eastern United States suggests that any attempt to make improvements significantly faster than projected under current new source performance standards and air quality standard implementation would be extremely costly. There is some question as to whether possible enhancement of visibility in the 35 Eastern Class I areas provides sufficient justification for an accelerated cleanup effort. A general reduction in sulfur oxide emissions would, however, probably improve visibility throughout the East. Depending on the extent to which the public views this objective as a desirable one, sufficient reason may exist for establishment of a secondary ambient air quality standard for fine particles. Besides mandating regional visibility improvements, a standard that reduces regional sulfur oxide emissions could provide other benefits, such as a reduction in acid rain.

No national ambient air quality standard could be established which would protect visibility in all class I areas and at the same time be attainable throughout the nation. This is true because of generally higher natural and man-made concentrations of fine particles in the East. Nevertheless, such a standard would accelerate progress toward improved visibility throughout the Eastern United States and might also increase the efforts for visibility improvements in major urban areas of the Western United States. Thus, a secondary air quality standard for fine particles could effectively complement visibility protection programs in class I areas.

Recently initiated research efforts in monitoring of fine-particles, transformation and transport studies, and progress in evaluating visibility values could provide support for a decision on the desirability of such an air quality standard by 1982 or 1983. Implementation is required under the Act within "a reasonable time". The consequences of such a standard for State programs are, however, far-reaching, and significant additional resources at the Federal and state level may be necessary to handle the additional load and to deal with multi-state emission control strategies.

7.3.4.2 Economic Incentives for Cost - Efficient Implementation -The problem of reducing existing impairment caused by regional haze, such as that found in the East and in the Los Angeles Basin, may well be more economically solved by means other than traditional air pollution control programs. Unlike plume blight, where the source of the plume can be identified by direct observation, pollutants that cause haze come from a multitude of sources and are so well mixed together that even the most sophisticated tracer studies are not reliable for identifying individual sources. Consequently, it may be necessary to consider polluting sources as a group rather than individually.

Macro-scale approaches such as marketable permits and fees may be suitable instruments for implementing a long-term strategy that must deal with such a group of sources. Such strategies define ways of allocating control burdens among sources that impair visibility; they differ from ambient standards that traditionally prescribe the total level of pollutants desired rather than the distribution of control requirements. Economic incentives distribute control requirements in a way that is different from and potentially more cost-effective than traditional air pollution control regulations.

1. Controlled Trading (Marketable Permits)

Under a controlled trading approach, EPA or the States would allocate pollution privileges among sources in a defined area and establish conditions for future exchanges of these privileges. The process would be implemented in several stages:

1. Draw boundaries around groups of sources that contribute to a common visibility problem; this action defines each "market" for allocating and exchanging pollution privileges.

2. Establish maximum loadings for each pollutant (or precursor) that impairs visibility in each area, or market, on the basis of the definition of visibility goals, air quality modeling data, and economic and energy considerations.

3. Allocate or auction off pollution privileges to sources in each market, to the point where total allocations equal the maximum loading of each pollutant consistent with visibility goals. The number of permits each source has would determine its allowable emissions.

4. Establish conditions for the purchase and sale of pollution privileges among sources that are part of the same market.

The advantage of a marketable permit system is that it produces the desired level of visibility protection at the lowest achievable cost by giving incentives to the sources with the lowest abatement costs to reduce emissions the most. Those sources with low abatement costs would find it more economical to install controls than to buy permits, and those sources with high abatement costs would find it more economical to buy permits than to install controls. As the permits are traded among sources, the total cleanup cost lessens while the burden of paying for it remains spread among all sources responsible for visibility impairment.

A disadvantage of this system is that the equilibrium price of the permits is unknown until the auction has stabilized. This price factor is crucial to businesses making investment decisions, and its uncertainty might lead to less than optimal decisions on the part of the regulated industries. Coordinating the system on a multi-state basis presents additional difficulties.

