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Visibility in the Northeast

Long-Term Visibility Trends and Visibility/ Pollutant Relationships

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VISIBILITY IN THE NORTHEAST
Long-Term Visibility Trends and Visibility/Pollutant Relationships

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ABSTRACT

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

Visibility in the Northeast is rather poor, median visual range being on the order of 10 miles. Visibility is not now substantially better in nonurban areas than in metropolitan areas of the Northeast. From the middle 1950's to the early 1970's, visibility exhibited only slight trends in large metropolitan areas but decreased on the order of 10 to 40% at suburban and nonurban locations. Over the same period, visual range declined remarkably during the third calendar quarter relative to other seasons, making the summer now the worst season for visibility. The decrease in visibility during the summer was especially notable at suburban and nonurban locations, where atmospheric extinction apparently increased on the order of 50 to 150% during the third calendar quarter.

Regression models based on daily variations in visibility and pollutant concentrations indicate that sulfate aerosol is the single major contributor to haze in the Northeast. Sulfates apparently account for approximately 50% of total extinction. The seasonal/spatial patterns in historical visibility trends also agree with the seasonal/spatial patterns in sulfate trends and SO_x emission trends.

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CHAPTER 1

INTRODUCTION AND SUMMARY

One of the most readily apparent effects of air pollution, visibility degradation, is receiving increased attention from researchers because it may be closely related to some of the most damaging effects of air pollution. Two obvious types of damage associated with visibility impairment are aesthetic/psychological costs and hindrance of aviation. There has also been speculation, partly supported by theory and data, that haze levels may play a significant role in climate modification. Finally, if (as several researchers have proposed) visibility is closely related to atmospheric sulfate concentrations, then haze is linked with other sulfate problems, such as acid rain and, possibly, health effects.

Part of the increased attention concerning visibility has focused on the Northeast* United States, where haze levels are especially intense. Ongoing field programs and modeling studies should help to provide a much better understanding of air quality in the Northeast, and ultimately of the relationship between air quality and visibility. However, we can also further our understanding of the visibility issue by analyzing the historical data base. A potential wealth of information is offered by over twenty-five years of airport visibility measurements 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 Northeast. The questions we address are as follows:

- What are existing visibility levels in the Northeast? What are the statistical distributions, spatial patterns, and seasonal variations of visual range?
- What trends have occurred in visual range over the past 25 years? What are the spatial and seasonal patterns in the visibility trends?
- What are the key atmospheric components contributing to haze in the Northeast?

*For the purposes of this study, the Northeast is defined as a quadrangle from Illinois and Tennessee on the west through New York and North Carolina on the east.

This report is organized in five 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 three chapters sequentially deal with the three sets of questions listed above.

SUMMARY OF CONCLUSIONS

Existing Visibility Levels (Chapter 3)

- Visibility in the Northeast tends to be rather low. Median visibility ranges from 8 to 12 miles among four metropolitan locations studied, 8 to 10 miles among four urban/suburban locations, and 9 to 14 miles among four nonurban locations. Best 10th percentile visibility is 15 to 22 miles for the metropolitan sites, 16 to 21 miles for the urban/suburban sites, and 14 to 27 miles for the nonurban sites. Worst 90th percentile visibility ranges from 2 to 4 miles among all the sites.
- The spatial patterns of visibility within the Northeast study area are not extremely pronounced. Only small differences in visibility appear when comparing metropolitan areas, urban/suburban areas, and nonurban areas. Regionally, an area of minimal visibility centers around the state of Ohio, but this minimum is not dramatic.
- The seasonal pattern for visibility now exhibits a distinct minimum during the third calendar quarter (summer), especially at urban/suburban and nonurban sites. Averaged over all twelve study locations, median visibility is 11.2 miles in the first calendar quarter, 11.7 miles in the second quarter, 8.5 miles in the third quarter, and 10.5 miles in the fourth quarter. The present summertime minimum for visibility is especially significant because, in the 1950's, visibility during the summer was better than average visibility during the remainder of the year.

Historical Visibility Trends (Chapter 4)

- From the middle 1950's to the early 1970's, visibility did not change greatly at metropolitan locations in the Northeast. Three of the four metropolitan locations studied exhibited a slight decrease in visibility; the other metropolitan location showed a slight increase in visibility. Viewed in aggregate, the metropolitan locations show a very slight decline in visibility, on the order of 5% from 1953-1955 to 1970-1972.

- Urban/suburban and nonurban locations in the Northeast underwent considerable decreases in visibility, on the order of 10 to 40%, from 1953-1955 to 1970-1972. These decreases in visibility correspond to increases in extra extinction (extinction above-and-beyond blue-sky scatter) of 10 to 80%. The two southernmost locations in the study area, Lexington, Ky. and Charlotte, N.C., exhibited the greatest declines in visibility, approximately 30 to 40% (corresponding to increases in extinction of 50 to 80%).

- When stratified by season, the trend data indicate remarkable deterioration in visibility during the summer (third) quarter. Visibility decreased at every location during the summer, and the summer decrease at each location was greater than the decrease in any other season. From 1953-1955 to 1970-1972, summertime visibility declined approximately 5 to 25% at the metropolitan locations and 25 to 60% at the urban/suburban locations. At Lexington and Charlotte, summertime visibility decreased 55 to 60%, corresponding to a 150% increase in extra extinction.

- The slight decline in yearly visibility at metropolitan locations is seen to be composed of moderate decreases in visibility during the summer which more than negated slight to moderate visibility increases during the winter. The decreasing trend in yearly visibility at urban/suburban and nonurban locations is composed of substantial visibility decreases during the summer and slight to moderate decreases during other seasons.

- A sensitivity analysis using data for Lexington and Charlotte indicates that trends in meteorology are not the basic cause of the decline in visibility (Chapter 2). Interesting questions are raised, however, concerning the possibility that increased haze levels may have affected climatology. It is intriguing to speculate whether an observed decline in daily maximum temperatures (approximately 3 to 4°F at Lexington and Charlotte from the middle 1950's to the early 1970's) may have been related to the substantial increase in haze at those locations.

- The spatial/seasonal patterns and trends in visibility are very consistent with the spatial/seasonal patterns and trends in sulfate concentrations. Previous studies indicate that sulfate concentrations reach a maximum during the third calendar quarter; have not changed greatly at metropolitan locations; have increased at nonurban locations; and have increased in the third quarter relative to other seasons. The spatial/seasonal trends in visibility and sulfates also agree qualitatively with the spatial/seasonal trends in SO_x emissions.

Visibility/Pollutant Relationships (Chapter 5)

- Visibility/pollutant regressions are attempted for three metropolitan areas (Chicago, Newark, and Cleveland) and three urban/suburban areas (Lexington, Charlotte, and Columbus). At all six locations atmospheric extinction, computed from visibility, correlates significantly with relative humidity (RH) and sulfates. In each case the best overall fit is achieved using a regression equation that incorporates relative humidity effects in a nonlinear manner, the single most important parameter being sulfates ÷ (1 - fractional RH). The total correlation achieved by the multiple regression is poor for Chicago (R = .52), excellent for Columbus (R = .90), and good for the other four locations (R = .71 to .73).

- Haze budgets, derived from the regression coefficients (extinction coefficients per unit mass for each pollutant species), vary somewhat from location to location. An aggregated haze budget for the five non-Chicago sites indicates that 5% of extinction is from blue-sky scatter, 49% is from sulfates, 2% is from nitrates, 16% is from the remainder of TSP, and 28% is unaccounted for. The unaccounted for fraction may represent additional contributions from sulfates, nitrates, and the remainder of TSP, as well as contributions from atmospheric components omitted from the analysis.

- The extinction coefficients per unit mass for sulfates that we estimate with the regression models agree with other values in the published literature and with known principles of atmospheric physics. There is also agreement that sulfates, because they tend to reside in the particle size range that is optically critical, contribute to extinction in greater proportion than their contribution to total aerosol mass. Sulfates appear to be the single most important atmospheric species related to visibility in the Northeast, even though they typically constitute only 15% of total aerosol mass.

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. In actuality, we have found most of the visibility data to be of good, if not excellent, quality. The data quality is evidenced by the consistency of the cumulative frequency distributions from one airport to another and by the high correlations (typically 0.7) obtained in regressing airport visibility measurements against relative humidity and Hi-Vol particulate data. The 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 particular, we selected airports that had adequate arrays of markers for estimating visibility.

In our analysis 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 detailed 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. We also note that one of our most significant conclusions, the substantial downward trend in visibility during the summer relative to other seasons, would be unaffected by procedural changes because the same observation procedures apply throughout the year.

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

(1) 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.

(2) the possibility that the independent variables may act as surrogates for pollutants that are not included in the analysis.

(3) potential errors in measurement techniques for sulfates, benzene solubles, and (especially) nitrates.

(4) statistical difficulties introduced by intercorrelations among the independent variables.

The first problem would tend to reduce the overall fit of the regressions, cause underestimates of extinction coefficients per unit mass, and increase the "unaccounted for" category in the haze budgets. The last three problems, especially the intercorrelations among the independent variables and the possible interferences in nitrate measurements (positive interferences from nitric acid and negative interferences from sulfates), might lead to distortions in the extinction coefficients per unit mass and the haze budgets. In spite of these potential limitations, the results of our regression models (especially for sulfates) are consistent with the published literature and with known principles of aerosol physics.

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 Northeast? Has visibility changed significantly over the past 25 years? What are the main contributors to haze in the Northeast? 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 and seasonal patterns in visual range. One could very easily disaggregate the data further to examine monthly, weekday/weekend, and diurnal patterns in visual range. Visibility observations could be analyzed in conjunction 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 trend analysis would benefit by the application of more sophisticated statistical techniques and by disaggregation of the data according to wind trajectories or meteorological classes. It would be interesting to investigate further the occurrence of long-term climatological changes and their effect on visibility trends. Conversely, it appears important to conduct a comprehensive study concerning the possible impact of haze levels on temperature patterns.

CHAPTER 2

DATA BASE PREPARATION AND DATA ANALYSIS METHODS

The objectives of this report are to document the historical trends of visibility* in the Northeast 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 of the horizon circle, but not necessarily in continuous sectors (Williamson 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.

*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.

NCC has compiled computerized records for 196 airports in the 13 states comprising the Northeast study area.* Fifteen of the 196 airports were chosen as potential sites for the present study. These 15 airports (listed in Table 1) provided good geographical coverage of the region, represented a variety of environments from metropolitan to nonurban, and had computerized records covering a long period of time.

TABLE 1. LIST OF FIFTEEN AIRPORTS CONSIDERED FOR THE NORTHEAST STUDY

Washington (National), D.C.	Columbus (Port Columbus), Ohio
Chicago (Midway), Illinois	Dayton (J.M. Cox), Ohio
Columbus (Bakalar), Indiana	Wilmington (Clinton Cnty.), Ohio
Lexington (Blue Grass Field), Kentucky	Williamsport (Lycoming Cnty.), Pa.
Newark (International), New Jersey	Smyrna (Stewart), Tennessee
Charlotte (Douglas), North Carolina	Dulles, Virginia
Raleigh/Durham, North Carolina	Elkins (Randolph Cnty.), West Virginia
Cleveland (Hopkins International), Ohio	

A detailed telephone survey was conducted with the meteorologists at each of the 15 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 criterion 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?

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

- How many members does the observation team include? Has there been a major discontinuity in the observation team?
- 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 resulted in several important discoveries. At three locations (Raleigh/Durham, Smyrna, and Elkins) a poor selection of visibility markers was available, making the quality of the visibility data very suspect. These three locations were eliminated from the study. Two Air Force bases (Columbus, Ind. and Wilmington) had been closed, so a survey could not be conducted. Examination of the data for those two airports revealed inconsistencies over time in reporting practices and periods of missing data. Columbus, Ind. and Wilmington were used to characterize the geographical pattern in visibility, but they were excluded from the study of historical visibility trends.

We also found that daytime and nighttime visibility measurements are not necessarily compatible. The daytime visibility criterion, dark object against the horizon sky, may not be equivalent to the nighttime criterion, unfocused light source. Also, the array of daytime markers often differs from the array of nighttime markers. We decided to use only the daytime visibility observations in our analyses.

The twelve airports finally selected for the Northeast study are listed in Table 2 and illustrated in Figure 1. Table 2 also classifies the airports as "metropolitan","urban/suburban", and "nonurban" based on the population of the nearest urban area and the distance to that area. It is difficult to arrive at a satisfactory classification scheme, and the one we have chosen is rather arbitrary. The distinction between the "urban/suburban" and "nonurban" categories is not as strong as the distinction between those two categories and the "metropolitan" category. It should also be noted that no locations in the Northeast study area could be called nonurban if nonurban were defined as "extremely remote".

<u>Survey of NASN Monitoring Sites</u>

At ten of the twelve airports (all but Wilmington and Williamsport) it is possible to link NASN pollutant data with the airport visibility data in

TABLE 2. CLASSIFICATION OF AIRPORTS FOR THE NORTHEAST VISIBILITY STUDY

CLASSIFICATION	AIRPORT	DISTANCE TO NEAREST URBAN AREA		POPULATION OF NEAREST URBAN AREA* (1,000's)	
		To Edge of Urbanized Area	To Center of Urbanized Area	Metropolitan Area	City
METROPOLITAN	Washington/National	0 km	5 km	3,220	730
	Chicago/Midway	0	8	7,650	3,170
	Newark/International	0	0	17,150	370
	Cleveland/Hopkins	0	4	2,300	680
URBAN/SUBURBAN	Lexington/Blue Grass	3 km	10 km	240	190
	Charlotte/Douglas	2	10	450	290
	Columbus (OH)/Port Columbus	2	8	950	540
	Dayton/J.M. Cox	8	15	940	210
NONURBAN	Columbus (IN)/Bakalar	3 km	5 km	60	30
	Wilmington (OH)/Clinton Cnty.	5	6	20	10
	Williamsport (PA)/ Lycoming Cnty.	5	7	90	40
	Dulles (VA)	19	38	3,220	730

*Population data are from Rand McNally (1977).

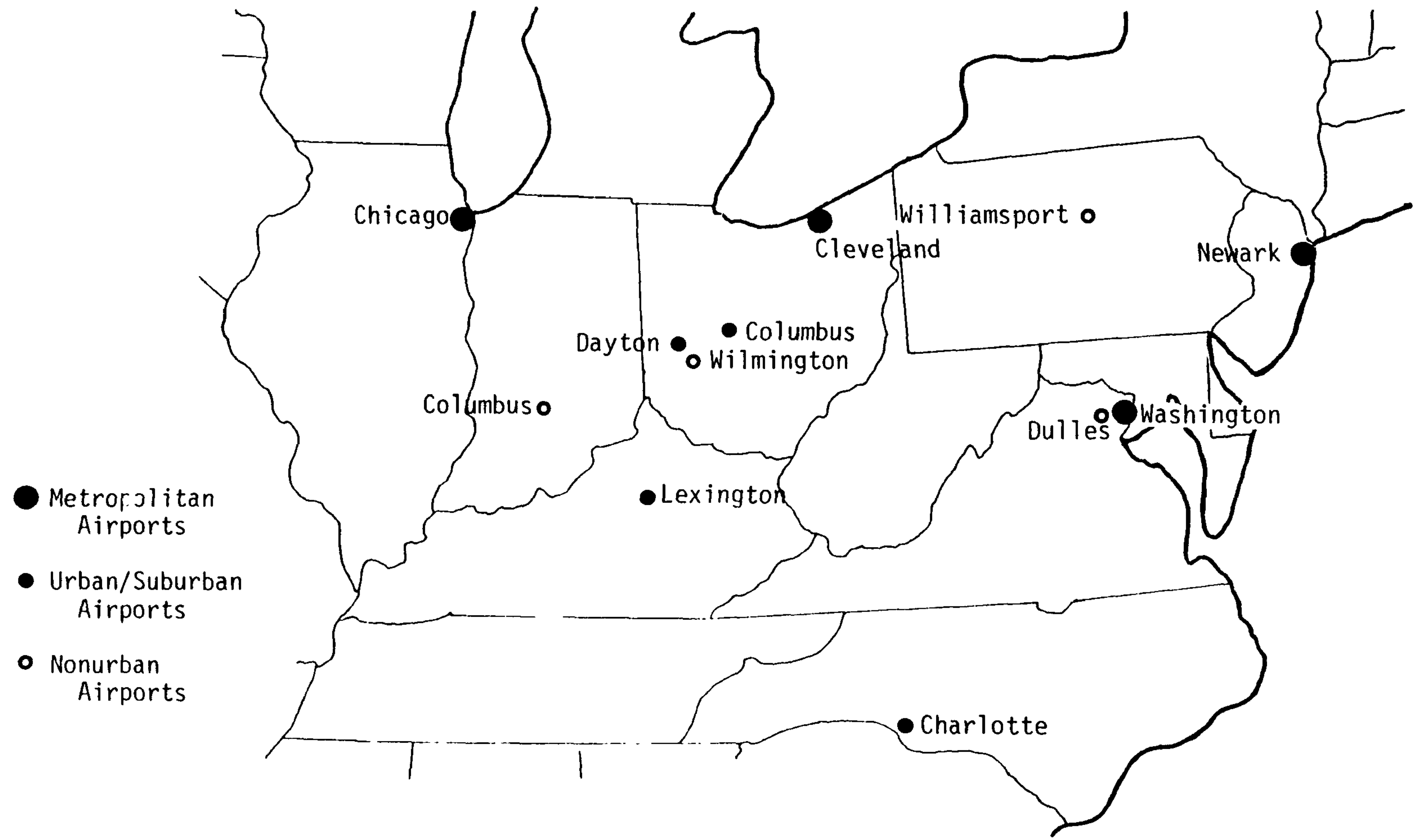


Figure 1. Airport weather stations used in the Northeast study.

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 ground? 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)?
- Is the NASN site representative of the 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?

The survey of airport observers and NASN monitoring agencies indicated that the visibility/pollutant studies had a fair to good chance of being successful at all ten locations. Because of budgetary constraints, however, the analysis was restricted to six locations where conditions (e.g., distance between airport and NASN site, data quality, etc.) appeared to be best for the study. These six locations were Chicago, Newark, Cleveland, Lexington, Charlotte, and Columbus (OH).

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.* 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.).

The nationwide NASN data for TSP, sulfate, nitrate, 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.

*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.

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

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 2, 3, and 4 present recent cumulative frequency distributions for all the sites studied. Figure 2 is for metropolitan locations; Figure 3 is for urban/suburban locations; and Figure 4 is for nonurban locations.

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:

Visibility	% of Time Reported	Cumulative Frequency
15 miles	20%	20%
12 miles	1%	21%
10 miles	29%	50%
7 miles	20%	70%

In this case, the 12 mile recordings produce a "kink" in the cumulative frequency distribution. It is obvious, in this example, that the 12 mile visibilities are not routinely reported but 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.

*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.

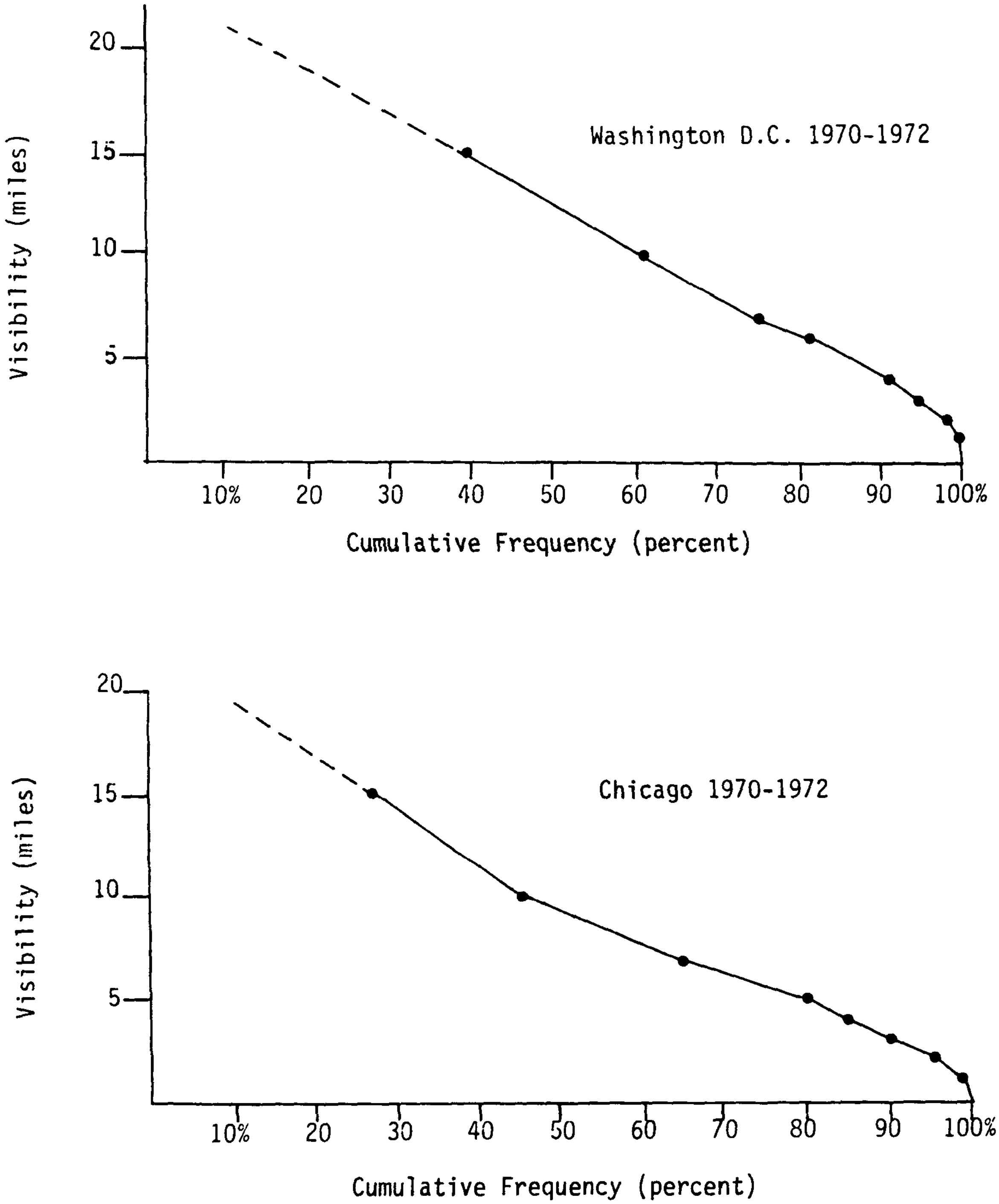
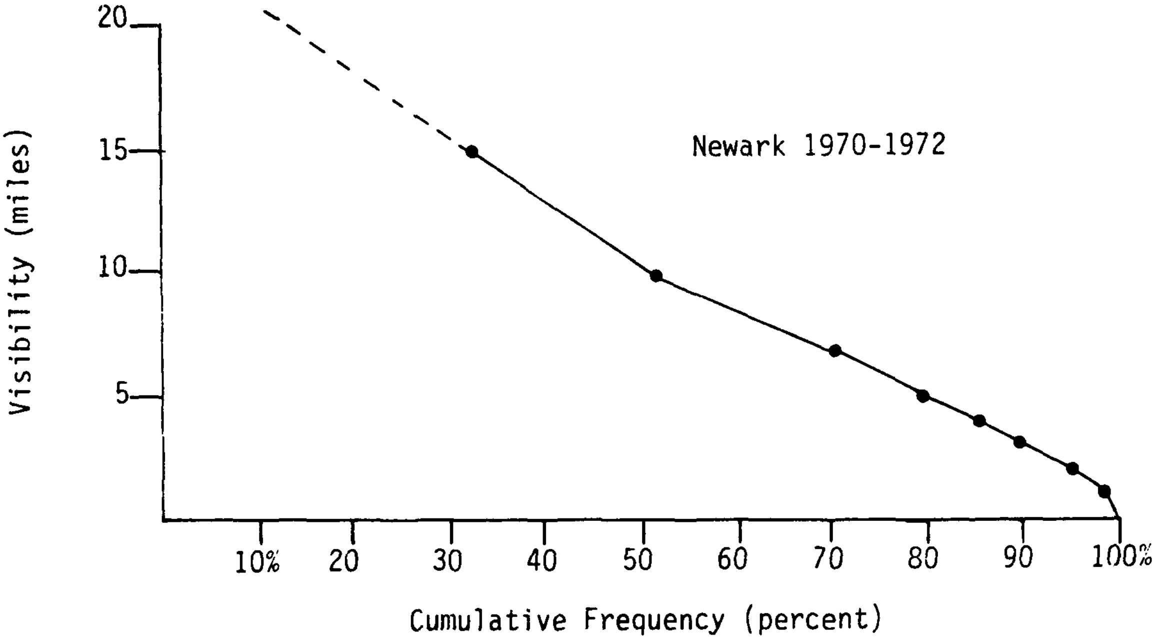


Figure 2. Cumulative frequency distributions of visibility at metropolitan locations.



