EPA-600/3-78-039
April 1978

VISIBILITY IN THE SOUTHWEST
An Exploration of the Historical Data Base

by

John Trijonis and Kung Yuan
Technology Service Corporation
2811 Wilshire Boulevard
Santa Monica, California 90403

Grant No. 803896
R.B. Husar, Principal Investigator
Washington University
St. Louis, MO 63130

Project Officers

John C. Butler
Office of Planning and Evaluation
Washington, D.C. 20460

and

William E. Wilson and Thomas G. Ellestad
Atmospheric Chemistry and Physics Division
Environmental Sciences Research Laboratory
Research Triangle Park, NC 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

DISCLAIMER

This report has been reviewed by the Environmental Sciences Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The historical data base pertinent to visibility in the Southwest is analyzed. The data base includes over 25 years of airport visibility observations and more than 10 years of NASN particulate measurements. The investigation covers existing levels of visibility, long-term trends in visibility, and visibility/pollutant relationships.

Although still quite good, visibility in the Southwest has deteriorated over the past two decades. The haze levels in the Southwest appear to be mostly the result of secondary aerosols, especially sulfates. These conclusions are verified by decreases in sulfates and increases in visibility during the 1967-1968 industry-wide copper strike.

This report was submitted in fulfillment of grant 802815 by Technology Service Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from March 1977 to November 1977, and work was completed as of November 1977.

CONTENTS

CONTENTS

FIGURES

FIGURES

TABLES

CHAPTER 1

INTRODUCTION AND SUMMARY

Perhaps the most important air quality concern in the Southwest* United States, where the high mountains, rugged terrain, and excellent visual range produce many exceptional vistas, is the issue of visibility. It is a common public opinion in the Southwest that the high visibility levels have already deteriorated, and there is concern that future population growth and energy development will lead to further visibility degradation. These concerns are reflected in the 1977 Clean Air Act Amendments which contain provisions for the prevention of significant deterioration and the protection of visibility in federally designated Class I areas.

In response to the growing interest in visibility, several field programs and modeling studies have been initiated in the Southwest. These studies will help provide the data and analytical tools necessary to include visibility considerations in future air quality planning.

We can also further our understanding of the visibility issue by analyzing existing data bases. A potential wealth of information is offered by over twenty-five years of airport visibility observations and more than ten years of NASN (National Air Surveillance Network) particulate measurements. The purpose of this report is to explore the historical data base in an attempt to answer several key questions concerning visibility in the Southwest. The

*For the purposes of this study, the Southwest is defined as Arizona, Colorado, New Mexico, Utah, eastern Nevada, and southern Wyoming.

questions we address are as follows:

- What are existing visibility levels in urban and nonurban parts of the Southwest? What are the statistical distributions and geographical patterns of visual range?
- What trends have occurred in visual range over the past 25 years? What is the spatial scale of the historical visibility changes?
- Based on regression models, what are the key contributors to haze in the Southwest? Is fugitive dust important to light extinction, or do secondary aerosols (e.g. sulfates) dominate visibility reduction?
- Recognizing that copper smelters were the major source of SO_x emissions in the Southwest during the late 1960's, what changes occurred in sulfate levels and visibility during the July 1967 - March 1968 industry-wide copper strike? Do these changes agree with the predictions of regression models?

This report is organized in six chapters. The present chapter provides a statement of purpose and a summary of conclusions. Chapter 2 describes the data bases that are used and the statistical methods that are applied. The remaining four chapters sequentially deal with the four sets of questions listed above.

SUMMARY OF CONCLUSIONS

Existing Visibility Levels (Chapter 3)

- Visibility in the Southwest tends to be quite high. Median visibility ranges approximately from 30 to 55 miles at urban locations and from 65 to 80 miles at nonurban locations. Best 10th percentile visibility ranges from 45 to 70 miles among urban airports and from 90 to 115 miles among the nonurban airports. For comparison, we note that an atmosphere consisting of air molecules alone would exhibit a visual range of approximately 160 miles due to blue-sky (Rayleigh) scatter by the air molecules.
- Three nonurban airports exhibit lower visibilities than the values listed above for nonurban locations. Of these three exceptions, one airport almost qualifies as an urban location; another is within ten miles of a copper smelter; and the third is within 150 miles of several large copper smelters.

- Worst-case 90th percentile visibility ranges approximately from 10 to 40 miles among both urban and nonurban locations. Unlike 10th percentile and median visibilities, the 90th percentile appears to be dominated by special meteorological events such as fog and precipitation.

- No obvious large-scale geographic patterns exist for visibility within the Southwest. With the three exceptions noted above, visibility tends to be quite good at nonurban airports throughout the study region.

- The visibility percentiles estimated from the airport data agree very well with the results of recent special field programs. The airport data indicate that median visibility is 65 to 80 miles in nonurban areas; field studies using photographic photometry and integrating nephelometry find median visibilities of 60 to 80 miles in remote areas of the Southwest.

Historical Visibility Trends (Chapter 4)

- Although still quite good, visibility in the Southwest appears to have deteriorated significantly over the past two decades. A study of trends at 4 urban and 8 nonurban airports indicates a distinct worsening of visual range from the early 1950's to the early 1970's at all locations but one. The 10th percentile, median, and 90th percentile visibilities all show a decrease on the order of 10 to 30%.

- The historical decrease in visibility becomes even more notable when one considers that blue-sky scatter (which of course remained constant) is a substantial fraction of extinction in the Southwest. The visibility trend data indicate that extra extinction (above-and-beyond blue-sky scatter) increased on the order of 20 to 70% from the early 1950's to the early 1970's.

- Although visibility is not uniform over the Southwest, and although quantitative visibility trends are not identical at all locations, indications are that visibility has deteriorated on a large spatial scale throughout the Southwest -- in urban areas, nonurban areas, and even very remote areas. From the conclusions of later chapters, we deduce that the historical decrease in visibility is most likely due to increases in secondary aerosols, the result of growth in SO_x, NO_x, and possibly hydrocarbon emissions from copper smelters, power plants, automobiles, and other sources. The large spatial scale involved in the visibility deterioration would be due to two factors: (1) growth of emission sources in many parts of the region, and (2) the tendency of secondary aerosols to be spread widely because of the mixing and transport that occurs during the time required for aerosol formation.

Visibility/Pollutant Relationships (Chapter 5)

- It is possible to complete visibility/pollutant regression models using two data bases for Phoenix and one for Salt Lake City. The multiple regressions between airport visibility data and Hi-Vol particulate data attain total correlation coefficients as high as 0.87 in Phoenix and 0.81 in Salt Lake City.

- Blue-sky scatter accounts, on the average, for approximately 17% of total extinction in Phoenix and for approximately 13% in Salt Lake City. The regression models for the three data bases indicate that secondary aerosols, particularly sulfates, dominate extra extinction (above-and-beyond blue-sky scatter). Among the three regression models, estimates of average contributions to extra extinction range from 32% to 53% for sulfates, 23% to 37% for nitrates, and 0% to 35% for the remainder of TSP.

- The extinction coefficients per unit mass for sulfates, nitrates, and the remainder of TSP that we estimate by the regression models are in agreement with other values in the published literature and with known principles of atmospheric physics. In particular, there is agreement that secondary aerosols, which tend to reside in the .1 to 1 micron size range, exhibit one order of magnitude greater extinction coefficient per unit mass than fugitive dust, which tends to have a much larger particle size.

- By using generalized extinction coefficients per unit mass for sulfates, nitrates, and the remainder of TSP, our visibility/pollutant model can be extended to remote areas. Based on NASN data from three national park locations, we predict that average visibility in remote areas should be approximately 70 to 80 miles; this is in agreement with observed visibility. Blue-sky scatter accounts for approximately 45% of total extinction in remote areas. We conclude that two-thirds of the extra extinction at the national park sites is due to sulfates, with one-sixth due to nitrates and one-sixth due to the remainder of TSP.

- Although they appear to dominate visibility reduction, sulfates and nitrates constitute only a relatively small fraction of total aerosol mass. Sulfates and nitrates account for about 10% of total aerosol mass in urban areas and 20% of total aerosol mass in nonurban areas of the Southwest.

The Copper Strike of 1967-1968 (Chapter 6)

- In the late 1960's copper smelters were the dominant source of regionwide SO_x emissions in the Southwest. During the nine-month, industry wide copper strike of 1967-1968 sulfates dropped by 38 to 76% (compared to seasonal averages in surrounding years) at the five NASN sites located within 70 miles of copper smelters. Sulfates also dropped 60% at Grand Canyon and 57% at Mesa Verde; these two national parks are located approximately two to three hundred miles from the main group of smelters.

- Visibility improvement during the strike ranged from approximately 5 to 25% at locations within 150 miles of copper smelters. The decrease in extra extinction (calculated from the visibility changes) was 10 to 30% at those locations.

- Our visibility/pollutant regression models for Phoenix and Salt Lake City are verified by changes during the strike. Predicted decreases in extinction (or increases in visibility), based on the sulfate reductions and the regression models, agree with actual decreases in extinction during the strike. The visibility/pollutant model extended to nonurban areas does not appear to be verified by the strike changes. Several possible reasons for this discrepancy are discussed.

- The sulfate reductions and visibility increases during the strike are statistically very significant. An examination of meteorological data for the strike period indicates that weather patterns were not notably different from normal. If anything, pollution potential appears to have been slightly greater than average during the strike. We conclude that meteorology was not a major factor in producing the observed air quality improvements.

LIMITATIONS OF THE ANALYSIS

We would expect a priori that the main limitation to our analysis would be the quality of the airport visibility data. The principal use of the visibility observations is air traffic control; for this purpose, low visibilities (i.e. less than 7 miles) are most critical. We would not expect extreme care to be taken with observations of visual range on the order of 20 to 100 miles (which constitute the preponderance of actual visibilities in the Southwest).

In actuality, we found most of the visibility data to be of good quality. The quality of the data is evidenced by the consistency of the cumulative frequency distributions from one airport to another. The frequency distributions of airport visibility have also been shown to be consistent with the results of special field programs using photographic photometry and integrating nephelometry. The quality of the data is further evidenced by the high correlations (from 0.68 to 0.87) obtained between airport visibility measurements and Hi-Vol particulate data. This surprisingly good data quality may be, in part, due to our airport survey; observation practices were screened before airports were selected for the study.

In our analyses of historical visibility trends, a question arises concerning the possibility that errors may have been introduced by changes in airport personnel, observation sites, and/or reporting practices. A careful survey was conducted at each airport in an attempt to eliminate such errors. If any undocumented procedural changes have occurred which affect visibility trends, it is expected that they would introduce random errors and would not bias our overall conclusions. Because of the consistency of the downward visibility trends at various airports, we are confident in our conclusion that visibility has deteriorated significantly over the Southwest during the past two decades.

The regression models relating visibility to particulate measurements involve several limitations. These limitations, discussed in Chapter 2, include the following:

- spatial nonhomogeneity of the atmosphere and consequent differences between measured pollutant levels at the Hi-Vol site and average pollutant levels over the visual range.
- statistical difficulties introduced by intercorrelations among the independent variables.
- the possibility that the independent variables may act as surrogates for pollutants that are not included in the analysis.
- potential errors in measurement techniques for sulfates, benzene solubles, and (especially) nitrates.

In spite of these potential limitations, the results of our regression models are consistent with the published literature, known principles of aerosol physics, and air quality changes during the 1967-1968 copper strike. These consistencies lend credence to our conclusions concerning the causes of haze in the Southwest.

Perhaps the most important limitation in the visibility/pollutant analysis involves the treatment of nitrates. Nitrate measurements are known to be subject to interferences, and nitrates may be partially acting as surrogates for related photochemical contributors to haze that are not included in the analysis. In order to account for these problems, it may be best to regard the nitrate variable as representing not only nitrate aerosols but also related photochemical pollutants such as NO_2 and secondary organic aerosols.

FUTURE WORK

In this investigation of the historical data base, we have sought answers to very basic questions: What are existing visibility levels in the Southwest? Has visibility changed significantly over the past 25 years? What are the main contributors to haze in the Southwest? There are other more detailed questions that may be answered by analyzing the historical data. The potential information available in over twenty-five years of airport data and more than ten years of NASN measurements should not be neglected in future studies of visibility.

In characterizing existing visibility levels, we have examined only the overall, yearly frequency distribution of visual range. One could very easily disaggregate the data and examine seasonal, weekday/weekend, and diurnal patterns in visual range. Visibility observations could be correlated with meteorological data to determine how meteorological parameters or weather patterns affect visibility. Correlations could be run among visibility measurements at various sites to ascertain the spatial scale of day-to-day visibility changes.

Similarly, the analysis of historical visibility trends could be performed in more detail. The trends could be disaggregated according to seasons, wind conditions, or meteorological classes. The trend analysis would benefit by the application of more sophisticated statistical methods. It would also be interesting to investigate the possible occurrence of long-term meteorological changes.

We have not been able to find coincident data on visual range and aerosol composition in remote areas. When such data become available, visibility/pollutant regressions should be performed to test our conclusions concerning the main contributors to extinction in nonurban areas.

CHAPTER 2

DATA BASE PREPARATION AND DATA ANALYSIS METHODS

The objectives of this report are to document the historical trends of visibility* in the Southwest and to characterize the relationships between visibility levels and pollutant concentrations. Before presenting our findings, it is worthwhile to summarize the data bases and statistical methods which serve as the foundation for those findings. This chapter describes the data bases used and the analysis methods applied.

AIRPORT WEATHER DATA AND NASN POLLUTANT DATA

Two types of data are used in this study: airport weather data (including measurements of visibility or visual range) and National Air Surveillance Network (NASN) particulate data. The airport weather data provide information on historical changes in visibility. The airport data and NASN data are combined to investigate the relationship between visibility and pollutant levels. Before any analyses were performed on these data sets, telephone surveys were conducted at each airport and pollutant monitoring site to uncover potential problems in the data.

Survey of Airport Weather Stations

The visibility data presented in this report consist of daytime "prevailing visibility" observations made by airport meteorologists. According to National Weather Service procedures, prevailing visibility is defined as the greatest visual range that is attained or surpassed around at least half the horizon circle, but not necessarily in continuous sectors (Williamson,

*In this report, the terms "visibility" and "visual range" will be used interchangeably. Both will refer to the distance at which a black object can just be distinguished against the horizon sky.

1973). Daytime visibility is measured by observing markers (e.g. buildings, mountains, towers,etc.) against the horizon sky; nighttime visibility measurements are based on unfocused, moderately intense light sources. Airport meteorologists perform visibility measurements each hour. In recent years, only the readings from every third hour are entered in the National Climatic Center (NCC) computerized data base.

NCC has compiled computerized data records for 105 airport weather stations in Arizona, Colorado, New Mexico, Utah, Nevada and Wyoming.* At only 45 of these stations do the computerized records cover a sufficient time period to be useful in this study, and only 35 of those stations are located in areas of prime interest. Appendix A provides a listing of the weather stations and distinguishes the 35 sites of potential utility to this study.

A detailed telephone survey was conducted with the meteorologists at each of the 35 airports. The purpose of the survey was to ascertain the overall quality of the visibility measurements, the utility of the measurements for historical trend studies, and the usefulness of the measurements for visibility/pollutant analyses. The questions contained in the survey were as follows:

- What are the farthest daytime visibility markers in various directions? (List directions and marker distances.) Over what percentage of the horizon does the observer have an unobstructed view to distant markers?
- Do the daytime markers generally meet the criteria of a black object against the horizon sky?
- Are visibility measurements made during the night as well as during the day? If so, what are the farthest markers at night?
- Are the observations made at ground level? If not, at what height above the ground?
- How many members does the observation team include? Has there been a major discontinuity in the observation team?

---

*Weather data are also available at other airports, but these data are not in computerized form.

- Have the observation techniques, reporting practices, or observation site changed significantly in the last 30 years?
- Are the visibility measurements significantly affected by very localized pollution sources?
- (If applicable) Are the visibility observations generally representative of the air mass and visibility at the nearby NASN site?
- Does the meteorologist have any comments or recommendations with regard to our trend studies or visibility/pollutant analyses?

The telephone survey led to several important discoveries. For instance, we found that nighttime and daytime visibility measurements are not compatible in the Southwest. Typically, the most distant daytime visibility marker is on the order of 30 to 100 miles, while the most distant nighttime marker is on the order of 10 to 20 miles. We decided to restrict all of our analyses to the four daytime measurements (i.e., 8 AM,11 AM, 2 PM, and 5 PM).

We also found that the farthest daytime marker at some locations was only at a distance of 10 to 40 miles and that this farthest marker was reported over 90% of the time. Using these sites to characterize visibility would be similar to conducting a traffic study with a speedometer that did not read above 15 mph. Thus, we eliminated many sites on the basis that the farthest marker was at too short a distance.

At a few locations we found that the observation site or reporting practices had changed significantly during the period of interest. Some of these sites we eliminated from our analysis; others we retained by restricting our analysis only to periods of consistent observation procedures.

Our survey of airport weather stations led us to select seventeen locations for the study; these locations are illustrated in Figure 1 and listed in Table 1. Table 1 also summarizes the types of analyses to which the data

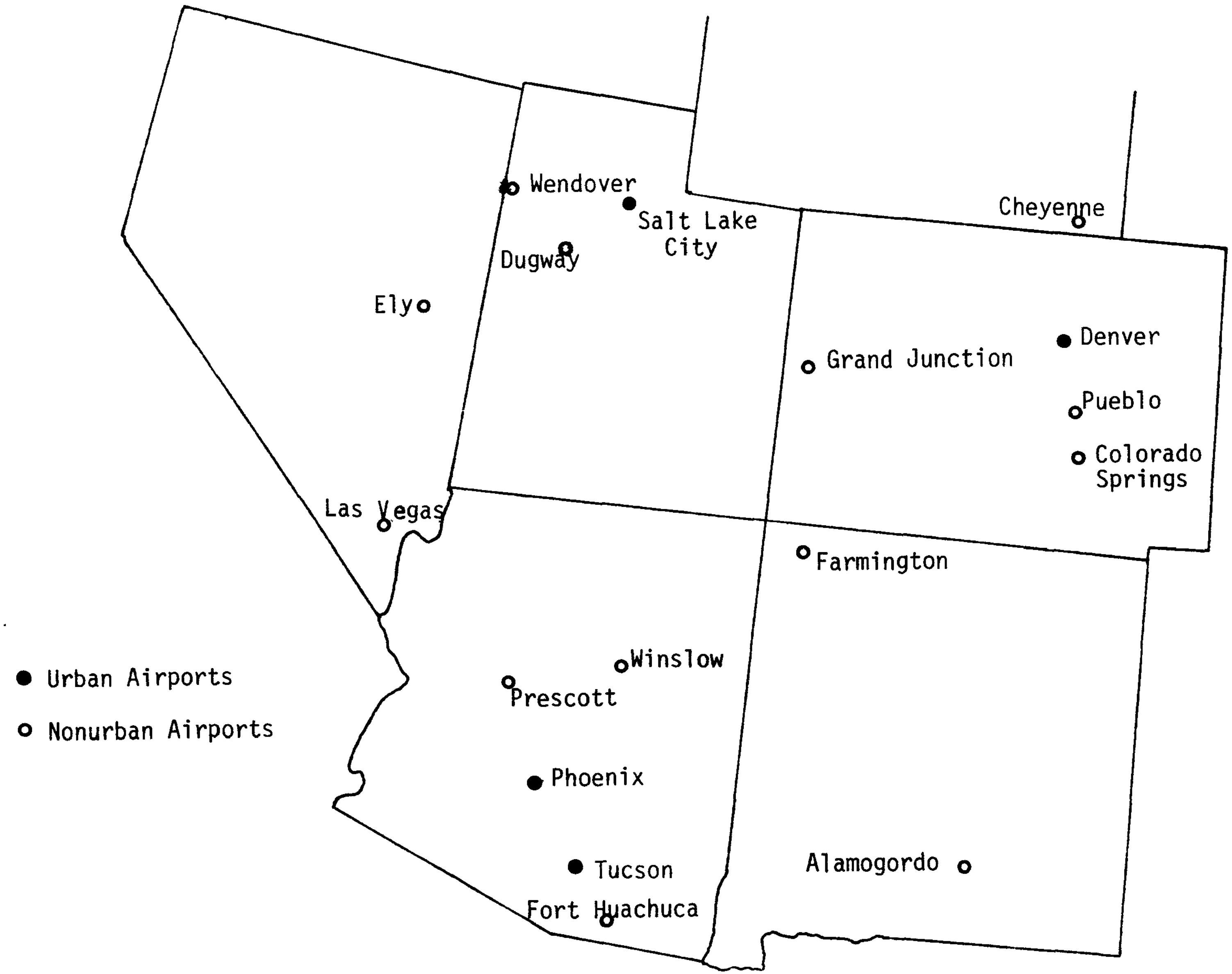

Figure 1. Airport weather stations used in the Southwest study.

TABLE 1. AIRPORT WEATHER STATIONS INCLUDED IN THE SOUTHWEST VISIBILITY STUDY

STATION	TYPES OF ANALYSES			
	Geographical Patterns in Visibility	Historical Trends in Visibility	Visibility/Pollutant Relationships	Effects of the Copper Strike
Fort Huachuca, Ariz.	X	X		X
Phoenix (Sky Har.), Ariz.	X	X	X	X
Prescott, Ariz.	X	X	X	X
Tucson (Internatl.), Ariz.	X	X	X	X
Winslow, Ariz.	X	X	X	X
Colorado Springs, Col.	X	X		
Denver (Stapleton), Col.	X	X	X	X
Grand Junction, Col.	X	X		X
Pueblo, Colo.	X	X		
Ely, Nev.	X	X	X	X
Las Vegas(McCarran), Nev.	X			X
Alamogordo, N. M.	X			X
Farmington, N. M.	X			X
Dugway, Utah	X			X
Salt Lake City, Utah	X	X	X	X
Wendover, Utah	X			X
Cheyenne, Wyo.	X	X		X

are applied. All seventeen stations are used to characterize present geographical patterns in visibility; data from certain stations are not useful for some of the other analyses.

We have classified the Phoenix, Tucson, Denver, and Salt Lake City airports as urban, and the rest of the airports as nonurban. Here, urban is defined as "in or near a city with population exceeding 150,000."*

Survey of NASN Monitoring Sites

There were several locations (Grand Canyon, Phoenix, Tucson, Denver, Mesa Verde, Ely, Albuquerque and Salt Lake) where we hoped to link NASN pollutant data with airport visibility data in order to study the visibility/pollutant relationship. For these locations, we contacted the local monitoring agencies which operate the NASN samplers. The purpose of these contacts was to assess the utility of the NASN TSP (total suspended particulates) data for visibility/pollutant studies.

The survey of the NASN TSP monitoring sites included the following questions:

- How long has the TSP Hi-Vol been operated? Has it been relocated?
- What is the height of the Hi-Vol above the gound? Is the sampler exposed to air flow in all four directions?
- Is the sampler exposed to significant local sources of dust (e.g., unpaved roads)?

---

*The urban/nonurban classification is complicated by the fact that most of the airports are on the outskirts of the cities or towns. The selection of a cut-off point at a city population of 150,000 is empirical; this is the cut-off point at which we observed a significant change in median visibilities. Our "nonurban" category actually includes a range from "suburban" to "nearly remote". With only three exceptions, however, all the nonurban sites have about the same visibility frequency distribution; this visibility frequency distribution appears to be the same as the one observed at very remote locations of the Southwest (see Chapter 3 for a discussion).

- Is the NASN site representative of area-wide pollution levels? In particular, is it representative of the air mass at the NCC site?

- Are there any suggestions or comments in regard to our visibility/pollutant studies?

From our survey of airport observers and NASN monitoring agencies we found that several locations were not appropriate for the visibility/pollutant studies. The main reasons were either that the airport and NASN sites were not representative of one another or that the visibility data were deficient. Phoenix and Salt Lake City were the only two sites where conditions for the study appeared quite good. Several other locations (See Table 1) were possibilities that at least merited an attempt to analyze the data.

The NASN pollutant data were also used to investigate air quality changes during the 1967-1968 industry-wide copper strike. Figure 2 shows the NASN locations that provided data for documenting the effects of the copper strike.

Initial Data Processing

For each of the airport locations studied, complete tapes of all surface weather data were obtained from NCC in the CD-144 format. These tapes were processed to extract data for the four daytime hours (8 AM, 11 AM, 2 PM, and 5 PM).* With data for these hours, we formed a "processed visibility data base" for each location; this data base included the date, hour, visibility, relative humidity, and special notations (storms, liquid precipitation, frozen precipitation, fog, blowing dust, smoke, haze, etc.).

---

* For some years, the original NCC tapes contained data for every hour rather than every third hour. For consistency, we extracted the same four daylight hours in all years.

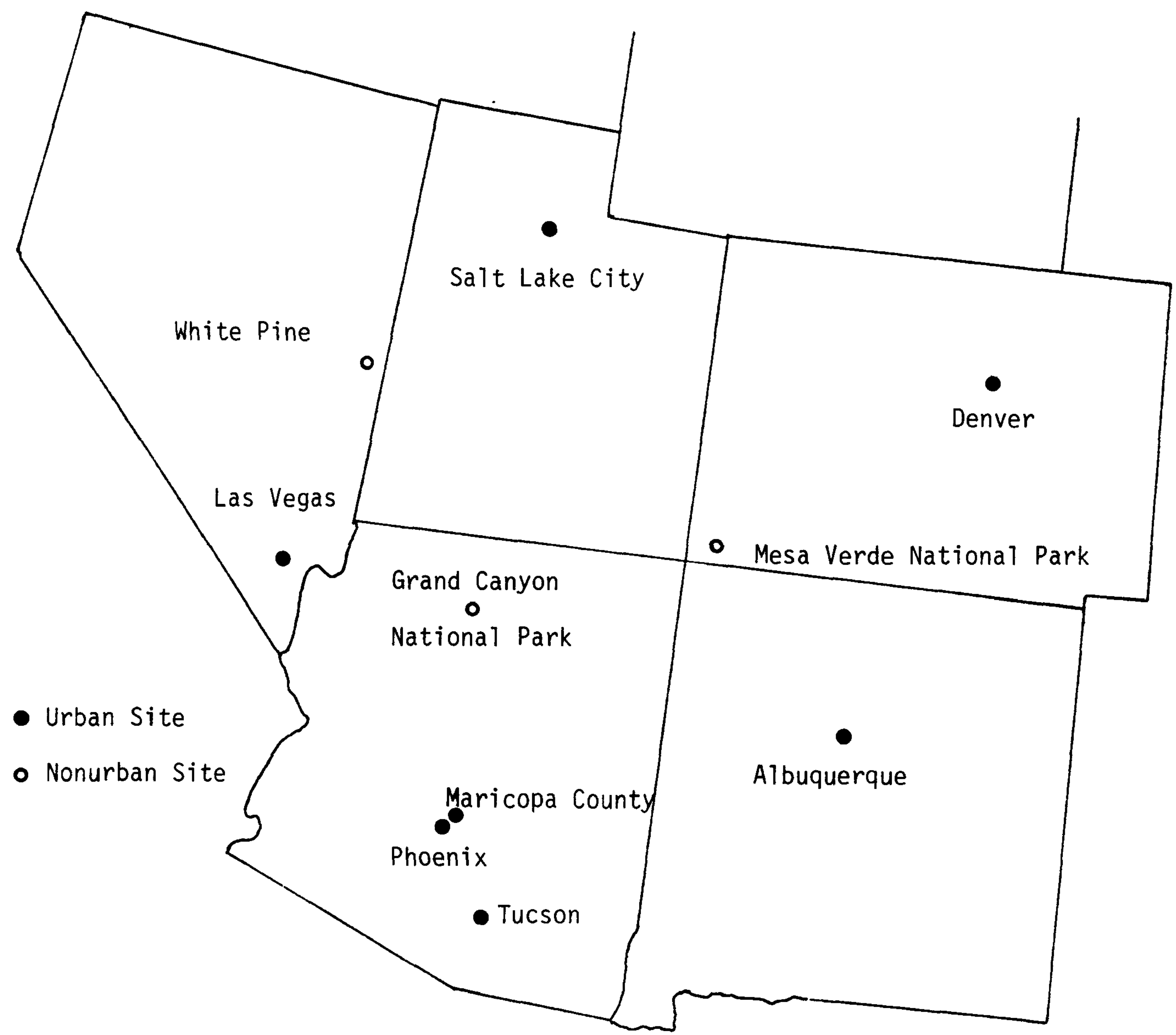

Figure 2. NASN monitoring sites in the Southwest.

The nationwide NASN data for TSP, sulfate, nitrate, benzene solubles, etc. were obtained in tape form from EPA's SAROAD data bank. We reorganized the original EPA data to create a "processed pollutant data base." For each site, this data base listed the date and the various pollutant measurements in a consistent, easy to access, format.

In order to investigate visibility/pollutant relationships for certain locations, the "processed visibility data base" was combined with the "processed pollutant data base" at these locations. The resultant data base listed, for each day, the 24 hour average pollutant concentrations and the daytime averages of visibility and relative humidity.

FREQUENCY DISTRIBUTIONS OF VISIBILITY DATA

Because of the nature of the reporting methods,* visibility data are most appropriately summarized by cumulative frequency distributions of the form "percent of time visibility is greater than or equal to X miles." Figures 3 and 4 present recent cumulative frequency distributions for all the sites studied. Figure 3 is for urban locations; Figure 4 is for nonurban sites.

When analyzing cumulative frequency distributions for visibility, it is important to use only those visibilities that are routinely reported by the observer. For instance, it is not uncommon to see the following type of situation:

---

*When an airport observer reports a visibility of X miles, this usually means that visibility is at least X miles, not that visibility is exactly X miles. This method of reporting is especially significant in the case of the farthest marker. Airport observers in the Southwest do not report visibilities greater than their farthest marker even if visual range obviously extends beyond the farthest marker.