2. Emission Fees

Under a fees approach, firms face a fixed charge for each unit of waste emitted (e.g. $X/lb sulfur). To control visibility, charges would be levied on sulfur oxides, nitrogen oxides, and all other constituents that can be shown to impair visibility. If the fees are set high enough, it will be cheaper for sources to reduce emissions than pay the charge. Ideally, sources would minimize their pollution control costs by abating their wastes up to the point where the incremental cleanup cost equals the level of the fee. The next increment of pollution reduction would cost more than the fees. The proper fee should be set so that the sum of residual discharges from all sources does not exceed the maximum amount of each pollutant that is consistent with the visibility goal. In theory, the amount of waste reduction from each firm will vary as a function of the firm's marginal abatement cost.

Unlike a marketable permits approach, a fees approach results in a known price for pollutants emitted but an unknown level of pollutant loading and, therefore, an unknown level of visibility protection. Consequently, several iterations of fee levels would be necessary before an optimal level is reached.

3. Supplemental Economic Approaches

Government cost-sharing, through tax incentives or direct subsidies, can be used along with visibility control strategies. Accelerated depreciation allowances, direct grants, interest-free loans, and guaranteed financing might be used selectively. Such cost-sharing schemes have proven to be most desirable in promoting control technology development. Incentives may be particularly useful in encouraging alternative means of disposing of forest debris, which is currently burned on site.

Noncompliance penalties, provided for in the Clean Air Act, can be imposed for violations of BART requirements. Such penalties remove the incentive to avoid compliance by assessing firms an amount equal to the economic benefits they receive from noncompliance.

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PROTECTING VISIBILITY

AN EPA REPORT TO CONGRESS

CHAPTER 8

8 RECOMMENDATIONS FOR VISIBILITY RESEARCH

The preceding chapters have identified a number of important information gaps and uncertainties in our current understanding of atmospheric visibility impairment. The extension and refinement of visibility protection programs will depend on improvement in available knowledge and techniques in several fundamental areas. These areas include monitoring, source identification, predictive modeling, atmospheric chemistry and transport, human perception, control techniques, implementation strategies, and value judgments. Increased communication among the various regulatory, scientific and technical disciplines represented by each of these areas is vital to the development of comprehensive research approaches to improve methods for making progress toward the national visibility goal.

EPA is currently developing an expanded visibility research program to be carried out over the next several years. In developing and implementing this program, EPA will continue coordination with major visibility studies conducted by the Federal Land Managers, Department of Energy, other governmental agencies, and industry groups. Important areas that should be addressed by these programs are summarized below.

8.1 CHARACTERIZATION OF EXISTING REGIONAL VISIBILITY CONDITIONS

Assessment of existing visibility in class I areas is an important need. Class I areas can be grouped into regions of similar climatology, scenery, prevailing visibility, and sources of impairment (such as those illustrated in Figure 7-1). Long-term comprehensive characterization of visibility-related parameters should be conducted in at least one class I area in each of these representative regions. Minimum requirements for such a program would include operation of a 10-to-20-station monitoring network for a period of 5 years. Priority should be given to pristine areas with significant emissions growth (or reduction) potential and areas with existing impairment problems. Approximately 3 to 5 Eastern sites (Northeast, mid-Atlantic, South Coast, Great Lakes) and 7 to 15 Western sites ("Golden Circle", Colorado, Pacific Northwest, California, Northern Plains, Southern Arizona, New Mexico-Texas) would give sufficient coverage. Each location should provide for comprehensive monitoring of optical, meteorological, and pollutant parameters. In addition to the human observation and instrumentation recommended in Chapter 3, instrumentation for monitoring light absorption by particles should be included. All identifiable major components of fine particulate mass should be monitored, and the contribution of coarse-mode particles to extinction estimated. The sampling strategy should be designed with data reduction and analysis methods in mind. Attempts should be made to separate natural and anthropogenic contributions and to characterize various air-mass influences. Supplemental regional aircraft sampling and auxiliary site "intensive " monitoring would be a useful adjunct to the base network.

The results of this comprehensive monitoring would include an improved understanding of natural and anthropogenic base-line contributions to visibility impairment, an indication of which parameters are necessary or most useful in characterizing visibility, better monitoring instruments and operating procedures, and more precise approaches to assessment of visibility impairment. The network would also serve as a focal point for other visibility-related studies.