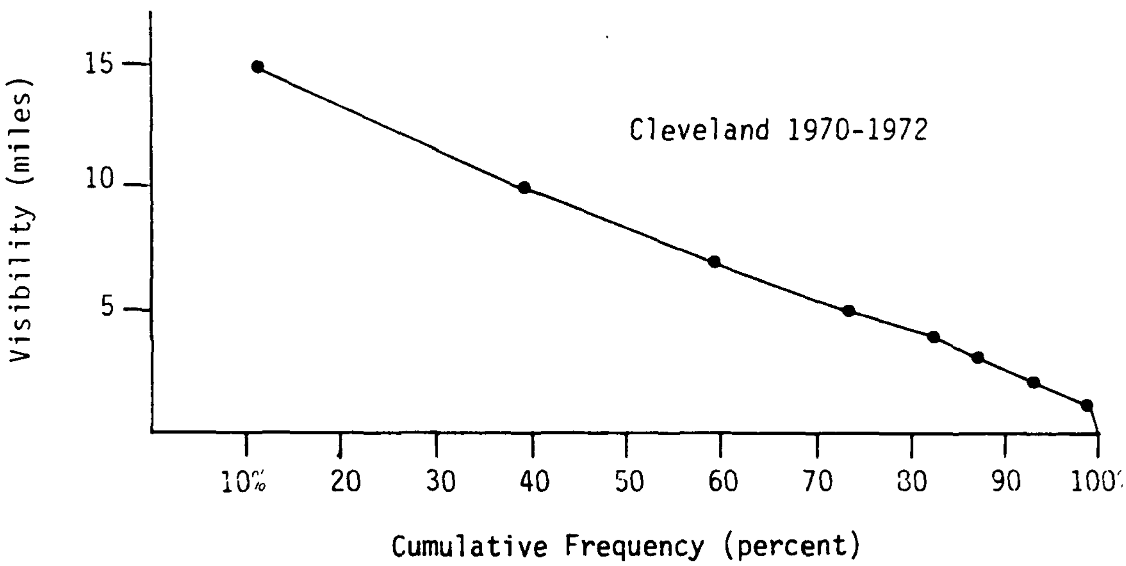


Figure 2. Cumulative frequency distributions of visibility at metropolitan locations. (Continued)

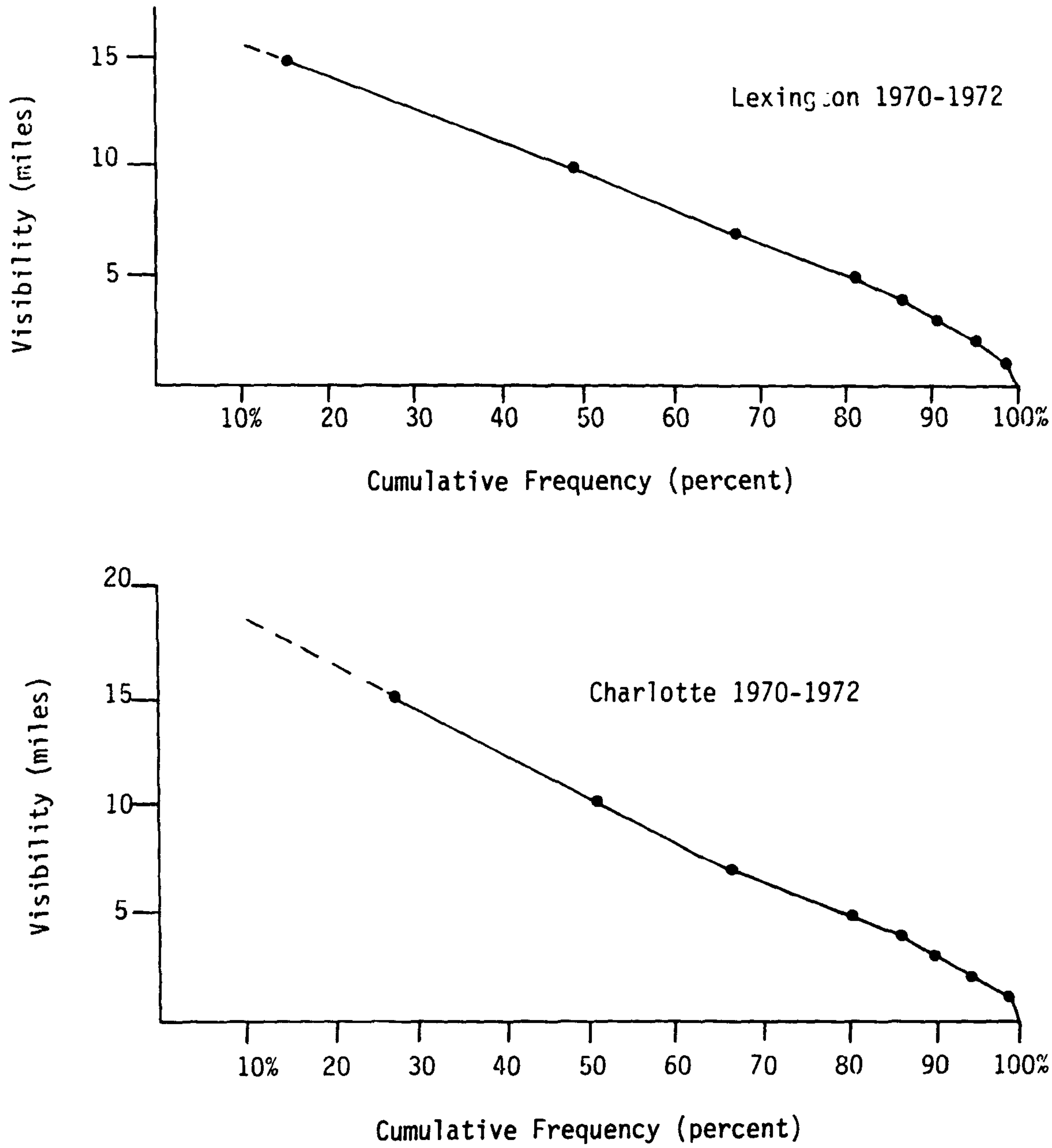
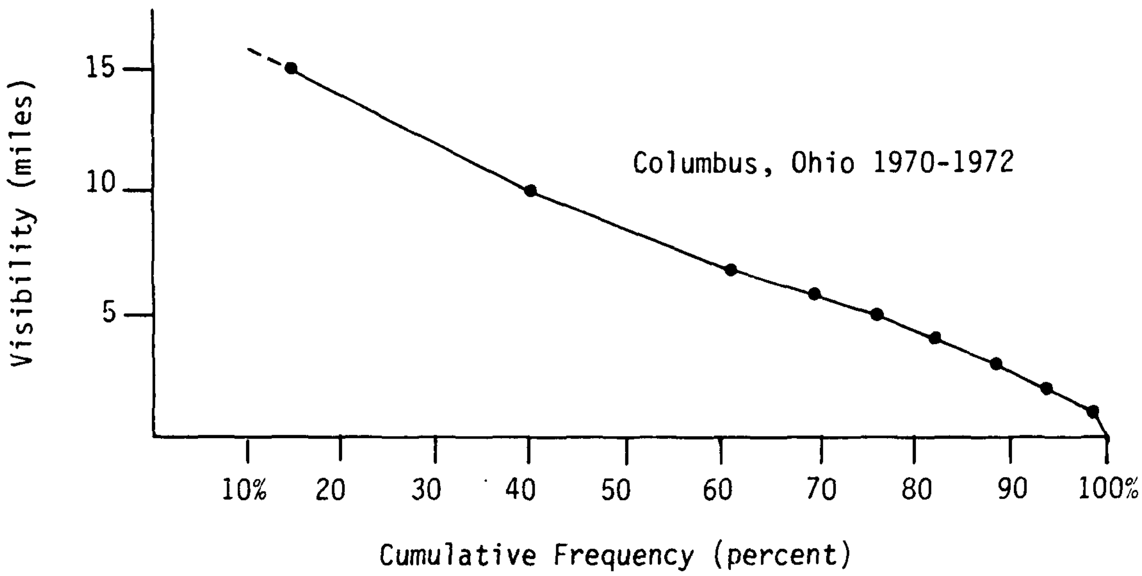


Figure 3. Cumulative frequency distributions of visibility at urban/suburban locations.



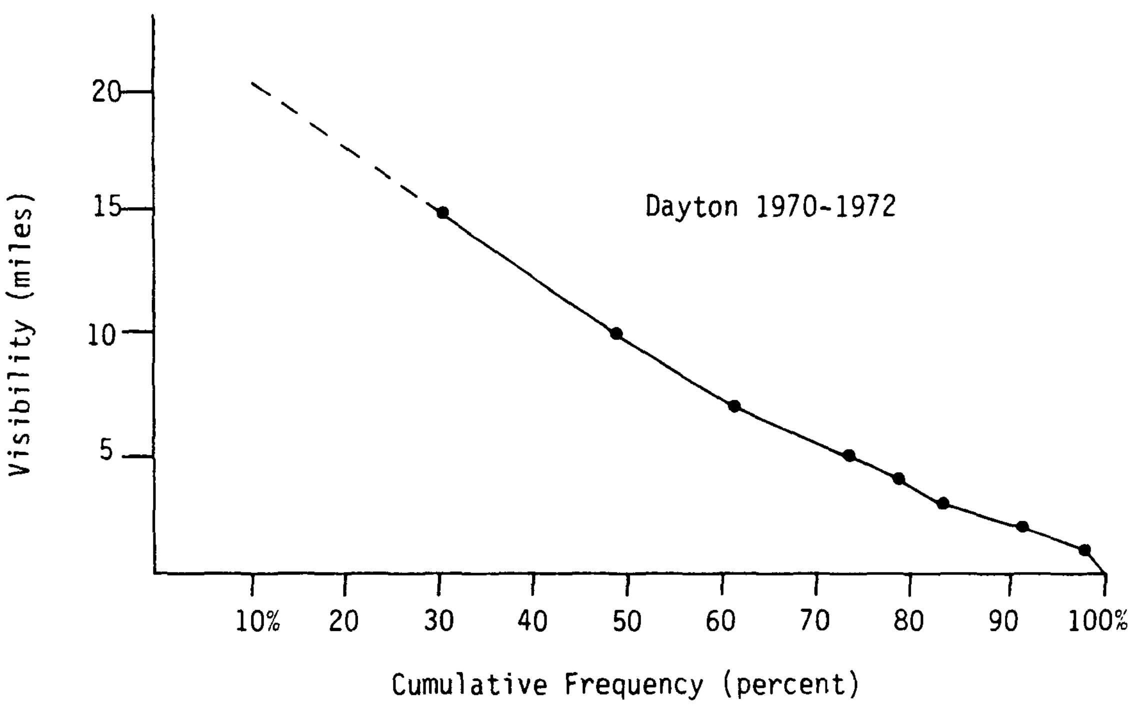
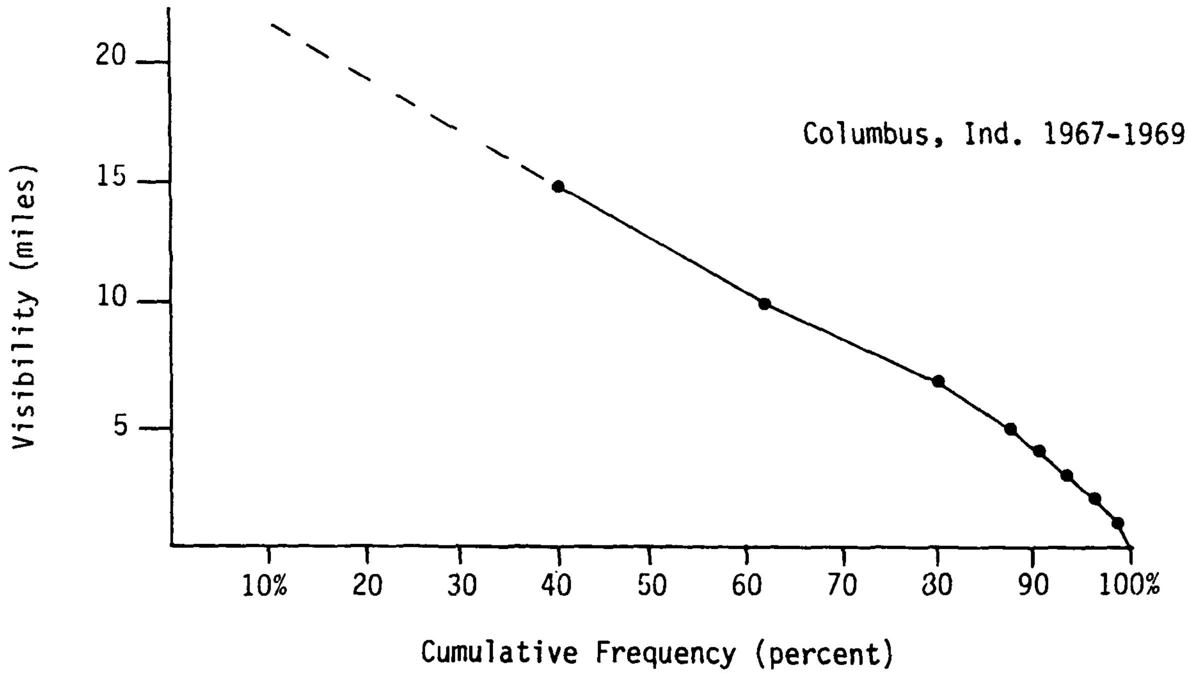


Figure 3. Cumulative frequency distributions of visibility at urban/suburban locations. (Continued)



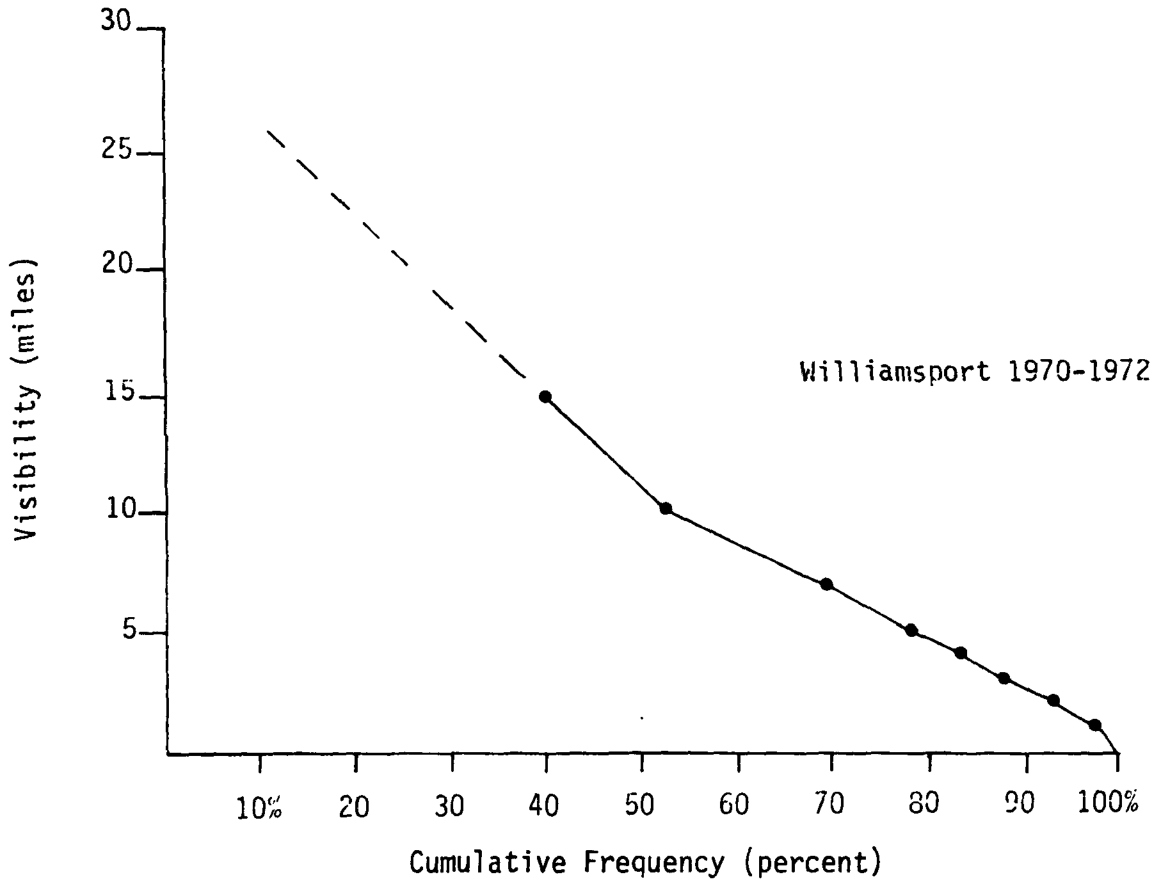
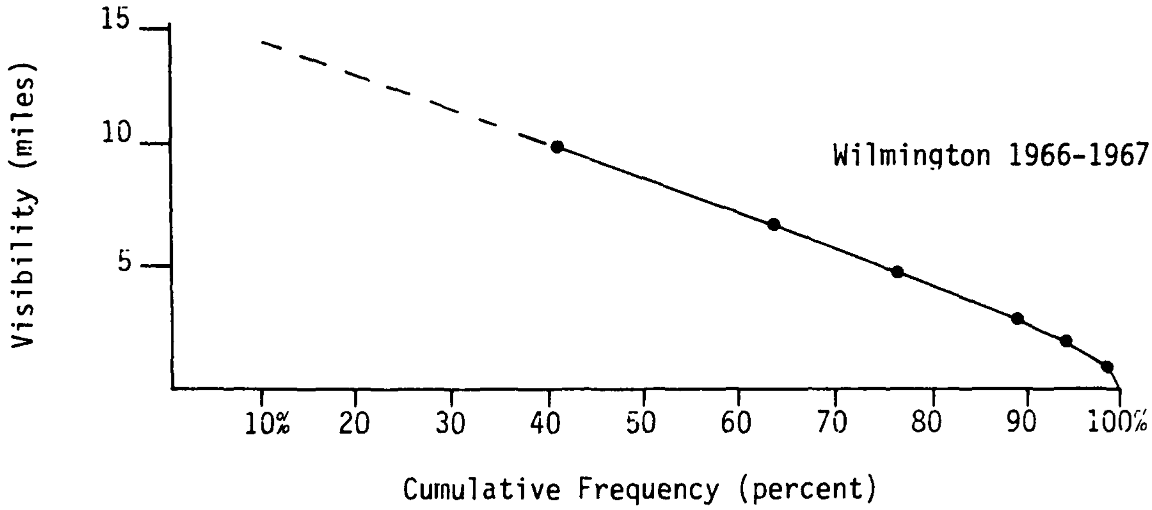


Figure 4. Cumulative frequency distributions of visibility at nonurban locations.