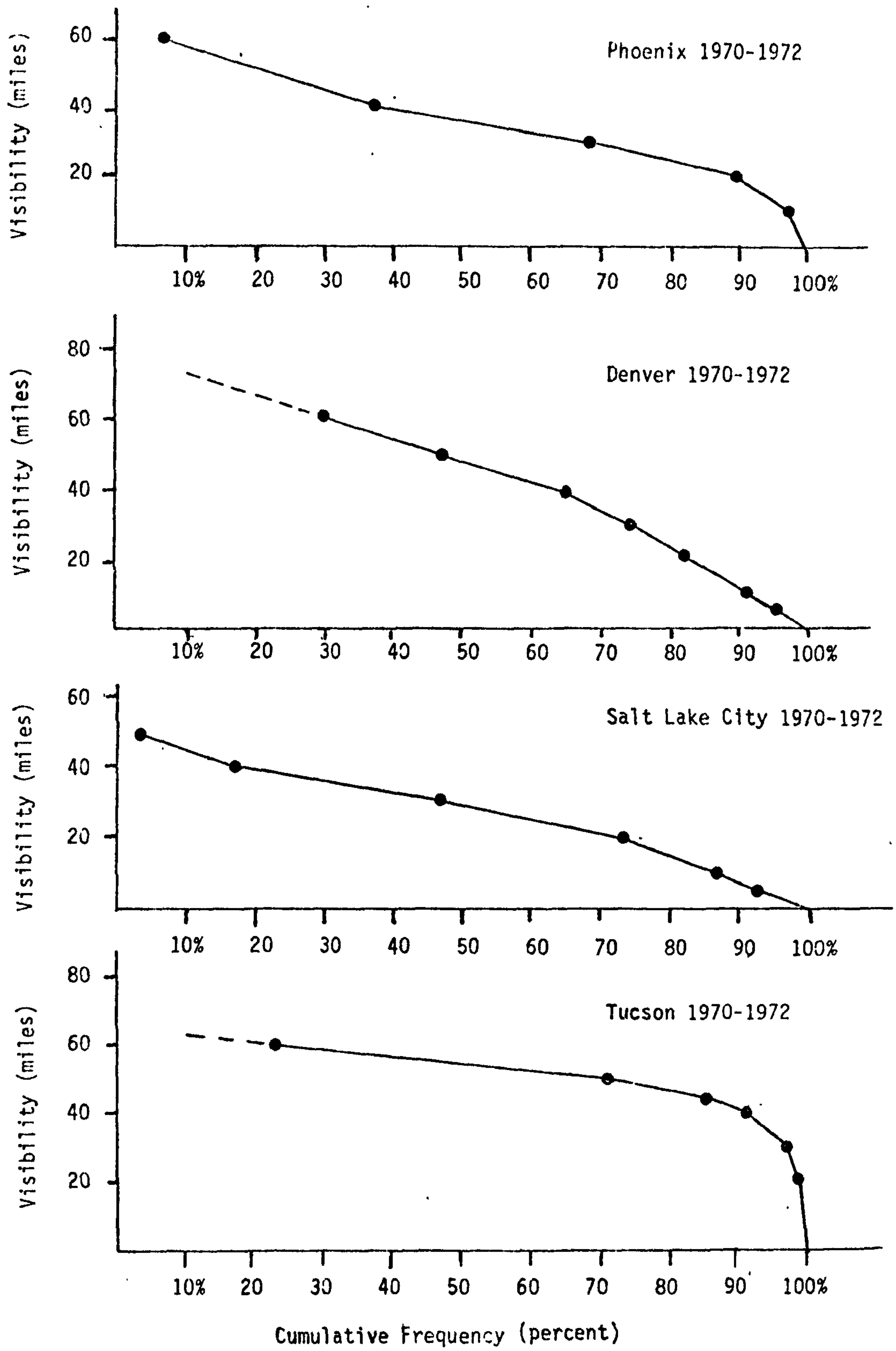

Figure 3. Cumulative frequency distributions of visibility at urban locations.

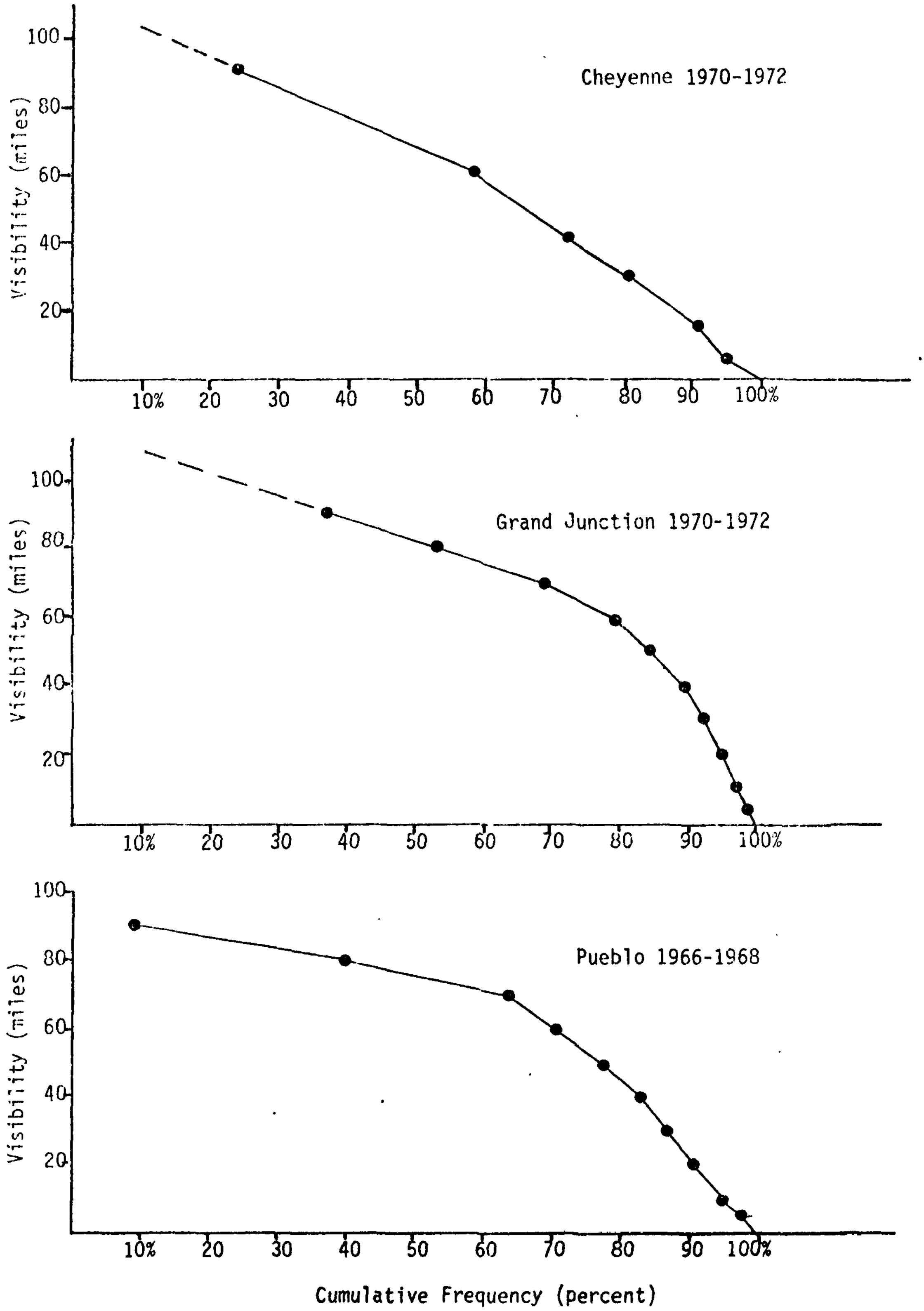

Figure 4. Cumulative frequency distributions of visibility at nonurban locations.

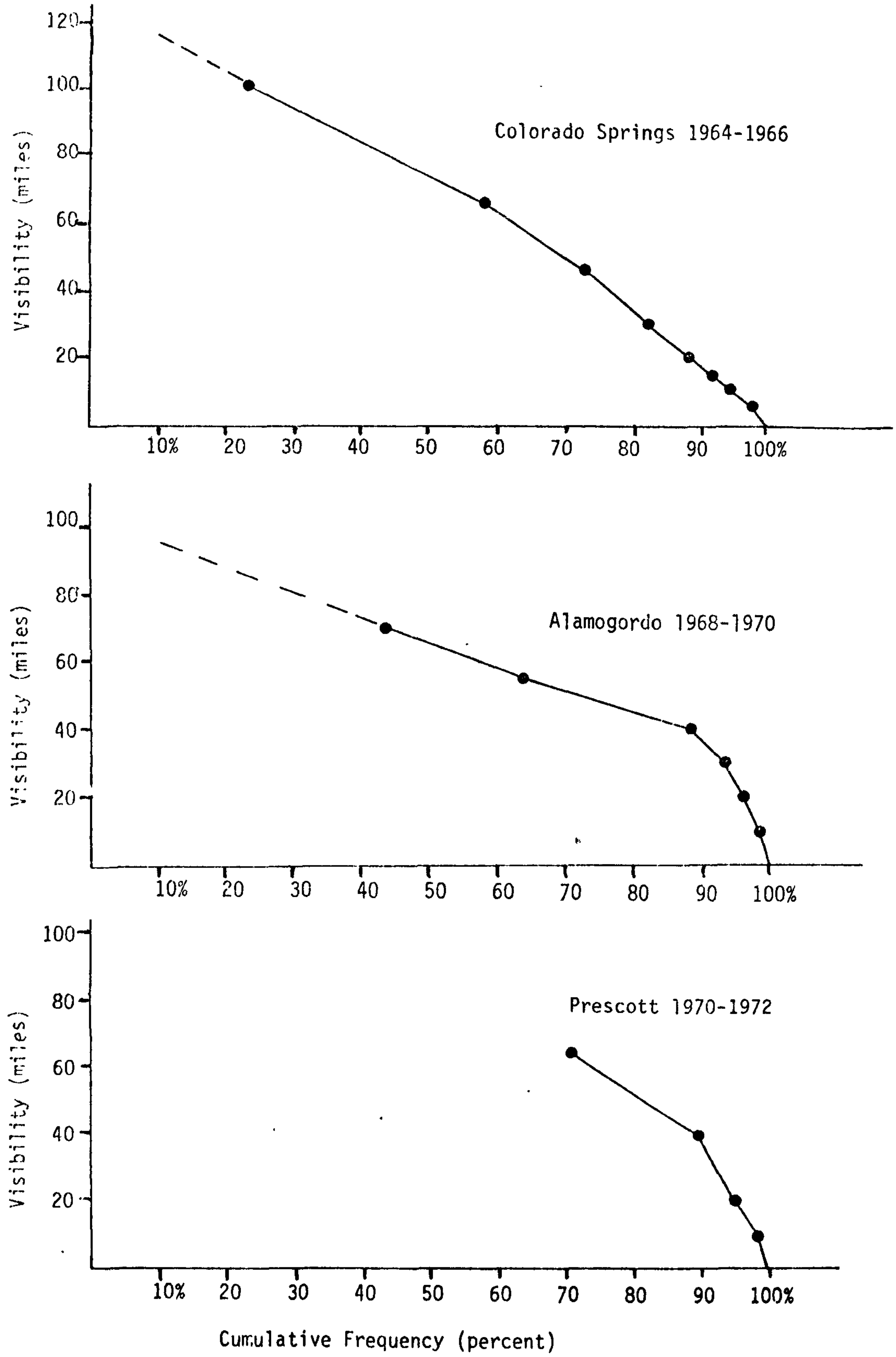

Figure 4. Cumulative frequency distributions of visibility at nonurban locations. (Cont'd)

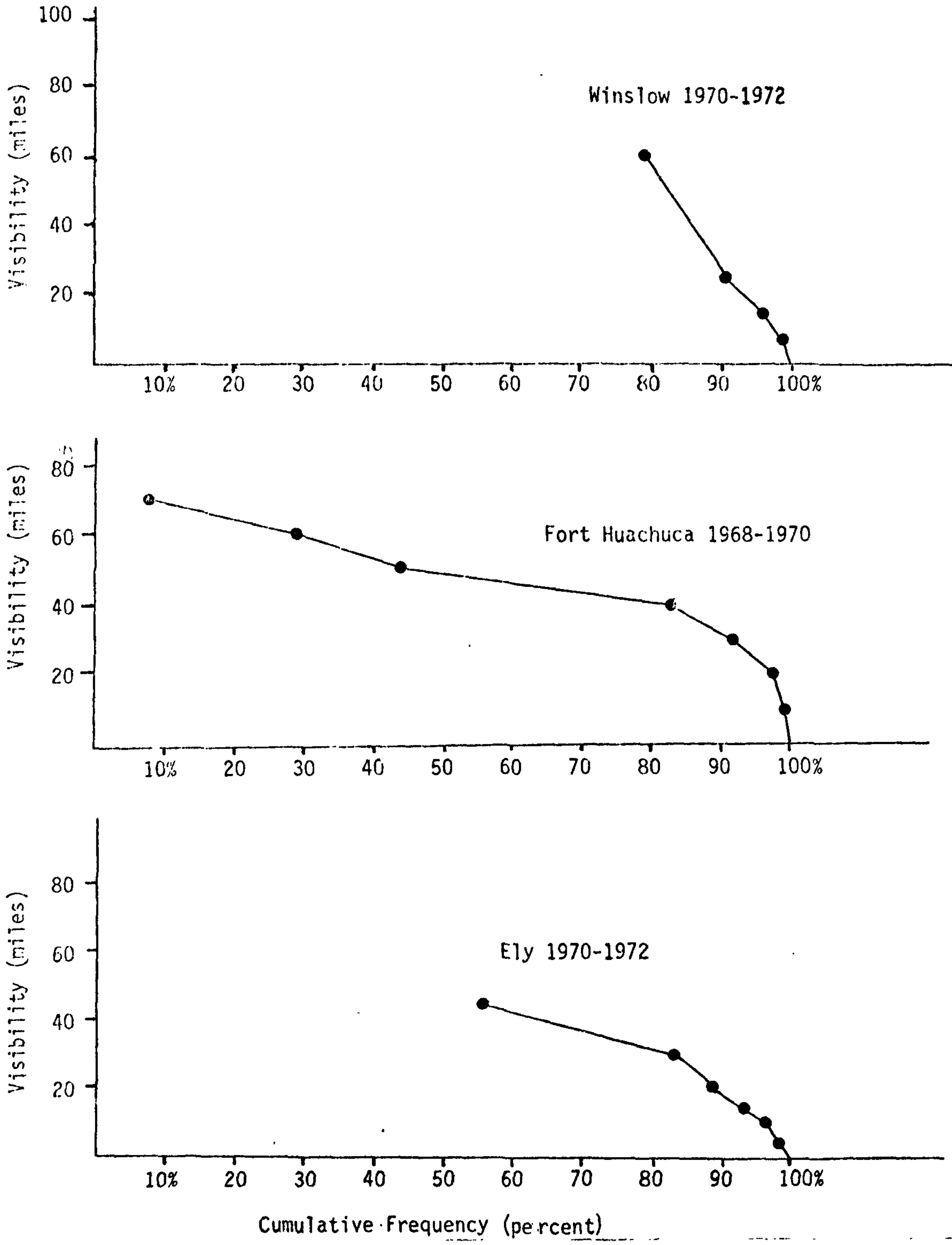

Figure 4. Cumulative frequency distributions of visibility at nonurban locations. (Cont'd)

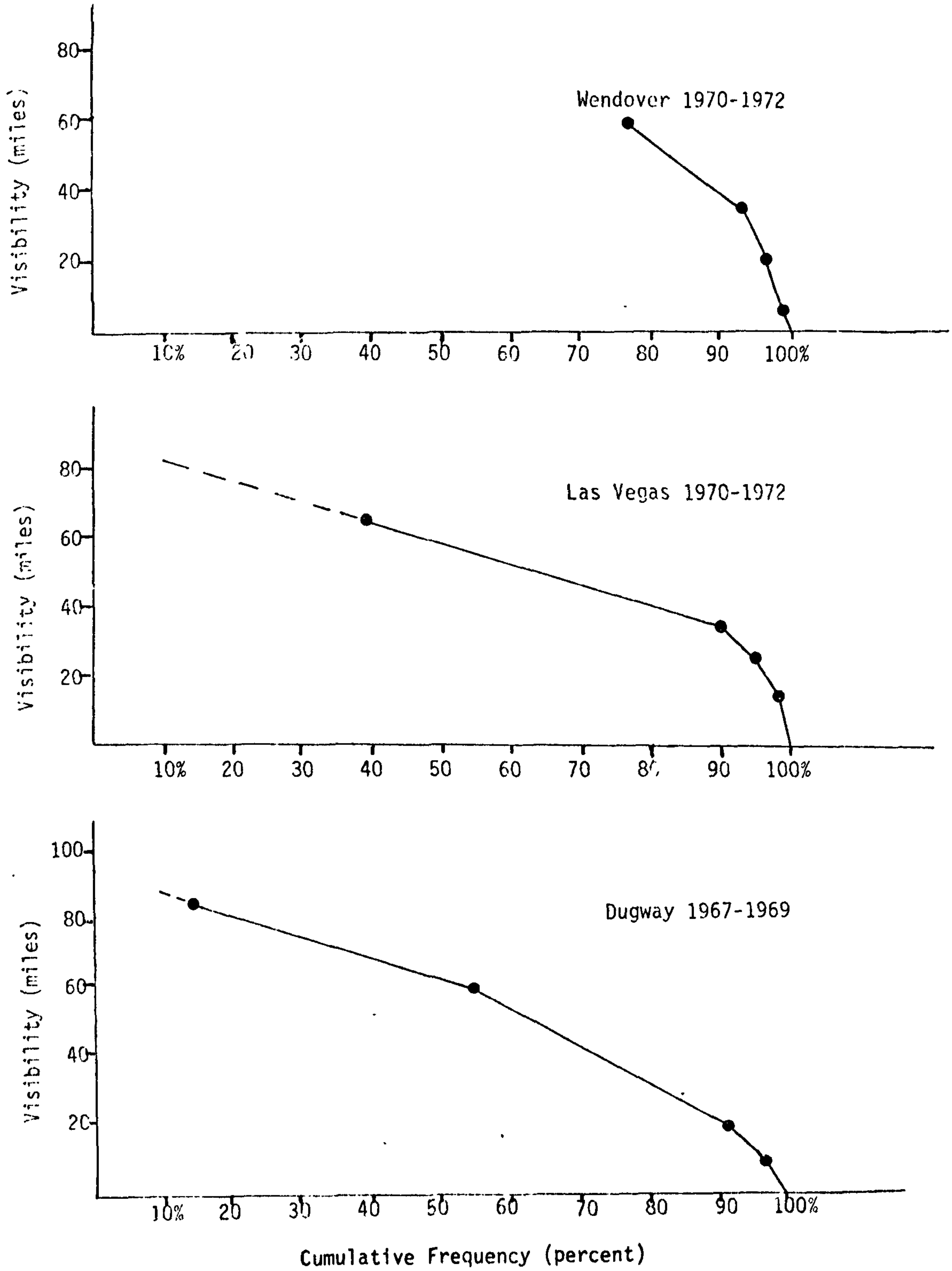

Figure 4. Cumulative frequency distributions of visibility at nonurban locations. (Cont'd)

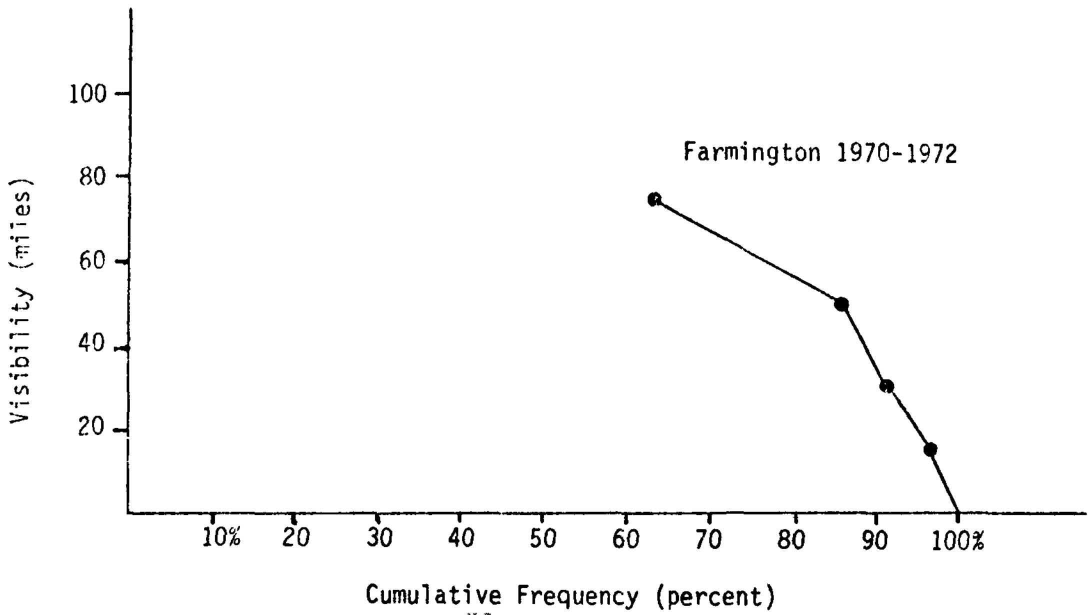

Figure 4, Cumulative frequency distributions of visibility at nonurban locations. (Cont'd)

Visibility	% of Time Reported	Cumulative Frequency
80 miles	10%	10%
70 miles	10%	20%
65 miles	.1%	20.1%
60 miles	9.9%	30%
50 miles	10%	40%
.	.	.
.	.	.
.	.	.

In this case, the 65 mile recordings produce a "kink" in the cumulative frequency distributions. It is obvious, in this case, that the 65 mile visibilities are not routinely reported, but they happened to be recorded a few times by a member of the observation team. In our analysis of frequency distributions for visibility data, we took care to use only those visibilities that are routinely reported.

The graphs in Figures 3 and 4 illustrate a property that we found to be nearly universal among the sites studied. The cumulative frequency distribution tends to be nearly linear at the higher visibilities (i.e., the lower percentiles). In many cases we have used this property to calculate the 10th percentile of visibility even if the actual recordings started at a higher percentile (e.g., the farthest marker might be reported 20% or 30% of the time). This calculation was done by linear extrapolation of the cumulative frequencies for the two farthest markers. The extrapolation is indicated by the dashed lines in Figures 3 and 4.

In this report, historical trends in visibility are based on changes in visibility percentiles. In most cases we use the 10th percentile (best conditions), the 50th percentile (median), and the 90th percentile (worst conditions). This method of reporting visibility trends differs from the traditional method

Each of the components of B should be directly proportional to aerosol or gas concentrations (assuming other factors such as light wavelength, aerosol size distribution, particle shape, and refractive index remain constant). In polluted urban air, it is thought that aerosol light scattering (B_{scat}) tends to dominate over the other contributions to the extinction coefficient (Charlson, 1969).

Slight transformations are also performed on the independent variables. SULFATE and NITRATE are defined as 1.3 $SO_4^=$ and 1.3 NO_3^- (White and Roberts 1975) in order to account for the mass of the cations (presumably ammonium) associated with the measured values of $SO_4^=$ and NO_3^- . The variable, TSP - SULFATE - NITRATE, is used to represent the non-sulfate, non-nitrate fraction of TSP.*

Multi-Variate Regression

When several independent variables (TSP, RH, SULFATE, and NITRATE) are affecting a dependent variable (B) it is important to perform a multi-variate analysis that can separate out the individual impact of each independent variable, discounting for the simultaneous effects of other independent variables. Uni-variate analyses, based on simple one-on-one relationships, can lead to spurious results because of intercorrelations among the independent variables. For instance, in some cases we found that TSP apparently correlated with B only because TSP is correlated with SULFATE and NITRATE which are in turn significantly related to B.

An appropriate tool for multi-variate analysis is multiple regression. Following the procedure of Cass (1976) and White and Roberts (1975), we perform multiple linear regressions of the form:

---

*When benzene solubles are also included in the analysis, this variable is defined as TSP-SULFATES-NITRATES-BSOL.

$$B = a + b_1(\text{TSP-SULFATE-NITRATE}) + b_2\ \text{RH} + b_3\ \text{SULFATE} + b_4\ \text{NITRATE} \ . \quad (3)$$

These regressions are run stepwise, retaining only those terms which are significant at a 95% confidence level. The regression coefficients (b_1, b_3, and b_4) represent the extinction coefficient per unit mass for each pollutant species, in units of $(10^4 \text{ meters})^{-1}/(\mu g/m^3)$.

We also perform regressions which include relative humidity effects in a nonlinear manner. Cass (1976) indicates that light scattering by a submicron, hygroscopic aerosol might be proportional to $(1 - \frac{RH}{100})^{\alpha}$, where the exponent α is expected to occur in the range -0.67 to -1.0. To account for this type of effect, we attempt regressions of the form

$$B = a + b_1 \frac{\text{TSP-SULFATE-NITRATE}}{(1 - \frac{RH}{100})} + b_2 \frac{\text{SULFATE}}{(1 - \frac{RH}{100})} + b_3 \frac{\text{NITRATE}}{(1 - \frac{RH}{100})} \ . \quad (4)$$

Average Extinction Budget

The regression equations can be used to compute the fraction of visibility loss, on the average, that is due to each pollutant species. These calculations are best illustrated by an example.

Using the Maricopa County pollution data, our regression equation for Phoenix reduces to the following:

$$B = .22 + .037\ \text{SULFATE} + .051\ \text{NITRATE} \ , \quad (5)$$

with a total correlation coefficient of 0.87. The average value for the extinction coefficient at Phoenix is .85 $[10^4 \text{ meters}]^{-1}$, corresponding to a visibility of 29 miles. Using Eq. (5), the average extinction (haze) level at Phoenix can be disaggregated as follows:

$$.85 = \underbrace{.15}_{\text{Blue-light scatter by air molecules}} + \underbrace{.07}_{\text{Remainder of .22 constant term}} + \underbrace{.037\ (\overset{\text{Average Sulfate}}{10.1}\ \mu g/m^3)}_{\text{Contribution of sulfates}} + \underbrace{.051\ (\overset{\text{Average Nitrate}}{5.1}\ \mu g/m^3)}_{\text{Contribution of nitrates}}$$

or

$$.85 = .15 + 0.7 + .37 + .26 \qquad (6)$$

Equation (6) indicates that, on the average, 44% of the extinction is from sulfates, 31% is from nitrates, 17% is from air molecules, and 8% is unaccounted for.

Alternately, we could examine only the <u>extra</u> extinction above-and-beyond the blue-light scattering by air molecules. In the Phoenix example, the extra extinction is .70, (0.85 - 0.15), with 53% from sulfates, 37% from nitrates, and 10% unaccounted for.

Limitations of the Regression Approach

There are several limitations in using regression equations to estimate the contribution of various pollutants to visibility loss. These limitations are best explained with reference to the Phoenix example.

Our analysis implicitly assumes that the air mass is of uniform composition over the entire visual range. In actuality, we would expect that the average pollutant concentrations over the entire visual range are lower than the concentrations measured at the downtown Phoenix monitor (Moyers et al. 1977). The relatively high pollutant measurements may cause us to <u>underestimate</u> the extinction coefficients per unit mass for sulfates and nitrates.

Conversely, the statistical regression equation may overstate the importance of sulfates and nitrates if these variables are correlated with other pollutants which are not included in the analysis. Our intuitive opinion is that this problem is greater for nitrates than for sulfates. Nitrates may in part be acting as a surrogate for other related photochemical pollutants: secondary organic aerosol and nitrogen dioxide.

Potential errors in measurement techniques also raise a caution flag. Artifact sulfate (formed by SO_2 conversion on the measurement filter) may cause us to underestimate slightly the extinction coefficient per unit mass for sulfates. In cases where we have included benzene soluble organics, we should note that the extraction efficiency for secondary organic aerosols is poor with the benzene method (Grosjean 1974). Perhaps the greatest measurement concern, however, involves nitrates (Spicer and Schumacher 1977). Because of potential difficulties in nitrate measurements, it might be best to regard the nitrate variable as a representation of ammonium nitrate, nitric acid, NO_2, and other related photochemical products rather than a measure of nitrate aerosols only.

A final difficulty in the regression analysis is the problem of colinearity, i.e. the correlations that exist between the "independent" variables (sulfates, nitrates, TSP, and relative humidity). Although multiple regression is designed to estimate the individual effect of each variable, discounting for the simultaneous effects of other variables, the colinearity problem can still lead to distortions in the results. These distortions should not be too great in our study, however, because the intercorrelations among the independent variables are not extremely large (typically 0.3 to 0.5).

Although the regression models are subject to several limitations, it should be noted that the results of these models have proven to be quite reasonable.

Chapter 5 demonstrates that our results are consistent with the published literature and with known principles of aerosol physics.

ALLOWANCES FOR METEOROLOGY

Special meteorological events, such as fog or precipitation, can have substantial effects on visibility. It is important to discount for these special weather conditions in the visibility/pollutant regression studies. Regression, based on minimization of squared errors, is very sensitive to outliers in the data, and the extremely low visibilities (extremely high extinction coefficients) associated with special weather conditions can dominate the results of the regressions. Accordingly, we have eliminated all days with fog or precipitation in our visibility/pollutant regression analysis.

We have also investigated the effect of sorting for meteorology in our analysis of historical visibility trends. In this case, we have eliminated all hours with RH>70%, fog, or precipitation. Figures 5 and 6 present some typical results.

As indicated in Figures 5 and 6, sorting for special meteorology has a very slight impact on 10th percentile visibility, a slight impact on 50th percentile visibility, and a substantial impact on 90th percentile visibility. From several test cases, we have concluded that sorting for meteorology will have essentially no effect on our conclusions concerning historical trends (changes) in 10th and 50th percentile visibilities. Sorting for meteorology can sometimes have significant effects on conclusions concerning trends in 90th percentile visibility.