8.2 IMPROVED VISIBIDY MONITORING APPROACHES

Additional work is needed to develop simplified and improved visibility measurement approaches. An initial priority is development of a standardized guideline for "context pertinent" human observations by trained personnel. A consistent index should be developed for the three classes of impairment (plume blight, haze layers and general haze) and a generalized daily observation form should be made available. Development on standardized human observer methods should be coordinated with studies of human perception (Section 8.5) and visibility values (Section 8.6).

Improvements are needed in optical instruments. If possible, a single instrument, useful in a variety of applications, should be developed and tested. A portable, low-power consumption device for use in remote wilderness areas is particularly needed. Instruments for routine measurements of scattering *and* absorption by particles would be most useful. More sophisticated monitoring techniques for research applications are also needed. Instruments for measuring aerosol mass and chemical composition over shorter time intervals (1 to 2 hours) in clean areas would be a useful adjunct to current optical instrumentation. More accurate sampling and analysis approaches are needed for particulate organics and nitrates.

8.3 FIELD STUDIES OF POINT AND AREA SOURCE IMPACTS

Plume flights conducted in the VISTTA, MISTT, MAP3S, SURE and other research programs have provided significant information on the visibility impacts of major point source and large urban plumes. Such programs should be continued. Additional field studies are needed to examine the visibility impacts of source/environment combinations not yet studied. Briefly, these combinations include:

1. Plumes from power plants equipped with wet and dry ~ SO_χ scrubbers.

2. Secondary sulfate, NO2, and nitrate formation rates in plumes from Western power plants.

3. Emissions from new energy technologies.

4. Impacts of Los Angeles, Phoenix, and Tucson urban plumes on Southwest regional visibility.

5. Impacts of medium to small urban areas on nearby (50 to 100 km) Class I areas in the Southwest.

6. Fugitive dust emissions from mining, agriculture, and unpaved roads.

7. Impact of prescribed burning in the Pacific Northwest.

8.4 IMPROVEMENT IN PREDICTIVE VISIBILITY MODELS

8.4.1 Single Point Source Models

Validation and improvement of existing visibility models are extremely important. It is particularly necessary to determine whether the predicted significant NO_2 impacts at distances of 20 to 80 kilometers from well-controlled plants are observable. Analysis of validation studies (plume flights and ground measurements of relevant optical, dispersion, and chemical parameters), conducted by the VISTTA program for 1978-1979, should be accelerated to the extent possible, and plans for additional studies made. Current models should be improved to deal more effectively with complex terrain, channeling effects, and variable meteorological conditions over the course of a day and through seasonal cycles. Models should be extended to permit impact analyses of area sources, mining operations, and new energy technologies. The results of empirical studies of atmospheric visual perception (Section 8.5) should be incorporated into improved models. The LASL color display technique should be further developed and adapted for routine use on less sophisticated computers.

8.4.2 Regional Scale Models

As a starting point in developing regional-scale visibility models, the available airport visibility/pollutant satellite database in the Western states should be examined to determine if any evidence of hazy air mass episodes exists. Planned field studies in the East (PEPE and SURE) to evaluate chemistry, transport, and removal processes in a variety of conditions will be of significant value. Additional studies of Western hazy air masses should be initiated.

Studies of regional dispersion in the complex terrain of the West are needed. Basic Western meteorological data, such as transport winds through the mixing layer (up to 3 km), should be gathered as input for regional models. Regional models should be capable of dealing with spatial/temporal variations in plume trajectories, diurnal patterns in mixing heights, turbulence, stagnation, recirculation, channeling by terrain, and moderate to large scale meteorological patterns.

8.5 STUDIES OF ATMOSPHERIC HUMAN VISUAL PERCEPTION IN CLEAN AREAS

Both visibility modeling and monitoring require improved specification of the response of the eye/brain to atmospheric visual stimuli. Tests of the relationship between visual range of large dark objects and extinction (Koschmeider) are needed in "clean" areas. Validation of the applicability of the MTF approach for predicting the visual range of contrast detail and perceptibility of small pollution increments in scenic vistas is also needed. Most importantly, a study of thresholds of perception for discoloration caused by NO_2 and haze layers in the atmosphere should be conducted. Such studies should be linked and compared to the predicted outputs of visibility models. Many of these perception studies could be conducted by use of panels of observers at or near comprehensive monitoring sites, discussed in Section 8.1. Initial studies by the American Petroleum Institute and the National Park Service will provide important insights for further work.