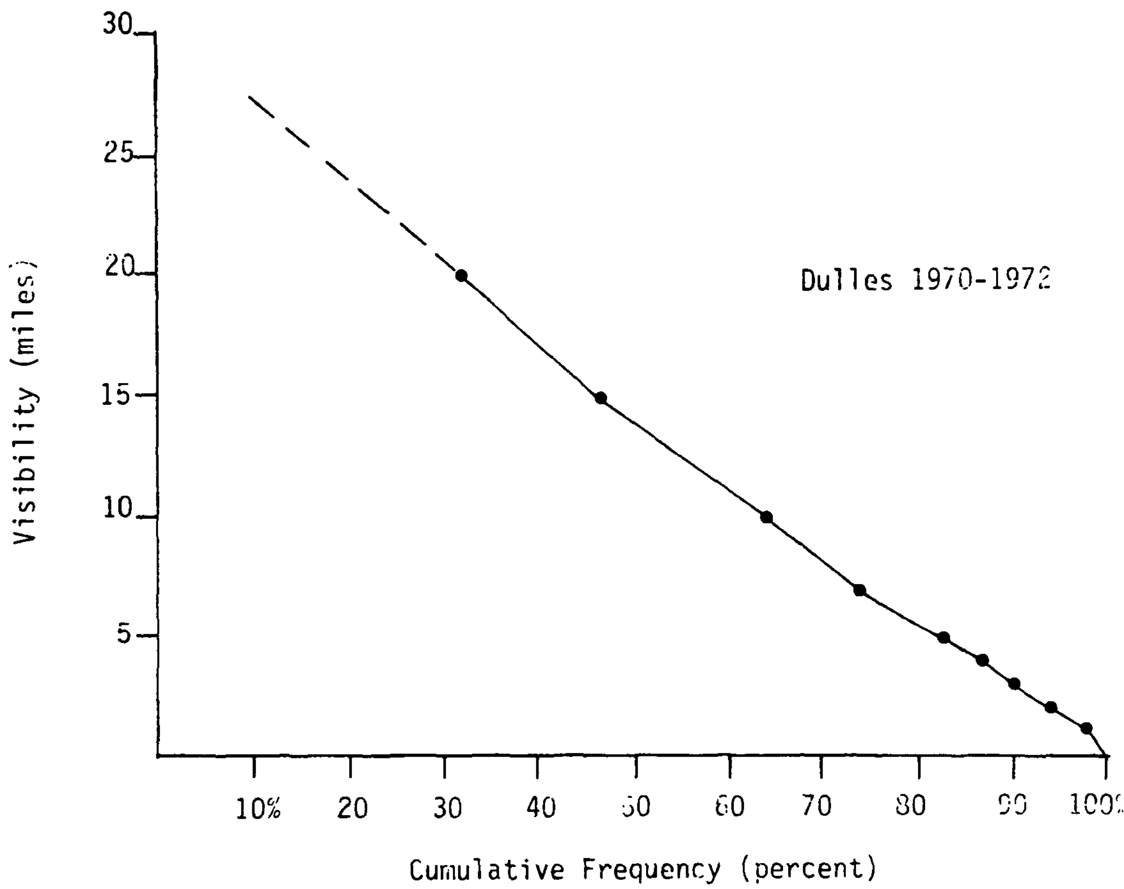


Figure 4. Cumulative frequency distributions of visibility at nonurban locations. (Continued)

The graphs in Figures 2 through 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 2 through 4.

In this report, historical trends in visibility are based on changes in visibility percentiles: 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 (Holzworth 1960, 1962; Neiburger 1955; Keith 1964, 1970; Green and Battan 1967; Miller et al. 1972; Hartman 1972) which examines shifts in the fraction of days (or hours) that visibility is in certain ranges. The units of our visibility trend index are [miles], while the units of the traditional index are [percent of days] or [percent of hours]. Our visibility trend index can be directly transformed into trends for "extinction coefficient" which are linearly related to pollutant trends (see discussion in next section).

ANALYSIS OF VISIBILITY/POLLUTANT RELATIONSHIPS

Our analysis of visibility/pollutant relationships follows the statistical procedures established by Cass (1976), White and Roberts (1977), and Trijonis and Yuan (1978). Regression equations are developed which relate daytime average visibility to daily averages of total suspended particulate (TSP), sulfates ($SO_4^=$), nitrates (NO_3^-), and relative humidity (RH). The coefficients in these regression equations can be interpreted as estimates of "extinction coefficient per unit mass" for each of the pollutant species. These extinction coefficients allow us to estimate the fraction of haze (or fraction of visibility loss) attributable to each pollutant. The following paragraphs summarize the statistical techniques and discuss some of the potential limitations in the methods.

Definition of Variables

The basic data for the study of visibility/pollutant relationships consist of the measurements listed in Table 3. Before conducting statistical analysis of the data, we perform some simple changes in the forms of variables. For instance, instead of using visual range (V) as the dependent variable, it is convenient to use the extinction coefficient, B,

$$B = \frac{24.3}{V} , \tag{1}$$

where the units of B are $[10^4 \text{ meters}]^{-1}$ and the units of V are [miles].* The extinction coefficient can be linearly divided into contributions from various atmospheric components, i.e.,

$$B = B_{Rayleigh} + B_{scat} + B_{abs\text{-}aerosol} + B_{abs\text{-}gas} \tag{2}$$

where $B_{Rayleigh}$ = light scattering by air molecules (blue-sky or Rayleigh scatter) ~.15 (Robinson 1968)

B_{scat} = light scattering by atmospheric aerosols

$B_{abs\text{-}aerosol}$ = light absorption by aerosols

$B_{abs\text{-}gas}$ = light absorption by gases

TABLE 3. DATA FOR VISIBILITY/POLLUTANT STUDIES

Variable	Units	Averaging Time
V... visibility or visual range	miles	4 daylight measurements
RH... relative humidity	percent	4 daylight measurements
TSP... total suspended particulates	$\mu g/m^3$	24-hour average
$SO_4^=$... sulfates	$\mu g/m^3$	24-hour average
NO_3^-... nitrates	$\mu g/m^3$	24-hour average

*Equation (1) is the Koschmieder formula based on a threshold brightness level of 0.02 for the human eye. In a uniform atmosphere with extinction coefficient B, a contrast level of 1 (black object against horizon sky) will be reduced to a contrast level of .02 at a distance of V = 24.3/B miles.

V = 18.6 mi

$V = \frac{3.0}{B_{ext}}$ Km

R = 3.91 km = 2.43 mi

1.86 mi

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. Following White and Roberts (1977) we define

$$S = SULFATE = 1.3\ SO_4^=$$

and

$$N = NITRATE = 1.3\ NO_3^- \quad (3)$$

in order to account for the mass of cations (presumably ammonium) associated with the measured values of $SO_4^=$ and NO_3^-. The variable,

$$T = TSP - SULFATE - NITRATE = TSP - S - N \quad (4)$$

is used to represent the non-sulfate, non-nitrate fraction of TSP.

Multi-Variate Regression

When several independent variables (RH, SULFATE, NITRATE, and T) 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 NITRATE and T apparently correlated with B only because they were correlated with SULFATE which, in turn, was significantly related to B.

An appropriate tool for multi-variate analysis is multiple regression. Following the precedure of Cass (1976), White and Roberts (1977), and Trijonis and Yuan (1978) we perform multiple linear regressions of the form

$$B = a + b_1RH + b_2(TSP - SULFATE - NITRATE) + b_3SULFATE + b_4NITRATE,$$

or

$$B = a + b_1RH + b_2T + b_3S + b_4N. \quad (5)$$

These regressions are run stepwise, retaining only those terms which are greater than zero at a 95% confidence level. The regression coefficients (b_2,

b_3, and b_4) represent the extinction coefficient per unit mass for each pollutant species, in units of (10^4 meters)$^{-1}$/($\mu g/m^3$).

For all the regressions according to Equation (5), the constant term "a" turns out to be a number on the order of minus 1 to minus 4 $[10^4 m]^{-1}$. The constant "a" represents the scattering when all four variables (RH, T, S, and N) are zero. It is reasonable to consider the possibility that T, S, and N are zero, but it is not reasonable to extrapolate the linear regression equation to values of zero relative humidity. To make the constant term better-behaved, and to facilitate interpretation of the results, we choose to write the results of the linear regressions as

$$B = a' + b_1(RH - \overline{RH}) + b_2T + b_3S + b_4N, \quad (6)$$

where $\overline{RH}$ = average relative humidity for the location, and $a' = a + b_1\overline{RH}$. The constant term "a′" now represents the scattering coefficient when the three pollutant variables are zero and relative humidity is at its average value.

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

$$B = a + b_1 \frac{\text{TSP-SULFATE-NITRATE}}{(1 - \frac{RH}{100})} + b_2 \frac{\text{SULFATE}}{(1 - \frac{RH}{100})} + b_3 \frac{\text{NITRATE}}{(1 - \frac{RH}{100})}. \quad (7)$$

For most locations, the constant "a" in Equation (7) turns out to be approximately the same as the constant "a′" in Equation (6).

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 examples.

The linear regression [Equation (6)] for Columbus, Ohio results in the formula,

$$B = 1.33 + .089(RH - \overline{RH}) + .120\ \text{SULFATE} + .091\ \text{NITRATE}, \quad (8)$$

with a total correlation coefficient of 0.81. The average value for the extinction coefficient at Columbus is B = 3.56 $[10^4 \text{ meters}]^{-1}$, corresponding to a visibility of 6.8 miles. Using Equation (8), the average extinction (haze) level at Columbus can be disaggregated into components by substituting in average values for the variables. With average values for B, RH, SULFATE, and NITRATE, Equation (8) reduces to

$$3.56 = \underbrace{.15}_{\substack{\text{Blue-sky}\\ \text{scatter by}\\ \text{air molecules}}} + \underbrace{1.18}_{\substack{\text{Remainder}\\ \text{of 1.33}\\ \text{constant}\\ \text{term}}} + \underbrace{.120(\overset{\text{Average SULFATE}}{15.7\mu g/m^3})}_{\substack{\text{Contribution}\\ \text{of sulfates}}} + \underbrace{.091(\overset{\text{Average NITRATE}}{3.9\mu g/m^3})}_{\substack{\text{Contribution}\\ \text{of nitrates}}}$$

or

$$3.56 = .15 + 1.18 + 1.88 + .35 \tag{9}$$

Equation (9) indicates that, on the average for Columbus, 53% of the extinction is from sulfates, 10% is from nitrates, 4% is from air molecules, and 33% is unaccounted for.

Alternately, we can compute an average extinction budget using the non-linear RH regression model. For Columbus, Equation (7) reduces to

$$B = 0.98 + 0.46\frac{\text{SULFATE}}{(1 - .01\ \text{RH})} + .022\ \frac{\text{NITRATE}}{(1 - .01\ \text{RH})}\ . \tag{10}$$

Substituting average values for B, SULFATE/(1 - .01 RH), and NITRATE/(1 - .01 RH), we obtain

$$3.56 = \underbrace{.15}_{\substack{\text{Blue-sky}\\ \text{scatter}}} + \underbrace{.83}_{\substack{\text{Remainder}\\ \text{of constant}}} + \underbrace{.046(50.0)}_{\substack{\text{Contribution}\\ \text{of sulfates}}} + \underbrace{.022(12.5)}_{\substack{\text{Contribution}\\ \text{of nitrates}}}$$

or

$$3.56 = .15 + .83 + 2.30 + .28 \tag{11}$$

Equation (11) indicates that, on the average for Columbus, 65% of the extinction is from sulfates, 8% is from nitrates, 4% is from air molecules, and 23% is unaccounted for.

Limitations of the Regression Approach

There are several limitations to using regression models to estimate the contribution of various pollutants to visibility loss. One limitation is that the NASN site and airport are not co-located. Random errors introduced by differences in the air masses at the two locations would tend to weaken the statistical relationship, leading to a lower correlation coefficient and lower regression coefficients. This could cause us to underestimate the extinction coefficients per unit mass for the pollutant species, and therefore to underestimate the contributions of the pollutant species to the total extinction budget.

A systematic error could result if the pollutant concentrations at the downtown NASN sites are consistently higher than the pollutant concentrations averaged over the visual range surrounding the airport. The bias caused by relatively high pollutant measurements would also result in an underestimate of extinction coefficients per unit mass for the pollutant species. A reverse type of bias, e.g. an overestimate of extinction coefficients per unit mass, would result if daytime pollution levels (corresponding to the time period of the visibility measurements) were higher than 24-hour average pollutant levels.

An overestimate of extinction coefficients per unit mass could also be produced by the loss of water associated with the aerosol during equilibriation of the Hi-Vol filter. The ambient aerosol mass tends to be greater than the measured aerosol mass because more water is usually attached to the former. The low estimate of actual aerosol mass could lead to a high estimate of extinction coefficient per unit mass. This effect should not bias the extinction budgets, however, because the extinction budgets are based on a product of extinction coefficient per unit mass and the measured mass of aerosol.

The statistical regression equation may also overstate the importance of the pollutant variables if these variables are correlated with other pollutants which are not included in the analysis. Nitrates (and possibly sulfates) may act, in part, as surrogates for other related photochemical pollutants, such as secondary organic aerosols 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. The greatest measurement concern, however, involves nitrates (Spicer and Schumacher 1977). Nitrate measurements may represent gaseous compounds (NO_2 and especially nitric acid) as well as nitrate aerosols.

Also, high sulfate concentrations may negatively interfere with nitrate measurements (Harker et al. 1977).

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

Although the regression models are subject to several limitations, it should be noted that the basic conclusions resulting from 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.

CONSIDERATION OF METEOROLOGY

In analyzing aerometric data, it is often important to make allowances for the effects of meteorology. This section discusses our treatment of meteorology in both the visibility pollutant regressions and the visibility trend studies.

Visibility/Pollutant Regressions

Special weather events, such as fog or precipitation, can have significant effects on the visibility/pollutant regression analyses. Regression, based on minimization of squared errors, is sensitive to outliers in the data. The extremely low visibilities (extremely high extinction coefficients) associated with special weather conditions might substantially affect the results of the regressions.

To help minimize the effects of special weather events, we eliminated all days with precipitation from the visibility/pollutant regression analysis. We did not, however, eliminate days with fog. The reasons for including days with fog in the regression studies were fourfold:

- In the Northeast, haze is often so intense that it is difficult to distinguish from fog (Holzworth 1977). Eliminating days with fog might entail the loss of the "very hazy" days that are important to the visibility/pollutant regressions.

- Eliminating days of fog would reduce the size of the data base by about 10 to 30% and would slightly reduce the statistical significance of the results.

- The presence of relative humidity as a variable in the regressions should help to minimize distortions that might be produced by including days with fog.

- A sensitivity analysis indicated that the results of the regressions were not very sensitive to the inclusion of days with fog.

Visibility Trend Studies

The historical visibility trends presented in this report are based on data for all daylight hours, without sorts for meteorology. As will be demonstrated in Chapter 4, these data indicate that visibility has deteriorated in the Northeast, especially in suburban and nonurban locations. It is of interest to determine whether the decreasing trend in visibility might be due to meteorology. To investigate this issue, we have conducted special trend studies for Lexington (Ky.) and Charlotte (N.C.), the two sites that exhibited the greatest historical decrease in visibility.

Figure 5 compares visibility trends for all hours at Lexington and Charlotte to trends for hours sorted by meteorology (hours of fog and precipitation deleted). It is apparent that the trends for the meteorologically sorted hours are nearly parallel to the trends for all hours. For all hours, the 50th and 90th percentile visibilities at Lexington decreased by 41% and 47%, respectively, from 1953-1955 to 1970-1972.* For the meteorologically sorted hours, the 50th and 90th percentiles decreased 35% and 29%. For all hours, the 50th and 90th percentile visibilities at Charlotte decreased by 31% and 33%, respectively, from 1955-1957 to 1970-1972. For the meteorologically sorted hours, the 50th and 90th percentiles decreased 22% and 29%. Although the net percent reductions in visibility are slightly less

*These percent reductions are based on net changes in three-year averages. Note that 10th percentile visibility is not considered here because computing the 10th percentile for the meteorologically sorted hours would involve excessive extrapolation of the cumulative frequency distribution.

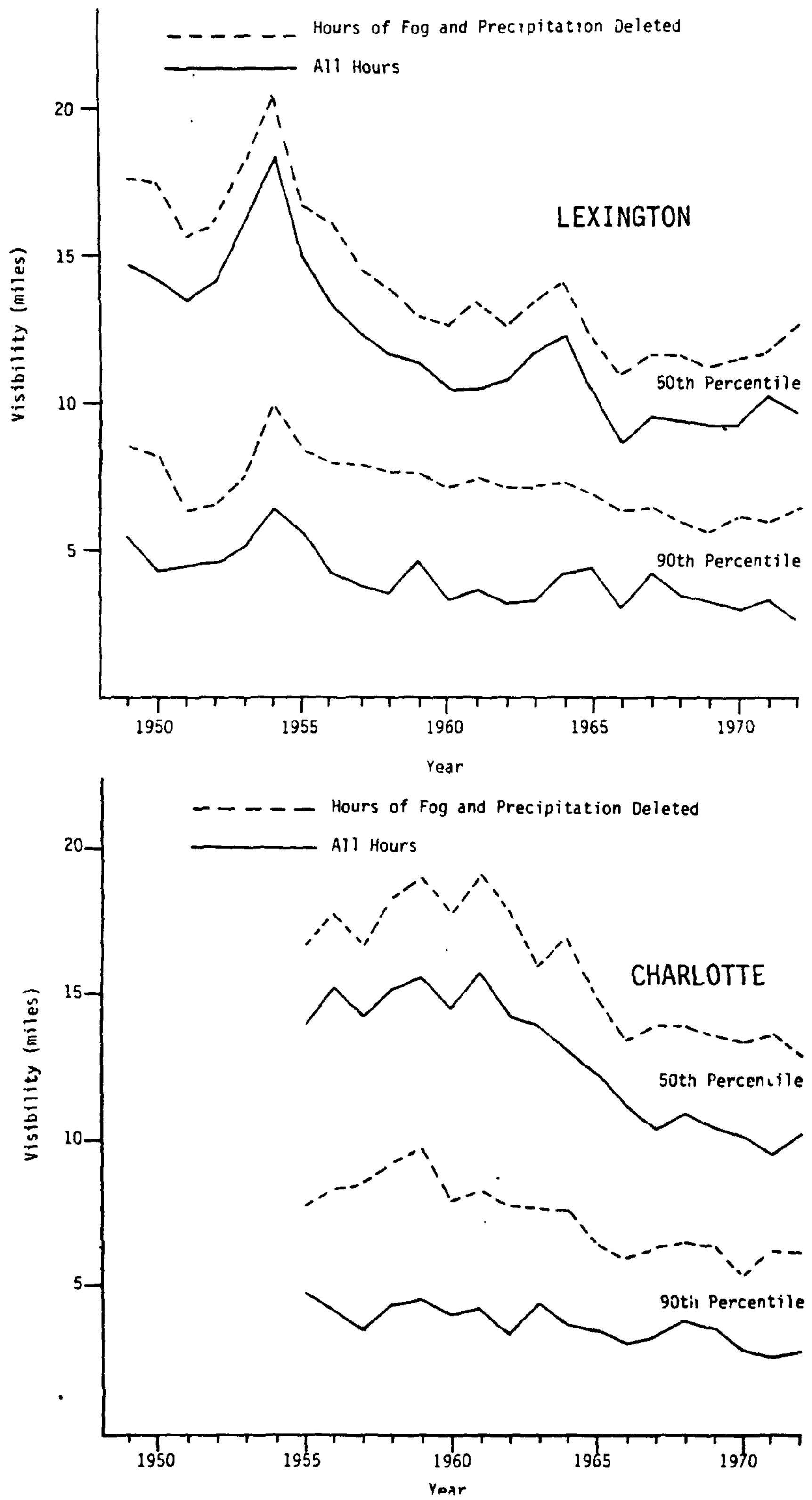


Figure 5. Long-term visibility trends at Lexington and Charlotte, raw trends compared to trends sorted for meteorology.

for the meteorologically sorted data, a definite decrease in visibility is still apparent in the meteorologically sorted data.*

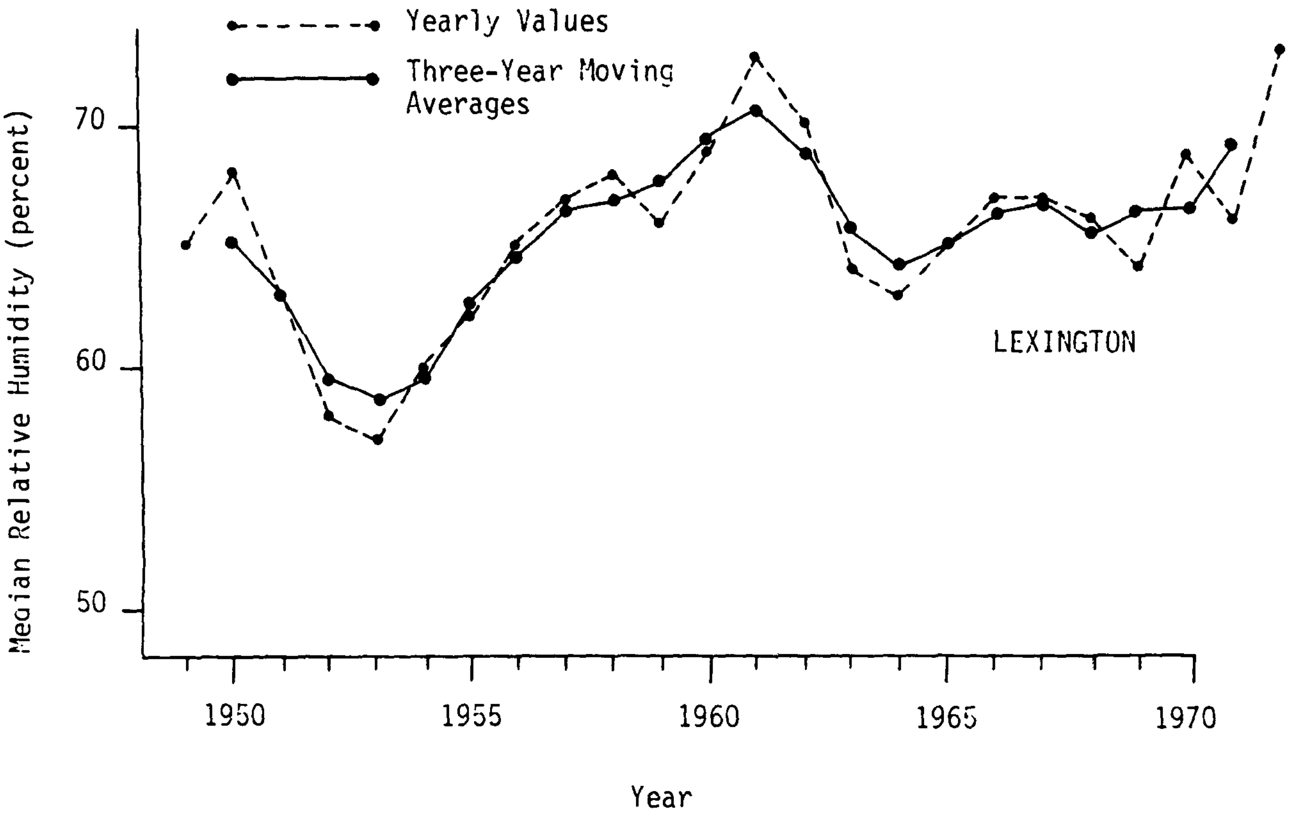
Another way to determine whether meteorology might have affected historical visibility trends is to examine trend data for meteorological variables. A key meteorological variable with respect to visibility in the Northeast is relative humidity, which typically exhibits a correlation coefficient of -0.3 to -0.7 with visibility on a day-to-day basis. Figure 6 illustrates long-term trends in median daytime relative humidity at Lexington and Charlotte. An upward trend in relative humidity is apparent. At Lexington median daytime RH was 69% in 1970-1972, compared to 60% in 1953-1955; at Charlotte it was 65% in 1970-1972 compared to 61% in 1955-1957.