The historical trends presented in this report (Chapter 4) will be based on all the data, without sorts for special meteorology. The main

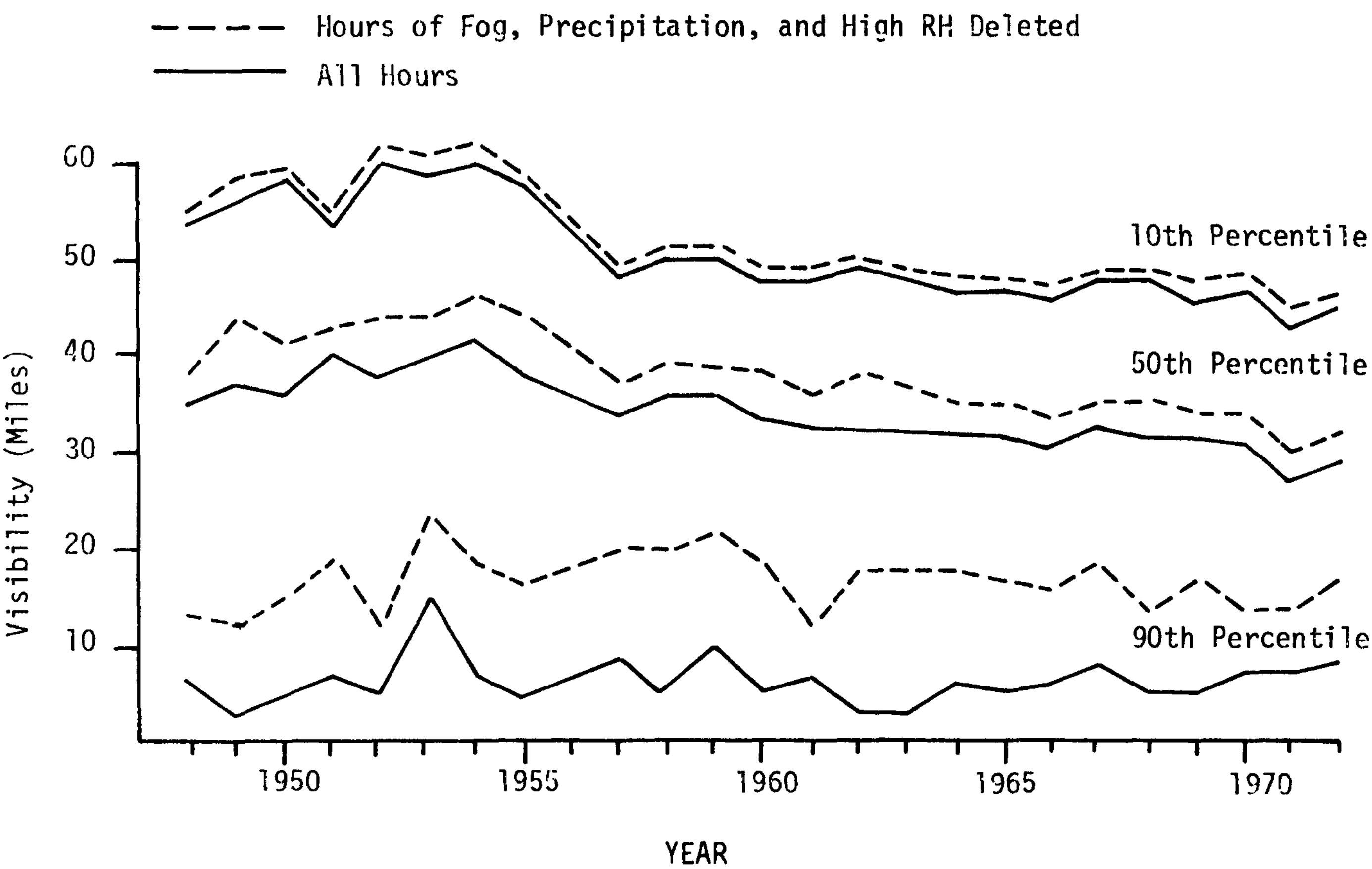

Figure 5. Historical visibility trends at Salt Lake City

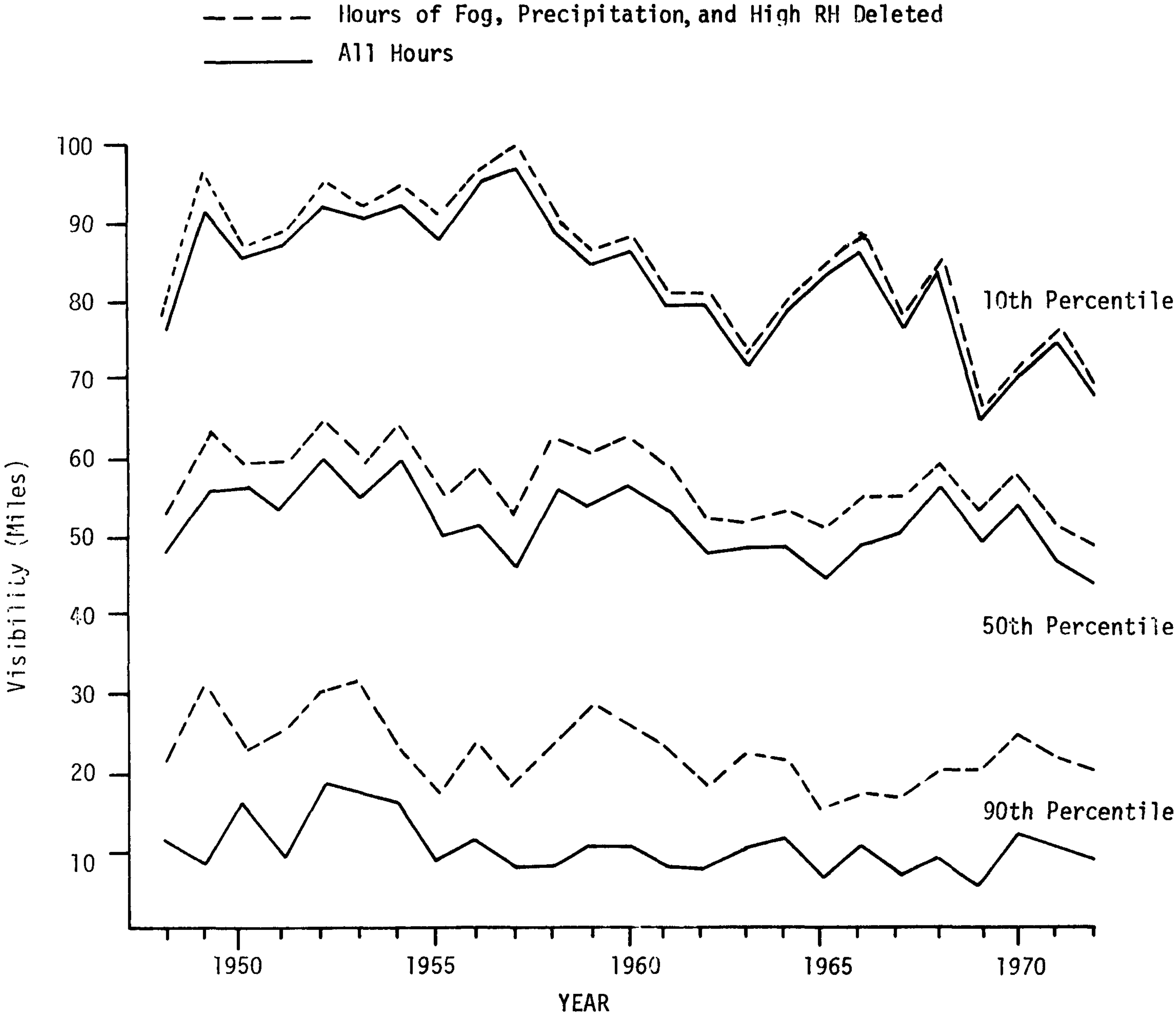

Figure 6. Historical visibility trends at Denver.

caveat that should be kept in mind is that the trends in 90th percentile visibility might be affected by special weather events such as fog or precipitation. The trends in 50th and 10th percentile visibilities should not be affected by such weather events.

In future studies, it may prove interesting to perform more detailed analyses of visibility trends; the data could be sorted by season, relative humidity, wind direction, precipitation conditions, etc. Our trend analysis, based on all measurements each year, is intended to document only the gross, overall history of visibility in the Southwest.

CHAPTER 3

EXISTING VISIBILITY LEVELS

A very basic issue that needs to be resolved is "what are existing visibility levels in the Southwest?" Specifically, we would like to quantify visual range on average days, "best-case" days, and "worst-case" days; we would also like to know if any large-scale geographic patterns exist in visibility within the Southwest. These questions can be answered by an analysis of airport visibility measurements.

VISIBILITY IN URBAN AND NONURBAN AREAS

Figures 3 and 4 (in Chapter 2) presented recent cumulative frequency distributions for visual range at four urban locations and thirteen nonurban locations. From these figures, one can easily read the 10th percentile (best), 50th percentile (median), and 90th percentile (worst) visibilities for each location. These percentile visibilities, rounded to the nearest five miles to reflect uncertainties, are listed in Table 3. It should be remarked that some of these visibility percentiles have been estimated by linearly extrapolating cumulative frequency distributions; some of the other percentiles have been estimated by comparing the "upper-end" of the frequency distribution among locations.

Table 3 indicates that visibility in the Southwest tends to be quite good, at least relative to visibility east of the Mississippi River*. Median visibility is on the order of 30 to 55 miles in and near urban centers

*Median visibility in the Northeast is approximately 10 miles at urban locations and 12 miles at nonurban locations (Trijonis and Yuan 1977).

TABLE 3. MEDIAN, BEST-CASE, AND WORST-CASE VISIBILITY LEVELS AT SEVENTEEN LOCATIONS IN THE SOUTHWEST

LOCATION	YEARS OF DATA	VISIBILITY PERCENTILES 10th% (Best)	50th% (Median)	90th% (Worst)
URBAN				
Phoenix, Ariz.	1970-1972	60 miles	35 miles	20 miles
Tucson, Ariz.	1970-1972	65*	55	40
Denver, Col.	1970-1972	70*	50	10
Salt Lake City, Utah	1970-1972	45	30	10
NONURBAN				
Fort Huachuca, Ariz.	1968-1970	70 miles	50 miles	30 miles
Prescott, Ariz.	1970-1972	110**	80**	40
Winslow, Ariz.	1970-1972	110**	80**	25
Colorado Springs, Col.	1964-1966	115*	75	20
Grand Junction, Col.	1970-1972	110*	80	40
Pueblo, Col.	1966-1968	90	75	20
Ely, Nev.	1970-1972	70**	50*	20
Las Vegas, Nev.	1970-1972	80*	60	35
Alamogordo, N.M.	1968-1970	95*	65	35
Farmington, N.M.	1970-1972	110**	80**	40
Dugway, Utah	1970-1972	90*	65	20
Wendover, Utah	1970-1972	110**	80**	40
Cheyenne, Wyo.	1970-1972	100*	65	15

*Estimated by linearly extrapolating the cumulative frequency distribution for this site

**Estimated by comparing frequency distribution to distributions for other locations (those in which population exceeds 150,000) in the Southwest. Median visibility tends to be around 65 to 80 miles at most sites away from large urban centers. For comparison, we note that an atmosphere containing air molecules only (with absolutely no aerosols and with no light-absorbing gaseous pollutants) would exhibit a visual range of approximately 160 miles.

The only nonurban airports exhibiting median visibilities less than 65 miles are Las Vegas (60 miles), Ely (50 miles), and Fort Huachuca (50 miles). The Las Vegas airport almost qualifies as an urban location; Ely is within 10 miles of a copper smelter; and Fort Huachuca is within 150 miles of several copper smelters.

Best 10th percentile visibility ranges from 45 to 70 miles among the four urban locations and from 90 to 115 miles at most nonurban locations. Again, the three exceptions among the nonurban locations are Las Vegas, Ely, and Fort Huachuca, with 10th percentile visibilities of 80, 70, and 70 miles, respectively.

Worst-cast 90th percentile visibilities range from 10 to 40 miles at the urban locations and from 15 to 40 miles at the nonurban locations. The site-to-site variations in 90th percentile visibility are not always consistent with the site-to-site variations in 10th and 50th percentile visibility. Unlike the 10th and 50th percentiles, the 90th percentile appears to be dominated by special, localized meteorological events such as fog and precipitation.

GEOGRAPHICAL PATTERNS IN VISIBILITY

Figures 7, 8, and 9 present maps of 50th, 10th, and 90th visibility percentiles, respectively. The visibility percentiles are plotted at the locations of the airports; circled numbers represent urban locations.

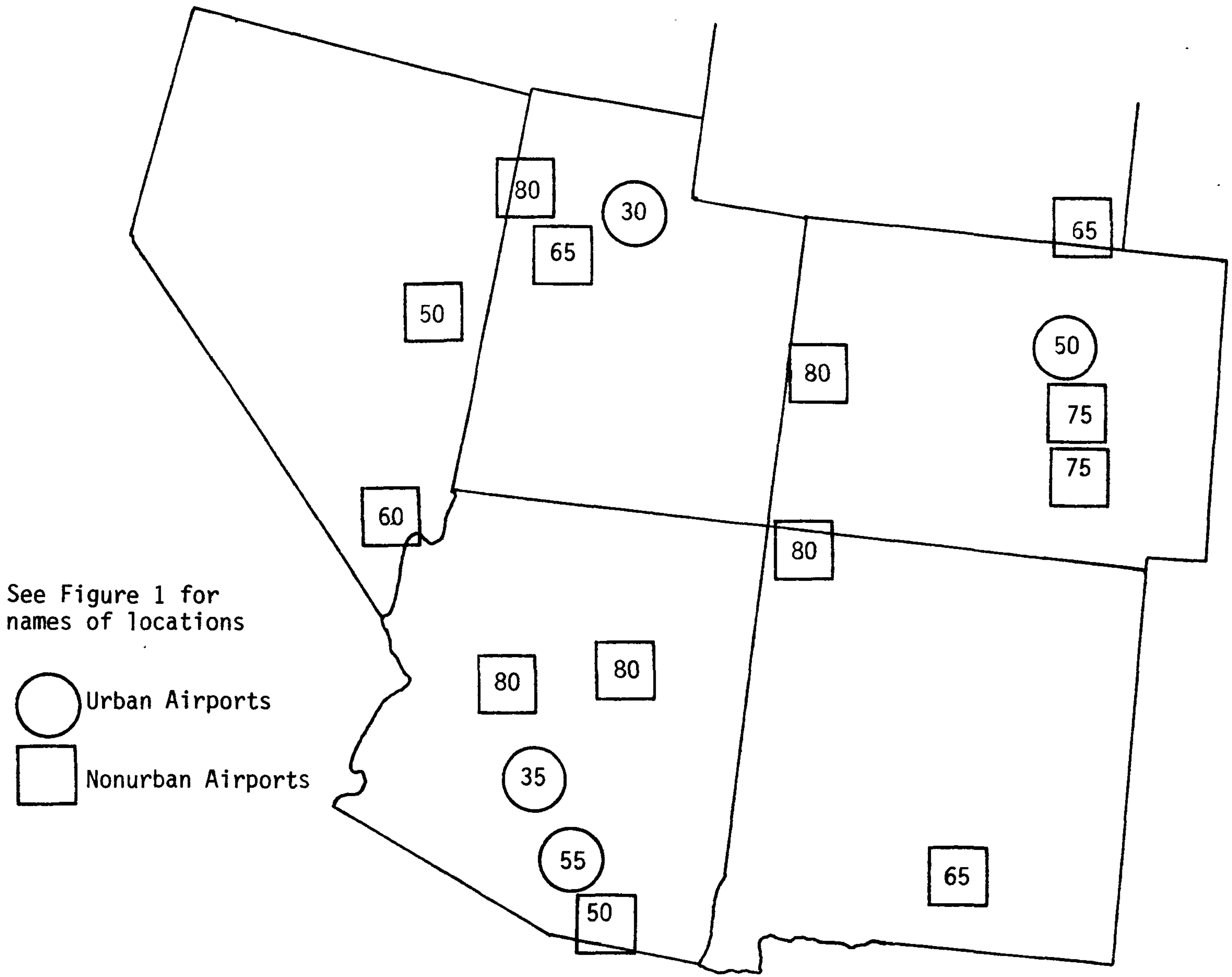

Figure 7. Geographical distribution of median visibilities (in miles).

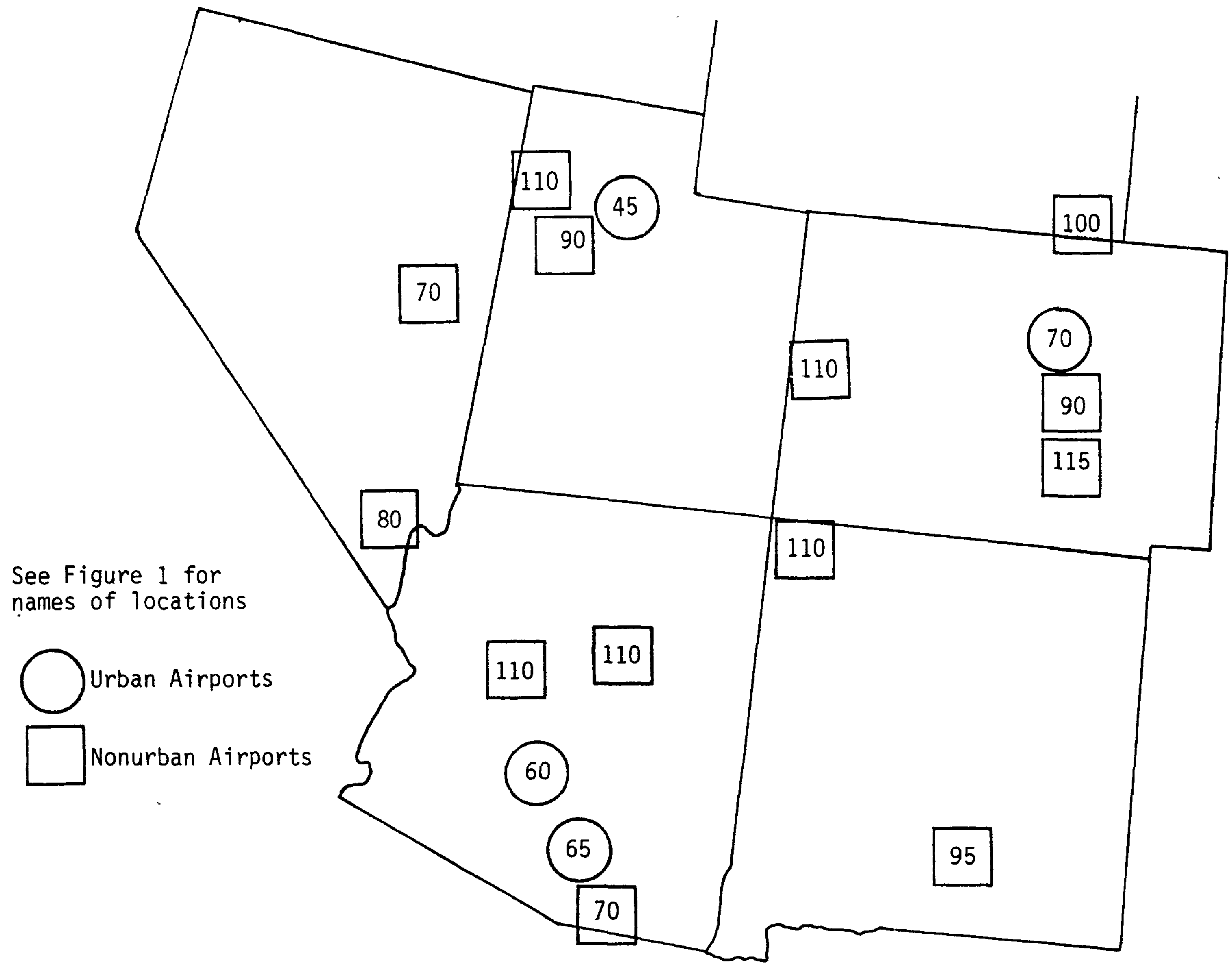

Figure 8. Geographical distribution of (best) 10th percentile visibilities (in miles).

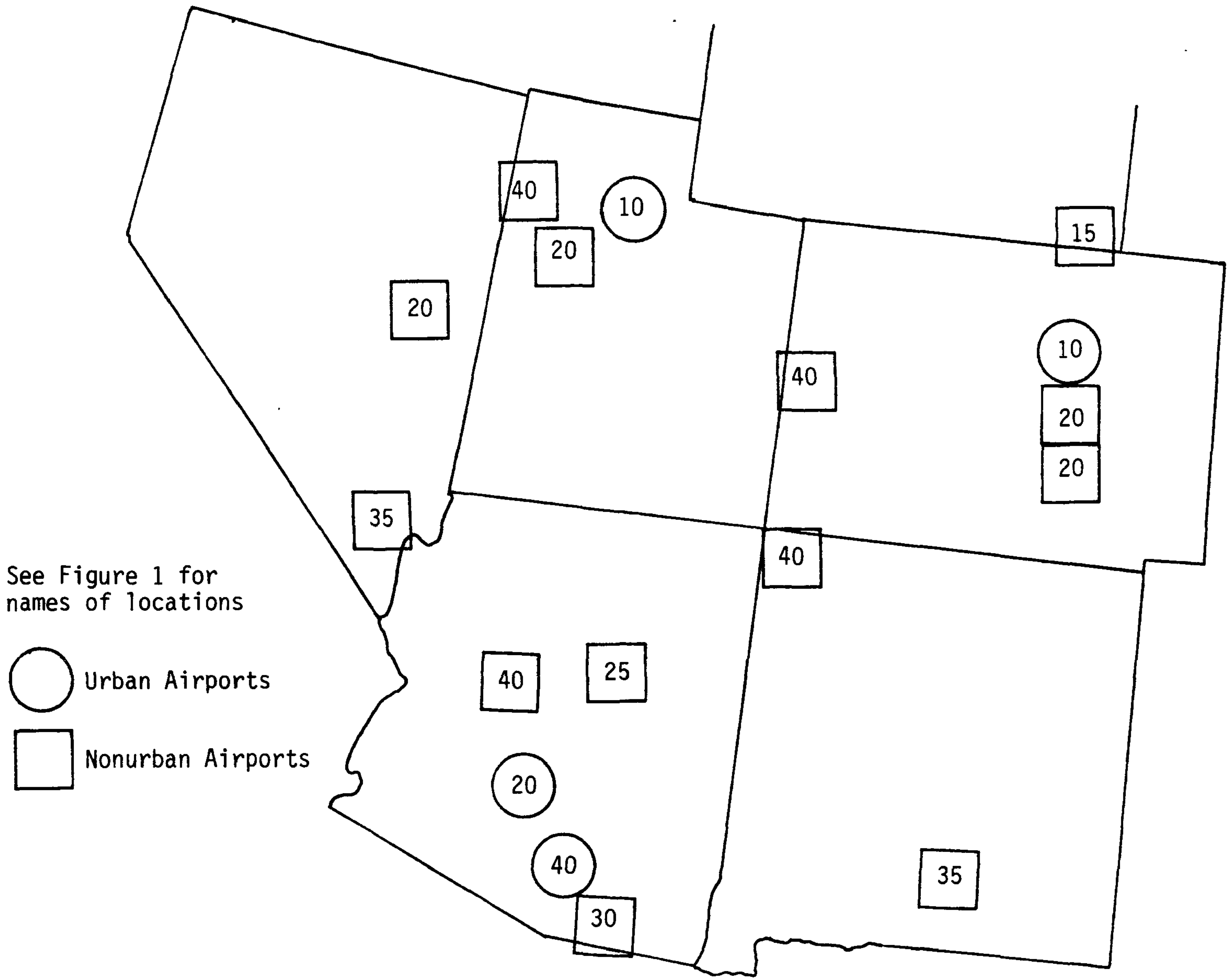

Figure 9. Geographical distribution of (worst) 90th percentile visibilities (in miles).

The main conclusion evident in Figures 7, 8, and 9 is that no dominant large-scale geographic patterns exist for visibility within the Southwest. With the three exceptions noted earlier, visibility tends to be quite good at nonurban sites throughout the study region. There is, of course, an obvious difference between urban and nonurban locations.

CONSISTENCY WITH RECENT FIELD PROGRAMS

The quality of the airport visibility data is evidenced by the consistency between the airport observations and special field programs. Based on the airport data, we have concluded that median visibility in nonurban areas of the Southwest is 65 to 80 miles. Using photographic photometry, Roberts et al. (1975) found a median visibility of 69 miles in the Painted Desert, Arizona. The C-b Oil Shale Venture (1977) reported a median visibility of 79 miles based on photographic photometry measurements in a remote area of northwest Colorado. Using an integrating nephelometer, Tombach and Chan (1977) determined a median visibility of 58 miles in remote northeast Utah.

The airport data indicate that 10th percentile visibility ranges from 90 to 115 miles in nonurban areas of the Southwest. Roberts et al. (1975) measured a 10th percentile of 98 miles in the Painted Desert; the C-b Oil Shale Venture (1977) reported a 10th percentile of 115 miles in remote NW Colorado. The only inconsistency is that Tombach and Chan (1977) found a 10th percentile of 146 miles (very near Rayleigh scattering) in remote NE Utah.

CHAPTER 4

HISTORICAL VISIBILITY TRENDS

It is a common public opinion in the Southwest that haze levels have increased substantially during the past two decades. This perception may be due to actual increases in pollution, or it may be due to nostalgia. The airport observations offer a unique opportunity to check whether or not visibility really has deteriorated. This chapter uses the airport data to document changes in visibility from the late 1940's to the early 1970's.

The trend study described here examines only gross, overall changes in yearly visibility indices. In future work, it may prove useful to investigate visibility trends in finer detail. The trend analysis could be stratified by season or by meteorological class; air quality and emission changes could be documented in order to help explain visibility trends at each location; more work could also be done to identify changes in observation practices that might have affected apparent trends. The present study, however, is directed only at answering the general question: "Has visibility changed in the Southwest during the past two to three decades? If so, by approximately how much?"

YEAR-TO-YEAR VISIBILITY TRENDS

Figures 10 through 21 illustrate historical visibility trends at four urban locations (Figures 10 to 13) and eight nonurban locations (Figures 14 to 21). Trends are presented for the 10th percentile (best visibility),

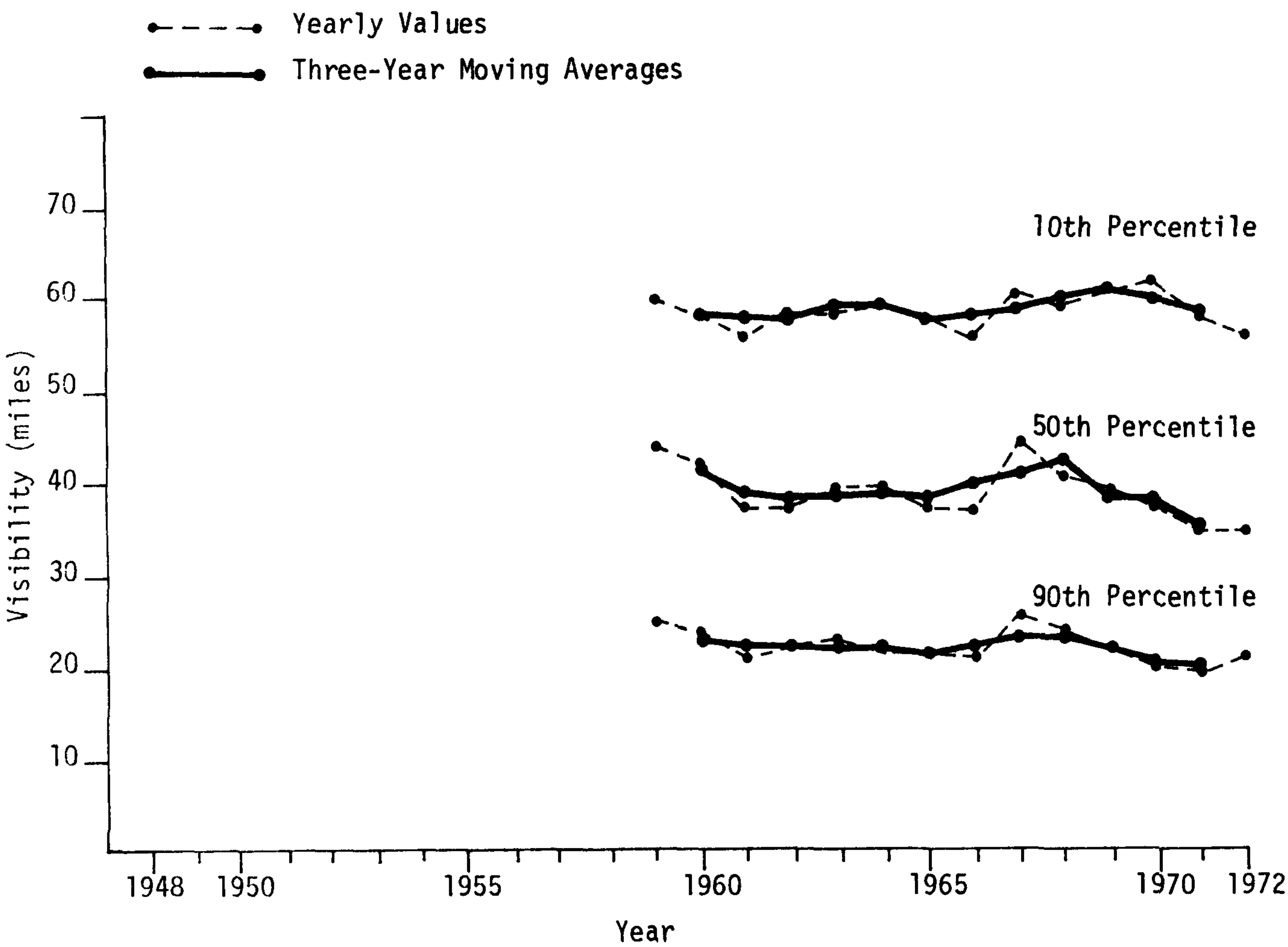

Figure 10. Long-term visibility trends at Phoenix.

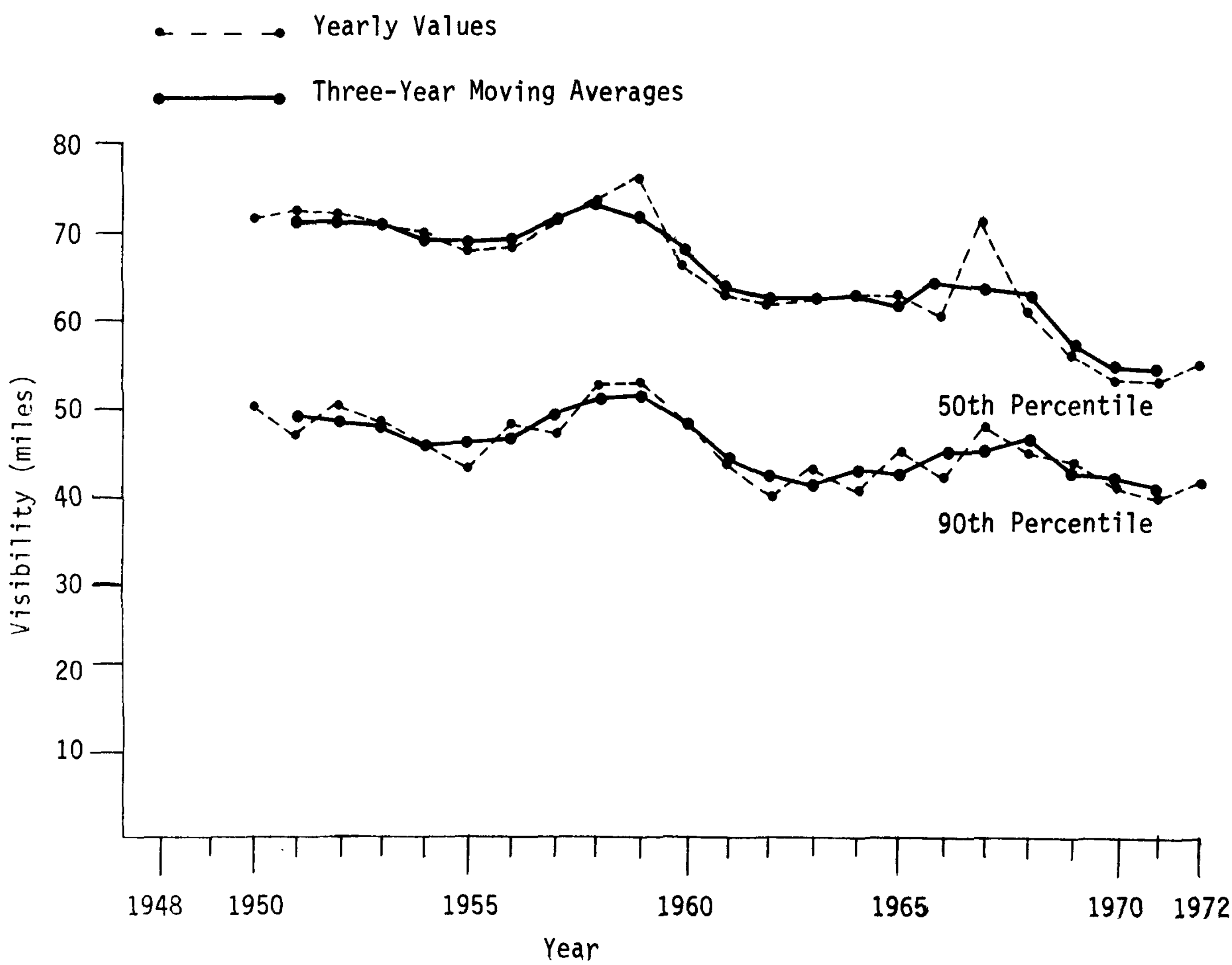

Figure 11. Long-term visibility trends at Tucson.