8.6 STUDIES OF THE VALUE OF VISIBILITY

Improved specification of the value of visibility, whether in economic, psychological, or social terms can assist in specific control/permitting decisions and in establishing interim objectives for making progress toward the national goal. A coordinated visibility values research program, tied to decision-making needs of the Land Managers and States, should be developed. The 1979 Visibility Values workshop represented a first step in this process (Fox et al., 1979). Values studies might be connected with studies of human perception and monitoring programs. Photography or field studies using observer panels could be conducted to define "significant" or "adverse " impairment better. Economic and psychological studies of activity, options, and existence values of class I area visibility might also prove useful. An analysis should be conducted of the benefits and desirability of improving visibility in Eastern class I areas, and hence, improving general visibility throughout the East. Such analyses may form the basis for deciding on long-term strategies for remedying existing impairment, as well as protecting general public welfare.

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APPENDIX A:
CLASS I AREAS WHERE VISIBILITY IS AN IMPORTANT VALUE

SUBPART D- IDENTIFICATION OF MANDATORY CLASS I FEDERAL AREAS WHERE VISIBILITY IS AN IMPORTANT VALUE

81,400 Scope.

Subpart D, Section 81.401 through 81.437 lists those mandatory Federal Class I areas, established under the Clean Air Act Amendments of 1977, where the Administrator, in consultation with the Secretary of the Interior, has determined visibility to be an important value.

The following listing of areas where visibility is an important value represents an evalation of all international parks (IP), national wilderness areas (Wild) exceeding 5,000 acres, national memorial parks (NMP) exceeding 5,000 acres, and national parks (NP) exceeding 6,000 areas, in existence on August 7, 1977. Consultation by EPA with the Federal Land Managers involved: the Department of Interior (USDI), National Park Service (NPS), and Fish and Wild Life Service (FWS); and the Department of Agriculture (USDA), Forest Service (FS).

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.401 Alabama.	Sipsey Wild	12,646	93-622	USDA–FS
S81.402 Alaska.	Bering Sea Wild	41,113	91-622	USDI-FWS
	Mount McKinley NP	1,949,493	64-353	USDI-NPS
	Simeonof Wild	25,141	94-557	USDI-FWS
	Tuxedni Wild	6,402	91-504	USDI-FWS
S81.403 Arizona	Chiricahua National Monument Wild	9,440	94-567	USDI-NPS
	Chiricahua Wild	18,000	88-577	USDA-FS
	Galiuro Wild	52,717	88-577	USDA-FS
	Grand Canyon NP	1,176,913	65-277	USDI-NPS
	Mazatzal Wild	205,137	88-577	USDA-FS
	Mount Baldy Wild	6,975	91-504	USDA-FS
	Petrified Forest NP	93,493	85-358	USDI-NPS
	Pine Mountain Wild	20,061	92-230	USDA-FS
	Saguaro Wild	71,400	94-567	USDI-NPS
	Sierra Ancha Wild	20,850	88-577	USDA-FS
	Superstition Wild	124,117	88-577	USDA-FS
	Sycamore Canyon Wild	47,757	92-241	USDA-FS
S81.404 Arkansas.	Caney Creek Wild	14,344	93-622	USDA-FS
	Upper Buffalo Wild	9,912	93-622	USDA-FS