The upward trend in relative humidity from the middle 1950's to the early 1970's raises the question as to whether this might have been the cause of the observed visibility decrease. To answer this question, we examined visibility trends for constant values of relative humidity. As illustrated in Table 4, visibility decreased significantly from the middle 1950's to early 1970's within each fixed range of relative humidity.

The last column of Table 4 presents trends in visibility that have been normalized for the historical relative humidity changes according to meteorological normalization procedures developed by Kerr (1974) and Zeldin and Meisel (1977). The meteorologically normalized trends show a 39% decrease in median visibility from 1953-1955 to 1970-1972 at Lexington and a 24% decrease in median visibility from 1955-1957 to 1970-1972 at Charlotte. These decreases are almost as great as the decreases observed in the raw visibility trend data (41% at Lexington and 31% at Charlotte). Thus, we conclude that the upward trend in relative humidity had only a very slight effect on the visibility trends.

The above discussion leads to a new and very intriguing question. We have found that the historical increase in relative humidity was not the

*There are at least three plausible explanations for the slightly lesser decrease in visibility for the meteorologically sorted hours. First, there may have been more occurrences of low visibility due to fog and precipitation conditions in later years. Second, the cause of the decrease in visibility may have been such that it had a relatively greater effect for hours of fog and/or precipitation. Third, because of the general increase in haziness, more hours may have been classified as foggy in the later years.



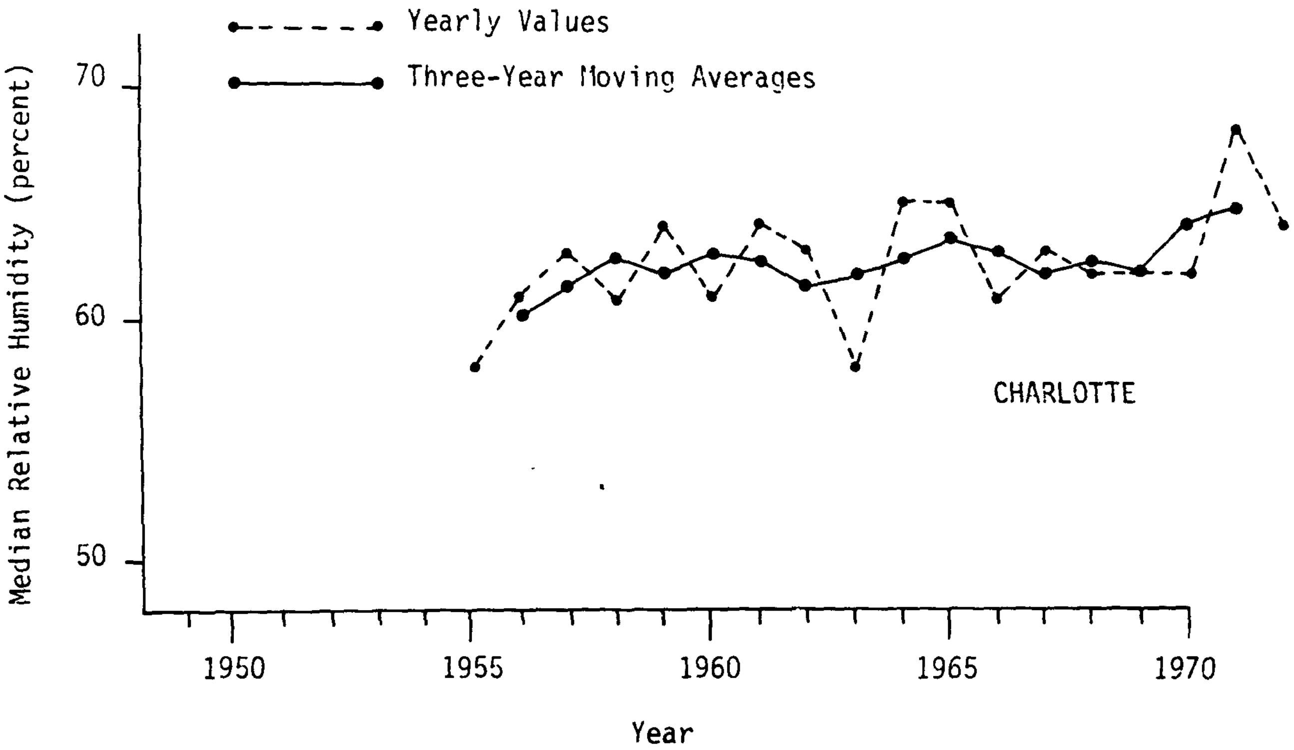


Figure 6. Long-term trends in median relative humidity for daylight hours at Lexington and Charlotte.

TABLE 4. LONG TERM TRENDS IN VISIBILITY AT LEXINGTON AND CHARLOTTE, NORMALIZED FOR CHANGES IN RELATIVE HUMIDITY

	VISIBILITY DATA STRATIFIED BY RH CLASS								METEOROLOGICALLY NORMALIZED VISIBILITY DATA*
	RH≤31	31<RH≤40	40<RH≤50	50<RH≤60	60<RH≤70	70<RH≤79	79<RH≤89	89<RH	
LEXINGTON									
Median Visibility (miles) 1953-1955	27.0	26.8	22.8	18.3	15.3	14.2	11.1	5.2	16.5 miles
Median Visibility (miles) 1970-1972	15.7	14.6	12.9	11.9	10.8	9.2	6.1	3.5	10.1 miles
Net Percent Change in Visibility, 1953-1955 to 1970-1972	-42%	-46%	-43%	-35%	-29%	-35%	-45%	-33%	-39%
CHARLOTTE									
Median Visibility (miles) 1955-1957	42.4	21.0	18.6	16.5	14.4	13.0	10.1	4.1	15.6 miles
Median Visibility (miles) 1970-1972	37.1	16.8	13.8	11.1	10.5	9.1	6.8	3.1	11.8 miles
Net Percent Change in Visibility, 1955-1957 to 1970-1972	-13%	-20%	-26%	-33%	-27%	-30%	-33%	-24%	-24%

*Meteorologically normalized median visibilities are weighted averages of the median visibilities in each RH class, with the weighting frequency for each class based on all six years of data. In this way, the distribution of relative humidity is made equivalent for the first three years and the last three years (Kerr 1974; Zeldin and Meisel 1977).

basic cause of the visibility decrease. However, could the converse be true? Possibly, the historical increases in haze levels have affected daytime relative humidity. In this regard, we note that Husar and Patterson (1978) in a companion study focusing on interactions among visibility, meteorology, and other parameters, have found distinct temperature trends at Lexington and Charlotte. As illustrated in Figure 7, mid-day (1 P.M.) temperatures at Lexington and Charlotte have decreased approximately 3 to 4°F from the middle 1950's to the early 1970's.* Early morning (4 A.M.) temperatures show no change over this period. Possibly, as hypothesized by Bolin and Charlson (1976), the increased haze levels have interacted with incoming solar radiation during the day and irradiation away from the earth during the night to produce these changes in temperature patterns. Long-term cycles in climatology constitute an alternative possible explanation for the temperature trends.

In summary, our cursory analysis of weather data indicates that changes im meteorology do not appear to be the cause of increased haze levels in the Northeast. However, questions are raised concerning the possibility that the haze levels may have affected climatology. Both of these issues should be addressed more thoroughly in future research. With respect to interactions between temperature and visibility, data for more locations, with varied trends in visibility, should be analyzed. The visibility trends should be normalized for long-term temperature changes, and the temperature trends should be normalized for long-term visibility changes. A theoretical analysis of the interactions among haze, solar radiation, and temperature should also be conducted.

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* The decrease in daytime temperature may, in fact, explain the increases in daytime relative humidity, because Husar and Patterson (1978) have noted that dew point remained constant.

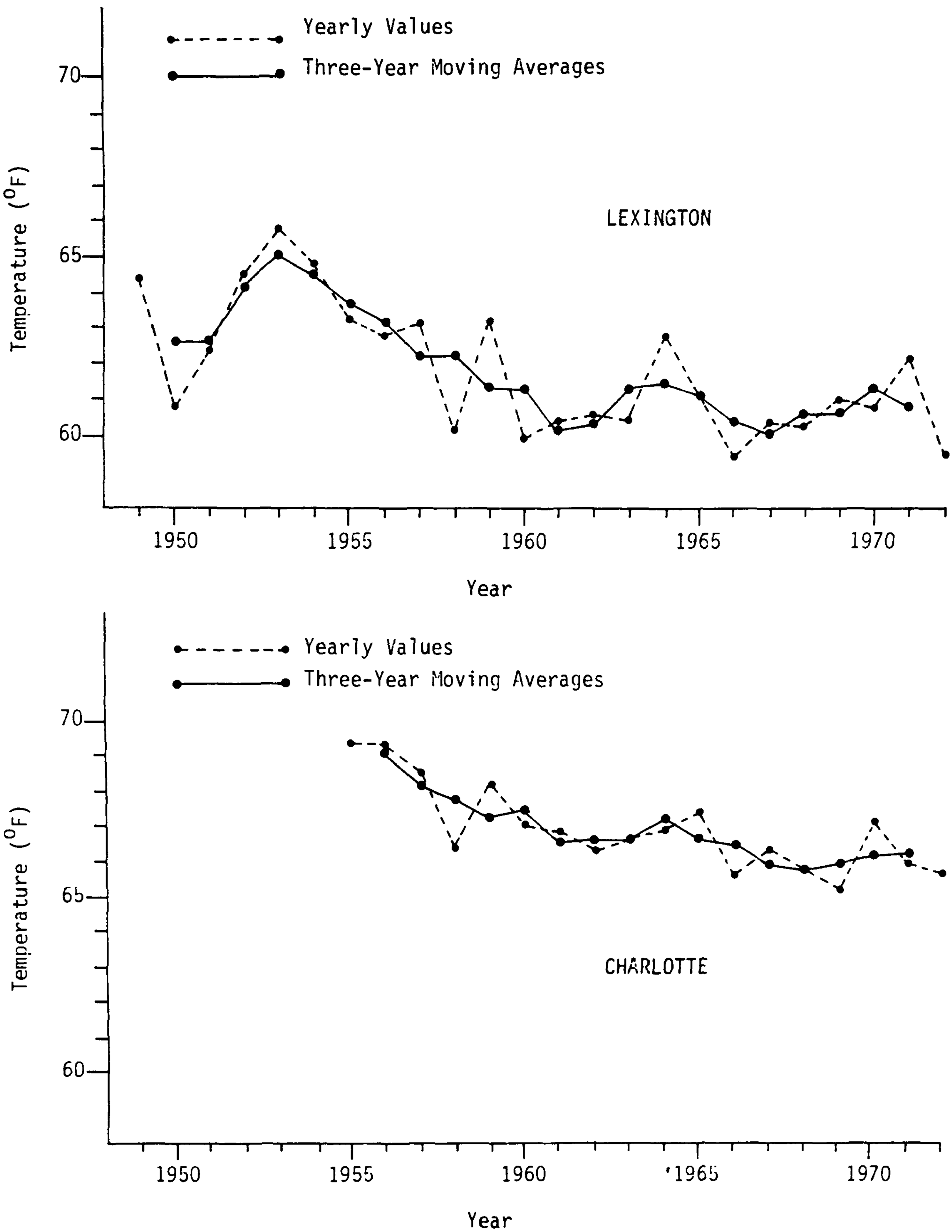

Figure 7. Long-term trends in yearly average 1 P.M. temperature at Lexington and Charlotte,(Husar and Patterson 1978).

CHAPTER 3

EXISTING VISIBILITY LEVELS

A very basic issue that needs to be resolved is "what are existing visibility levels in the Northeast?" 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 Northeast. These questions can be answered by an analysis of airport visibility measurements.

VISIBILITY VERSUS DEGREE OF URBANIZATION

Figures 2, 3, and 4 (in Chapter 2) presented recent cumulative frequency distributions for visual range at four metropolitan locations, four urban/suburban locations, and four 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 are listed in Table 5.

Table 5 indicates that visual range is rather low in the Northeast and that visibility does not depend a great deal on the degree of urbanization. Median visibility ranges from 8 to 12 miles among the metropolitan locations, 8 to 10 miles among the urban/suburban locations, and 9 to 14 miles among the nonurban locations. Best 10th percentile visibility is 15 to 22 miles for the metropolitan sites, 16 to 21 miles for the urban/suburban sites, and 14 to 27 miles for the nonurban sites. Worst 90th percentile visibility ranges from 2 to 4 miles among all the sites.

These results for the Northeast contrast strikingly with results for the Southwest. In the Southwest, median visual range is 30 to 55 miles in large urban areas and 65 to 80 miles in nonurban areas (Trijonis and Yuan 1978). Thus, visibility is 4 to 8 times greater in the Southwest. Also, unlike the Northeast, a distinct urban-nonurban difference exists in the Southwest.

TABLE 5. MEDIAN, 10TH PERCENTILE, AND 90TH PERCENTILE VISIBILITY AT TWELVE NORTHEASTERN LOCATIONS

LOCATION	VISIBILITY PERCENTILES (1970-1972)† 10th% (Best)	50th% (Median)	90th% (Worst)
METROPOLITAN			
Washington, D.C.	22* miles	12 miles	4 miles
Chicago, IL	19*	9	3
Newark, NJ	21*	10	3
Cleveland, OH	15	8	2
URBAN/SUBURBAN			
Lexington, KY	16* miles	10 miles	3 miles
Charlotte, NC	19*	10	3
Columbus, OH	16*	8	3
Dayton, OH	21*	10	2
NONURBAN			
Columbus, IN	22* miles	13 miles	4 miles
Williamsport, PA	27*	11	3
Wilmington, OH	14*	9	3
Dulles, VA	27*	14	3

†Data are for the three years 1970-1972 with the exceptions of Columbus, Indiana (1967-1969) and Wilmington, Ohio (1966-1967).

*Estimated by linearly extrapolating the cumulative frequency distribution.

GEOGRAPHICAL PATTERNS IN VISIBILITY

Figures 8, 9, and 10 present maps of 50th, 10th, and 90th percentile visibilities, respectively. The maps distinguish between metropolitan, urban/suburban, and nonurban locations. It is apparent that the state of Ohio exhibits the lowest visibilities. The exceptionally low visibility in the upper Ohio river valley has also been noted in a previous study (Husar et al 1976).

SEASONAL PATTERNS IN VISIBILITY

Figure 11 summarizes recent* seasonal patterns in visibility. The most notable feature in Figure 11 is that the summer (third) quarter exhibits visibilities about 2 to 3 miles lower than the other seasons. Median visibility, averaged over the twelve locations, is 11.2 miles in the first quarter, 11.7 miles in the second quarter, 8.5 miles in the third quarter, and 10.5 miles in the fourth quarter. The dip in visibility during the summer is especially apparent at the urban/suburban and nonurban locations.

The peaking of haze levels during the summer season has special significance. As will be demonstrated in the next chapter, this is a rather new feature of visibility patterns. By contrast, in the 1950's, visibility during the summer tended to be <u>better</u> than average visibility during the rest of the year.

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* All data in Figure 11 are for the years 1970-1972 except Columbus, Indiana (1967-1969) and Wilmington, Ohio (1966-1967).

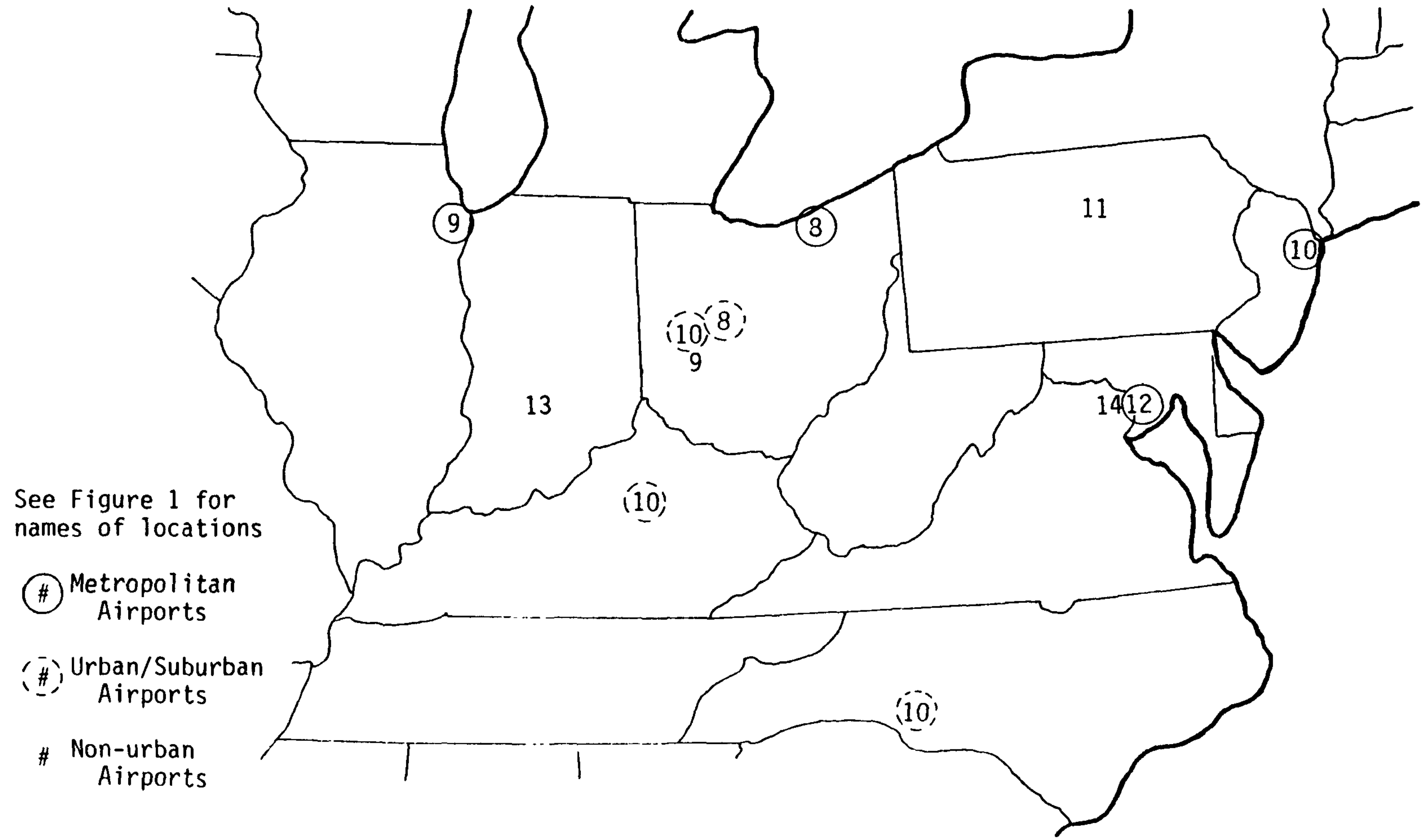

Figure 8. Geographical distribution of median visibilities (in miles).

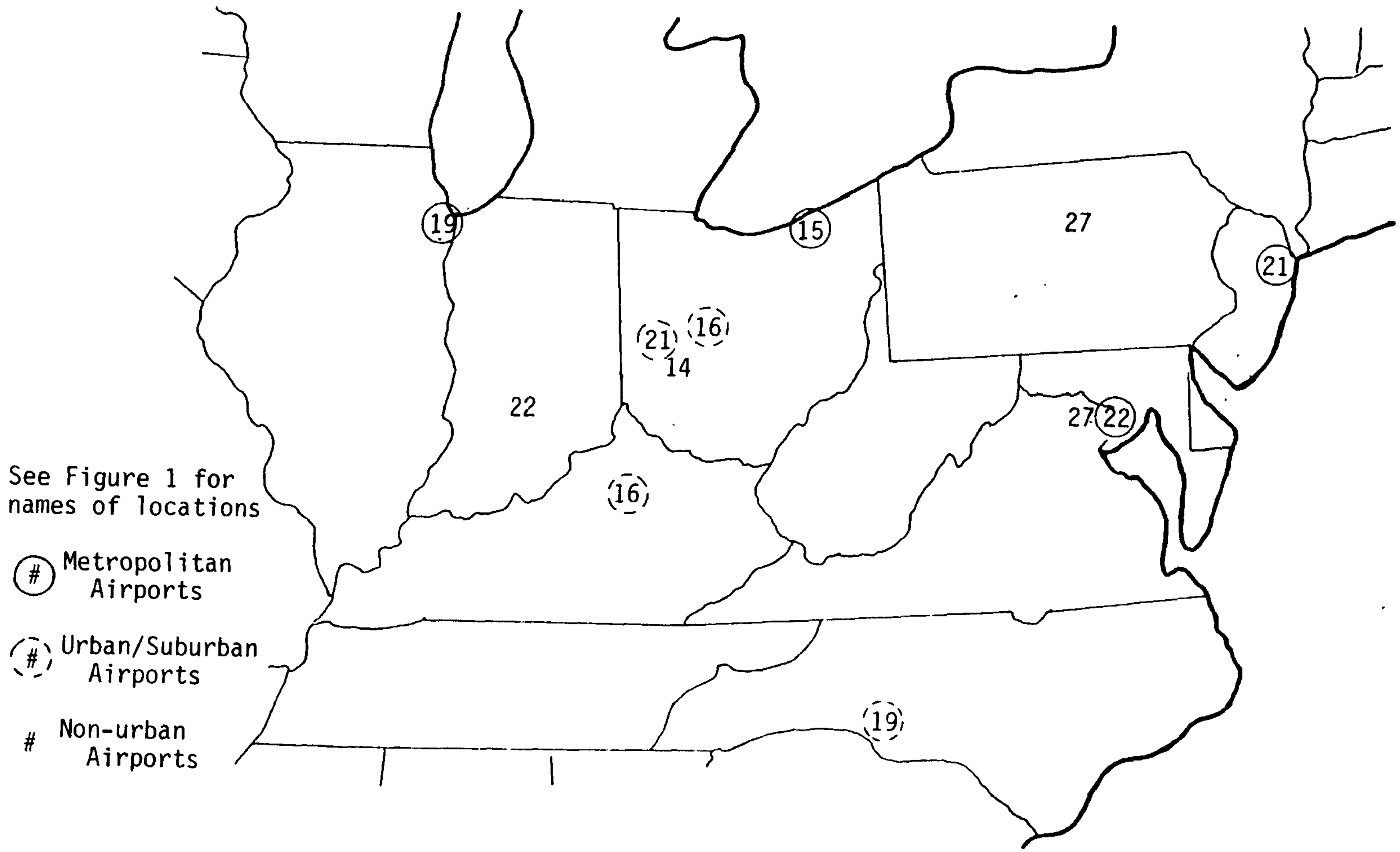

Figure 9. Geographical distribution of (best) 10th percentile visibilities (in miles).