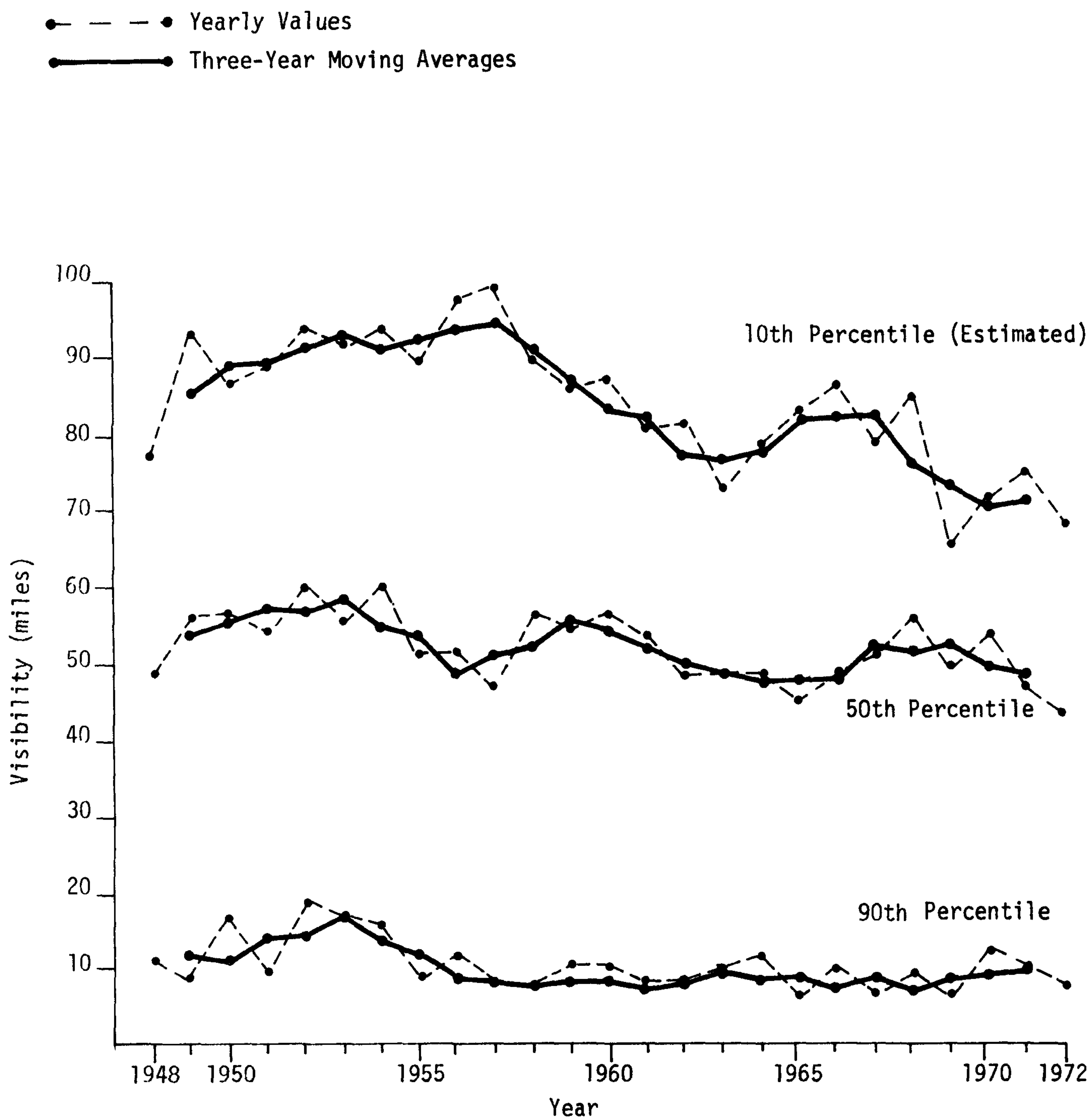

Figure 12. Long-term visibility trends at Denver.

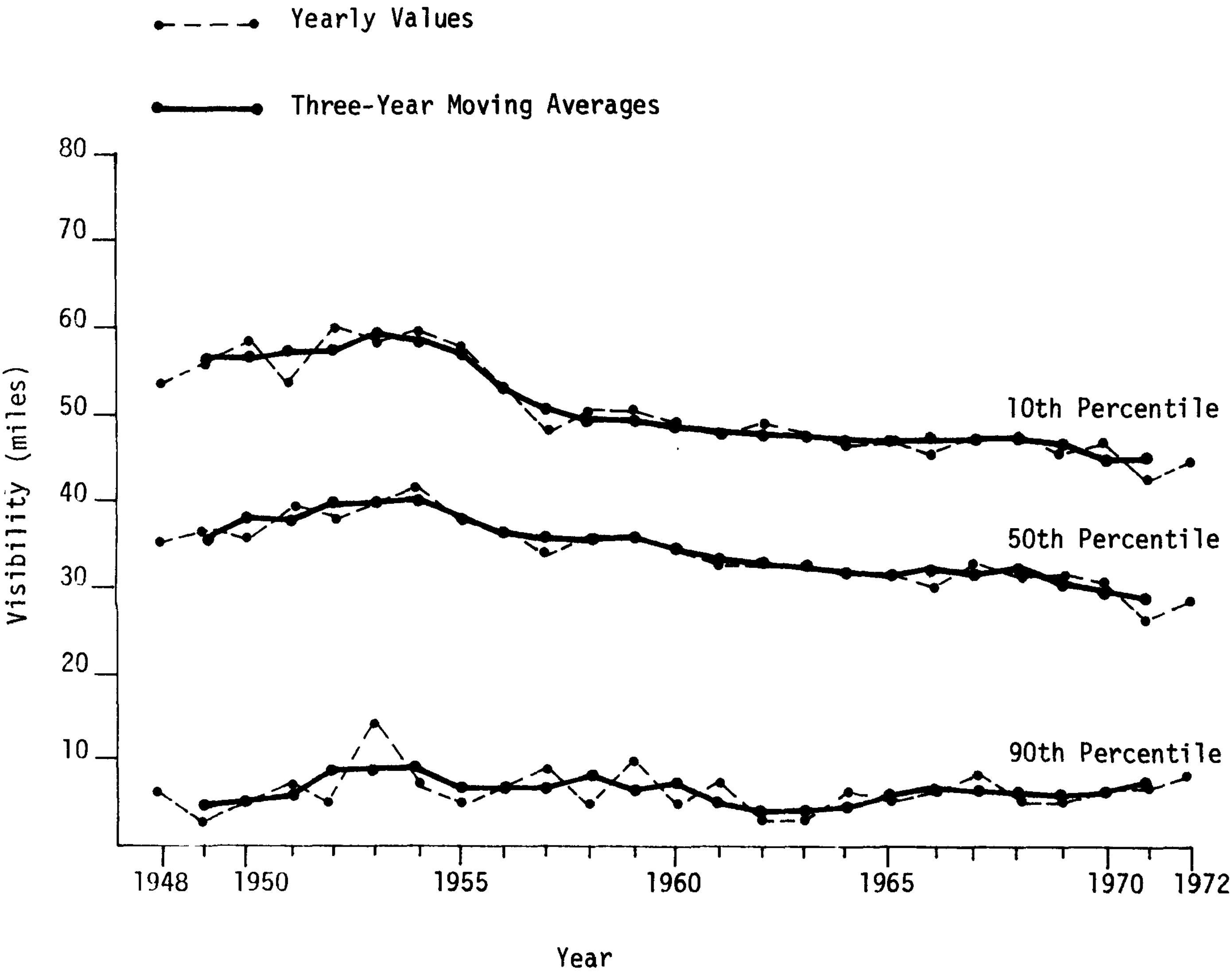

Figure 13. Long-term visibility trends at Salt Lake City.

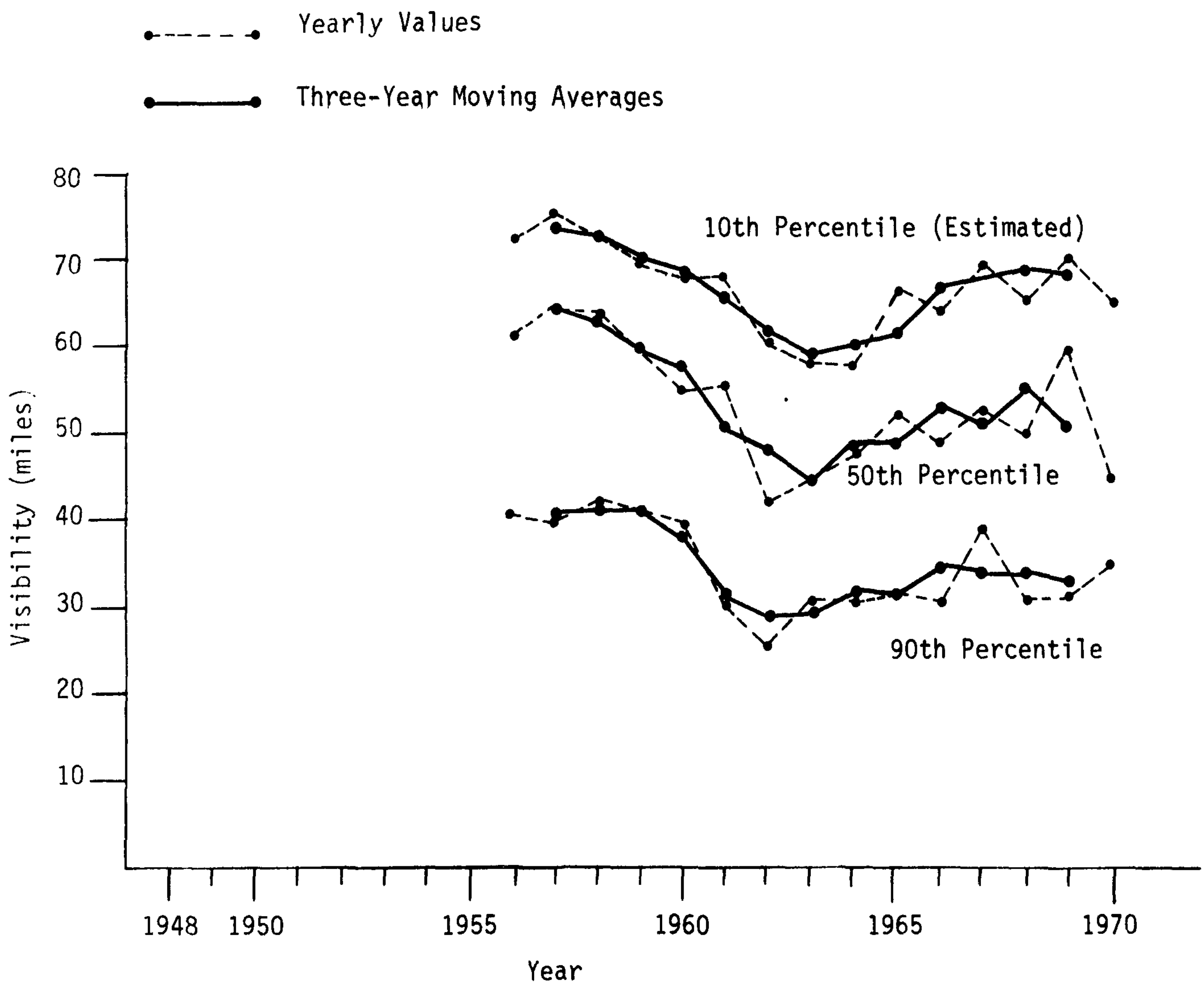

Figure 14. Long-term visibility trends at Fort Huachuca.

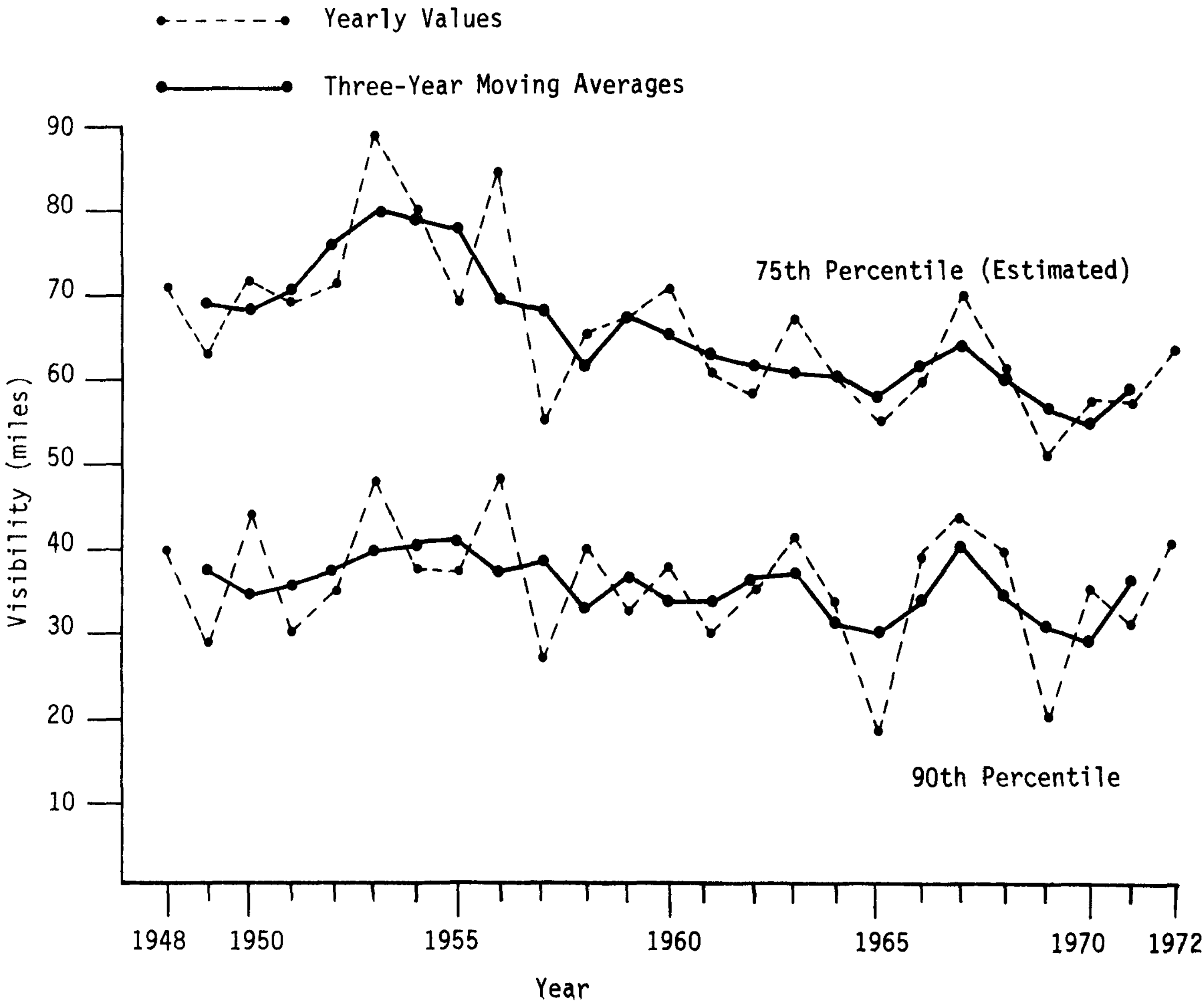

Figure 15. Long-term visibility trends at Prescott.

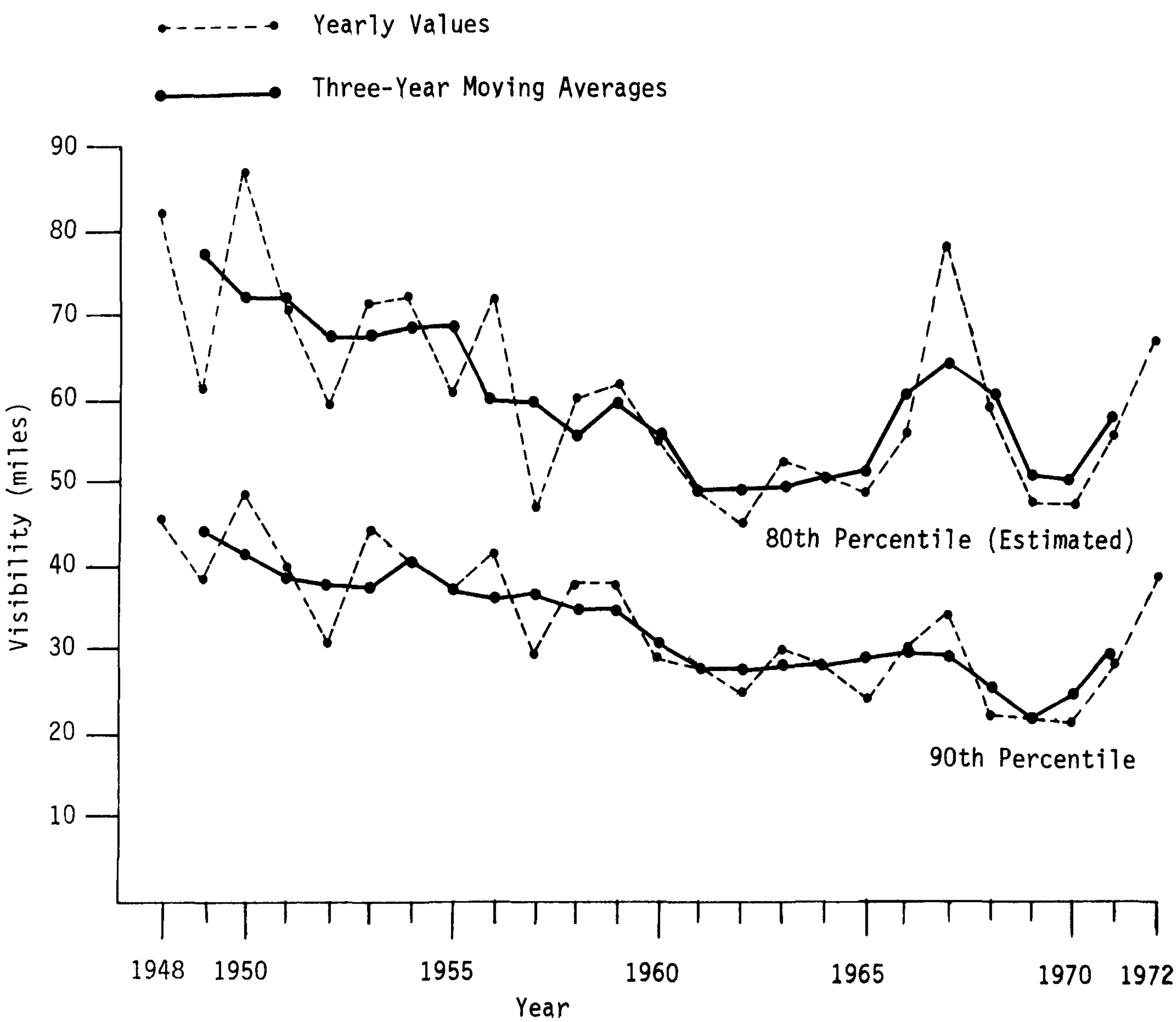

Figure 16. Long-term visibility trends at Winslow.

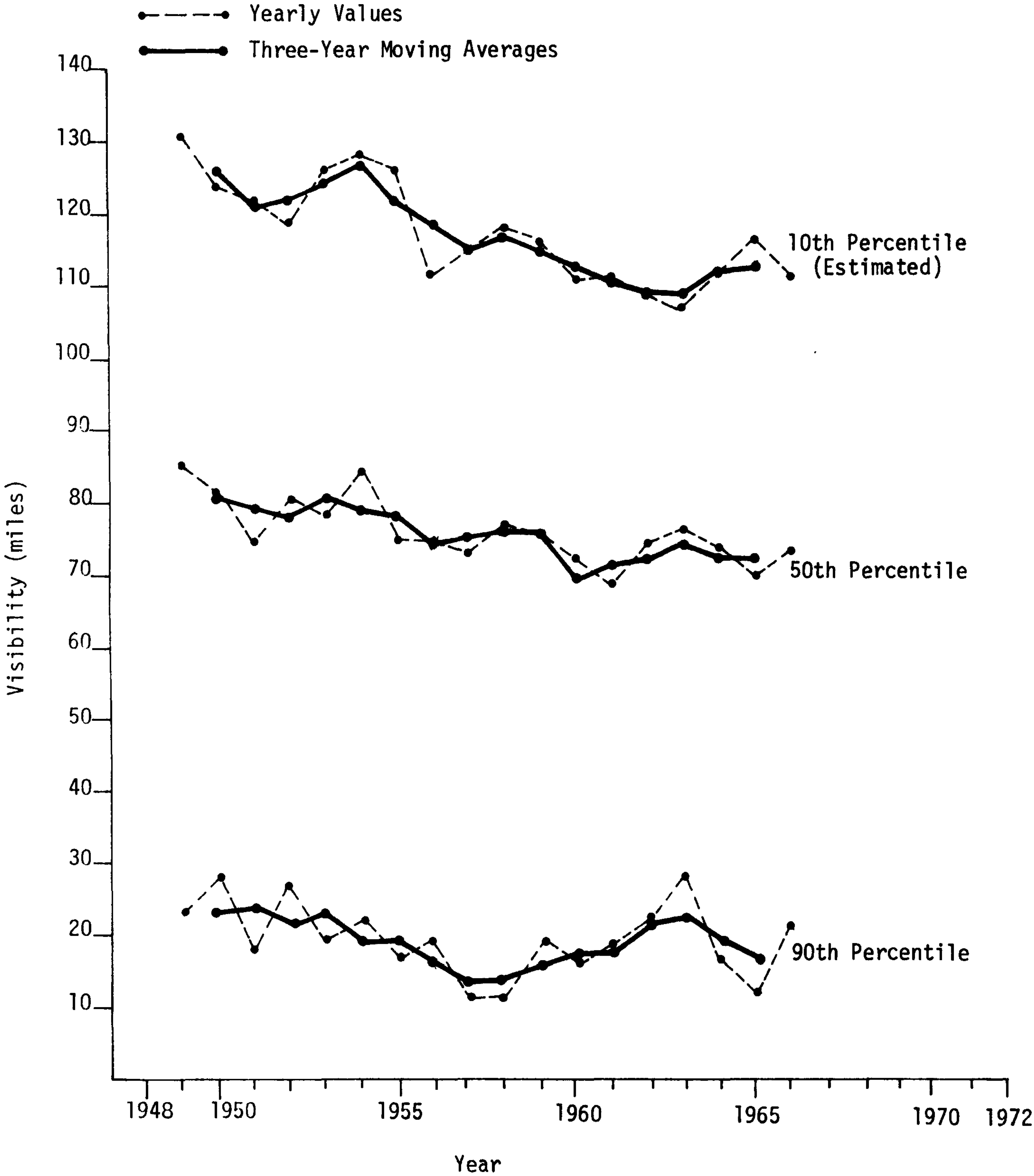

Figure 17. Long-term visibility trends at Colorado Springs.

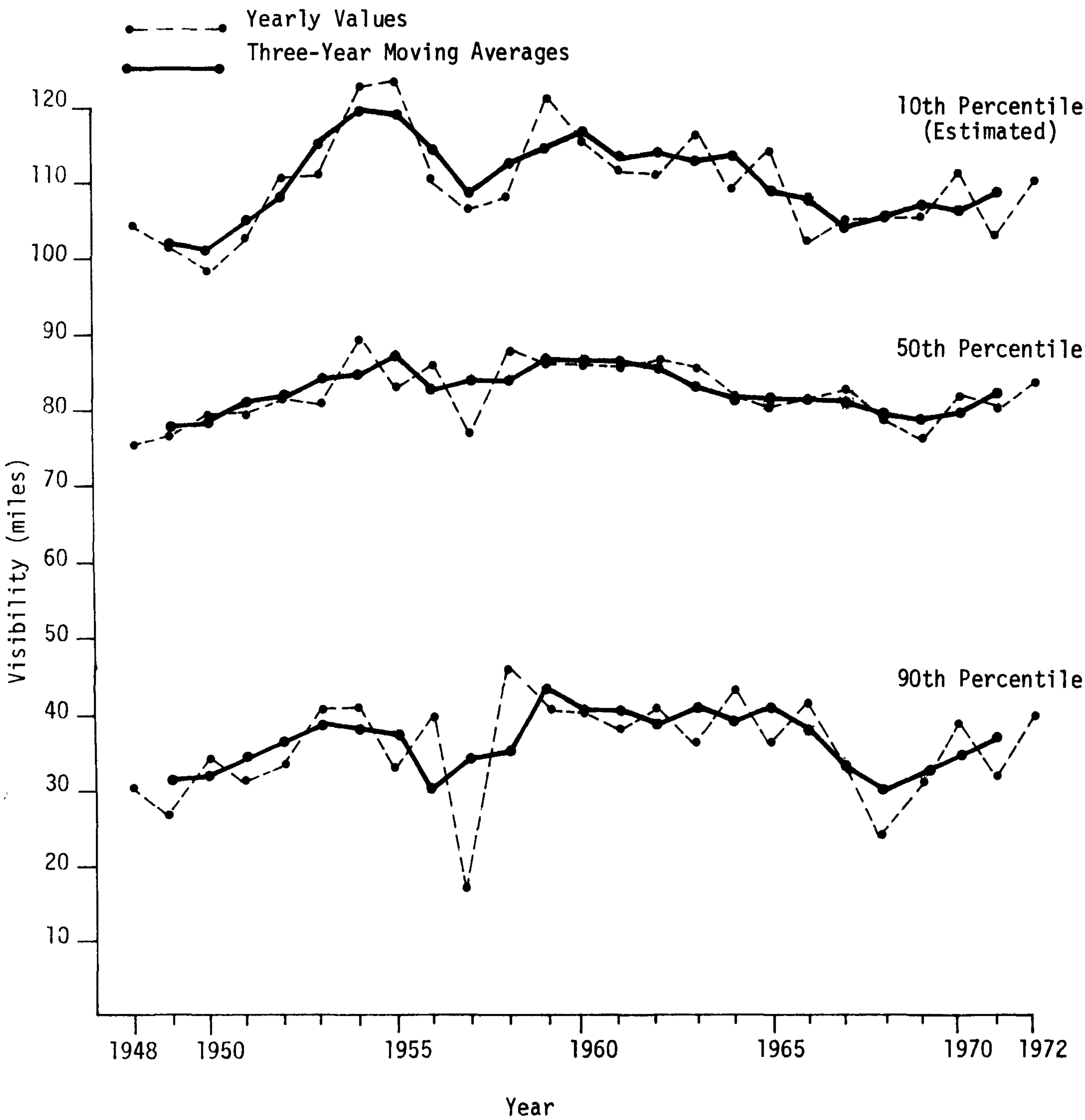

Figure 18. Long-term visibility trends at Grand Junction.

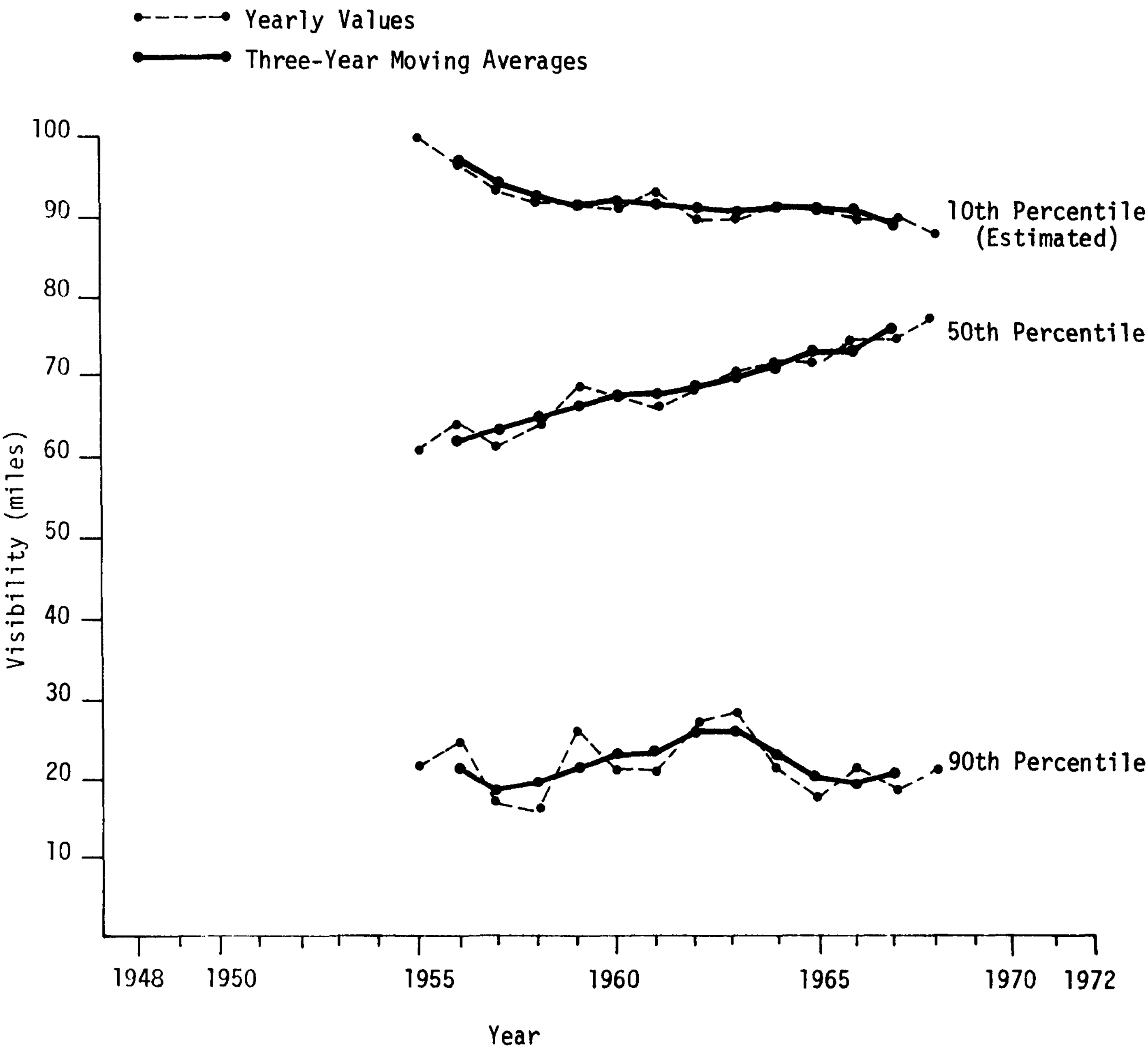

Figure 19. Long-term visibility trends at Pueblo.