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.405 California	Aqua Tibia Wild	15,934	93-632	USDA-FS
	Caribou Wild	19,080	88-577	USDA-FS
	Cucamonga Wild	9,022	88-577	USDA-FS
	Desolation Wild	63,469	91-82	USDA-FS
	Dome Land Wild	62,206	88-577	USDA-FS
	Emigrant Wild	104,311	93-632	USDA-FS
	Hoover Wild	47,916	88-577	USDA-FS
	John Muir Wild	484,673	88-577	USDA-FS
	Joshua Tree Wild	429,690	94-567	USDI-NPS
	Kaiser Wild	22,500	94-577	USDA-FS
	Kings Canyon NP	459,994	76-424	USDI-NPS
	Lassen Volcanic NP	105,800	64-184	USDI-NPS
	Lava Beds Wild	28,640	92-493	USDI-NPS
	Marble Mountain Wild	213,743	88-577	USDA-FS
	Minarets Wild	109,484	88-577	USDA-FS
	Mokelumme Wild	50,400	88-577	USDA-FS
	Pinnacles Wild	12,952	94,567	USDA-NPS
	Point Reyes Wild	25,370	94-544,94-567	USDI-NPS
	Redwood NP	27,792	90-545	USDI-NSP
	San Gabriel Wild	36,137	90-318	USDA-FS
	San Gorgonio	34,644	88-577	USDA-FS
	San Jacinto Wild	20,564	88-577	USDA-FS
	San Rafael Wild	142,722	90-271	USDA-FS
	Sequoia NP	386,642	26 Stat. 478 (51st Cong.)	USDI-NPS
	South Warner Wild	68,507	88-577	USDA-FS
	Thousand Lakes Wild	15,695	88-577	USDA-FS
	Ventana Wild	95,152	91-58	USDA-FS
	Yolla-Bolly-Middle-Eel Wild	109,091	88-577	USDA-FS
	Yosemite NP	759,172	58-49	USDI-NPS
S81.406 Colorado.	Black Canyon of the Gunnison Wild	11,180	94-567	USDI-NPS
	Eagles Nest Wild	133,910	94-352	USDA-FS
	Flat Tops Wild	235,230	94-146	USDA-FS
	Great Sand Dunes Wild	33,450	94-567	USDI-NPS
	La Garita Wild	48,486	88-577	USDA-FS
	Maroon Bells - Snowmass Wild	71,060	88-577	USDA-FS
	Mesa Verde NP	51,488	59-353	USDI-NPS
	Mount Zirkel Wild	72,472	88-577	USDA-FS
	Rawah Wild	26,674	88-577	USDA-FS
	Rocky Mountain NP	263,138	63-238	USDI-NPS
	Weminuche Wild	400,907	93-632	USDA-FS
	West Elk Wild	61,412	88-577	USDA-FS
S81.407 Florida.	Chassahowitzka Wild	23,360	94-557	USDI-FWS
	Everglades NP	1,397,429	73-267	USDI-NPS
	St. Marks Wild	17,745	93-632	USDI-FWS
S81.408 Georgia.	Cohotta Wild	33,776	93-622	USDA-FS
	Okefenokee Wild	343,850	93-429	USDI-FWS
	Wolf Island Wild	5,126	93-632	USDI-FWS
S81.409 Hawaii.	Haleakala NP	27,208	87-744	USDI-NPS
	Hawaii Volcanoes	217,029	64-171	USDI-NPS
S81.410 Idaho.	Craters of the Moon Wild	43,243	91-504	USDI-NPS
	Hells Canyon Wild[a]	83,800	94-199	USDA-FS
	Sawtooth Wild	216,383	92-400	USDA-FS
	Selway-Bitterroot Wild[b]	988,770	88-577	USDA-FS
	Yellowstone NP[c]	31,488	17 Stat. 32 (42nd Cong.)	USDI-NPS

[a] HellsCanyon Wilderness, 192,700 acres overall, of which 108,900 acres are in Oregon and 83,800 acres are in Idaho.
[b] Selway Bitterroot Wilderness, 1,240,700 acres overall, of which 988,700 acres are in Idaho and 251,930 acres are in Montana.
[c] Yellowstone National Park, 2,219,737 acres overall, of which 2,020,625 acres are in Wyoming, 167,624 acres are in Montana, and 31,488 acres are in Idaho.