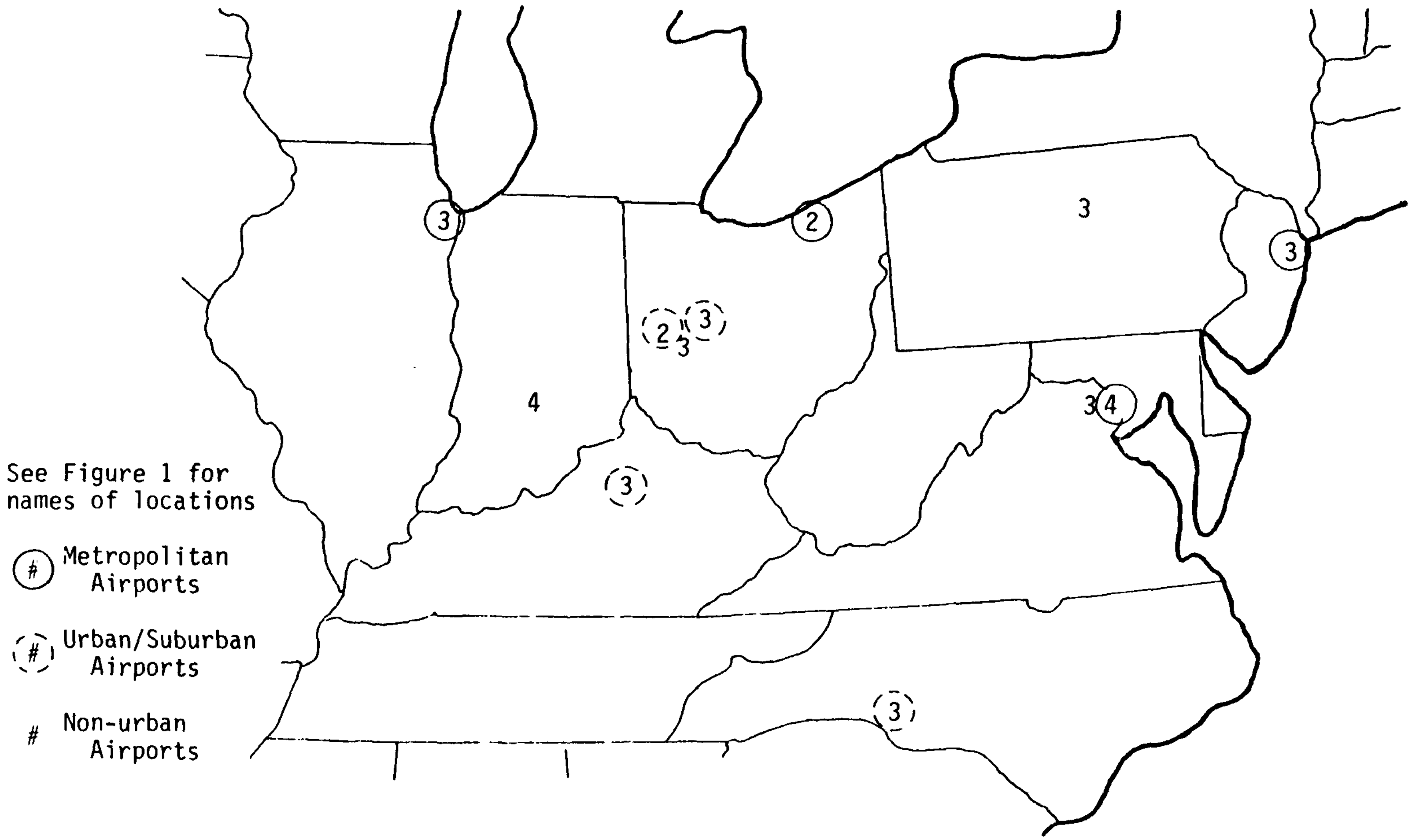

Figure 10. Geographical distribution of (worst) 90th percentile visibilities (in miles).

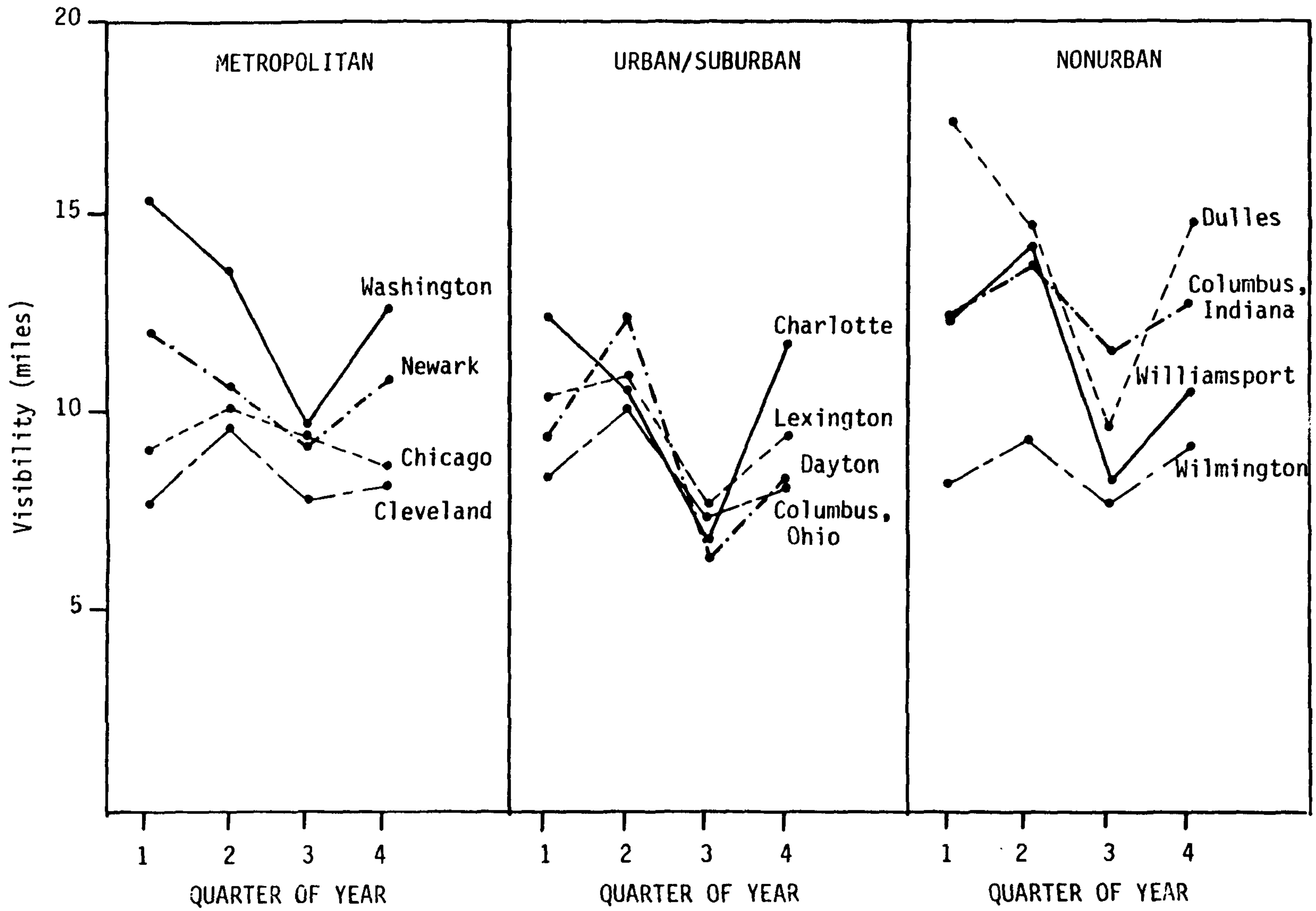

Figure 11. Recent seasonal patterns in median visibility levels.

CHAPTER 4

HISTORICAL VISIBILITY TRENDS

The airport observations offer a unique opportunity to examine historical changes in visibility within the Northeast. This chapter uses the airport data to document changes in visibility from the late 1940's to the early 1970's.

YEARLY TRENDS IN VISIBILITY

Figures 12 through 21 illustrate historical visibility trends at four metropolitan locations (Figures 12 to 15), four urban/suburban locations (Figures 16 to 19), and two nonurban locations (Figures 20 and 21). Trends are presented for the 10th percentile (best visibility), 50th percentile (median visibility), and 90th percentile (worst visibility). For each year, the percentiles are computed from cumulative frequency plots, such as Figures 2 through 4, based only on those visibilities that are routinely reported. Most of the 10th percentiles have been estimated by linear extrapolation of the cumulative frequency distribution.

The basic period for which trend data are available is 1949 to 1972. For Charlotte (Figure 17), the trend analysis is started in 1955 because of a change in the observation site in 1954. Data for Dulles do not start until 1963. As explained in Chapter 2, the two Air Force bases (Columbus, Ind. and Wilmington, Ohio) have been excluded from the trend study because of missing data and inconsistencies over time in reporting practices.

As evidenced by Figures 12 to 21, most of the sites show improvement in visibility from the late 1940's to the middle 1950's, followed by either decreasing or nearly constant visibility from the middle 1950's to the early 1970's. The improving trend in the late 1940's and early 1950's has been noted earlier by Holzworth (1962), who attributed the improvement to the switch toward cleaner fuels (from coal to oil and gas) during that period. Some of the improvement may also have been due to meteorological trends.

Table 6 summarizes net changes in visibility from the middle 1950's to the early 1970's. As indicated by the table, little change occurred in the

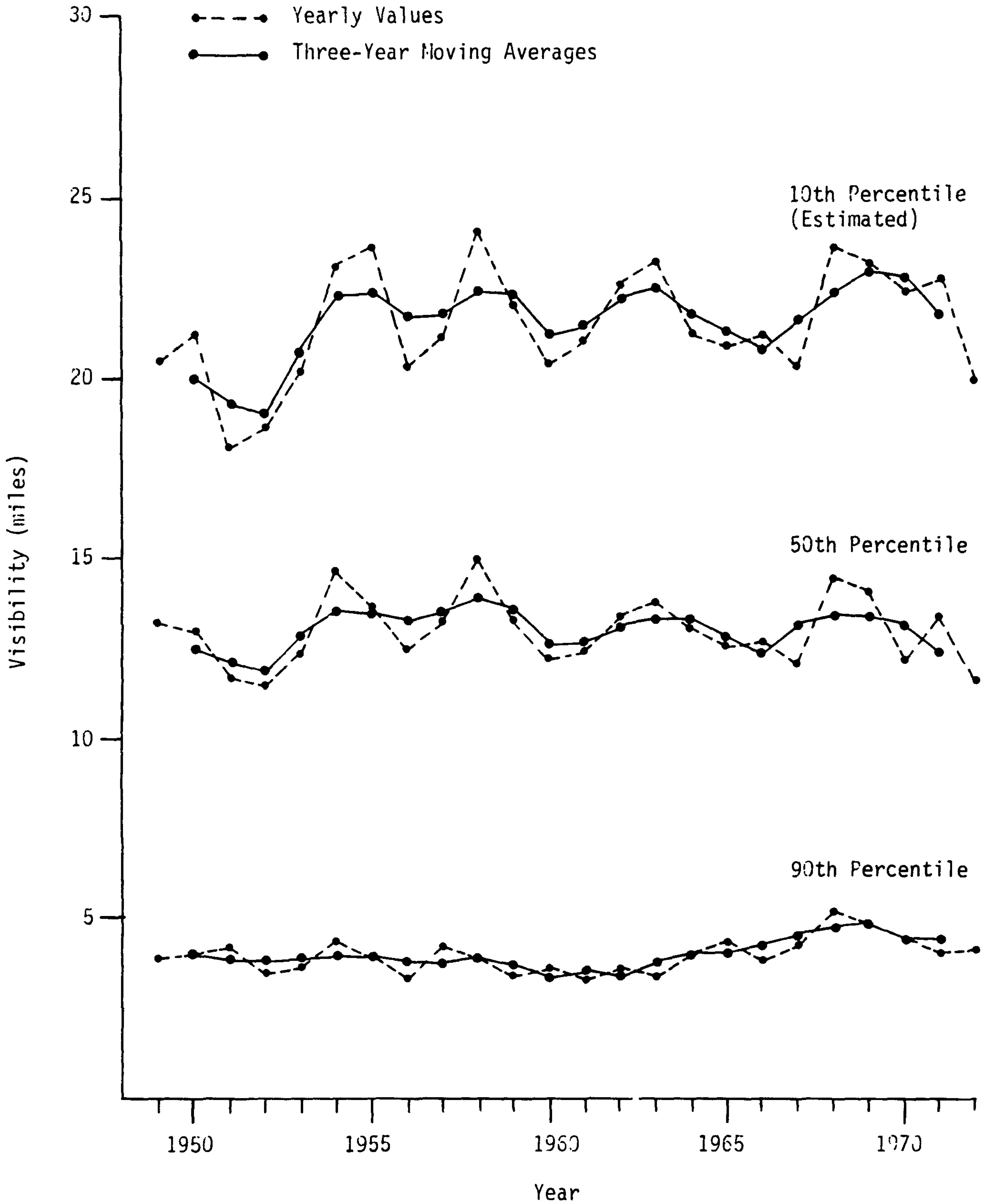

Figure 12. Long-term visibility trends at Washington National.

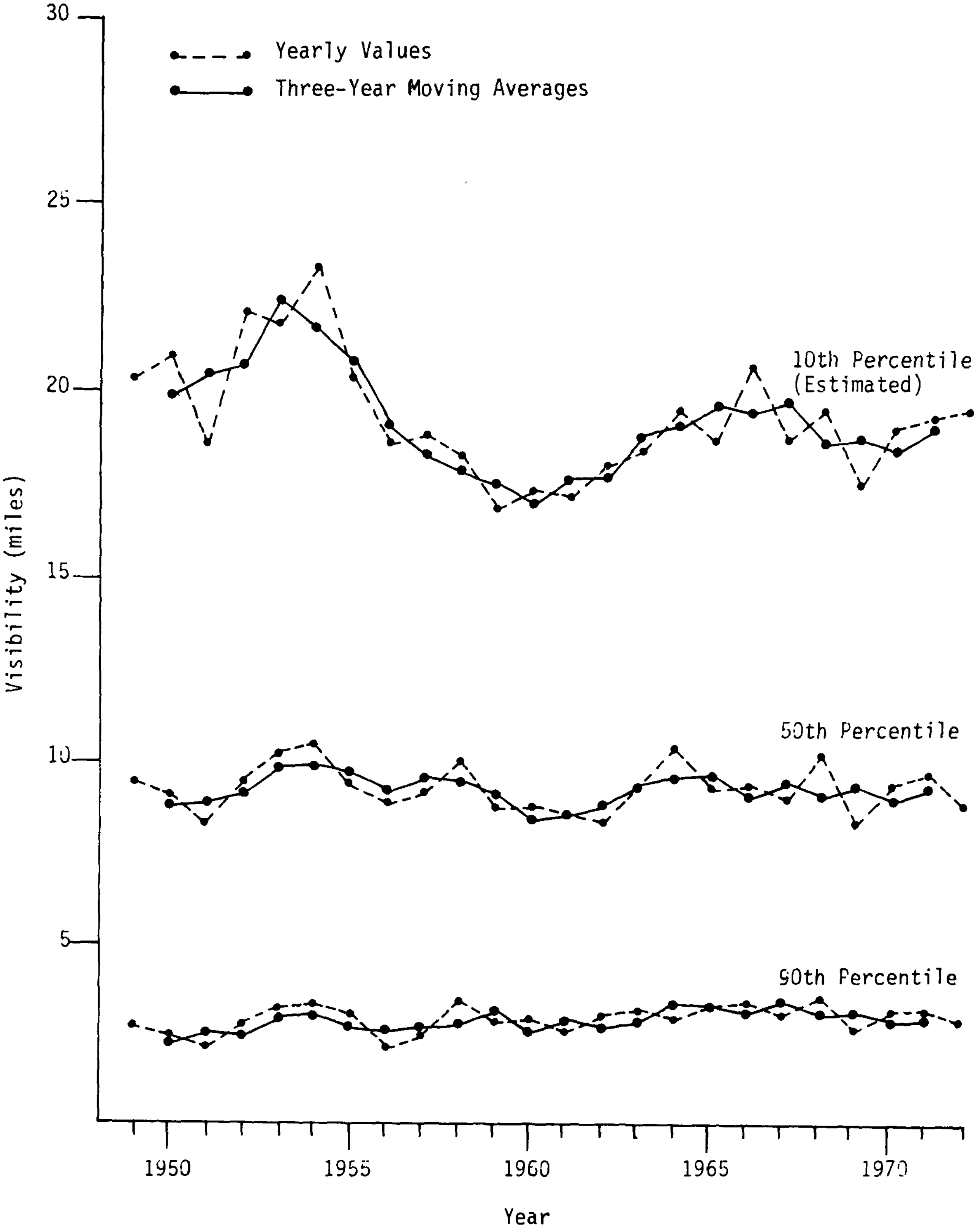

Figure 13. Long-term visibility trends at Chicago.

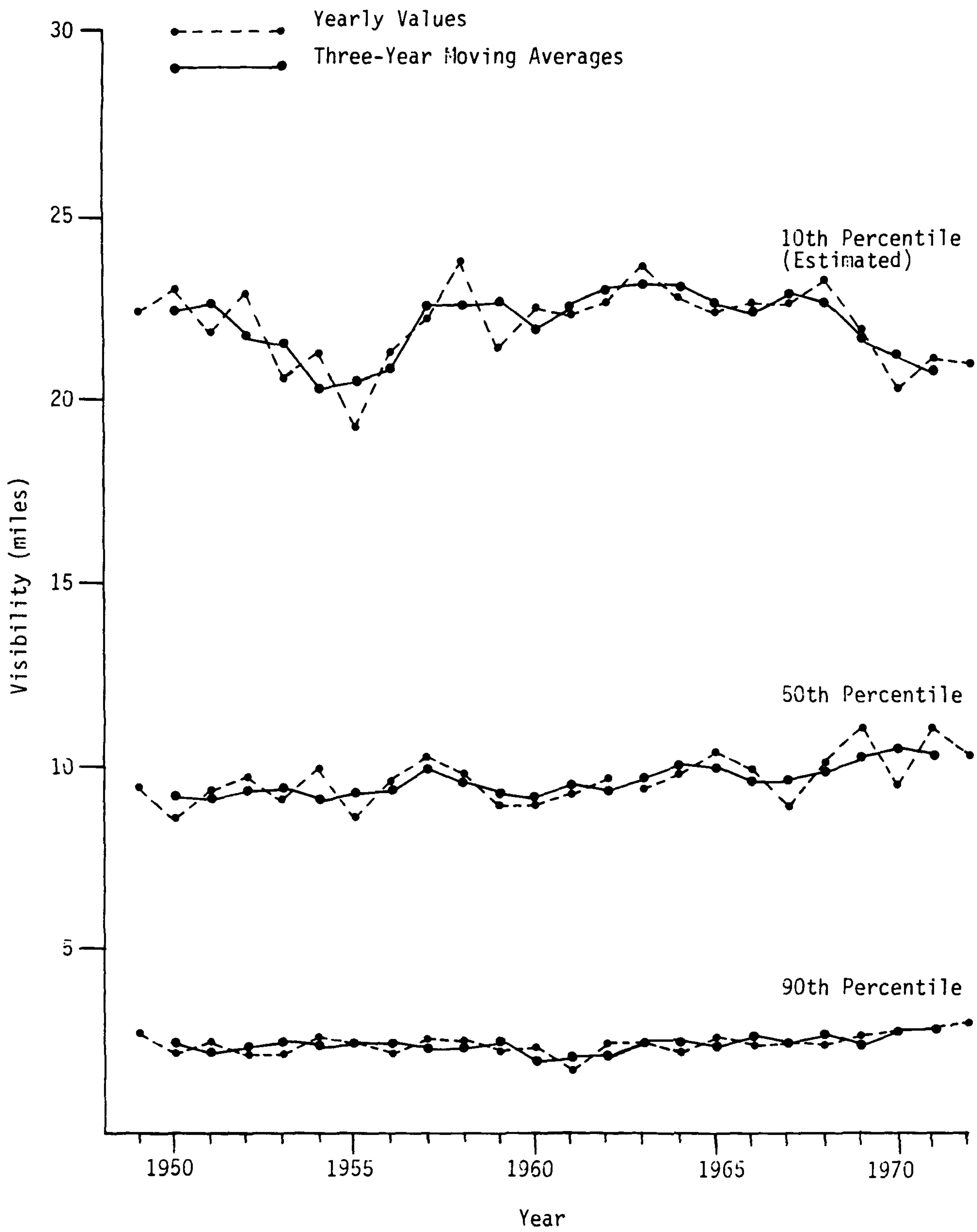

Figure 14. Long-term visibility trends at Newark.