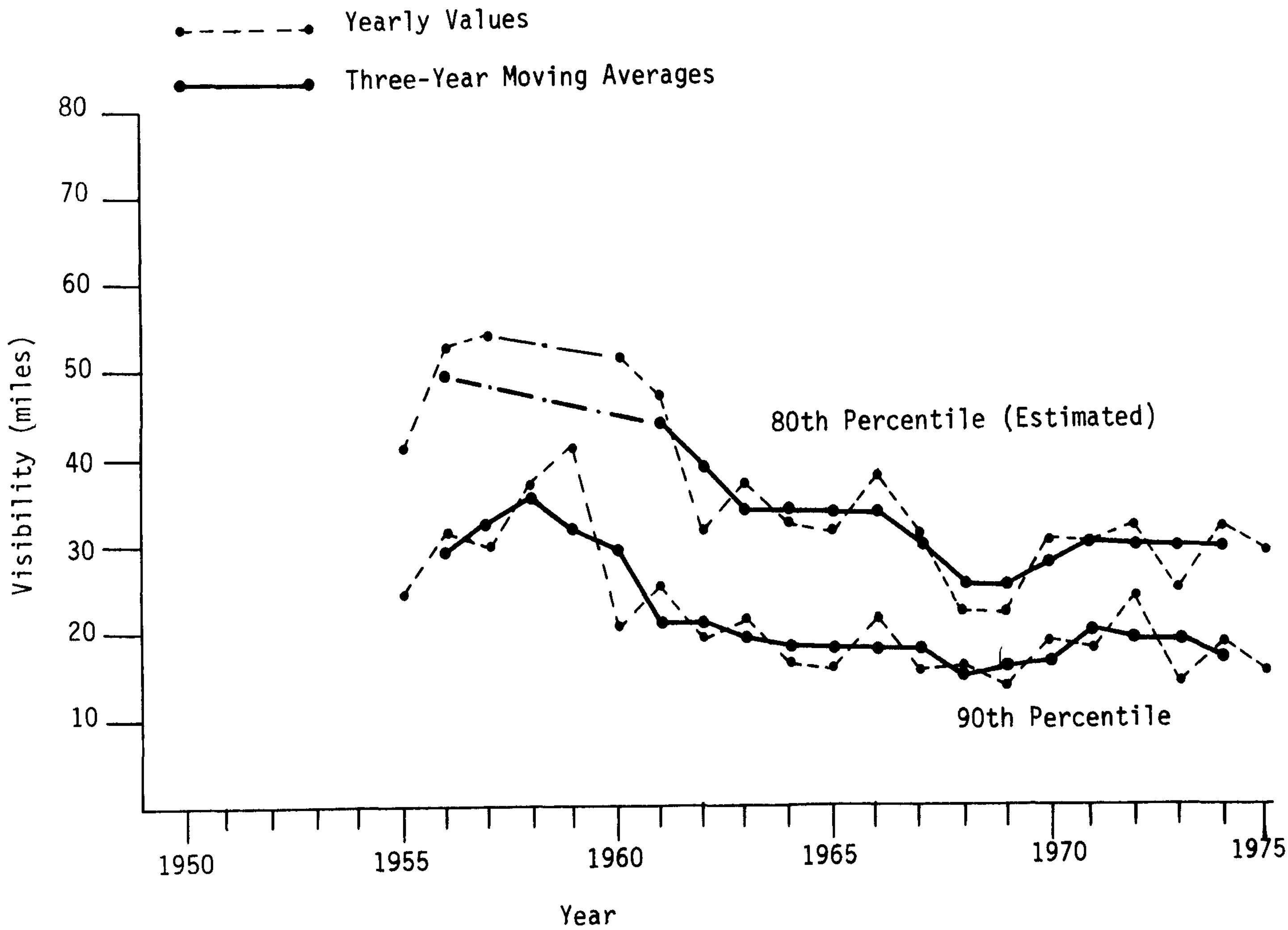

Figure 20. Long-term visibility trends at Ely.

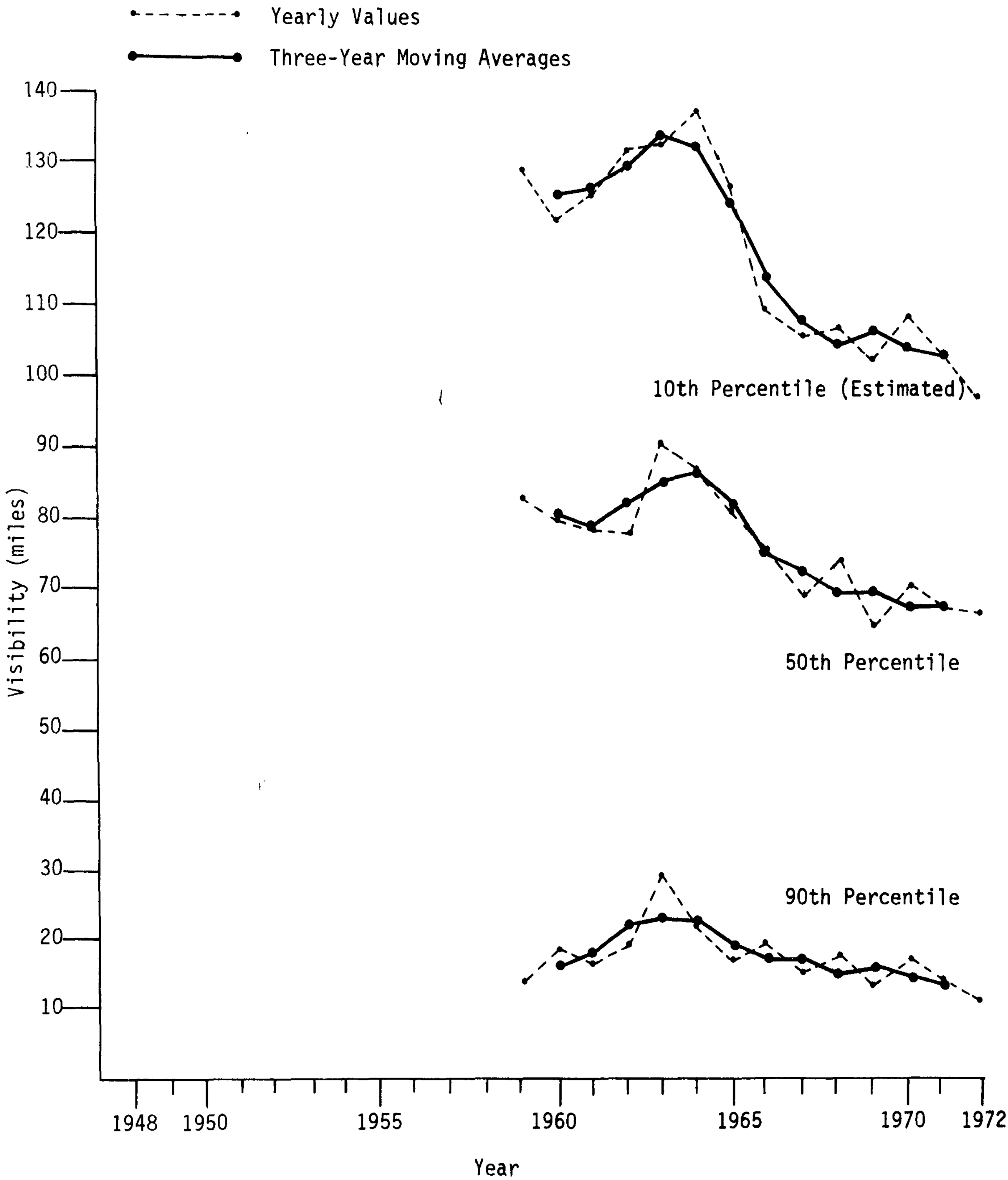

Figure 21. Long-term visibility trends at Cheyenne.

50th percentile (median visibility), and 90th percentile (worst visibility). For each year, the percentiles are computed from cumulative frequency plots, such as Figures 3 and 4, based only on those visibility markers that are routinely reported. In cases where the data do not permit computation of the 10th and 50th percentiles, trends are presented for the 75th or 80th visibility percentiles.

The basic period for which trend data are available is 1948 to 1972. For several sites, this period was shortened due to unavailability of data, relocation of observation sites, or changes in observation procedures (e.g., changes in visibility markers used).

As evidenced by Figures 10 to 21, many of the sites show some improvement in visibility from the late 1940's to the middle 1950's, followed by deterioration from the middle 1950's to the early 1970's. The improvement in the late 1940's and early 1950's most likely occurred because of the switch to cleaner fuels (from coal to oil and gas) during that period. This improvement has been noted earlier in the work of Holzworth (1962).

All locations but one show a downward trend in visibility after the middle 1950's. From analyses presented later in Chapters 5 and 6, we suspect that much of the deterioration in visibility is related to increases in secondary aerosols (e.g., sulfates and nitrates*). The increases in secondary aerosols would be due to growth in SO_x, NO_x, and possibly hydrocarbon emissions from copper smelters, power plants, motor vehicles and other sources.

A very unusual feature in Figure 19 (for Pueblo, Colorado) deserves special comment. Pueblo is the only location that does not exhibit a definite

*We call these aerosols "secondary" because they tend to be formed from gas-to-particle conversion. However, they may also be partly "primary" (directly emitted) in the sense that the gas-to-particle conversion occurs before emission into the atmosphere.

downward trend in visibility after the middle 1950's.* The 10th percentile visibility at Pueblo decreases somewhat; the 90th percentile visibility remains about constant; but the median visibility increases substantially! There appear to be two possible explanations:

- Subtle changes may have occurred in reporting practices which resulted in higher visibilities being recorded when visibility was in the range 40 to 80 miles. The changes in reporting practices would be "subtle" because, in examining the data, we could not find any obvious variations in marker selection, and, in interviewing the observers, we could not document any procedural modifications.
- Local emission reductions may have improved median visibility levels at Pueblo, while 10th percentile visibility deteriorated due to emission increases on a regionwide scale. Emission reductions did occur during the period at the largest industry in Pueblo, CF&I Steel. However, these reductions were not very great, and it does not seem plausible that they would have lead to a substantial visibility improvement (Pearson 1977).

Neither explanation is very satisfactory, and the unusual trends in the visibility data for Pueblo remain somewhat of a puzzle.

NET CHANGES IN VISIBILITY AND EXTINCTION, 1954 TO 1971

Table 4 summarizes net changes in visibility since the middle 1950's. Visibility has decreased by about 10 to 30 percent at most sites from 1954 to 1971; the deterioration is evident in all three visibility percentiles.

There is considerable variation in the visibility trends from one location to another. Some of this variation represents actual site-to-site differences in the rate of visibility deterioration. Some of the variation

---

* We did examine data for one other airport (Las Vegas, McCarran International) which exhibited an increasing trend in visibility. The airport observers at Las Vegas considered this to be an artifact produced by personnel changes, (Taylor 1977). Thus, we did not include visibility trends for Las Vegas in this report.

TABLE 4. NET PERCENT CHANGES IN VISIBILITY, 1953-1955 TO 1970-1972

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 TO 1971		
	Best (10th %) Visibility	Median Visibility	Worst (90th %) Visibility
URBAN			
Phoenix,† Ariz.	0%	-23%	-20%
Tucson, Ariz.	N.A.	-22%	-11%
Denver, Col.	-22%	-13%	-29%
Salt Lake City, Utah	-24%	-27%	-19%
NONURBAN			
Fort Huachuca,† Ariz.	-12%	-27%	-28%
Prescott, Ariz.	N.A.	-25%*	-21%
Winslow, Ariz.	N.A.	-17%**	-27%
Colorado Springs,† Col.	-17%	-12%	-17%
Grand Junction, Col.	-9%	-4%	-3%
Pueblo,† Col.	-9%	+35%	0%
Ely,† Nev.	N.A.	-42%**	-33%
Cheyenne,† Wyo.	-28%	-23%	-19%

†Trends for these sites are extrapolated from data covering most, but not all, of the period 1954-1971.

*75th percentile visibility instead of median visibility.

**80th percentile visibility instead of median visibility.

N.A. Not available.

may also be due to errors in estimating trends at individual locations (e.g., errors induced by undocumented changes in observation procedures). Considering the potential for errors, we are more confident of the overall conclusion (that visibility has generally deteriorated about 10 to 30%) than we are of the exact visibility changes at the individual locations.

Another way of expressing visibility trends is to compute changes in the extinction coefficient. Here it is useful to examine only "extra" extinction, the fraction of extinction above and beyond the constant contribution from blue-sky (Rayleigh) scatter. Given visibility, V in [miles], extra extinction is computed according to the expression

$$\frac{24.3}{V} - 0.15 \quad ,$$

with units of $[10^4 \text{ meters}]^{-1}$.

Table 5 summarizes the net changes in extra extinction since the middle 1950's. The increases in extra extinction are relatively greater than the decreases in visibility because we have subtracted out the constant contribution from blue-sky scattering. At most sites, extra extinction has increased on the order of 20 to 70% from 1954 to 1971.

One of the most interesting features of the visibility decrease (or extinction increase) is the large spatial scale that appears to be involved. The evidence points to the conclusion that visibility has decreased throughout the Southwest--in urban areas, nonurban areas, and even very remote areas. The ubiquitous nature of the visibility deterioration is indicated by the following:

TABLE 5. NET PERCENT CHANGES IN (EXTRA) EXTINCTION, 1953-1955 TO 1970-1972

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 TO 1971 Best (10th %) Extinction	Median Extinction	Worst (90th %) Extinction
URBAN			
Phoenix,† Ariz.	0%	+35%	+20%
Tucson, Ariz.	N.A.	+50%	+17%
Denver, Col.	+64%	+22%	+43%
Salt Lake City, Utah	+49%	+50%	+25%
NONURBAN			
Fort Huachuca,† Ariz.	+25%	+43%	+48%
Prescott, Ariz.	N.A.	+67%*	+38%
Winslow, Ariz.	N.A.	+37%**	+50%
Colorado Springs,† Col.	+91%	+24%	+21%
Grand Junction, Col.	+39%	+8%	+4%
Pueblo,† Col.	+26%	-46%	0%
Ely,† Nev.	N.A.	+97%**	+57%
Cheyenne,† Wyo.	+152%	+52%	+29%

†Trends for these sites are extrapolated from data covering most, but not all, of the period 1954-1971.

*75th percentile visibility instead of median visibility.

**80th percentile visibility instead of median visibility

N.A. Not available.

- Nearly every station exhibits a decreasing trend in visual range. The twelve stations studied include urban and nonurban locations scattered over the Southwest.

- Even though most of the nonurban airports would not qualify as extremely remote locations, we have found (in Chapter 3) that present visibility at the nonurban airports is essentially the same as present visibility measured at remote locations (Roberts et al. 1975; Tombach and Chan 1977; C-b Oil Shale Venture 1977). Since visibility has deteriorated at nonurban airports, we deduce that visibility has also deteriorated in extremely remote areas. Otherwise we would have to accept the improbable conclusion that, twenty years ago, visibility at nonurban airports was significantly greater than visibility in remote areas!

- At the nonurban airports, the most frequently used markers are on the order of 50 to 100 miles. Thus, the scale of the measurements is itself quite large.

As noted earlier, we hypothesize that much of the visibility deterioration is due to increases in secondary aerosol concentrations. The large spatial scale in visibility deterioration is consistent with this hypothesis. Secondary aerosol concentrations, produced by chemical transformation of gaseous pollutants, tend to be widely spread because mixing and transport occur during the time required for aerosol formation. The increased haze in nonurban areas could be the result of diffuse secondary aerosols (e.g., sulfates and nitrates), the products of transported, diluted, and aged gaseous emissions (e.g., SO_x and NO_x). As will be evident from the results of Chapter 5, even very small increments in secondary aerosols can produce noticeable deterioration in the high visibilities characteristic of the Southwest; our results indicate that a 1 $\mu g/m^3$ increase in secondary aerosols would reduce a visual range of 100 miles to 85 miles.

CHAPTER 5

VISIBILITY/POLLUTANT RELATIONSHIPS

Before control strategies can be planned for maintaining or improving visibility in the Southwest, we must identify the atmospheric components that contribute to visibility reduction. This chapter relates airport visibility measurements to Hi-Vol particulate measurements in order to gain insight as to the causes of haze in the Southwest. The analyses are based on statistical techniques discussed in Chapter 2; the basic procedure is to regress daily estimates of extinction coefficient against TSP, sulfate, nitrate, and relative humidity. Potential limitations in this procedure are also discussed in Chapter 2.

PHOENIX, MARICOPA COUNTY DATA

Data for analyzing the visibility/pollutant relationship in Phoenix were made available through the courtesy of the Maricopa County Health Department. The data base consisted of visibility and relative humidity measurements taken by the National Weather Service at Phoenix Sky Harbor Airport, and TSP, $SO_4^=$, NO_3^-, and benzene soluble (BSOL) measurements taken by the Maricopa County Health Department at the central Phoenix station. The air quality monitor is located approximately two miles northwest of the airport.

The data covered the years 1973-1974.* Because of the standard procedure of intermittent Hi-Vol sampling, only 106 days during the two years provided complete

---

* Data were later supplied by Maricopa County for the period 1968 to 1976. Over these nine years, there appeared to be several step jumps in the composition data (sulfate, nitrate, and organics), possibly due to changes in Hi-Vol filter type (Layden 1977). Data for the years 1973-1974 were internally consistent and were consistent with the NASN data. We therefore restricted the analyses to the 1973-1974 period.

data for all five variables. Several of these days were eliminated because fog and/or precipitation was reported by the airport observer.* This left 87 days for the statistical study.

The type of data used for the study is summarized in Table 2 (page 26). The sulfate and nitrate measurements were made by the colorimetric and 2-4 xylenol methods, respectively.

Uni-Variate Analysis

As a first step in the data analysis, we examined the simple relationship between extinction coefficient (B) and each of the independent variables (TSP, RH, SULFATE, NITRATE, and BSOL) one at a time.** Figures 22 through 26 show scatter plots of B versus each of the other variables. Included in the plots are (least-square) regression lines. The regression equations and the correlation coefficients are summarized in Table 6.

TABLE 6. RESULTS OF UNI-VARIATE REGRESSIONS FOR PHOENIX, MARICOPA COUNTY DATA

Variable	Correlation Coefficient, R	Regression Equation	Significance level, F†
TSP	.31	B = .41 + .0025 TSP	9
RH	.34	B = .54 + .012 RH	11
SULFATE	.81	B = .35 + .050 SULFATE	159
NITRATE	.71	B = .36 + .097 NITRATE	87
BSOL	.31	B = .60 + .024 BSOL	9

† F statistic of 4 corresponds to 95% significance level.

---

* Two other days were eliminated from the data base: 12/6/73 when benzene soluble organics were inordinately high, and 1/23/74 when sulfates and nitrates at the central Phoenix site were an order of magnitude greater than values reported at other Maricopa County stations. Including these two days in the analysis would have lowered our total correlation coefficient from 0.87 to 0.81.

** As explained in Chapter 2, extinction coefficient is 24.3 ÷ visibility. SULFATE and NITRATE are 1.3 $SO_4^=$ and 1.3 NO_3^-, respectively.

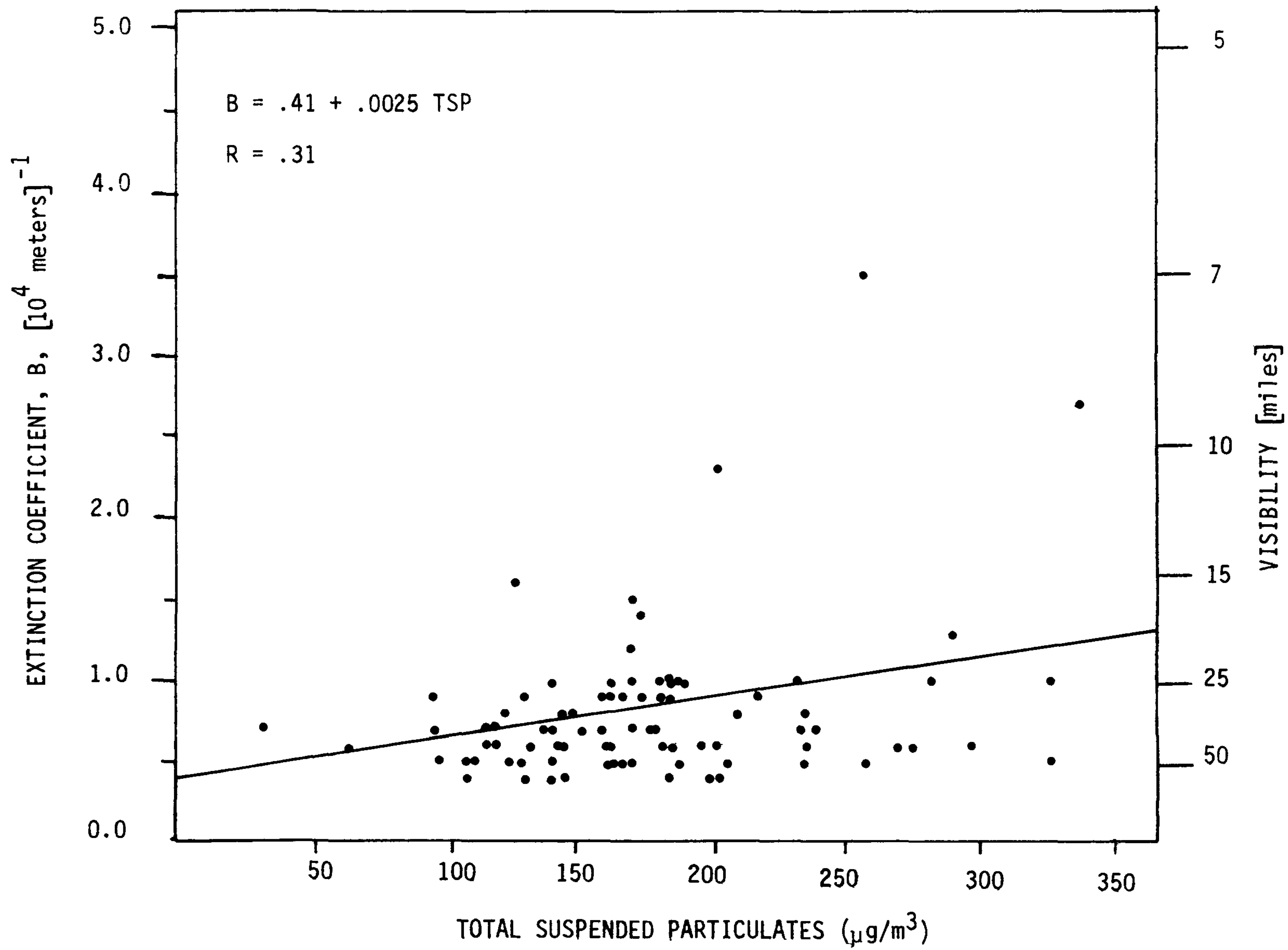

Figure 22. Extinction coefficient versus TSP in Phoenix.

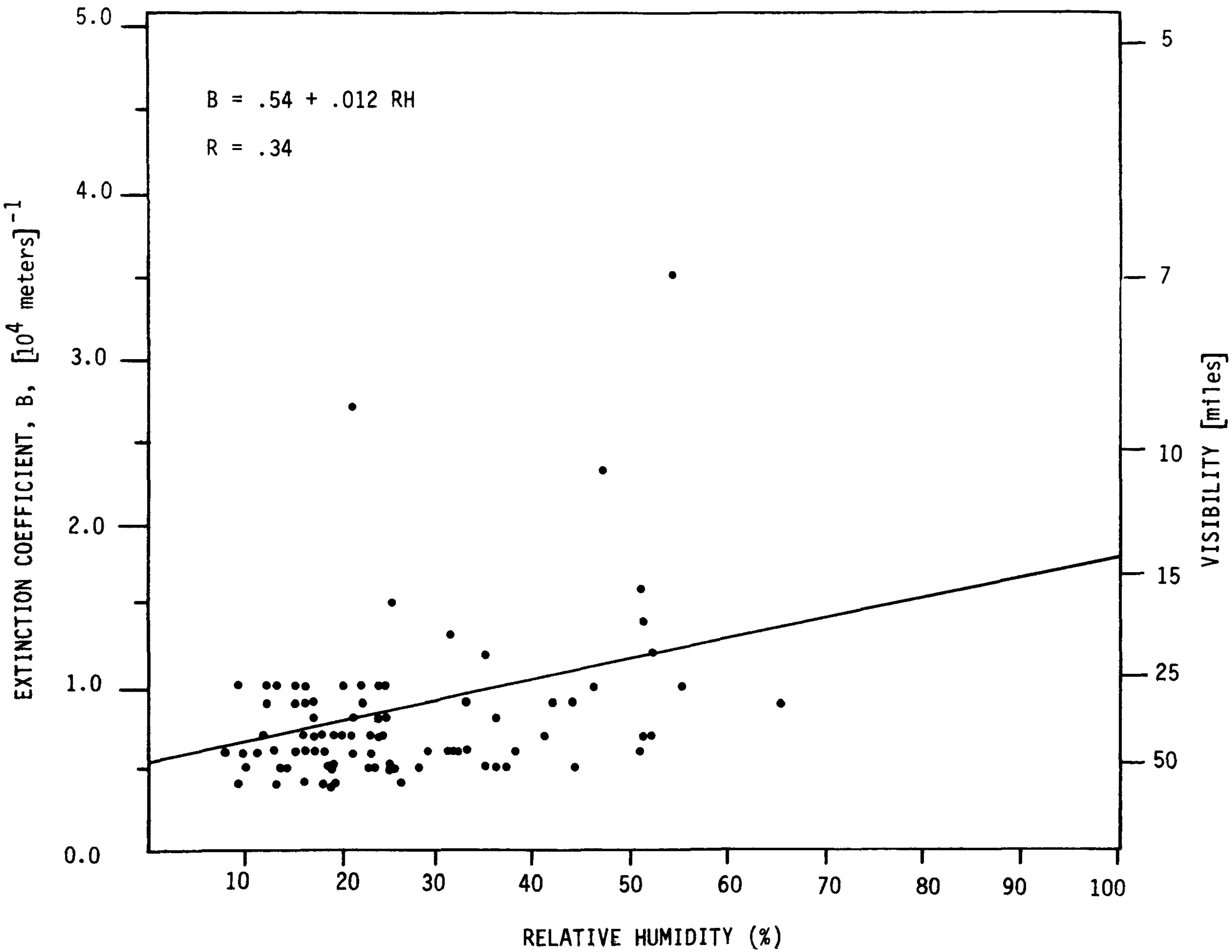

Figure 23. Extinction coefficient versus RH in Phoenix.

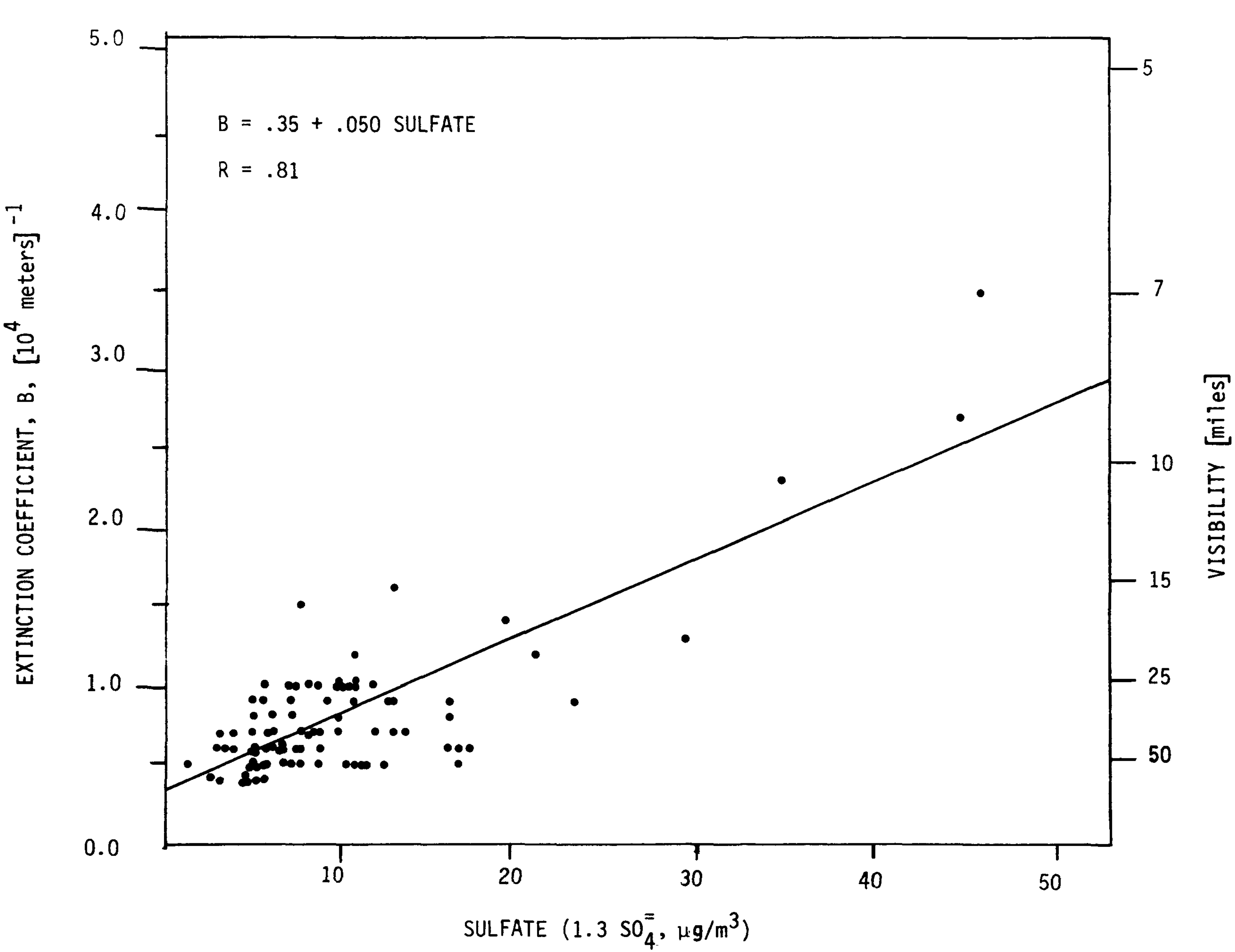

Figure 24. Extinction coefficient versus SULFATE in Phoenix.