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.411 Kentucky.	Mammoth Cave NP	51,303	69-283	USDI-NPS
S81.412 Louisiana.	Breton Wild	5,000+	93-632	USDI-FWS
S81.413 Maine.	Acadia NP	37,503	65-278	USDI-NPS
	Moosehorn Wild	7,501		USDI-FWS
	(Edmunds Unit)	(2,782)	91-504	
	(Baring Unit)	(4,719)	93-632	
S81.414 Michigan.	Isle Royale NP	542,428	71-835	USDI-NPS
	Seney Wild	25,150	91-504	USDI-FWS
S81.415 Minnesota.	Boundary Waters Canoe Area Wild	747,840	99-577	USDA-FS
	Voyageurs NP	114,964	99-261	USDI-NPS
S81.416 Missouri.	Hercules-Glades Wild	12,315	94-557	USDA-FS
	Mingo Wild	8,000	94-557	USDI-FWS
S81.417 Montana.	Anaconda-Pintlar Wild	157,803	88-577	USDA-FS
	Bob Marshall Wild	950,000	88-577	USDA-FS
	Cabinet Mountains Wild	94,272	88-577	USDA-FS
	Gates of the Mtn Wild	28,562	88-577	USDA-FS
	Glacier NP	1,012,599	61-171	USDI-NPS
	Medicine Lake Wild	11,366	94-557	USDI-FWS
	Mission Mountain Wild	73,877	93-632	USDA-FS
	Red Rock Lakes Wild	32,350	94-557	USDI-FWS
	Scapegoat Wild	239,295	92-395	USDA-FS
	Selway-Bitterroot Wild[a]	251,930	88-577	USDA-FS
	U. L. Bend Wild	20,890	94-557	USDI-FWS
	Yellowstone NP[b]	167,624	17 Stat. 32 (42nd Cong.)	USDI-NPS

[a] Selway-Bitterroot Wilderness, 1,240,700 acres overall, of which 988,770 acres are in Idaho and 251,930 acres are in Montana.
[b] Yellowstone National Park, 2,219,737 acres overall, of which 2,020,625 acres are in Wyoming, 167,624 acres are in Montana, and 31,488 acres are in Idaho.

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.418 Nevada.	Jarbridge Wild	64,667	88-577	USDA-FS
S81.419 New Hampshire.	Great Gulf Wild	5,552	88-577	USDA-FS
	Presidential Range-Dry River Wild	20,000	93-622	USDA-FS
S81.420 New Jersey.	Brigantine Wild	6,603	93-632	USDI-FWS
S81.421 New Mexico.	Bandelier Wild	23,267	94-567	USDI-NPS
	Bosque del Apache Wild	80,850	93-632	USDI-FWS
	Carlsbad Caverns NP	46,435	71-216	USDI-NPS
	Gila Wild	433,690	88-577	USDA-FS
	Pecos Wild	167,416	88-577	USDA-FS
	Salt Creek Wild	8,500	91-504	USDI-FWS
	San Pedro Parks Wild	41,132	88-577	USDA-FS
	Wheeler Peak Wild	6,027	88-577	USDA-FS
	White Mountain Wild	31,171	88-577	USDA-FS
S81.422 North Carolina.	Great Smoky Mountains NP[a]	273,551	69-268	USDI-NPS
	Joyce Kilmer-Slickrock Wild[b]	10,201	93-622	USDA-FS
	Linville Gorge Wild	7,575	88-577	USDA-FS
	Shining Rock Wild	13,350	88-577	USDA-FS
	Swanquarter Wild	9,000	94-557	USDI-FWS

[a] Great Smoky Mountains National Park, 514,758 acres overall, of which 273,551 acres are in North Carolina, and 241,207 acres are in Tennessee.
[b] Joyce Kilmer-Slickrock Wilderness, 14,033 acres overall, of which 10,201 acres are in North Carolina and 3,832 acres are in Tennessee.