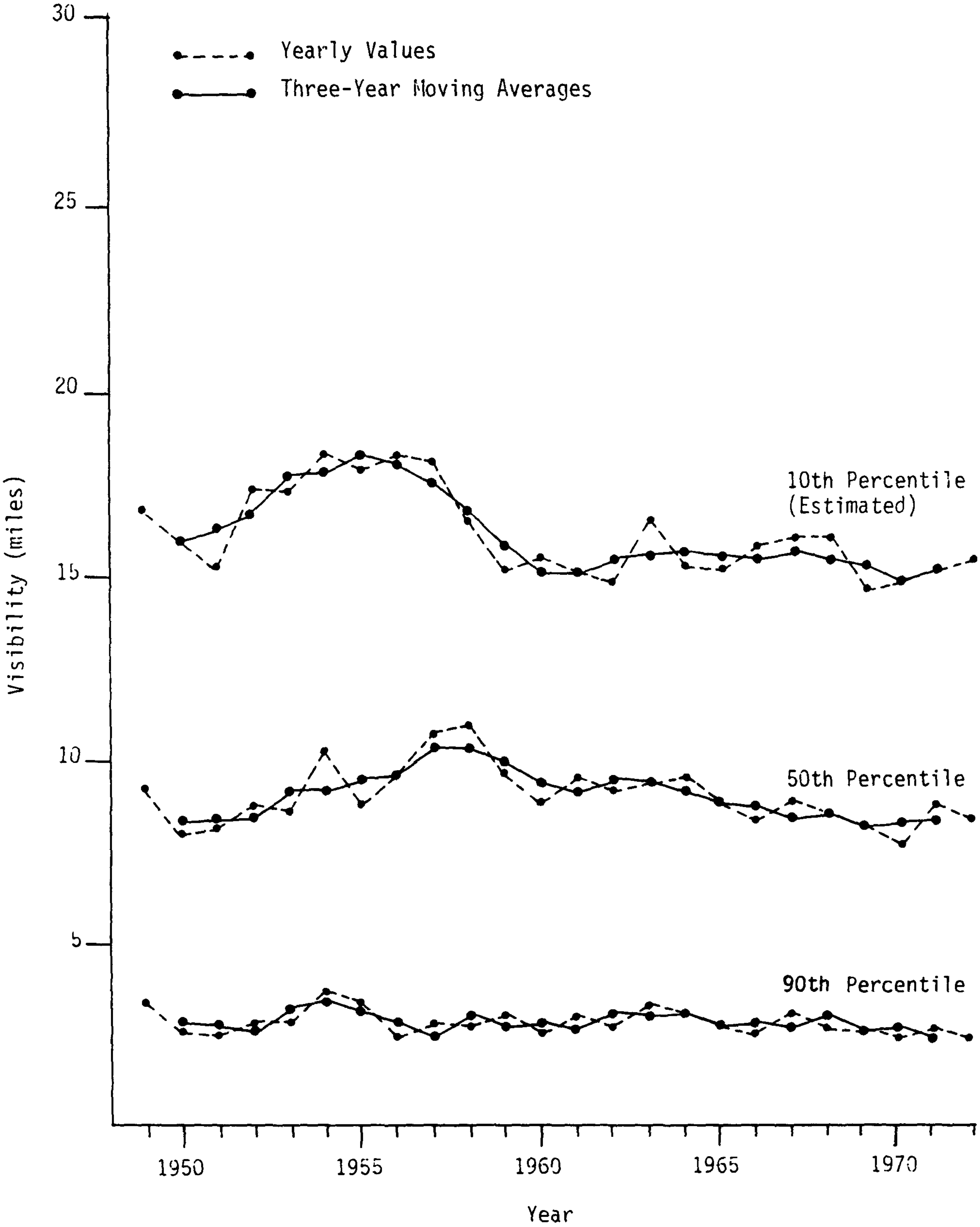

Figure 15. Long-term visibility trends at Cleveland.

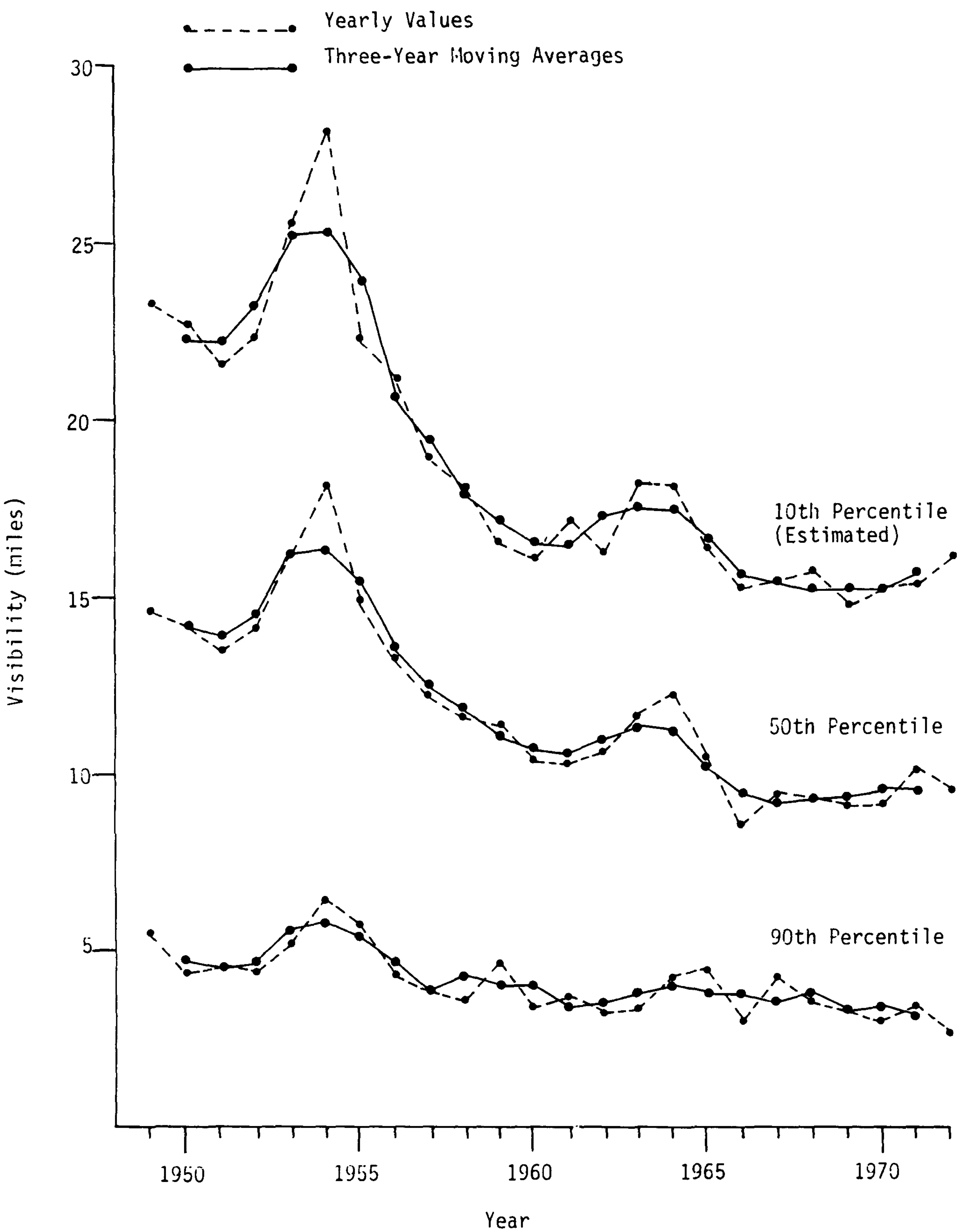

Figure 16. Long-term visibility trends at Lexington.

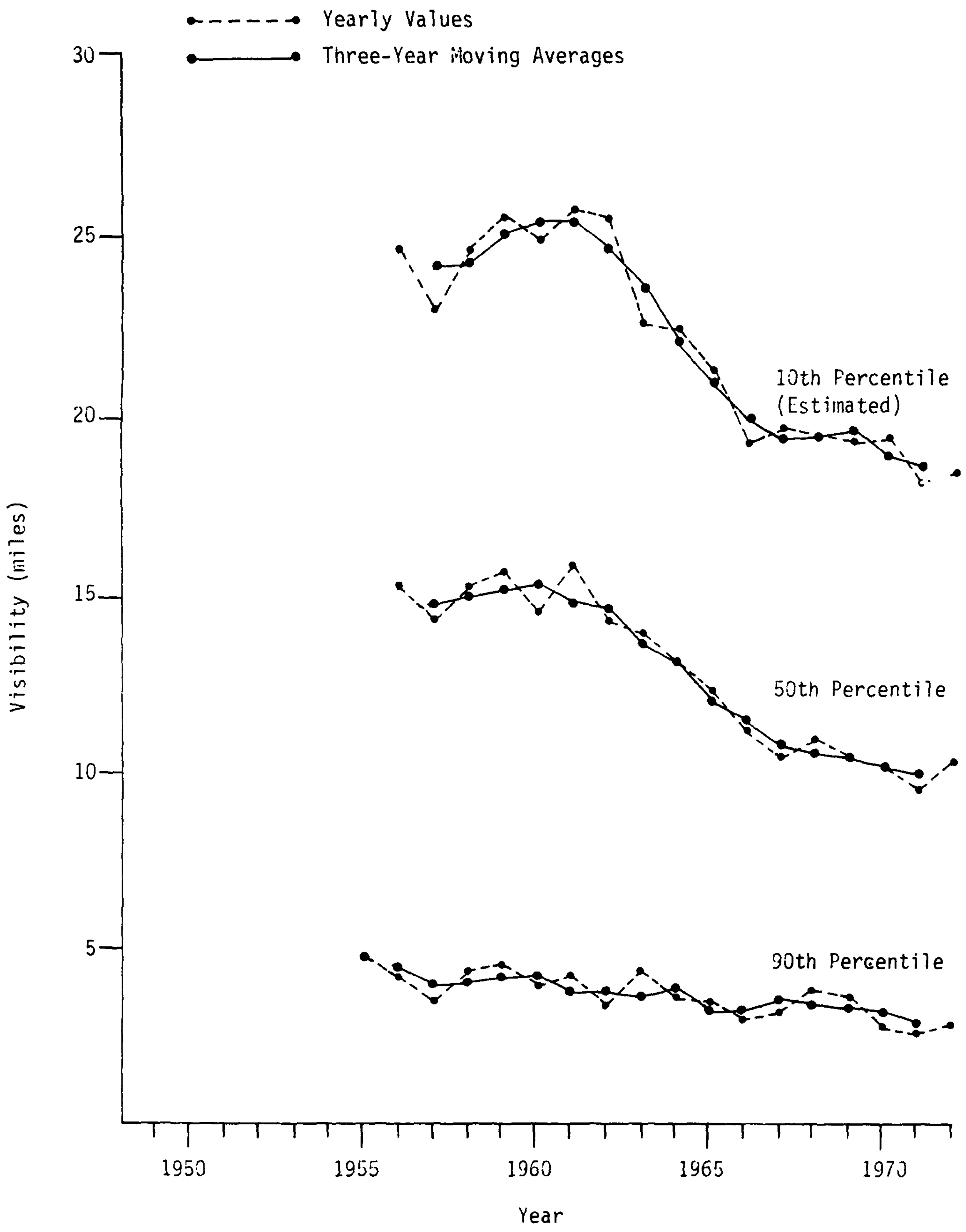

Figure 17. Long-term visibility trends at Charlotte.

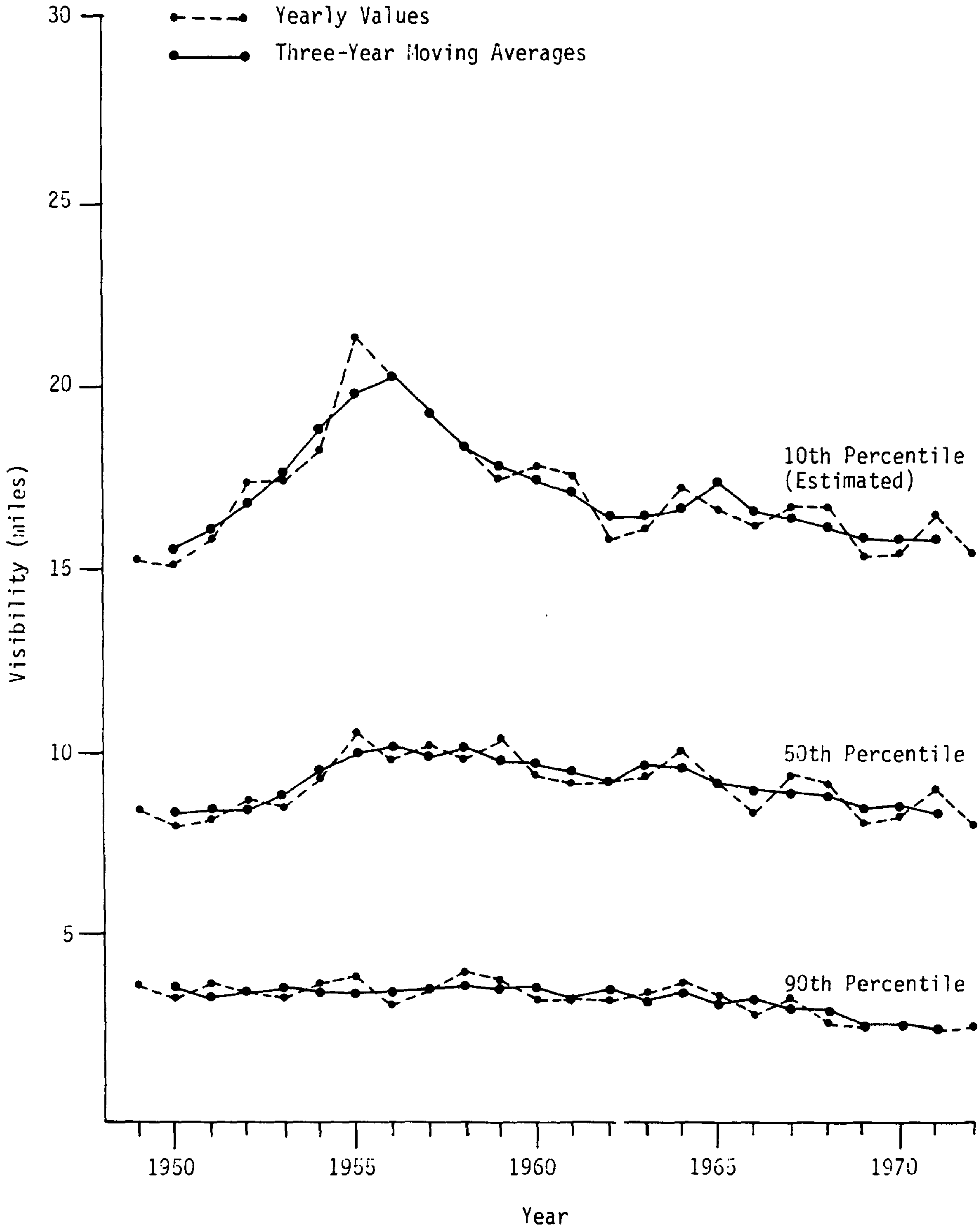

Figure 18. Long-term visibility trends at Columbus.

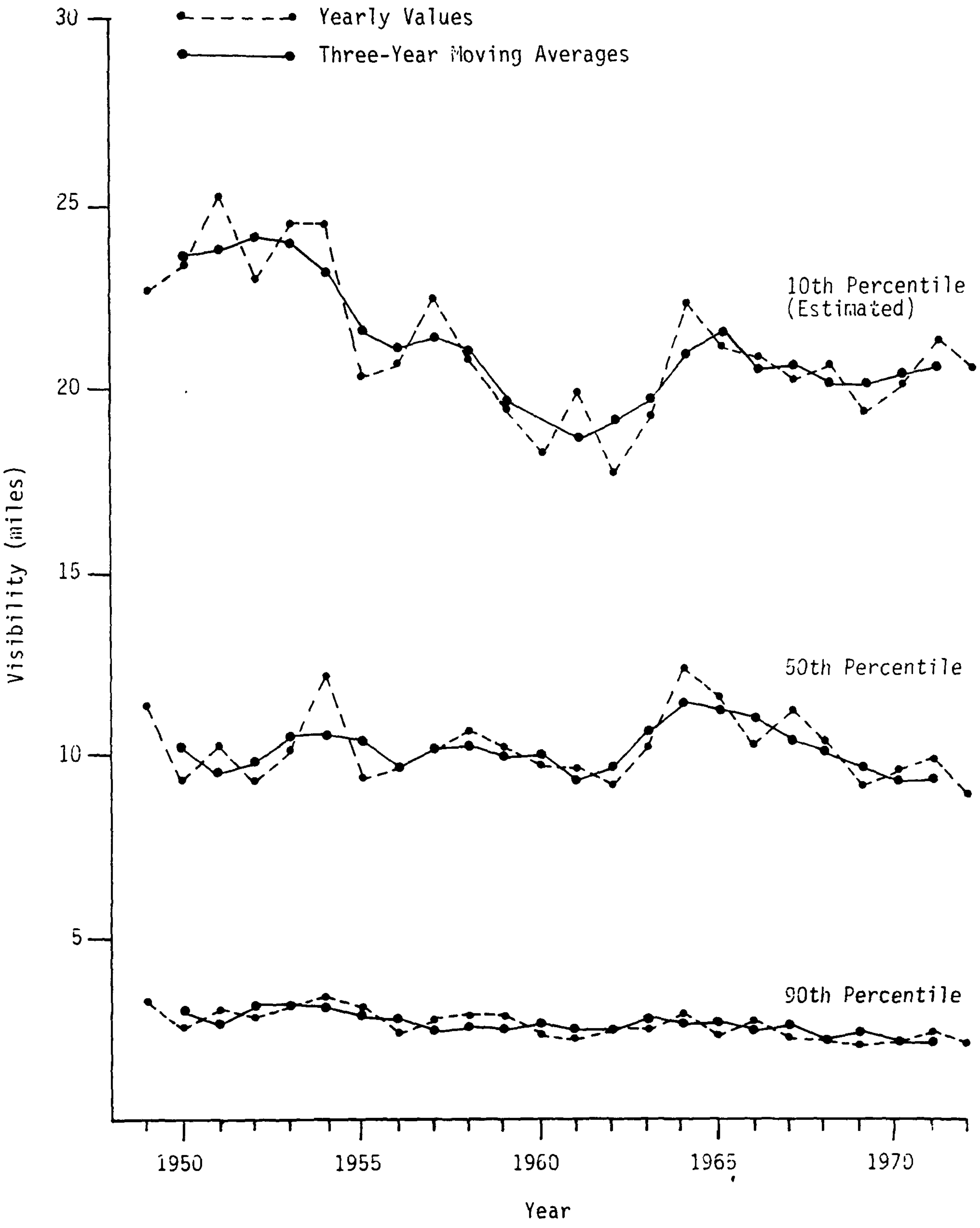

Figure 19. Long-term visibility trends at Dayton.

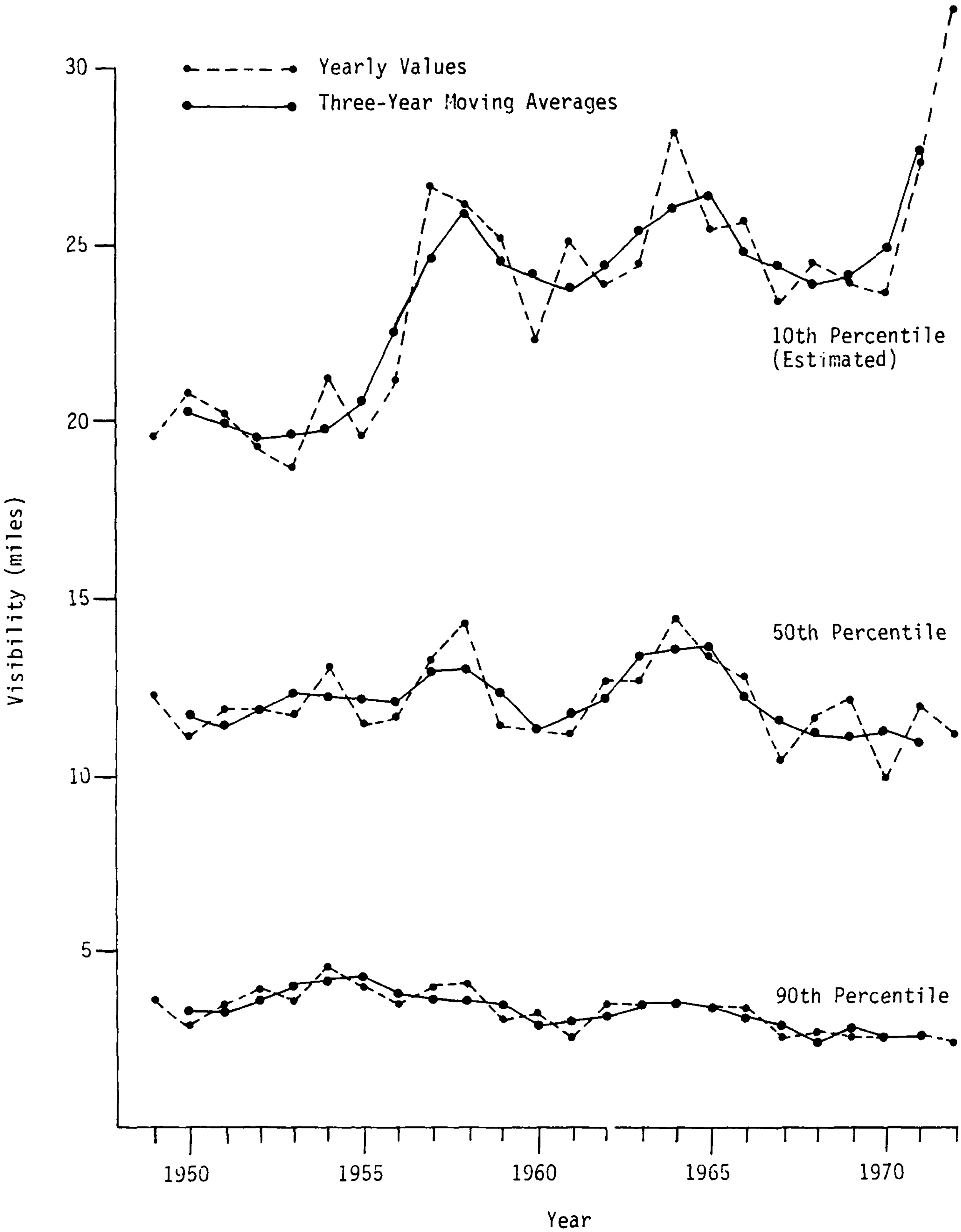

Figure 20. Long-term visibility trends at Williamsport.