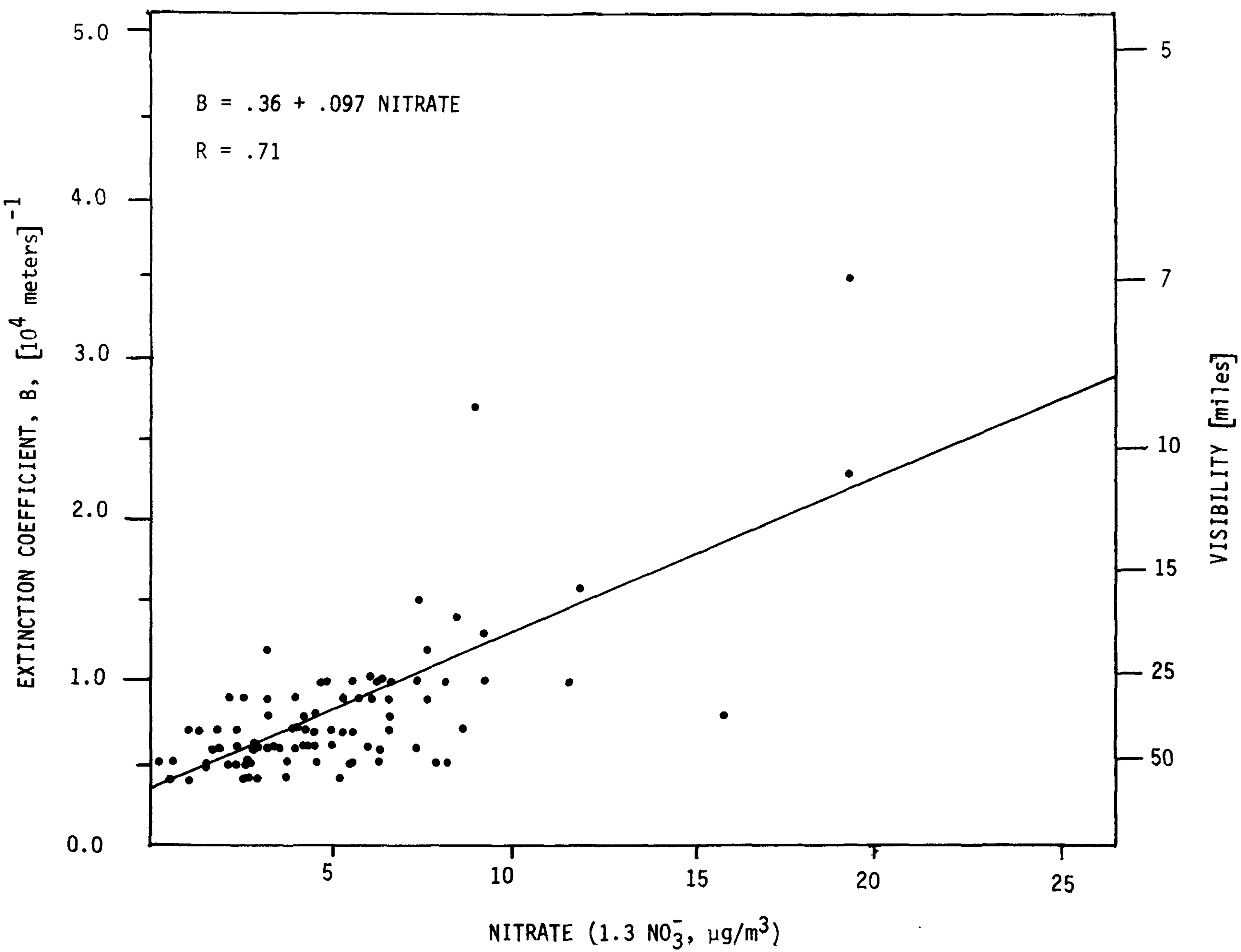

Figure 25. Extinction coefficient versus NITRATE in Phoenix.

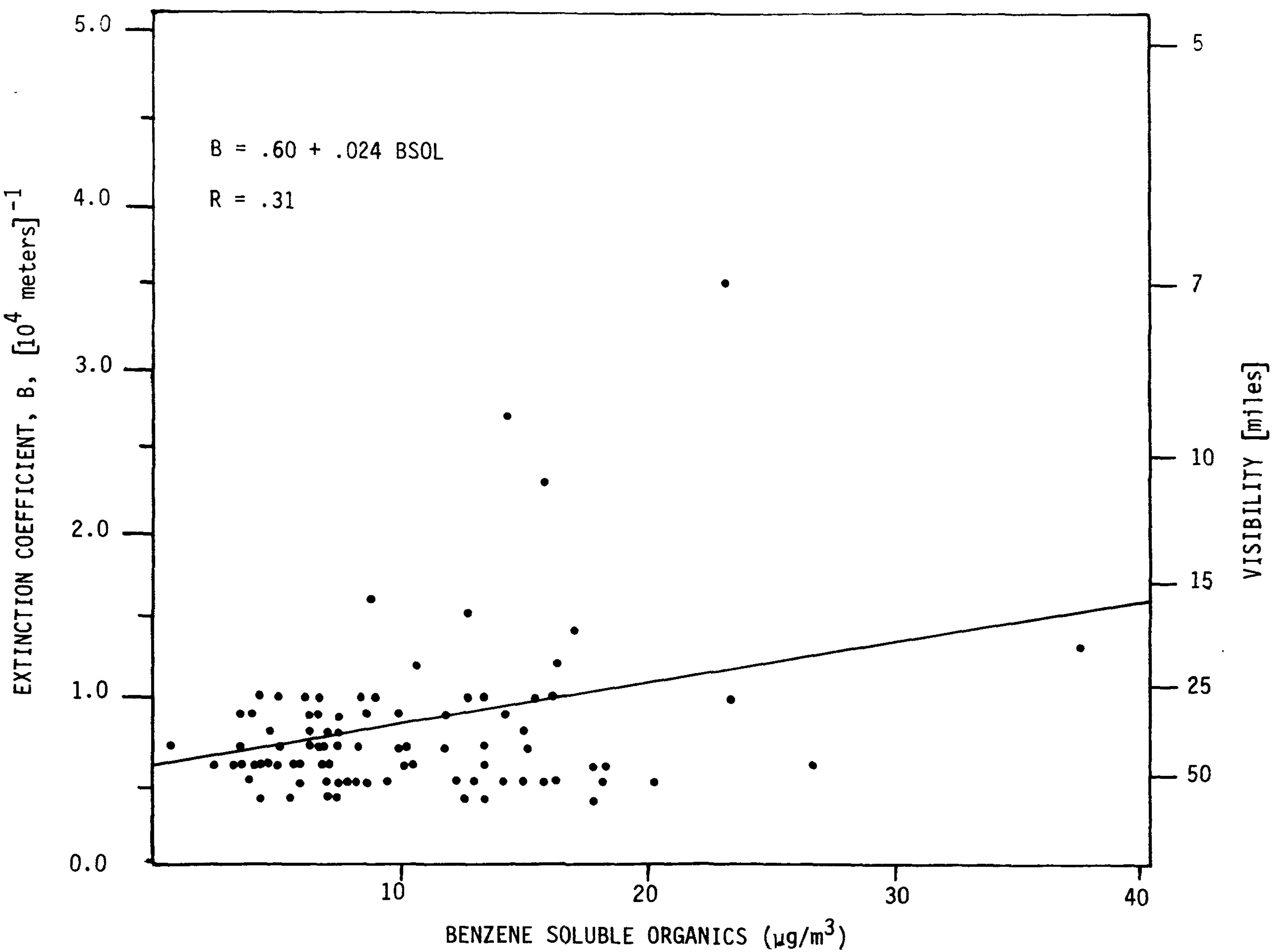

Figure 26. Extinction coefficient versus BSOL in Phoenix.

Table 6 indicates that all five variables are significantly correlated with B at a 95% confidence level. SULFATE and NITRATE show especially high correlations and significance levels. That a positive relationship exists between B and SULFATE (or NITRATE) is also evident by a cursory examination of the scatter plots (Figure 24 and 25).

Figures 24 and 25 also reveal one of the main limitations of the visibility/pollutant regressions for the Southwest. Most of the B values correspond to quite high visibilities (20-60$^+$ miles); only three days in the data base exhibit visibility less than 14 miles. At high visibility levels, errors in measuring visual range tend to be greater because of the sparsity of distant visibility markers; this may account for the relatively greater scatter at low B values. Also, at high visibility levels, the extinction coefficient may vary more with location over the visual range. An implicit assumption in our analysis is that the extinction coefficient is spatially uniform out to the most distant markers. The high correlation between B and SULFATE (or NITRATE) is quite suprising in light of these potential errors.

Multi-Variate Analysis

As explained in Chapter 2, it is important to conduct a multi-variate analysis that can separate out the individual impact of each independent variable, discounting for the simultaneous effects of other independent variables. Univariate analyses can lead to spurious conclusions because of inter-correlations among the independent variables. In particular, TSP, RH, or BSOL might correlate with B only because each of these variables is correlated with SULFATE and NITRATE (see Table 7) which in turn are correlated with B.

TABLE 7. INTERCORRELATIONS AMONG INDEPENDENT VARIABLES AT PHOENIX, MARICOPA COUNTY DATA

	TSP	RH	SULFATE	NITRATE	BSOL
TSP	1.00	-.25	.44	.34	.51
RH	-.25	1.00	.31	.38	.34
SULFATE	.44	.31	1.00	.56	.45
NITRATE	.34	.38	.56	1.00	.43
BSOL	.51	.34	.45	.43	1.00

Following the procedures outlined in Chapter 2, we performed a multiple stepwise regression of the form

$$B = a + b_1T + b_2RH + b_3SULFATE + b_4NITRATE + b_5BSOL$$

where T = TSP - SULFATE - NITRATE - BSOL

The variables T, RH, and BSOL did not retain significance in the multiple regression; the resulting equation was

$$B = .23 + .037\ SULFATE + .051\ NITRATE \qquad (7)$$

with R = 0.87, $F_{SULFATE}$ = 81, and $F_{NITRATE}$ = 32. The coefficients, .037 and .051, represent extinction coefficients per unit mass for sulfates and nitrates, respectively, in units of $(10^4\ \text{meters})^{-1}/(\mu g/m^3)$.

A regression model incorporating relative humidity effects in a nonlinear manner (Equation (4), page 28) was also attempted. This model did not improve on the correlation obtained with Equation (7).

Average Extinction Budget

As explained in Chapter 2, Equation (7) can be used to estimate the fraction of visibility loss, on the average, due to each pollutant species. Substituting in average values for SULFATE and NITRATE in Equation (7), we arrive at the results listed in Table 8.

TABLE 8. AVERAGE EXTINCTION BUDGET FOR PHOENIX, MARICOPA COUNTY DATA

Category	Contribution to Total Extinction	Contribution to Extra Extinction[†]
SULFATE	44%	53%
NITRATE	31%	37%
BLUE-SKY SCATTER	17%	-
UNACCOUNTED FOR	8%	10%

[†]Above-and-beyond blue-sky scatter.

PHOENIX, NASN DATA

The visibility/pollutant analysis for Phoenix was repeated using NASN particulate data for the years 1966 through 1974. The Phoenix NASN site is located near the Maricopa County monitoring site, two miles northwest of the Sky Harbor Airport.

The type of data used and the averaging times are summarized in Table 2 (page 26). The NASN sulfate and nitrate measurments are made with the colorimetric and the reduction/diazo coupling methods, respectively.

After eliminating days with fog and/or precipitation, there were 202 NASN sampling days providing complete data for TSP, $SO_4^=$, and NO_3^-. The basic correlations in the NASN and airport data are summarized in Table 9.

Multi-Variate Analysis

As occurred with the Maricopa County data, stepwise multiple regression with the NASN data retained only sulfates and nitrates as significant contributors to extinction. The resulting equation was

$$B = .42 + .027\ \text{SULFATE} + .030\ \text{NITRATE} \qquad (8)$$

with R = 0.68 $F_{SULFATE}$ = 85 and $F_{NITRATE}$ = 27. The regression coefficients (extinction coefficients per unit mass) for SULFATE and NITRATE are about one-third lower than those obtained with the Maricopa County data.

A regression model incorporating relative humidity effects in a nonlinear manner was also attempted. This model failed to improve upon the linear regression exemplified by Equation (8).

TABLE 9. CORRELATIONS AMONG ALL VARIABLES AT PHOENIX, NASN DATA

	B	TSP	RH	SULFATE	NITRATE
B	1.00	.40	.19	.62	.48
TSP	.40	1.00	.00	.38	.55
RH	.19	.00	1.00	.16	.23
SULFATE	.62	.38	.16	1.00	.36
NITRATE	.48	.55	.23	.36	1.00

Average Extinction Budget

The extinction budget obtained from Equation (8) is summarized in Table 10. Because of a weaker relationship between the pollutant data and visibility data, we were not able to account for as much of the extinction with the NASN data as we were with the Maricopa County data.

TABLE 10. AVERAGE EXTINCTION BUDGET FOR PHOENIX, NASN DATA

Category	Contribution to Total Extinction	Contribution to Extra Extinction[†]
SULFATE	25%	32%
NITRATE	19%	23%
BLUE-SKY SCATTER	20%	-
UNACCOUNTED FOR	36%	45%

[†]Above-and-beyond blue-sky scatter.

SALT LAKE CITY, NASN DATA

The visibility/pollutant analysis for Salt Lake City was conducted using observations from the International Airport and pollutant measurements from the downtown NASN site. The airport is located about six miles northwest of downtown, on the outskirts of the city and near Great Salt Lake.

The data for the analysis covered the years 1966 through 1972. Eliminating days with fog and/or precipitation left 130 NASN sampling days with complete pollutant data.[*] The correlations in the NASN and airport data are summarized in Table 11.

Multi-Variate Analysis

A stepwise multiple linear regression with the Salt Lake City data yielded the equation

$$B = -.53 + .004\ T + .016\ RH + .036\ SULFATE + .130\ NITRATE$$

where T = TSP - SULFATE - NITRATE.

[*]Two other days were also eliminated: 1/19/66 when the meteorologist remarked that visibility was obscured by low clouds just after a snowstorm, and 11/19/69 when the meteorologist remarked that visibility was fair at the airport but poor downtown. Including these two days in our analysis would lower the total correlation coefficient from 0.72 to 0.69 in the multiple linear regression.

Unlike the Phoenix results, all four variables retained significance at a 95% confidence level. The total correlation coefficient was 0.72, and the F-statistics were 7, 23, 6, and 12 for T, RH, SULFATE, and NITRATE respectively.

The regression model including nonlinear RH effects attained an even better correlation, R = .81. The resulting equation was

$$B = .14 + \frac{.0022\ T}{(1 - .01\ RH)} + \frac{.024\ SULFATE}{(1 - .01\ RH)} + \frac{.057\ NITRATE}{(1 - .01\ RH)} . \qquad (10)$$

Our findings indicate that relative humidity is a more important factor in Salt Lake City than in Phoenix. This is physically plausible because relative humidity is greater in Salt Lake City than in Phoenix. Extinction is much more sensitive to changes in relative humidity at higher relative humidity levels (RH > 60%) because of the hygroscopic and/or deliquescent properties of sulfates, nitrates, and other aerosols.

TABLE 11. CORRELATIONS AMONG ALL VARIABLES AT SALT LAKE CITY. NASN DATA

	B	TSP	RH	SULFATE	NITRATE
B	1.00	.54	.48	.50	.59
TSP	.54	1.00	.24	.45	.61
RH	.48	.24	1.00	.24	.25
SULFATE	.50	.45	.24	1.00	.59
NITRATE	.59	.61	.25	.59	1.00

Average Extinction Budget

Table 12 presents an average extinction budget based on Equation (10). The results indicate that sulfate, nitrate, and the remainder of TSP each account for about one-third of the extinction above-and-beyond blue-sky scatter.

TABLE 12. AVERAGE EXTINCTION BUDGET FOR SALT LAKE CITY, NASN DATA

Category	Contribution to Total Extinction	Contribution to Extra Extinction[†]
SULFATE	30%	34%
NITRATE	27%	31%
REMAINDER OF TSP	30%	35%
BLUE-SKY SCATTER	13%	-

[†]Above-and-beyond blue-sky scatter.

ANALYSIS OF OTHER DATA BASES

An attempt was made to derive visibility/pollutant relationships at five other locations: Denver, Tucson, Grand Canyon/Prescott, Grand Canyon/Winslow, and White Pine/Ely. Not unexpectedly, these attempts met with little success because the airport was not representative of the NASN monitoring site* and/or because relatively poor resolution was available in the visibility measurements. Sulfate (in two of the cases) and nitrate (in one of the cases) showed marginally significant** correlations with extinction, but the relationships were not strong enough to allow estimation of extinction coefficients per unit mass.

*The Denver and Tucson airports are located about 7 and 10 miles from the downtown NASN sites, respectively. Prescott and Winslow are each 90 miles from Grand Canyon; Ely is 40 miles from the White Pine monitor.

**At a 95% confidence level.

DISCUSSION AND GENERALIZATION OF RESULTS

Considering the potential errors in the data bases, the regression studies for Phoenix and Salt Lake have been quite encouraging. The results indicate that visibility reduction in Phoenix is significantly related to sulfate and nitrate concentrations. Because the remainder of TSP in Phoenix consists largely of fugitive dust (Richard et al. 1977), and because the remainder of TSP is not significantly related to extinction in a multi-variate analysis, we conclude that visibility in Phoenix is <u>not</u> highly related to fugitive dust.

These conclusions are not surprising in light of known principles of atmospheric physics. Sulfates and nitrates are secondary aerosols that tend to occur in the particle size range of 0.1 to 1 micron. Fugitive dust particles reside in a size range considerably larger than 1 micron. As shown in Figure 27, light scattering per unit mass of aerosol exhibits a pronounced peak in the 0.1 to 1 micron range, around the wavelength of visible light. Even though sulfates and nitrates (including the cation) account for only 9% of the aerosol mass in Phoenix, it is not unreasonable for them to dominate the light scattering and visibility reduction.

The regression analysis also indicates that sulfates and nitrates are the main contributors to haze in Salt Lake City. In Salt Lake City, however, the remainder of TSP is significant, contributing about one-third of the visibility reduction.

Comparison With Published Literature

Table 13 compares our estimates of extinction coefficients per unit mass with other results published in the literature. Fairly good agreement is evident.

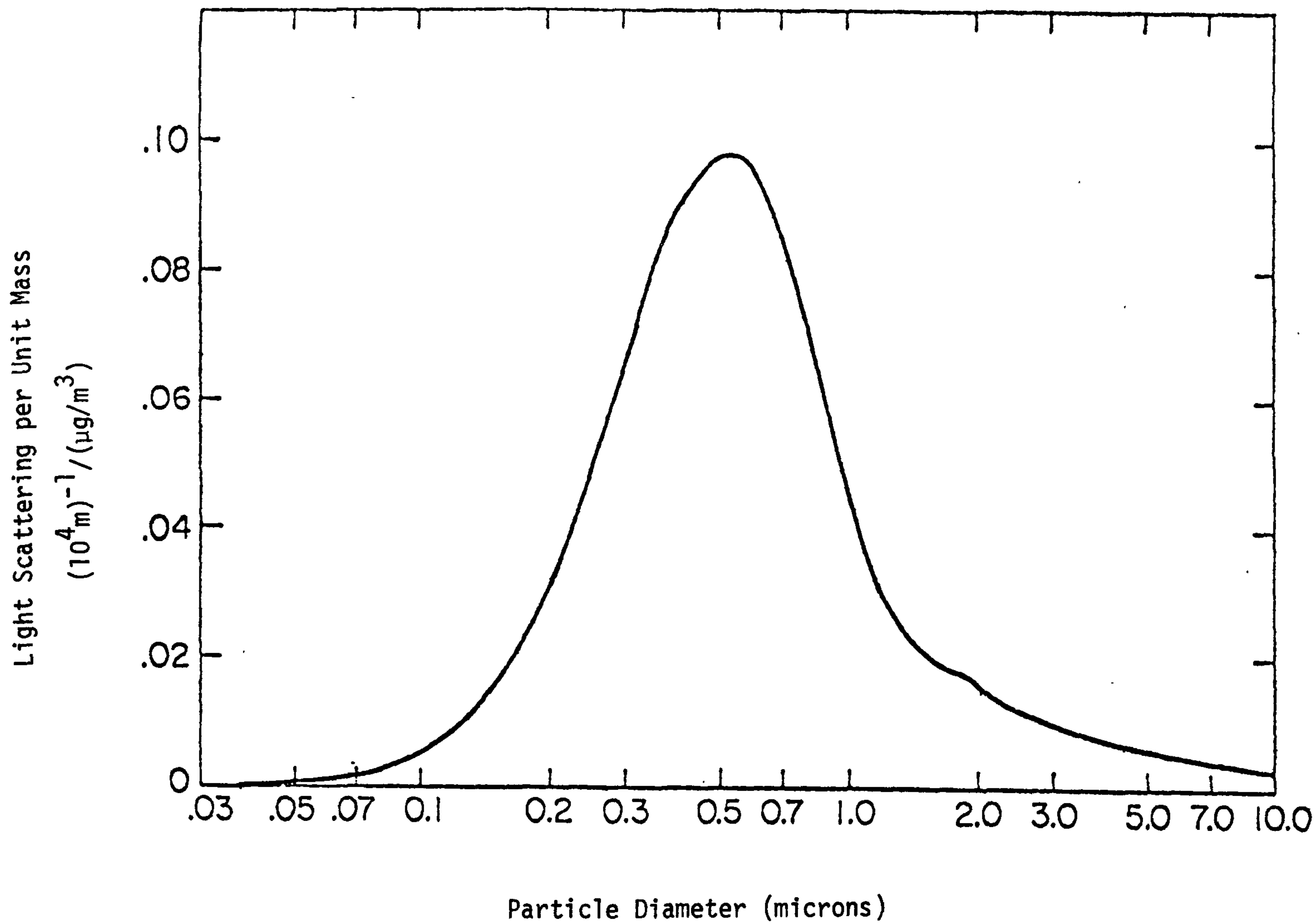

Figure 27. Normalized light scattering by aerosols as a function of particle diameter. Computed for unit density spherical particles of refractive index 1.5 (White, Roberts, and Friedlander 1975).

TABLE 13. ESTIMATES OF EXTINCTION COEFFICIENTS PER UNIT MASS

SOURCE	LOCATION	EXTINCTION COEFFICIENTS $(10^4 \text{meters})^{-1}/(\mu g/m^3)$		
		Sulfates	Nitrates	Remainder of TSP
Regression models applied in this study	Phoenix (cnty. data)	.04	.05	< .001
	Phoenix (NASN data)	.03	.03	< .001
	Salt Lake City	.04 .04*	.13 .10*	.004 .004*
Theoretical calculations by Ursenbach et al. (1976)	remote areas of the Southwest	.10	not calc.	.005
Duststorms (Hagen and Woodruff 1973)	Great Plains	not calc.	not calc.	.001
Regression model (White and Roberts 1975)	Los Angeles	.07	.05	.015
Regression model (Cass 1976)	Los Angeles	.16 .09*	< .01 .05*	.008 < .004*
Calculations for a model aerosol of $(NH_4)_2 SO_4$ at 70% RH (Waggoner et al. 1976)	-	.05 to .10	not calc.	not calc.
Regression model (Waggoner er al.1976)	Southern Sweden	.05	not calc.	not calc.

* Based on nonlinear RH regression model, with insertion of average RH

In particular, there is agreement that the extinction coefficients per unit mass for sulfates and nitrates are an order of magnitude greater than the extinction coefficient per unit mass for the remainder of TSP.

Our estimates of extinction coefficient per unit mass tend to be lower than other estimates found in the literature, especially for sulfates. Two facts could account for these differences. First, relative humidity is low in Phoenix and Salt Lake City.* Lower relative humidity should lead to a smaller extinction coefficient per unit mass for sulfates and other hygroscopic particles. Second, visibility measurements at Phoenix and Salt Lake City are made over rather large distances. The pollution concentrations measured at the downtown monitors might be higher than the average concentrations over the entire visual range. This effect could artificially lower the estimate of extinction coefficient per unit mass.

That even higher extinction coefficients per unit mass are found in the literature makes our results appear conservative. That is -- based on published extinction coefficients, we would have concluded that there is <u>more than enough</u> sulfate and nitrate in Phoenix to account for <u>all</u> of the observed light scattering.

<u>Extension to Nonurban Areas</u>

It is unfortunate that data are not available for completing regression models in nonurban areas. However, using the urban models for the Southwest, we can attempt to extend the analysis to nonurban areas. The extension is made by using general extinction coefficients (derived from Table 13) for sulfates, nitrates, and the remainder of TSP.

---

* Daytime average RH is 27% in Phoenix and 41% in Salt Lake City. In comparison, daytime average RH is 53% in downtown Los Angeles.

Based on the models for Phoenix and Salt Lake City (and tempered slightly by other published results listed in Table 13), our estimates of extinction coefficients per unit mass appropriate to the Southwest are as follows:

sulfates:	.03 to .06	$(10^4 m)^{-1}/(\mu g/m^3)$
nitrates:	.04 to .09	"
remainder of TSP:	.001 to .005	"

These coefficients can be applied to NASN pollutant data at three national park sites (Grand Canyon, Mesa Verde, and White Pine) to predict visibility levels at those locations. Since the three national parks in question are in the more arid parts of the Southwest, we chose relatively low coefficients-- .04 for sulfates, .05 for nitrates, and .002 for the remainder of TSP.

Table 14 presents recent NASN data for the three national park sites and lists predictions of average visibility based on our estimates of extinction coefficients for each aerosol component.* The predicted average visibilities agree very well with the median visibilities, 65 to 80 miles (see Chapter 3), actually observed in nonurban parts of the Southwest.

The data and assumptions that serve as the bases for Table 14 also can be used to estimate the fraction of extinction contributed by each aerosol component; Table 15 presents an average extinction budget for each of the three national park sites. Because average visibility is quite good (65 to 80 miles) at these locations, blue-sky scatter accounts for a significant fraction of total extinction (~40 to 50%). If our assumptions on extinction coefficients for the aerosol species are correct, sulfates account for the dominant part (~ two-thirds) of the extra extinction. The other one-third is about equally divided between nitrates and the remainder of TSP.

---

*Note that 0.15 $(10^4 \text{meters})^{-1}$ is added to account for blue-sky scatter.

TABLE 14. PREDICTIONS OF AVERAGE VISIBILITY AT NATIONAL PARK SITES [†]

LOCATION	ANNUAL AVERAGE PARTICULATE DATA (1970's)			PREDICTED AVERAGE VISIBILITY
	SULFATE (S)	NITRATE (N)	REMAINDER OF TSP (T)	$V = \frac{24.3}{.15 + .04S + .05N + .002T}$
	$(1.3\ SO_4^{=})$	$(1.3\ NO_3^{-})$	TSP - S - N	
Grand Canyon	3.2 $\mu g/m^3$	0.66 $\mu g/m^3$	20 $\mu g/m^3$	69 miles
Mesa Verde	3.5 "	0.57 "	16 "	69 "
White Pine	2.8 "	0.44 "	11 "	79 "

† Based on the assumption that extinction coefficients per unit mass are .04 for sulfates, .05 for nitrates, and .002 for the remainder of TSP.

TABLE 15. AVERAGE EXTINCTION BUDGETS FOR NATIONAL PARK SITES†

CATEGORY	CONTRIBUTION TO TOTAL EXTINCTION	CONTRIBUTION TO EXTRA EXTINCTION*
	Grand Canyon	
Sulfates	36%	64%
Nitrates	9%	16%
Remainder of TSP	12%	20%
Blue-Sky Scatter	43%	--
	Mesa Verde	
Sulfates	40%	70%
Nitrates	8%	14%
Remainder of TSP	9%	16%
Blue-Sky Scatter	43%	--
	White Pine	
Sulfates	37%	72%
Nitrates	7%	14%
Remainder of TSP	7%	14%
Blue-Sky Scatter	49%	--

† Based on the assumption that extinction coefficients per unit mass are .04 for sulfates, .05 for nitrates, and .002 for the remainder of TSP.

* Above-and-beyond blue-sky scatter.

CHAPTER 6

THE COPPER STRIKE OF 1967-1968

The data presented in Chapter 4 point to the conclusion that visibility has deteriorated in the Southwest over the past two decades. Although visibility levels are not uniform over the Southwest, and although quantitative trends in visibility are not the same at all locations, the pattern of deteriorating visibility appears to be ubiquitous. Indications are that visual range has decreased in urban, suburban, and remote areas.

The analyses of Chapter 5 indicate that extinction above-and-beyond blue-sky scatter is dominated by secondary aerosols, sulfates and to a lesser degree nitrates. This conclusion is reasonable on physical grounds because secondary aerosols tend to occur in the particle size range of .1 to 1 micron and because particles in that size range are extremely efficient at scattering visible light.

From these conclusions we hypothesize that the deteriorating trend in visibility is related to increases in secondary aerosols, the result of growth in SO_x, NO_x, and possibly hydrocarbon emissions from copper smelters, power plants, motor vehicles, and other sources. We further hypothesize that the large spatial scale in visibility deterioration is due to two factors: (1) growth in sources <u>throughout</u> the region and (2) the tendency for secondary aerosols to be spread widely because of the mixing and transport that occurs during the time required for aerosol formation.

A unique opportunity to test our conclusions and hypotheses is provided by the industry-wide copper strike of July 1967 to March 1968. During the late 1960's and early 1970's, copper smelters accounted for about 80 percent of the SO_x emissions in the Southwest (NEDS 1976)*. The nine-month shutdown during a labor strike allows us to test the impact of a substantial reduction in regional SO_x emissions. We would expect to find decreases in sulfate and increases in visibility on a large spatial scale.

COPPER PRODUCTION AND VISIBILITY AT TUCSON

The relationship between copper-smelter emissions and visibility was first noted in data for Tucson, Arizona (Lockwood and Hartmann 1970; Hartmann 1972, 1976, 1977). Tucson is located in the southeast quadrant of Arizona, an area containing several copper smelters (see later Figure 32). The smelter nearest to Tucson is at a distance of about 30 miles.