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.423 North Dakota.	Lostwood Wild	5,557	93-632	USDI-FWS
	Theodore Roosevelt, NMP	69,675	80-38	USDI-NPS
S81.424 Oklahoma.	Wichita Mountains Wild	8,900	91-504	USDI-FWS
S81.425 Oregon.	Crater Lake NP	160,290	57-121	USDI-NPS
	Diamond Peak Wild	36,637	88-577	USDA-FS
	Eagle Cap Wild	293,476	88-577	USDA-FS
	Gearhart Mountain Wild	18,709	88-577	USDA-FS
	Hells Canyon Wild[a]	108,900	94-199	USDA-FS
	Kalmiopsis Wild	76,900	88-577	USDA-FS
	Mountain Lakes Wild	23,071	88-577	USDA-FS
	Mount Hood Wild	14,160	88-577	USDA-FS
	Mount Jefferson Wild	100,208	90-548	USDA-FS
	Mount Washington Wild	46,116	88-577	USDA-FS
	Strawberry Mountain Wild	33,003	88-577	USDA-FS
	Three Sisters Wild	199,902	88-577	USDA-FS

[a] Hells Canyon Wilderness, 192,700 acres overall, of which 108,900 acres are in Oregon, and 83,800 acres are in Idaho.

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.426 South Carolina	Cape Romain Wild	28,000	93-632	USDI-FWS
S81.427 South Dakota.	Badlands Wild	64,250	94-567	USDI-NPS
	Wind Cave NP	28,060	57-16	USDI-NPS
S81.428 Tennessee.	Great Smoky Mountains NP[a]	241,207	69-268	USDI-NPS
	Joyce Kilmer-Slickrock Wild[b]	3,832	93-622	USDA-FS

[a] Great Smoky Mountains National Park, 514,758 acres overall, of which 273,551 acres are in North Carolina, and 241,207 acres are in Tennessee.

[b] Joyce Kilmer-Slickrock Wilderness, 14,033 acres overall, of which 10,201 acres are in North Carolina and 3,832 acres are in Tennessee.

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.429 Texas.	Big Bend NP	708,118	74-157	USDI-NPS
	Guadalupe Mountains NP	76,292	89-667	USDI-NPS
S81.430 Utah.	Arches NP	65,098	92-155	USDI-NPS
	Bryce Canyon NP	35,832	68-277	USDI-NPS
	Canyonlands NP	337,570	88-590	USDI-NPS
	Capitol Reef NP	221,896	92-507	USDI-NPS
	Zion NP	142,462	68-83	USDI-NPS
S81.431 Vermont.	Lye Brook Wild	12,430	93-622	USDA-FS
S81.432 Virgin Islands	Virgin Islands NP	12,295	84-925	USDI-NPS
S81.433 Virginia.	James River Face Wild	8,703	93-622	USDA-FS
	Shenandoan NP	190,535	69-268	USDI-NPS
S81.434 Washington.	Alpine Lakes Wild	303,508	94-357	USDA-FS
	Glacier Peak Wild	464,258	88-577	USDA-FS
	Goat Rocks Wild	82,680	88-577	USDA-FS
	Mount Adams Wild	32,356	88-577	USDA-FS
	Mount Rainier NP	235,239	30 Stat. 993 (55th Cong.)	USDI-NPS
	North Cascades NP	503,277	90-554	USDI-NPS
	Olympic NP	892,578	75-778	USDI-NPS
	Pasayten Wild	505,524	90-544	USDA-FS

State	Area Name	Acreage	Public Law Establishing	Federal Land Manager
S81.435 West Virginia.	Dolly Sods Wild	10,215	93-622	USDA-FS
	Otter Creek Wild	20,000	93-622	USDA-FS
S81.436 Wyoming.	Bridger Wild	392,160	88-577	USDA-FS
	Fitzpatrick Wild	191,103	94-567	USDA-FS
	Grand Teton NP	305,504	81-787	USDI-NPS
	North Absaroka Wild	351,104	88-577	USDA-FS
	Teton Wild	557,311	88-577	USDA-FS
	Washakie Wild	686,584	92-476	USDA-FS
	Yellowstone NP[a]	2,020,625	17 Stat. 32 (42nd long)	USDI-NPS

[a] Yellowstone National Park, 2,219,737 acres overall, of which 2,020,625 acres are in Wyoming, 167,624 acres are in Montana, and 31,488 acres are in Idaho.

S81.437 New Brunswick, Canada.	Roosevelt Campobello International Park	2,721	88-363	Not applicable