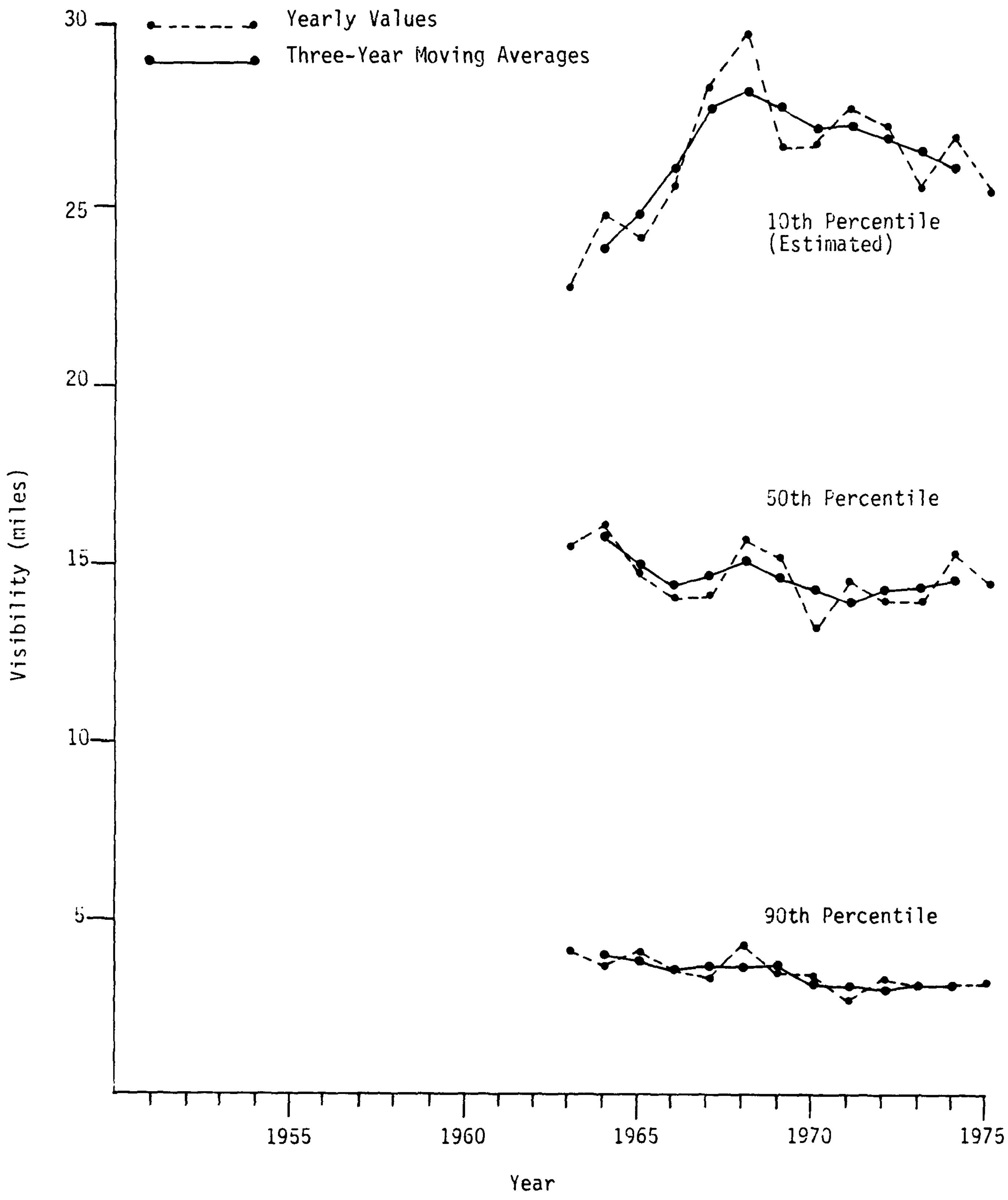

Figure 21. Long-term visibility trends at Dulles.

TABLE 6. 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
METROPOLITAN			
Washington, DC	-2%	-8%	+5%
Chicago, IL	-12%	-6%	-3%
Newark, NJ	+3%	+14%	+21%
Cleveland, OH	-16%	-10%	-24%
Average for Metropolitan Sites	-7%	-2%	0%
URBAN/SUBURBAN			
Lexington, KY	-38%	-41%	-47%
Charlotte*, NC	-24%	-33%	-36%
Columbus, OH	-16%	-11%	-30%
Dayton, OH	-10%	-9%	-31%
Average for Urban/Suburban Sites	-22%	-23%	-36%
NONURBAN			
Williamsport, PA	+39%	-9%	-37%
Dulles*, VA	+44%	-25%	-42%
Average for Nonurban Sites	+41%	-17%	-39%

*Trends for these two locations are extrapolated to cover the period 1954-1971.

haze levels at the metropolitan sites. Visibility increased slightly at Newark, while visibility decreased slightly at Washington, Chicago, and Cleveland. In aggregate, the metropolitan sites show approximately a 5% decrease in visibility from 1953-1955 to 1970-1972.

With the exception of the 10th percentiles at Williamsport and Dulles,* the urban/suburban and nonurban locations show considerable decreases in visibility, on the order of 10 to 40%, from 1953-1955 to 1970-1972. The greatest decrease in visibility, approximately 30 to 40%, occurred at the two southernmost locations, Lexington and Charlotte. The increase in haze at urban/suburban and nonurban locations is consistent with other findings published in the literature. Miller et al (1972) reported substantial decreases in summertime visibility from 1962 to 1969 at three suburban airports (Akron, Ohio; Lexington, Kentucky; and Memphis, Tennessee). Using sun photometers, Peterson and Flowers (1977) found increases in atmospheric turbidity from the 1960's to the 1970's at four suburban/nonurban locations (Meridian, Mississippi; St. Cloud, Minnesota; Oak Ridge, Tennessee; and Raleigh, North Carolina).

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

$$B - B_{Rayleigh} = \frac{24.3}{V} - 0.15 \qquad (12)$$

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

Table 7 summarizes the net changes in extra extinction from 1953-1955 to 1970-1972. Viewed as a whole, the net change in extra extinction at the metropolitan sites was quite small, an increase of about 5%. With the exception of the 10th percentiles at Williamsport and Dulles, the urban/suburban and nonurban sites showed substantial increases in extra extinction, on the order of 10 to 80%. The two largest increases occurred at Lexington (approximately 80%) and Charlotte (approximately 50%).

*The anomalous trends in the 10th percentiles at Williamsport and Dulles may, in part, be an artifact produced by the extrapolation techniques used to estimate 10th percentile visibility.

TABLE 7. NET PERCENT CHANGES IN EXTRA EXTINCTION, 1953-1955 TO 1970-1971

LOCATION	CHANGES IN THREE-YEAR AVERAGES, 1954 to 1971		
	Best (10th%) Extinction	Median Extinction	Worst (90th%) Extinction
METROPOLITAN			
Washington, DC	+2%	+9%	-5%
Chicago, IL	+17%	+7%	+3%
Newark, NJ	-4%	-13%	-18%
Cleveland, OH	+21%	+12%	+33%
Average for Metropolitan Sites	+9%	+4%	+3%
URBAN/SUBURBAN			
Lexington, KY	+74%	+79%	+90%
Charlotte*, NC	+37%	+55%	+59%
Columbus, OH	+21%	+12%	+43%
Dayton, OH	+13%	+11%	+47%
Average for Urban/Suburban Sites	+36%	+39%	+60%
NONURBAN			
Williamsport, PA	-32%	+11%	+58%
Dulles*, VA	-35%	+37%	+74%
Average for Nonurban Sites	-33%	+24%	+66%

*Trends for these two locations are extrapolated to cover the period 1954-1971.

SEASONAL TRENDS IN VISIBILITY

It is of interest to examine historical trends in visibility according to season. Figures 22 through 31 present historical visibility at the ten study locations, disaggregated by quarter of the year. The striking feature of Figures 22 to 31 is the strong downward trend in visibility during the summer (third) quarter. In the early 1950's, the third quarter tended to be either the best or second best season for visibility. By the early 1970's, the third quarter was almost invariably the worst season for haze.

The historical changes in seasonal visibility from 1954 to 1971 are highlighted in Table 8. Visibility decreased at every location during the summer, and the summer decrease at each location was greater than the decrease in any other season. The net percentage reductions in summer visibility from 1953-1955 to 1970-1972 are approximately 5 to 25% for metropolitan locations and 25 to 60% for urban/suburban and nonurban locations. At four locations (Lexington, Charlotte, Dayton, and Dulles) summer visibility decreased by approximately a factor c⁻ 2 to 2.5 from 1953-1955 to 1970-1972.

Table 8 indicates that the slight downward trend in yearly visibility at metropolitan sites is composed of moderate visibility decreases during the summer which more than negate slight to moderate visibility increases during the winter. The moderate downward trend in yearly visibility at urban/suburban and nonurban locations is basically composed of substantial visibility decreases during the summer and slight to moderate decreases during other seasons.

Table 9 presents seasonal trends in extra extinction (above-and-beyond blue-sky scatter), calculated according to Equation (12). Qualitatively, the trends in extra extinction are essentially reverse images of the trends in visibility. It is notable that, at urban/suburban and nonurban locations, extra extinction during the summer approximately doubled from 1953-1955 to 1970-1972. The largest summertime increases were at Lexington (161%), Charlotte (136%), Dulles (120%), and Dayton (102%).

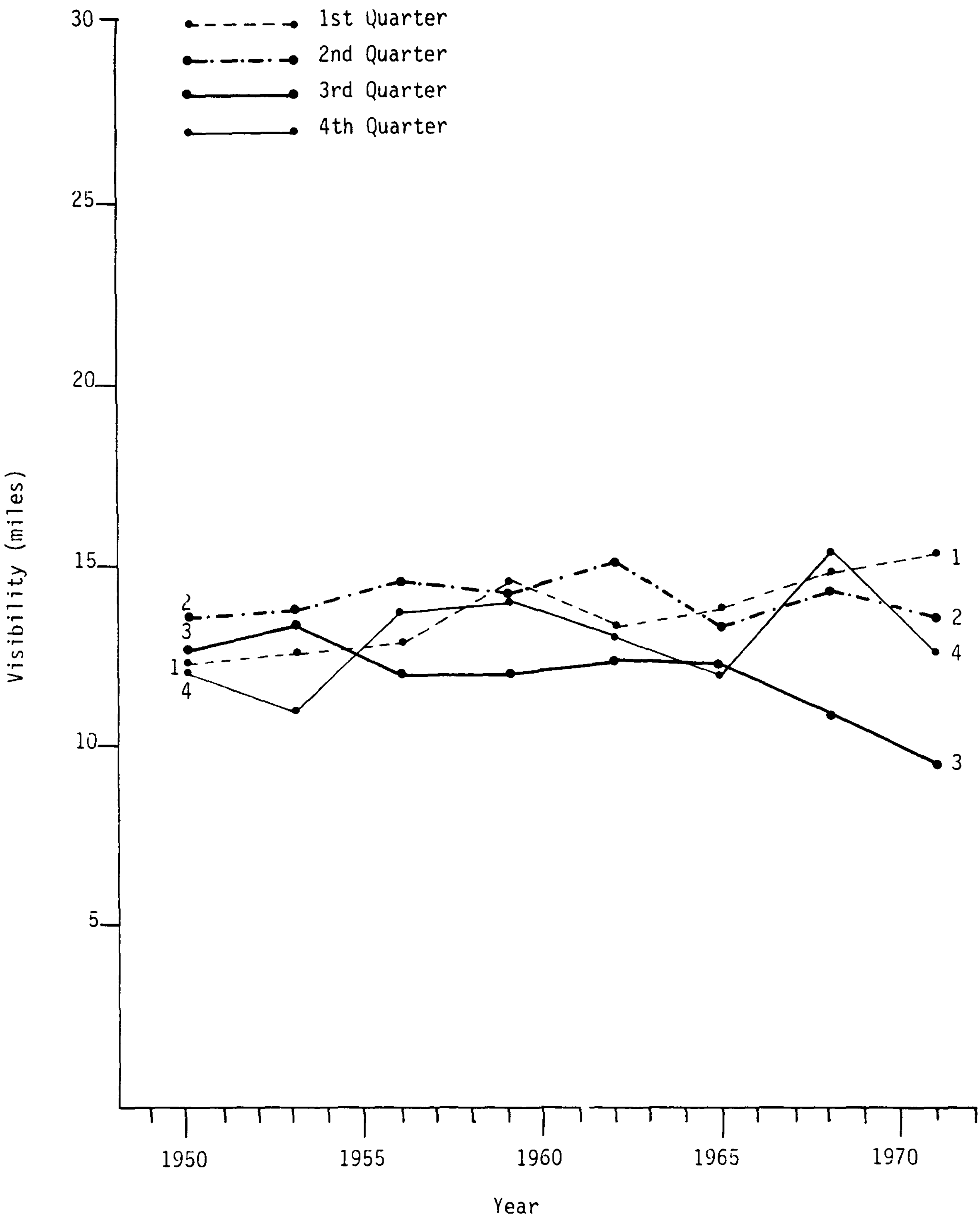

Figure 22. Seasonal visibility trends at Washington National (median level, 3 year averages).

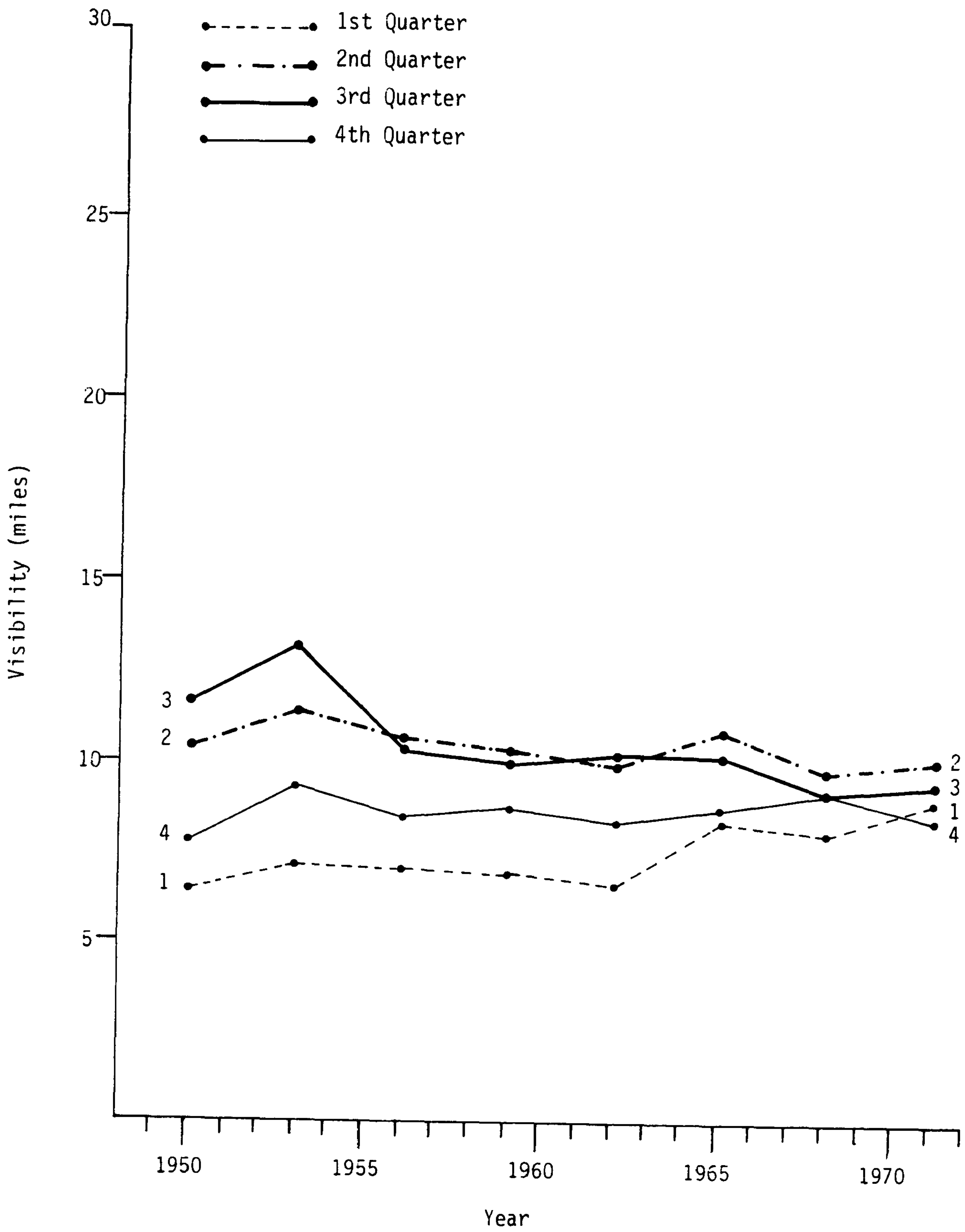

Figure 23. Seasonal visibility trends at Chicago (median level, 3 year averages).

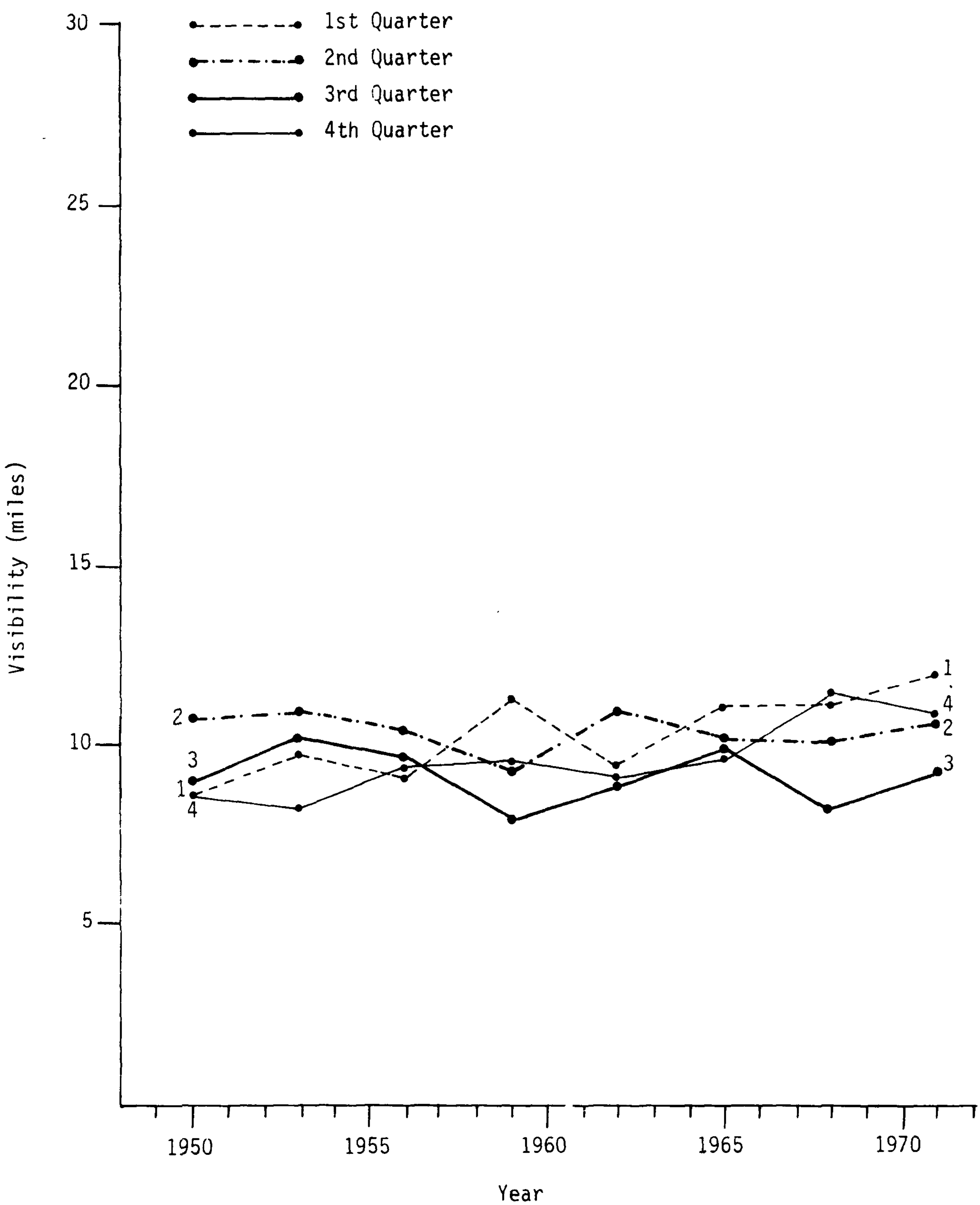

Figure 24. Seasonal visibility trends at Newark (median level, 3 year averages).