Figure 28 compares trends in frequency of hazy days at Tucson (for six month periods) with trends in yearly copper production for the state of Arizona. Figure 28 indicates that the frequency of haze increased from about 15% in 1957-1959 to about 80% in 1969-1972. The long-term increase in haze appears to be very well correlated with trends in copper production. In particular, during the first six months of the 1967-1968 copper strike, haze incidence dropped to 25%. An improvement in haze levels is also noticeable after 1973; Hartmann (1976) attributes this improvement to partial control of smelter SO_x emissions in the early 1970's and to control of automotive emissions.

---

*The Southwest is defined as the four corner states plus Nevada and Wyoming. Note that copper production accounts for less than 1% of regional NOx emissions and less than 10% of regional particulate emissions from conventional (non-fugitive-dust) sources.

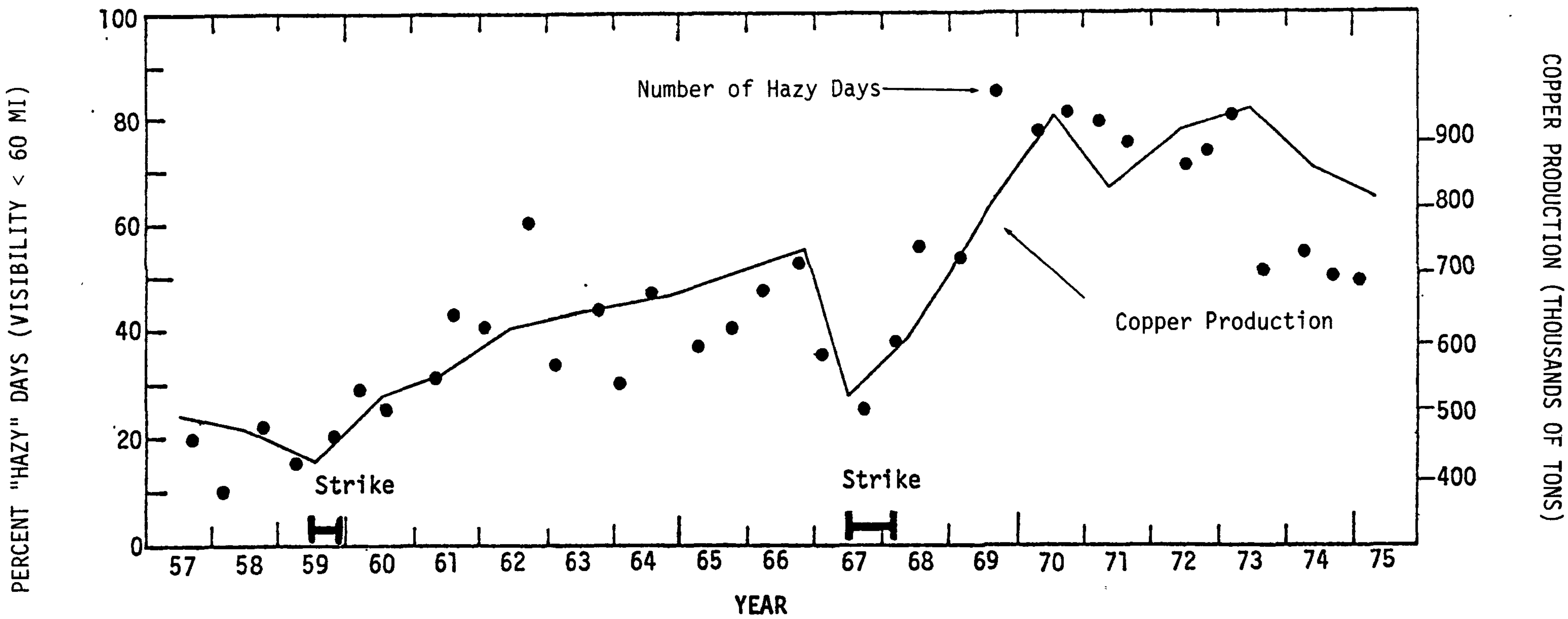

Figure 28. Long-term increase in haze correlated with copper production.
(Lockwood and Hartman 1970; Hartman 1977)

A more detailed illustration of haze levels at Tucson before, during, and after the 1967-1968 strike is presented in Figure 29. The step-function change in haze incidence during the strike is quite obvious. Hartmann (1972) attributes the improvement in visibility during the copper strike to reductions in sulfur oxide emissions; Figure 30 demonstrates that sulfation rate (a gross measure of SO_2 concentrations) dropped dramatically in Tucson during the strike. Hartmann also noted that TSP levels did <u>not</u> change significantly during the strike.

In order to check Hartmann's conclusions about changes in pollution levels during the strike, we plotted bi-monthly averages of TSP, NO_3^-, and $SO_4^=$ at Tucson from 1966 to 1969 using the NASN data. Figure 31 confirms that sulfates did show a pronounced drop during the strike; TSP and nitrates exhibited no significant change.

REGIONWIDE CHANGES IN SULFATES DURING THE COPPER STRIKE

It is of interest to examine <u>regionwide</u> changes in sulfates and visibility during the nine-month copper strike. Using the NASN data, it is possible to document sulfate changes at ten locations in the Southwest. Table 16 indicates that most of these locations did experience a substantial drop in sulfates during the strike as compared to (July - March) seasonal averages for surrounding years.

Figure 32 compares the spatial distribution of sulfate changes during the strike to the spatial distribution of smelter SO_x emissions. Substantial decreases in sulfate occurred at the five locations (Maricopa County, Phoenix, Tucson, Ely, and Salt Lake City) that are within 12 to 70 miles of copper smelters. More significantly, sulfates appeared to drop by about 60% at Grand Canyon and Mesa Verde; these national park sites are located about <u>two to three hundred</u> miles from the smelter areas.

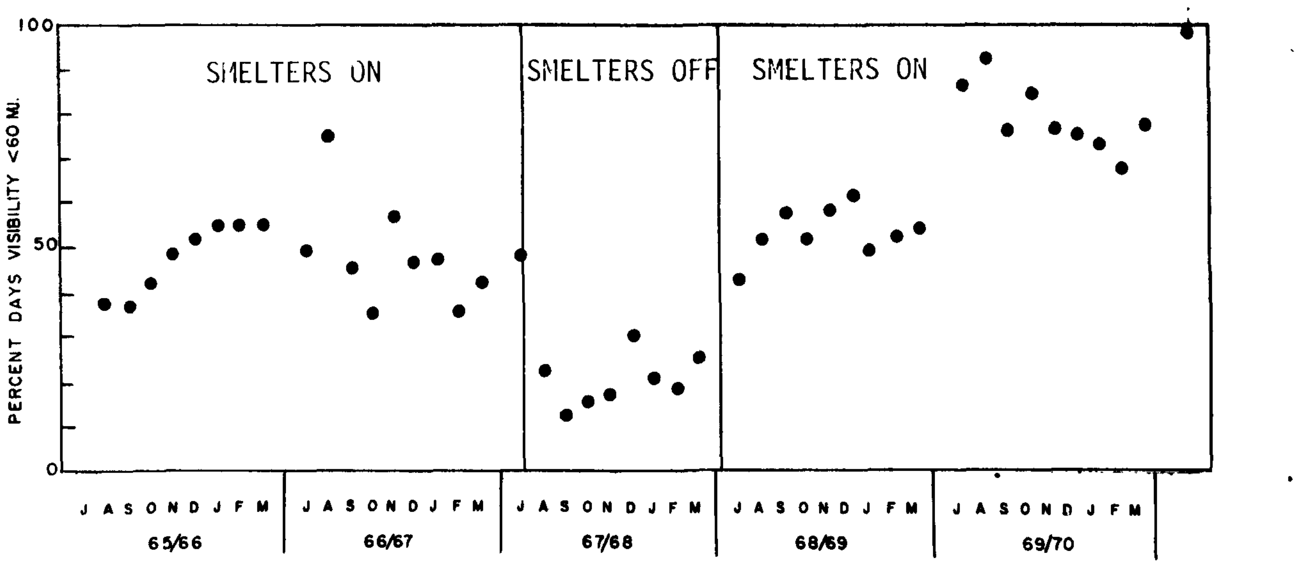

Figure 29. Changes in number of hazy days at Tucson during 1967-1968 copper strike (Hartman 1972).

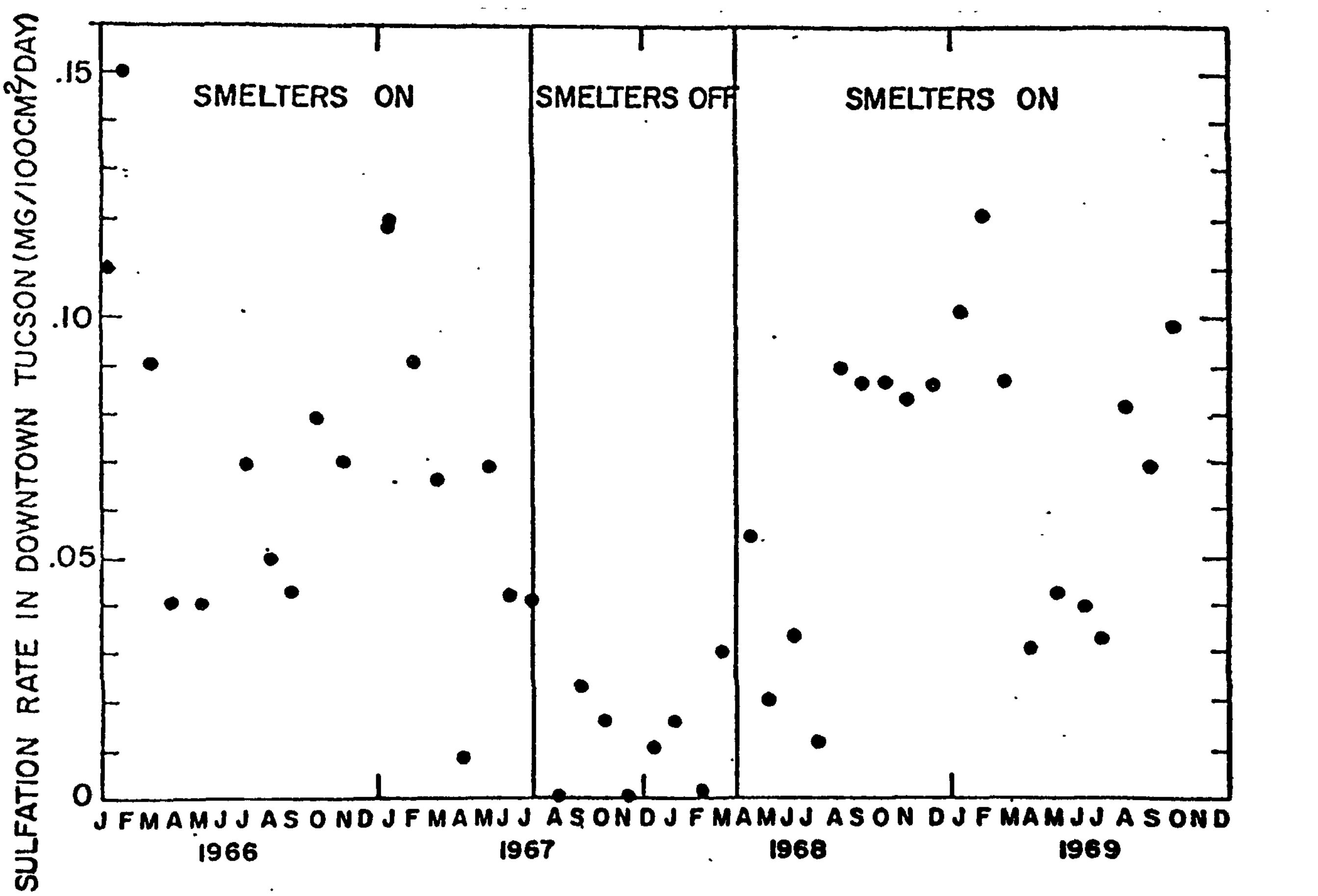

Figure 30. Changes in sulfation rate at Tucson during 1967-1968 copper strike (Hartman 1972).

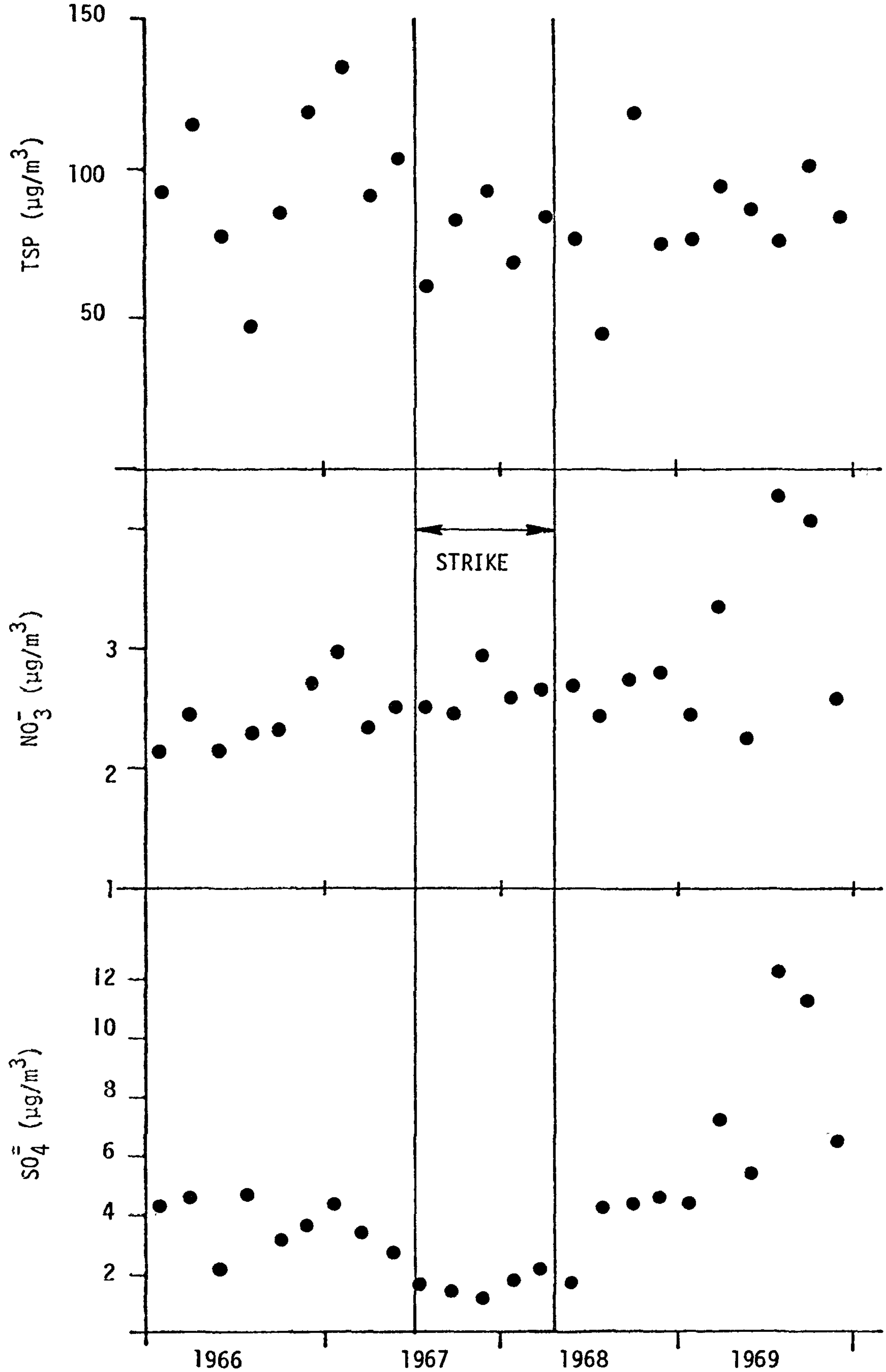

Figure 31. Variations in pollutant levels at Tucson during 1967-1968 copper strike (NASN data, bi-monthly averages).

TABLE 16. CHANGES IN SULFATE LEVELS DURING THE COPPER STRIKE COMPARED TO SEASONAL AVERAGES*

LOCATION	NUMBER OF SURROUNDING YEARS OF DATA	AVERAGE SULFATE DURING STRIKE	AVERAGE SULFATE OTHER YEARS	PERCENT CHANGE
ARIZONA				
Grand Canyon**	4	1.00 μg/m^3	2.51 μg/m^3	-60%†
Maricopa County	4	1.60	4.23	-62%†
Phoenix	6	2.17	5.73	-62%†
Tucson	4	1.68	5.05	-67%†
COLORADO				
Denver	4	3.62	4.41	-18%
Mesa Verde**	4	.80	1.85	-57%†
NEVADA				
Las Vegas	6	2.20	4.52	-51%†
White Pine**	4	.47	1.92	-76%†
NEW MEXICO				
Albuquerque	6	3.37	3.45	-2%
UTAH				
Salt Lake City	6	4.37	7.10	-38%†

*The season of the strike was July through March.

**National park locations

†Significant from zero at 95% confidence level

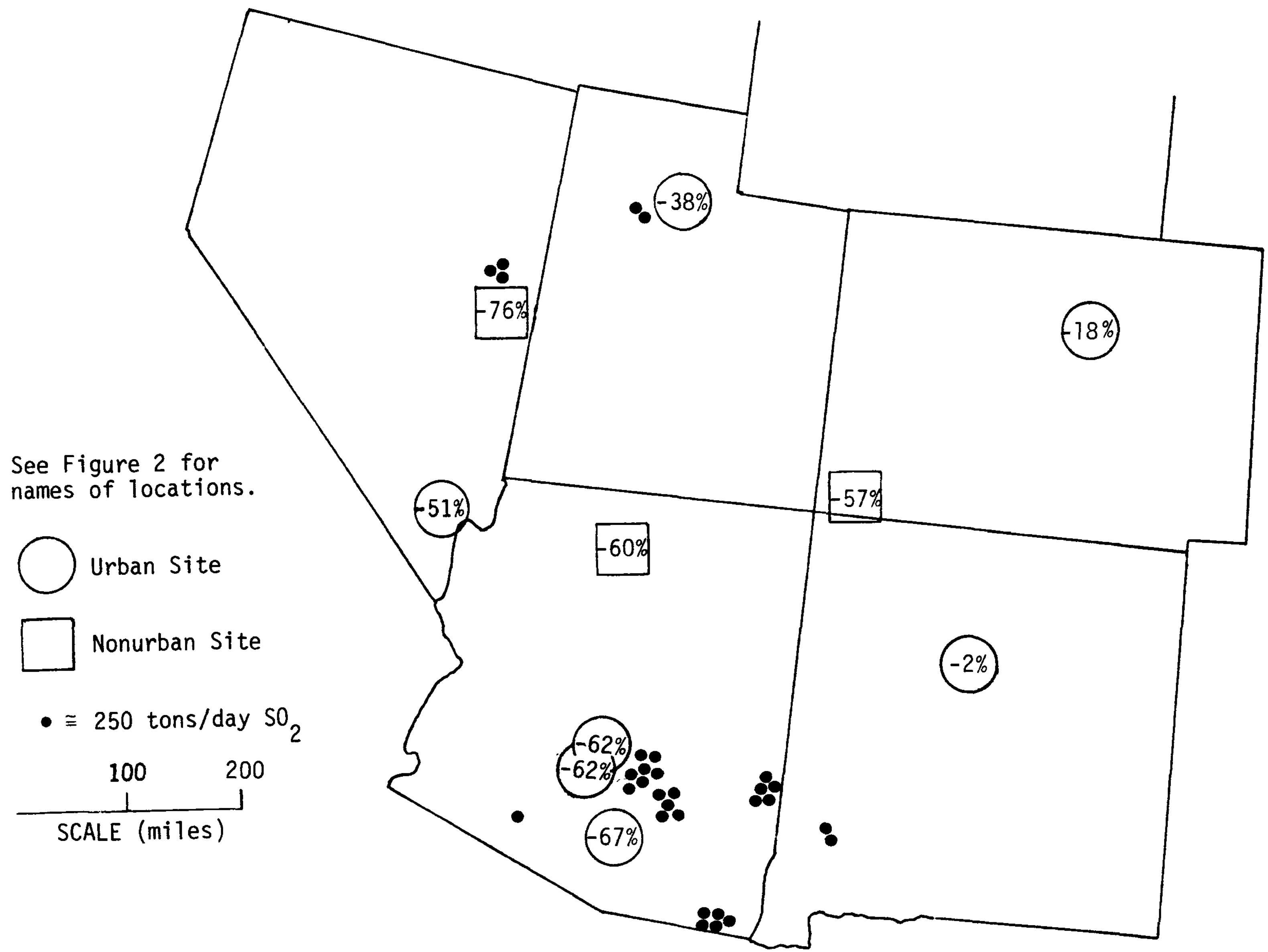

Figure 32. Seasonally Adjusted Changes in Sulfate During the Copper Strike Compared to the Geographical Distribution of Smelter SO_x Emissions.

The sulfate decreases at Grand Canyon, Mesa Verde, and most of the other locations easily pass tests for statistical significance at a 95% confidence level. That the changes at Grand Canyon and Mesa Verde are significant can be seen qualitatively in Figure 33.* The statistical distribution of sulfate levels during the strike appears very different from the statistical distribution before and after the strike.

To put some of the above observations in better perspective, we note that Los Angeles basin produces haze at distances greater than 75 miles from the main source areas (Blumenthal et al 1974). The entire Los Angeles basin emits on the order of 500 tons/day SO_x and 1500 tons/day NO_x (AQMP 1976). Although copper smelters emit negligible NO_x, they do produce very large amounts of SO_x. During the late 1960's, the largest smelter emitted more than 1300 tons/day of SO_x, and the group of smelters in southeast Arizona emitted over 5000 tons/day of SO_x (NEDS 1976; Oliver 1977).**

REGIONWIDE CHANGES IN VISIBILITY AND EXTINCTION DURING THE COPPER STRIKE

Table 17 and Figure 34 summarize changes in visibility during the copper strike. Visibility improved at almost all locations, 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.

Table 17 also lists percent changes in extra extinction (above-and-beyond blue-sky scatter) during the copper strike. These percent changes are plotted in Figure 35. Figure 36 shows the changes in extinction coef-

---

*Note, the monitoring dates at Grand Canyon and Mesa Verde were usually <u>not</u> coincident.

**Note that sulfur oxide controls were installed at several of these smelters in the early 1970's.

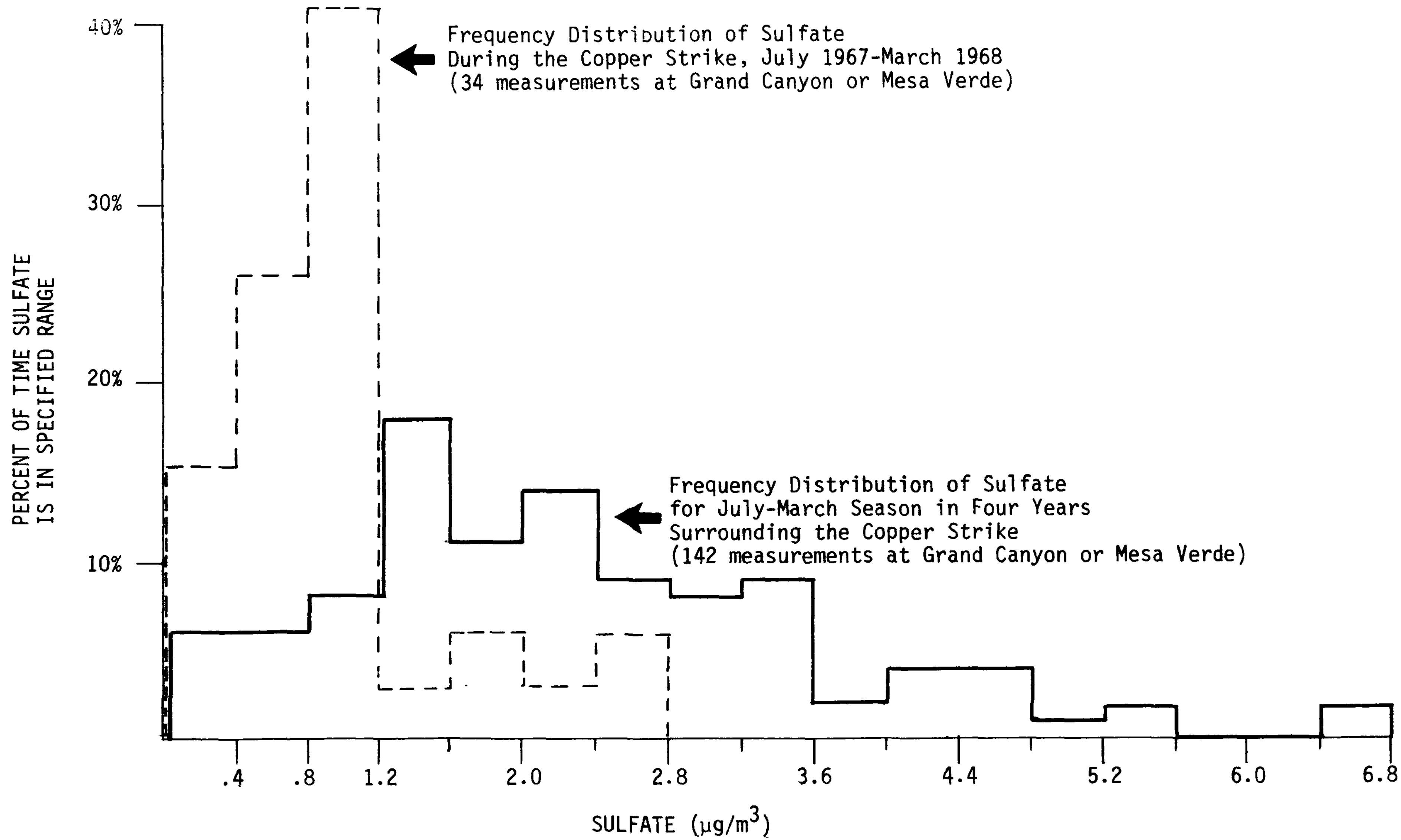

Figure 33. Frequency distribution of sulfate concentrations during the copper strike compared to seasonal average distribution, Grand Canyon and Mesa Verde data combined.

TABLE 17. CHANGES IN VISIBILITY AND EXTINCTION DURING THE COPPER STRIKE COMPARED TO SEASONAL AVERAGES

LOCATION	VISIBILITY PERCENTILE*	VISIBILITY DURING STRIKE**	VISIBILITY OTHER YEARS***	PERCENT CHANGE IN VISIBILITY	PERCENT CHANGE IN EXTRA EXTINCTION
URBAN					
Phoenix, Arizona	50th	47.4 miles	36.8 miles	+29%†	-29%†
Tucson, Arizona	75th	62.1	50.4	+23%†	-27%†
Denver, Colorado	50th	52.6	50.3	+ 5%	- 6%
Salt Lake City, Utah	50th	31.8	29.8	+ 7%†	- 8%†
NONURBAN					
Fort Huachuca, Ariz.	50th	56.0 miles	48.1 miles	+16%†	-20%†
Prescott, Arizona	75th	65.7	57.0	+15%†	-20%†
Winslow, Arizona	80th	52.5	48.6	+ 8%†	-11%†
Grand Junction, Col.	50th	81.6	78.4	+ 4%	- 8%
Ely, Nevada	85th	26.8	22.3	+20%†	-19%†
Las Vegas, Nevada	50th	61.7	60.5	+ 2%	- 3%
Alamogordo, N.M.	50th	72.3	68.7	+ 5%†	- 9%†
Farmington, N.M.	75th	67.3	69.6	- 3%	+ 6%
Dugway, Utah	50th	64.6	62.9	+ 3%	- 4%
Wendover, Utah	75th	60.9	51.7	+18%†	-22%†
Cheyenne, Wyo.	50th	71.2	72.9	- 2%	+ 4%

*We attempted to use the 50th percentile for all locations. In some cases we were forced to use higher percentiles to avoid extrapolation of the frequency distributions.

**The strike season was July - March and included 1100 3-hourly daytime observations.

***For all cases but Alamogordo, Farmington, and Dugway we were able to use six surrounding years (6600 measurements) to determine seasonal averages.

†Significant from zero at 95% confidence level. In calculating significance we assume that the 4 measurements each day are totally dependent but that the days are independent. This assumption is, of course, rather crude.

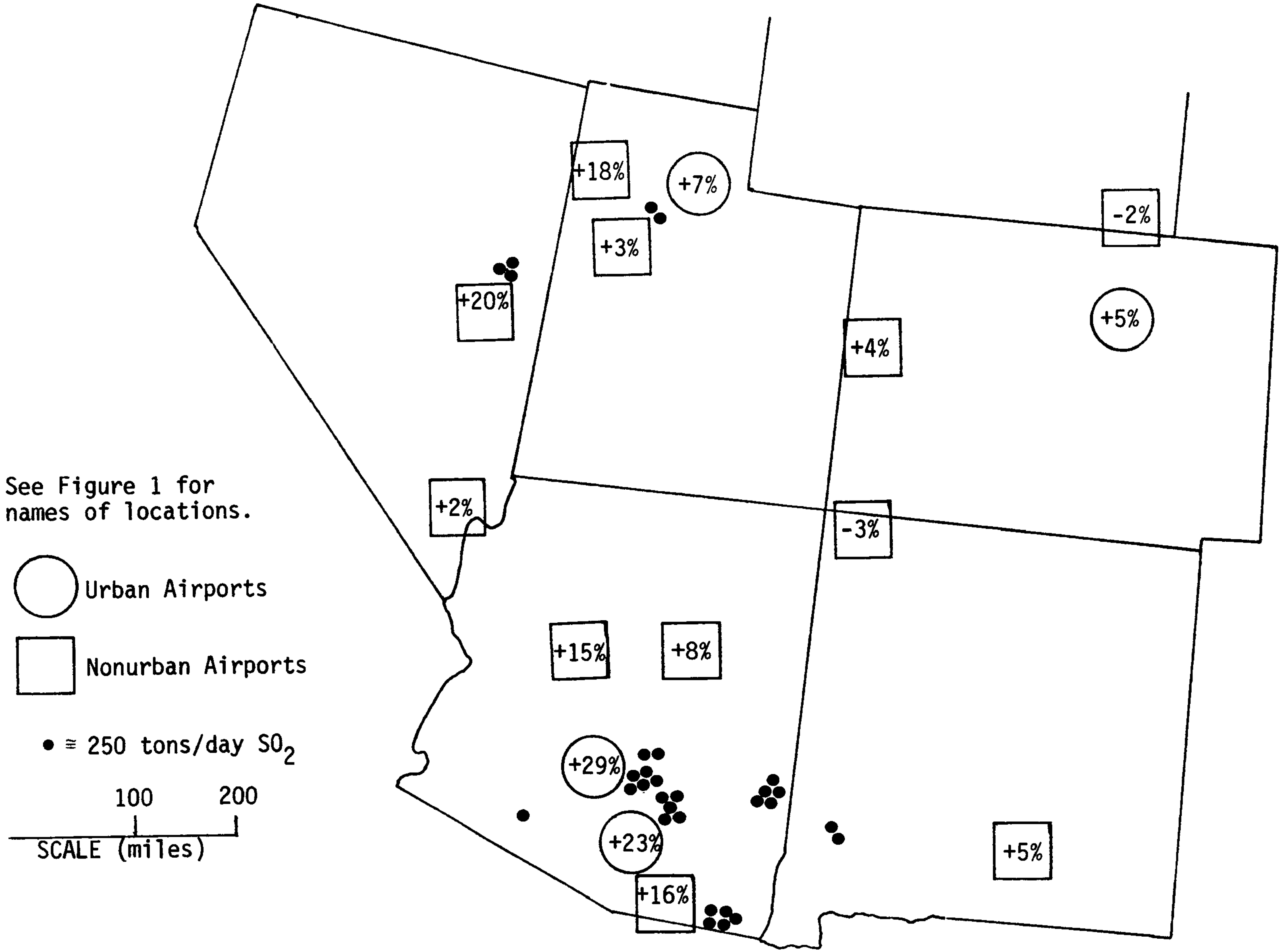

Figure 34. Seasonally adjusted percent changes in visibility during the copper strike.

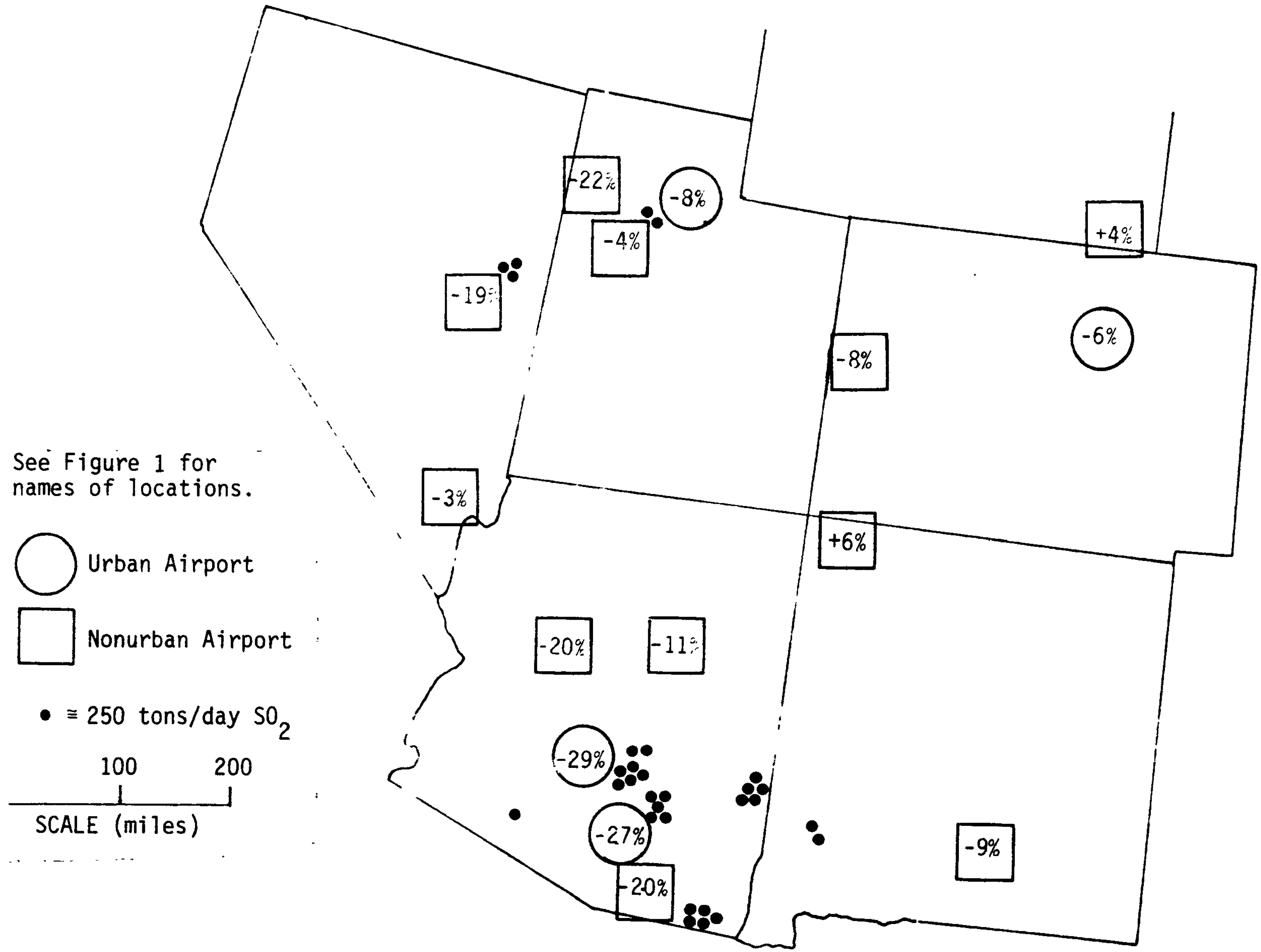

Figure 35. Seasonally adjusted percent changes in extra extinction during the copper strike.

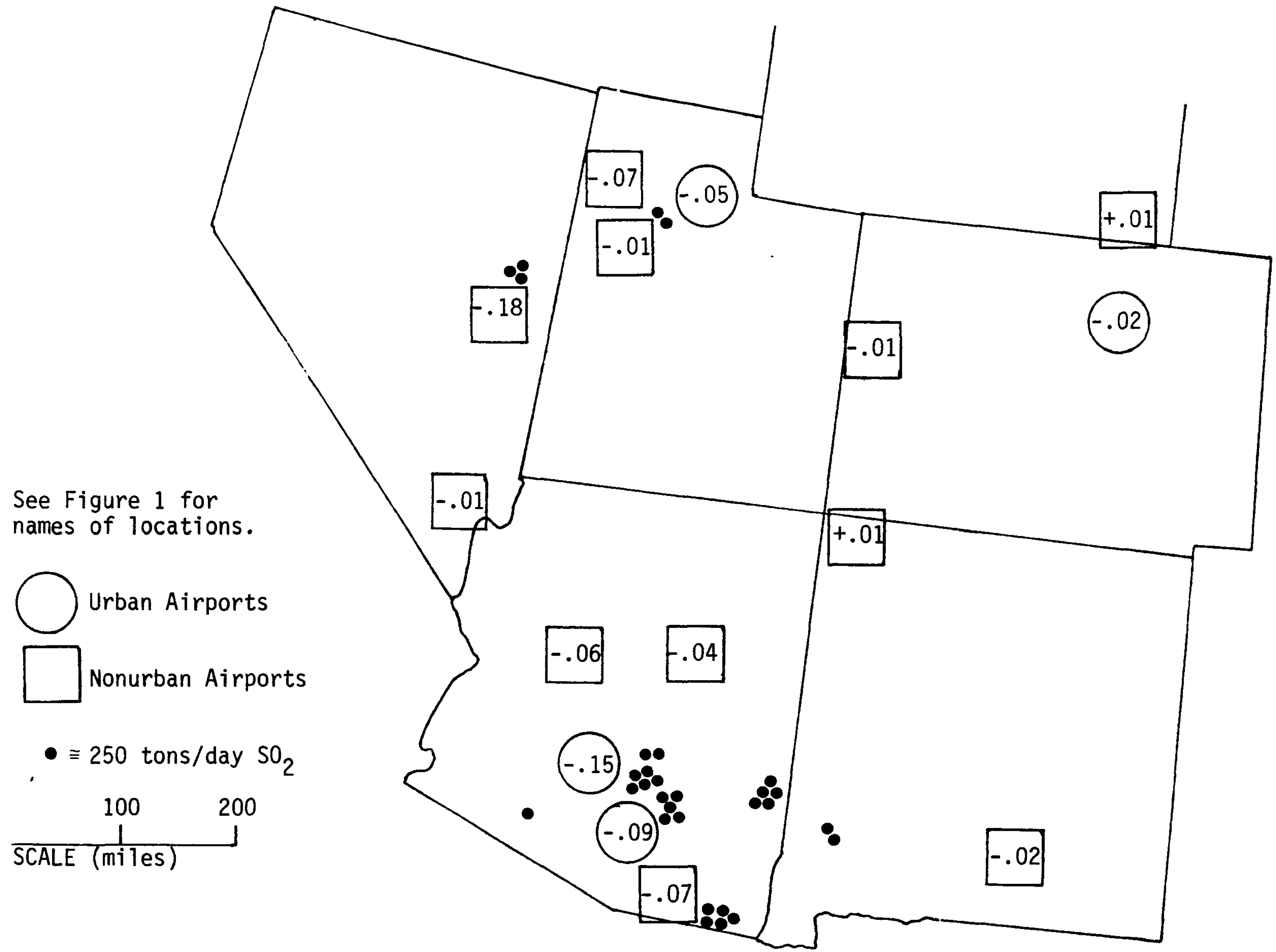

Figure 36. Seasonally adjusted changes in extinction during the copper strike, units of $[10^4 \text{ meters}]^{-1}$

ficient in absolute terms, units of $[10^4 \text{ meters}]^{-1}$. Again it is evident that the greatest improvements occurred within 150 miles of the copper smelters.

The spatial scale of the visibility impact during the strike (apparently on the order of 150 miles away from the smelters) does not agree with the spatial scale of the sulfate changes during the strike (apparently on the order of 300 miles away from the smelters). Some of the potential reasons for this discrepancy will be covered in the discussion at the end of the next section.

CHANGES IN EXTINCTION COMPARED TO CHANGES IN SULFATE

The reductions in sulfate during the copper strike offer us an opportunity to check the results of our regression studies (Chapter 5). For instance, using the Maricopa County data we concluded that sulfates account for 53% of the extra extinction in Phoenix (Table 8). Since sulfates decreased 62% in Phoenix during the strike (Table 16), we would predict that extra extinction should decrease by 33% (.53 x 62%). The actual decrease in extra extinction was 29% (Table 17)...quite good agreement!*

Similarly, based on our regressions using the Phoenix NASN data, we would predict that the decrease in extra extinction at Phoenix during the strike should be 20% (.32 x 62%). Again this is not far from the actual decrease of 29%. For Salt Lake City, our regression model would lead us to predict a 13% (.34 x 38%) decrease in extra extinction during the strike. The actual decrease was 8%.

*The copper strike provides a completely independent check of the Phoenix (Maricopa County data) regression model because the strike occurred in 1967-1968, while the regression model is based on data for 1973-1974. The Phoenix/NASN and Salt Lake City/NASN regression studies are based on data from 1966-1974 and 1966-1972 respectively, and thus include the strike period. The strike still should provide an independent test, however, because the regression models are dominated by order-of-magnitude, day-to-day variations over several years and should be relatively unaffected by the lesser changes during the nine month strike.

The extension we made of our regression results to nonurban areas (Table 15) does not fare as well in this test. Based on the sulfate changes during the strike, we would predict that extra extinction should decrease by 38% (.64 x 60%) at Grand Canyon and by 40% (.70 x 57%) at Mesa Verde. The actual decrease in extra extinction was only 11 to 20% in north/central Arizona, and extinction appeared to increase slightly at Farmington, New Mexico. There are four plausible explanations for these discrepancies:

- At the nonurban airports in northern Arizona and northern New Mexico we were forced to use 75th or 80th percentile visibility to estimate changes in extra extinction during the strike. It is very possible that we would have found greater changes in extinction during the strike had data been available for median (50th percentile) visibility. The 75th and 80th percentile visibilities reflect extinction produced by weather events (fog and/or precipitation) more so than do the median visibilities.

- The changes in sulfate at Grand Canyon and Mesa Verde during the strike are based on only 2 samples per month. Part of the observed drop in sulfates may be due to statistical error. If our estimates were off by one standard error, the sulfate changes at Grand Canyon and Mesa Verde would be on the order of 45 - 50% rather than 60%.

- The extension of our regression results to nonurban areas could be in error. We estimated that sulfates account for about two-thirds of the extra extinction in nonurban areas. A rudimentary error analysis of our assumptions (as listed on page 79) indicates that sulfates may account for a smaller fraction, possibly less than one-half, of the extinction in nonurban areas.

- Farmington, New Mexico is near a very large power plant. It is possible that visibility at Farmington is more dependent on this local source than it is on regionwide sources.

ANALYSIS OF METEOROLOGY

A question naturally arises as to whether the changes in sulfates and visibility during the copper strike could be due to unusual meteorology.

Possibly the nine month copper strike coincided with a period of weather conducive to good visibility, or with a period of extremely low pollution potential. We have examined this question and have arrived at the conclusion that favorable weather was not a major factor contributing to the observed decreases in sulfates and extinction. In fact, pollution potential during the strike appears to be slightly greater than in surrounding years.

Statistical Significance of the Changes

Many of the sulfate and visibility changes during the strike are statistically significant from zero at very high confidence levels. With crude significance tests we find "t" statistics as great as 8 for the sulfate changes and as great as 12 for the visibility changes.* The statistical significance of the changes can also be appreciated by inspection of the raw data (see for instance Figures 29 and 33).

If meteorology were to account for these highly significant changes during the nine-month copper strike, we would expect that weather patterns would have been notably unusual. To the contrary, inspection of weather data for the period (Smith 1977; Zeldin 1977) indicates that weather patterns were not remarkably different from normal. The small anomalies that did occur indicate that pollution potential might have been slightly higher during the strike than under normal conditions (Smith 1977).

Korshover Analysis

Stagnating anticyclones often result in very low wind speeds and restricted vertical mixing and are known to be associated with heavy air

---

*$t \approx 1.7$ for 95% confidence level and $t \approx 3.9$ for 99.95% confidence level.

pollution in urban areas. Korshover (1976) has investigated pollution potential for the eastern United States by counting the occurrences of stagnating anticyclones. An extension of Korshover's analysis to the Southwest (Niemann, 1977) may provide us with an indication of pollution potential during the copper strike.

Niemann's results indicate that 20 stagnating anticyclones occurred in the Southwest during the nine month copper strike; this compares to a long-term seasonal average of 17.1 stagnating anticyclones. The 1967-1968 strike period included more stagnating anticyclones than any of the six surrounding nine month periods (1964-1965 to 1970-1971) and ranked as the fifth highest period among the nineteen years (1957 to 1976) included in Niemann's study. If we accept the Korshover method as a measure of pollution potential, we conclude that pollution potential during the 1967-1968 copper strike was slightly higher than normal.

Stratification by Meteorological Class

Sorting the data by meteorological class can explicitly account for the effects of meteorology. We have attempted this type of meteorological stratification with the sulfate data for Grand Canyon. Sorting by the occurrence of stagnating anticyclones indicates a 51% decrease in sulfates during the strike. Sorting by conditions most conducive to transport from the smelters in southeast Arizona indicates a 71% decrease in sulfates during the strike. These results are in basic agreement with the 60% reduction calculated using all of the sulfate data at Grand Canyon.

Stratifying the sulfate data by meteorological class creates a problem of small sample size. NASN sulfate data are collected once every fourteen days; if we attempt to sort the data in meteorological classes, we are left with very few samples. Thus, the statistical significance of the sulfate changes at Grand Canyon using the sorted data ($t \sim 3$) is smaller than the significance level using all the data ($t \sim 6$), even though the absolute level of the change (~60%) agrees in all cases.

In future work it may prove interesting to conduct further sorts of the visibility and sulfate data according to meteorology. However, our present results concerning the statistical significance of changes during the strike and concerning meteorology during the strike provide us with confidence that the copper strike did produce obvious reductions in sulfate and increases in visibility.

REFERENCES

AQMP (Air Quality Maintenance Plan), Preliminary Emissions Inventory and Air Quality Forecast 1974-1995, Final Report of the Boundary and Forecasting Committee of the Air Quality Maintenance Planning Policy Task Force for Southern California, April 1976.

Blumenthal, D.L.. W.H. White, R.L. Peace, and T.B. Smith, "Determination of the Feasibility of the Long-Range Transport of Ozone Precursors", EPA-450/3-74-061, 1974.

Cass, G.R., "The Relationship Between Sulfate Air Quality and Visibility at Los Angeles", Caltech Environmental Quality Laboratory Memorandum No. 18, Pasadena, August 1976.

C-b Oil Shale Venture, Environmental Baseline Program for Oil Shale Tract C-b, Nov. 1974- Oct. 1976, Final Report, Available through Area Oil Shale Office, Grand Junction, Colorado, 1977.

Charlson, R.J., "Atmospheric Visibility Related to Aerosol Mass Concentration, A Review", Environmental Science and Technology, Vol. 3, No. 10, pp. 913-918, October 1969.

Green, C.R. and L.J. Battan, "A Study of Visibility Versus Population Growth in Arizona", Journal of the Arizona Academy of Science, Vol. 4, Arizona University Press, pp. 226-228, October 1967.

Grosjean, D,, Post Doctoral Atmospheric Chemist, California Institute of Technology, Personal Communication, April 1974.

Hagen, L.J. and N.P. Woodruff, "Air Pollution from Duststorms in the Great Plains", Atmospheric Environment, Vol. 7, pp. 323-332, 1973.

Hartman, W.K., "Pollution: Patterns of Visibility Reduction in Tucson", Journal of the Arizona Academy of Science, Vol. 7, pp. 101-108, October 1972.

Hartman, W.K., "Air Quality: Pollution Forecast and Application to Planning", Final Report to the City of Tucson Department of Planning, Planetary Science Institute, Tucson, Arizona, March 1976.

Hartman, W.K., Planetary Science Institute, Tucson, Arizona, Personal Communication of data, April 1977.

Holzworth, G.C. and J.A. Maga, " A Method of Analyzing the Trend in Visibility", Journal of the Air Pollution Control Association, Vol. 10, No. 6, pp. 430-435, December 1960.

Holzworth, G.C.,"Some Effects of Air Pollution on Visibility In and Near Cities", Symposium: Air Over Cities, SEC Technical Report A62-5, pp. 69-88, 1962.

Keith, R.W., "A Study of Low Visibilities in the Los Angeles Basin, 1950-1961", Los Angeles Air Pollution Control District, Air Quality Report No. 53, 1964.

Keith, R.W., "Downtown Los Angeles Noon Visibility Trends, 1933-1969", Los Angeles Air Pollution Control District, Air Quality Report No. 65, 1970.

Korshover, J., "Climatology of Stagnating Anticyclones East of the Rocky Mountains, 1936-1975", NOAA Technical Memorandum ERL ARL-55, Air Resources Laboratory, Silver Spring, Maryland, March 1976.

Layden, J., Air Quality Division, Maricopa County Health Department, Phoenix, Arizona, Personal Communication, September 1977.

Lockwood, G.W. and W.K. Hartman, "Visibility Variations at Tucson, Arizona and Kitt Peak National Observatory", Publications of the Astronomical Society of the Pacific, Vol. 82, pp. 1346-1350, 1970.

Miller, M.E., N.L. Canfield, T.A. Ritter, and C.R. Weaver, "Visibility Changes in Ohio, Kentucky, and Tennessee from 1962 to 1969", Monthly Weather Review, Vol. 100, No. 1, pp. 67-71, January 1972.

Moyers, J.L., L.E. Ranweiler, S.B. Hopf, and N.E. Korte, "Evaluation of Particulate Trace Species in the Southwest Desert Atmosphere", Environmental Science and Technology, Vol. II, pp. 789-795, August 1977.

NEDS (National Emission Data System), 1973 National Emissions Report, EPA-450/2-76-007, EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, 1976.

Neiburger, M., "Visibility Trend in Los Angeles", Southern California Air Pollution Foundation Report No. 11, 1955.

Nieman, B., Meteorologist, Teknekron, Berkeley, California, Personal Communication of data, July 1977.

Oliver, W., EPA Region IX, San Francisco, California, Personal Communication of data, September 1977.

Pearson, E., Air Quality Engineer with C F & I Steel, Pueblo, Colorado, Personal Communication, September 1977.

Richard, G. et al., An Implementation Plan for Suspended Particulate Matter in the Phoenix Area, Vols. 1-4, TRW Environmental Engineering, EPA Contract No. 68-01-3152, April 1977.

Roberts, F.M., J.L. Gordon, D.L. Haase, R.E. Kary. and J.R. Weiss, "Visibility Measurements in the Painted Desert", Paper No. 75-26.1, Presented at the 68th Annual Meeting of the Air Pollution Control Association, June 1975.

Robinson, E., "Effects of Air Pollution on Visibility", in Air Pollution, A.C. Stern, editor, Vol. 1, 2nd edition, Academic Press, New York, 1968.

Smith, T., Meteorologist, Meteorology Research Inc., Altadena, California, Personal Communication, April 1977.

Spicer, C.W. and P.M. Schumacher, "Interferences in Sampling Atmospheric Particulate Nitrate", Submitted to Atmospheric Environment, Battelle Columbus Laboratories, 1977.

Taylor, F., Meteorologist, McCarran Airport, Las Vegas, Nevada, Personal Communication, September 1977.

Tombach, I.H. and M.W. Chan. "Physical, Chemical, and Radiological Characterization of Background Particulate Matter in Northeastern Utah", Paper No. 77-48.6, Presented at the 70th Annual Meeting of the Air Pollution Control Association, June 1977.

Trijonis, J. and K. Yuan, "Visibility in the Northeast", Report in Preparation at Technology Service Corporation under Contract to EPA Office of Research and Development, to be released in December 1977.

Ursenbach, W.O., A.C. Hill, W.H. Edwards, and S.M. Kunen, "Atmospheric Particulate Sulfate in the Western United States", Paper No. 76-7.5, Presented at the 69th Annual Meeting of the Air Pollution Control Association, June 1976.

Waggoner, A.P., A.J. Vanderpool, R.J. Charlson, S. Larsen, L. Granat, and C. Tragardh, " Sulfate-Light Scattering Ratio as an Index of the Role of Sulphur in Tropospheric Optics", Nature, Vol. 261, No. 5556, pp. 120-122, May 1976.

White, W.H., P.T. Roberts, and S.K. Friedlander, "On the Nature and Origins of Visibility-Reducing Aerosols in the Los Angeles Basin", Caltech Working Paper, Pasadena, California, March 1975, (Note that this figure also appears in Characterization of Aerosols in California (ACHEX), by G.M. Hidy et al.).

White, W.H. and P.T. Roberts, "The Nature and Origins of Visibility-Reducing Aerosols in Los Angeles", Paper No. 75-28.6, Presented at the 68th Annual Meeting of the Air Pollution Control Association, June 1975 (Note that this work also appears in Characterization of Aerosols in California (ACHEX), by G.M. Hidy et al.).

Williamson, S.J., Fundamental Air Pollution, Addison Wesley, Reading, Massachusetts, 1973.

Zelden, M., Meteorologist, Technology Service Corporation, Santa Monica, California, Personal Communication, June 1977.

APPENDIX A

LIST OF NCC WEATHER SITES IN THE SOUTHWEST

● = Sites of Prime Interest for this Study

ARIZONA

SERVICE		STATION		PERIOD	NO. REELS
A	●	Chandler/Williams	*	01/49-12/70	4
F		Douglas/Bisbee		11/48-12/54	1
W		Flagstaff/WBO		01/48-01/50	2
W	●	Flagstaff/Pullian	*	01/50-12/75	3
A	●	Fort Huachuca	#	10/54-12/70	2
W		Gila Bend		11/48-12/54	1
A		Gila Bend	*	09/68-12/70	1
W		Payson	*	07/48-05/52	1
W	●	Phoenix/Sky Harbor		01/48-12/75	3
N		Phoenix/Litchfield Pk.	*	04/48-09/66	2
A		Phoenix/Luke		04/51-12/70	3
F	●	Prescott/Mun.		01/48-12/75	3
W	●	Tucson/Int.		10/48-12/75	3
W		Tucson		01/48-10/48	1
A	●	Tucson/Davis Monthan		01/49-12/70	3
A		Tucson/Marana		09/42-09/45	2
W	●	Winslow/Mun. (24 obs 1968)		01/48-12/75	3
W		Yuma/Int.		09/48-12/75	3
W		Yuma/WBO	*	01/48-09/48	1
A		Yuma/Sig		01/55-12/62	1

COLORADO

SERVICE		STATION		PERIOD	NO. REELS
A		AF Academy	*	11/67-12/70	1
F		Akron/Washington Cnty.		01/48-12/54	1
W	●	Alamosa	*	01/48-12/75	3
W	●	Colorado Springs/Peterson		07/48-12/75	3
W	●	Denver/Stapleton		01/48-12/75	3
A		Denver/Lowry		01/49-06/66	2
A		Denver/Buckley		03/61-12/70	1
N		Denver	*	10/47-03/59	2
F	●	Eagle/Cnty.		01/48-12/75	3
A		Ft. Carson/Butts	*	09/66-12/70	1
W	●	Grand Junction/Mun.		01/48-12/75	3
F		La Junta/Mun.		01/48-12/64	2
W	●	Pueblo		01/48-06/54	1
W		Pueblo/Mem.		07/54-12/75	2
F		Trinidad/Las Animas	#	01/48-09/61	2

NEW MEXICO

SERVICE		STATION			PERIOD	NO. REELS
F		Acomita			07/48-04/53	1
A	●	Alamogordo/Holloman			01/49-12/70	3
W	●	Albuquerque/Int.			07/48-12/75	3
A		Albuquerque/Kirtland			01/49-01/52	1
F		Carlsbad/Cavern City			07/48-12/54	1
W	●	Clayton/Mun.		*	07/48-12/75	3
A	●	Clovis/Cannon			11/51-12/70	3
F		Columbus			07/48-12/54	1
F		Eagle			07/48-05/50	2
F	●	Farmington/Mun.			02/52-12/75	3
W		Gallup/Sen. Clarke Fld.		*	01/73-12/75	1
F		Grants/Milan			05/53-12/54	1
F		Hobbs/Lea County		*	07/48-12/54	1
A		Las Cruces/White Sands		*	01/49-12/62	2
F		Las Vegas/Mun.			07/48-12/64	2
A		Melrose Gun Range	#	*	07/63-12/70	2
F		Otto			07/48-12/54	1
W		Raton/Crews			07/48-08/53;	
				*	11/55-11/68	1
F		Rodeo			07/48-12/54	2
W	●	Roswell/Mun.		*	07/48-01/69	2
A		Roswell/Walker			01/49-03/67	2
W		Roswell/Industrial Air Center			01/73-12/75	1
F		Santa Fe/Mun.			07/48-12/54	1
W		Silver City/Grant Cnty.			05/60-08/68	1
W	●	Truth or Consequences/Mun.			05/50-12/75	3
F	●	Tucumcari/Mun.			07/48-12/75	3
F	●	Zuni/Intermediate Fld.			02/49-01/73	3

UTAH

SERVICE		STATION		PERIOD	NO. REELS
F	●	Bryce Canyon		11/48-12/75	3
F	●	Cedar City/Mun.		11/48-12/75	3
F		Delta		11/48-12/54	1
A	●	Dugway PG/Michales	# *	12/49-12/70	4
F		Fairfield		11/48-07/50	1
F		Hanksville		11/49-12/54	1
F		Lucin		11/48-03/50	1
W	●	Milford/Mun.	*	07/48-12/75	3
W		Ogden/Mun.	#	01/48-12/54	1
A		Ogden/Hill		01/49-12/70	4
W	●	Salt Lake City/ Int.		01/48-12/75	3
F		St. George		11/48-12/54	1
F	●	Wendover/Auxiliary	# *	03/50-12/75	3
A		Wendover		01/49-11/49; 11/56-10/57	1

WYOMING

SERVICE		STATION		PERIOD	NO. REELS
W		Casper/Wardell Fld.		01/48-03/50	1
W	●	Casper/Air Ter.		03/50-12/75	3
W	●	Cheyerne/Mun.		01/48-12/75	3
F		Douglas		01/48-12/54	1
F		Ft. Bridger		01/48-12/54	1
W	●	Lander/Hunt	# *	01/48-12/75	3
F		Laramie/Gen. Brees		01/48-12/54	1
F		Moorcroft		01/50-07/52	1
F		Rawlins/Mun.		01/55-12/64	1
F	●	Rock Springs/Mun.		01/48-12/75	3
W		Sheridan/Cnty	*	01/48-12/75	3
F		Sinclair		01/48-02/51	1

NEVADA

SERVICE		STATION		PERIOD	NO.REELS
F		Battle Mountain/Lander Cnty.		11/48-12/54	1
W		Elko/Mun.	#	01/48-12/75	3
W	●	Ely/Yelland Fld.	*	01/48-12/48;	
			*	01/53-12/75	3
N		Fallon	*	03/45-04/46;	
			*	01/49-12/74	4
F		Fallon	*	11/48-12/54	1
A		Indian Springs	*	09/63-06/64;	
			*	01/65-12/70	1
W		Las Vegas		01/48-12/48	1
W	●	Las Vegas/McCarran Int.		12/48-12/75	3
A		Las Vegas/Nellis		01/49-12/70	3
F		Lovelock/Derby		11/48-12/75	3
A		Mercury/Camp Mercury		02/51-06/53;	
				03/54-05/54	1
W		Reno/Int.		01/49-12/75	3
A		Reno/Stead		08/52-03/66	2
F		Tonopah/Mun.		04/51-12/75	2
W		Winnemucca/WBO	*	01/48-02/49	1
W		Winnemucca/Mun.	*	09/49-12/75	3
N		Yucca Flats		12/61-12/74	2

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-78-039	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE VISIBILITY IN THE SOUTHWEST An Exploration of the Historical Data Base		5. REPORT DATE April 1978 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J. Trijonis and Kung Yuan		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Technology Service Corporation 2811 Wilshire Boulevard Santa Monica, California 90403		10. PROGRAM ELEMENT NO. 1AA603 AG-17 (FY-77) 11. CONTRACT/GRANT NO. 803896
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED Interim 3/77 - 11/77 14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

This research was supported under EPA grant 803896 to Washington Univeristy, R.B. Husar, Principal Investigator.

16. ABSTRACT

The historical data base pertinent to visibility in the Southwest is analyzed. The data base includes over 25 years of airport visibility observations and more than 10 years of NASN particulate measurements. The investigation covers existing levels of visibility, long-term trends in visibility, and visibility/pollutant relationships.

Although still quite good, visibility in the Southwest has deteriorated over the past two decades. The haze levels in the Southwest appear to be mostly the result of secondary aerosols, especially sulfates. These conclusions are verified by decreases in sulfates and increases in visibility during the 1967-1968 industry-wide copper strike.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Air pollution * Aerosols * Sulfates * Visibility	Southwest	13B 07D 07B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 118
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)