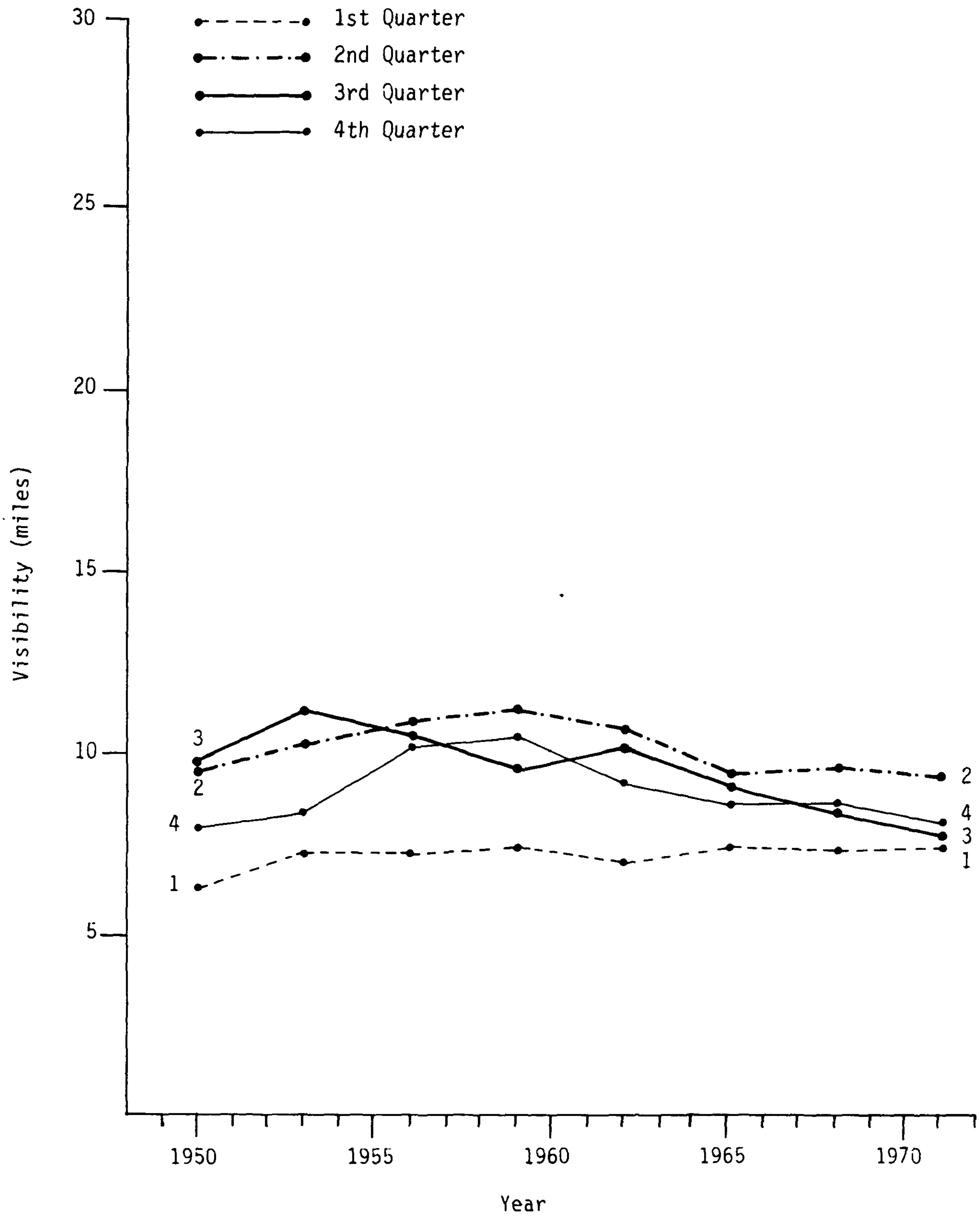

Figure 25. Seasonal visibility trends at Cleveland (median level, 3 year averages).

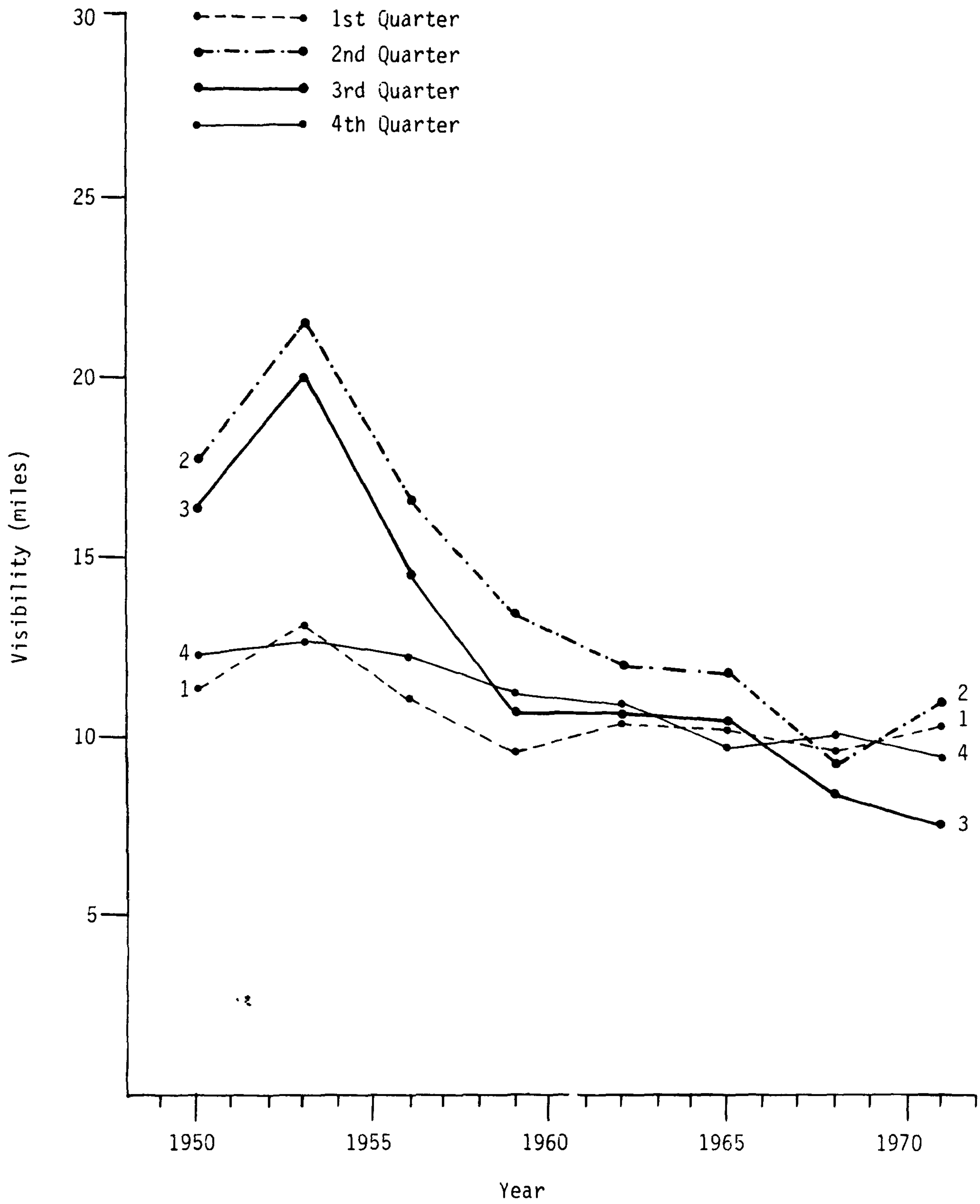

Figure 26. Seasonal visibility trends at Lexington (median level, 3 year averages).

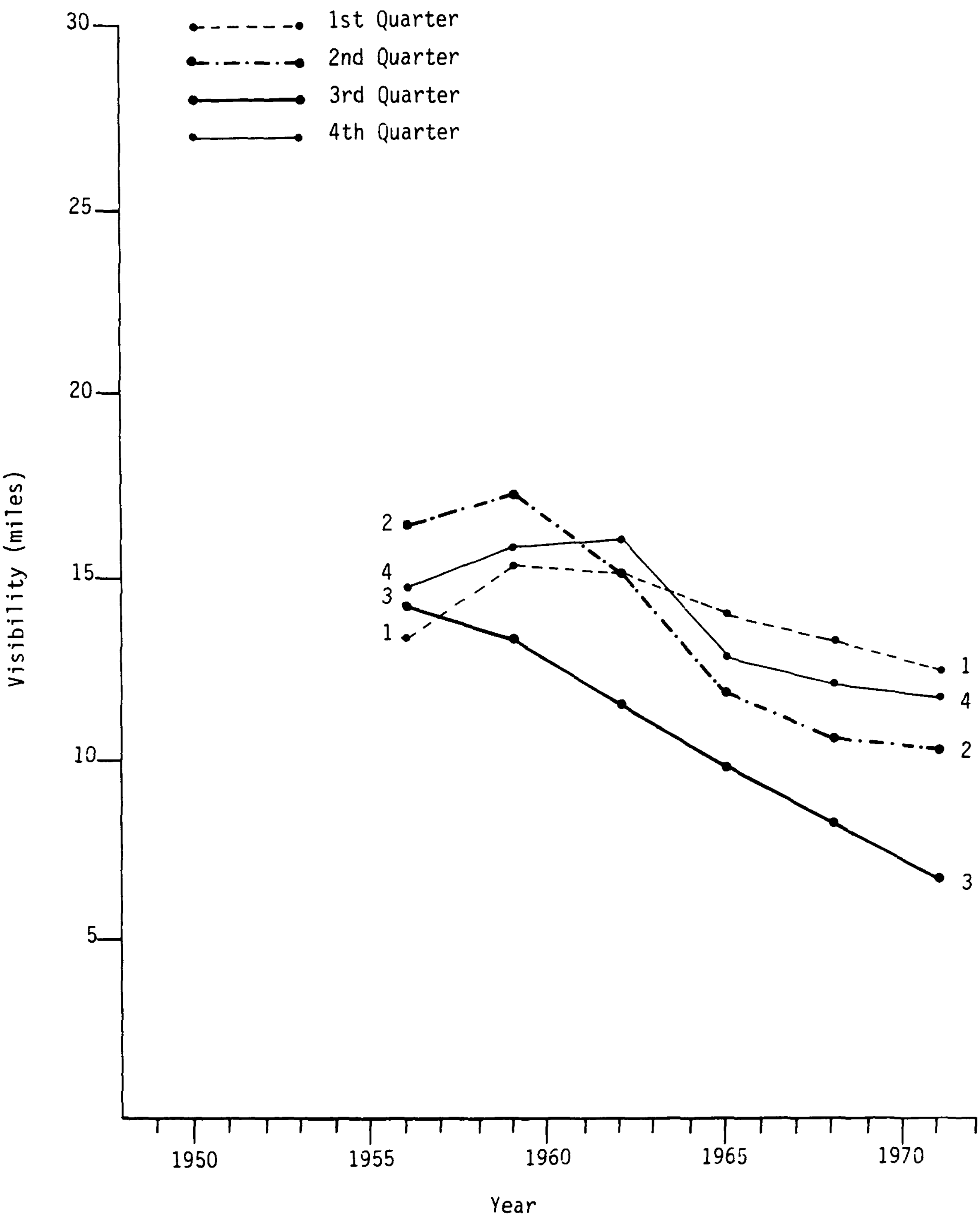

Figure 27. Seasonal visibility trends at Charlotte (median level, 3 year averages).

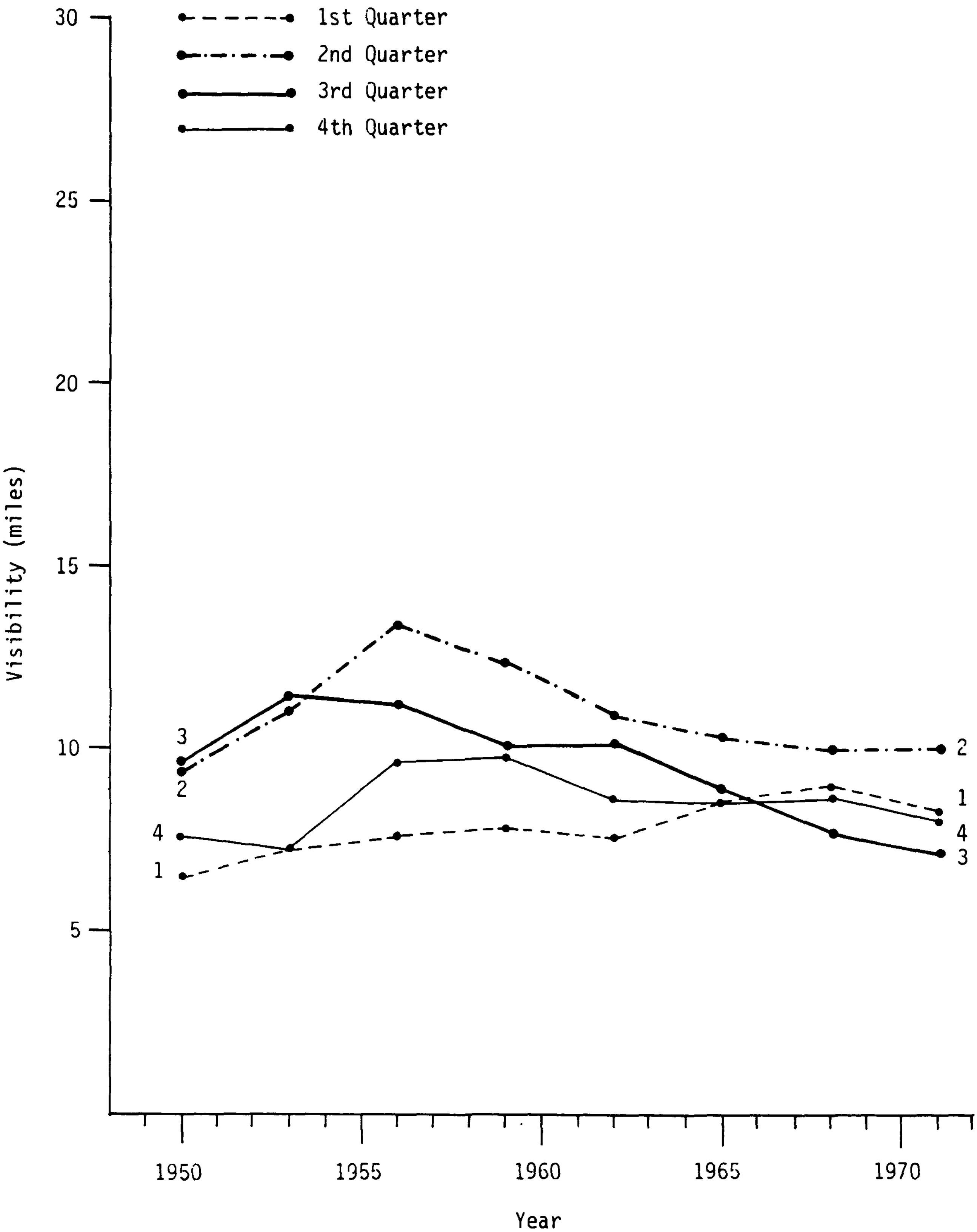

Figure 28. Seasonal visibility trends at Columbus (median level, 3 year averages).

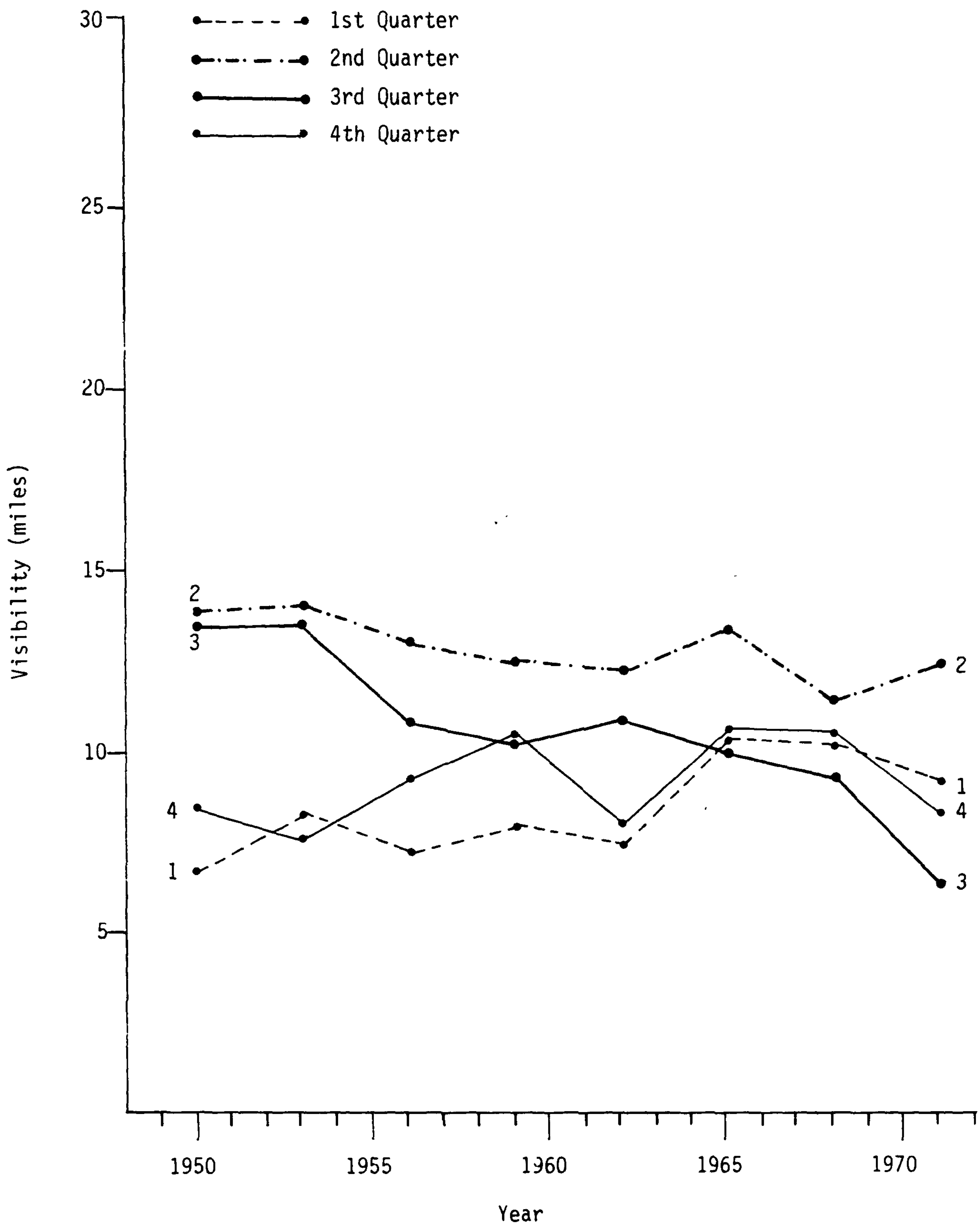

Figure 29. Seasonal visibility trends at Dayton (median level, 3 year averages).

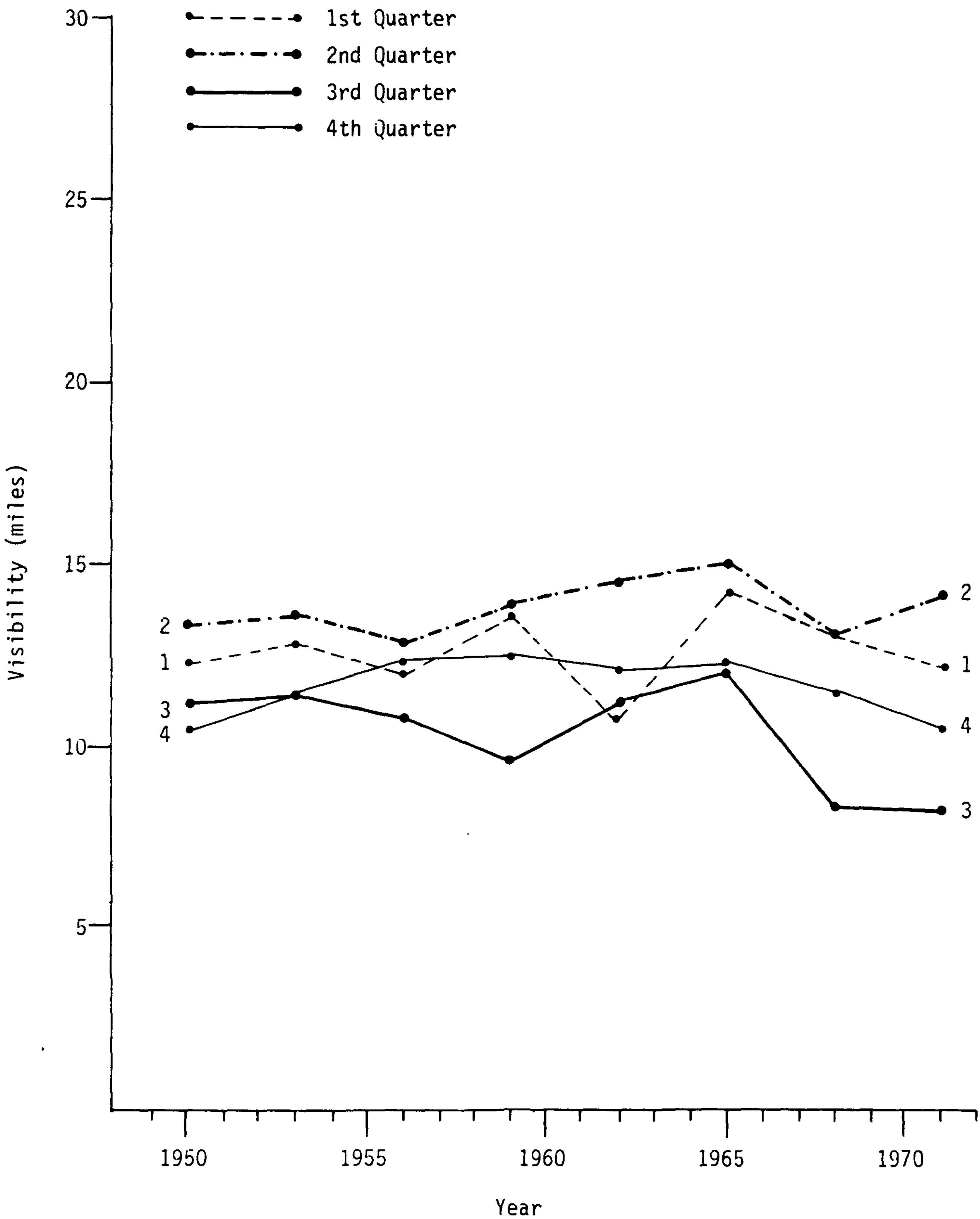

Figure 30. Seasonal visibility trends at Williamsport
(median level, 3 year averages).

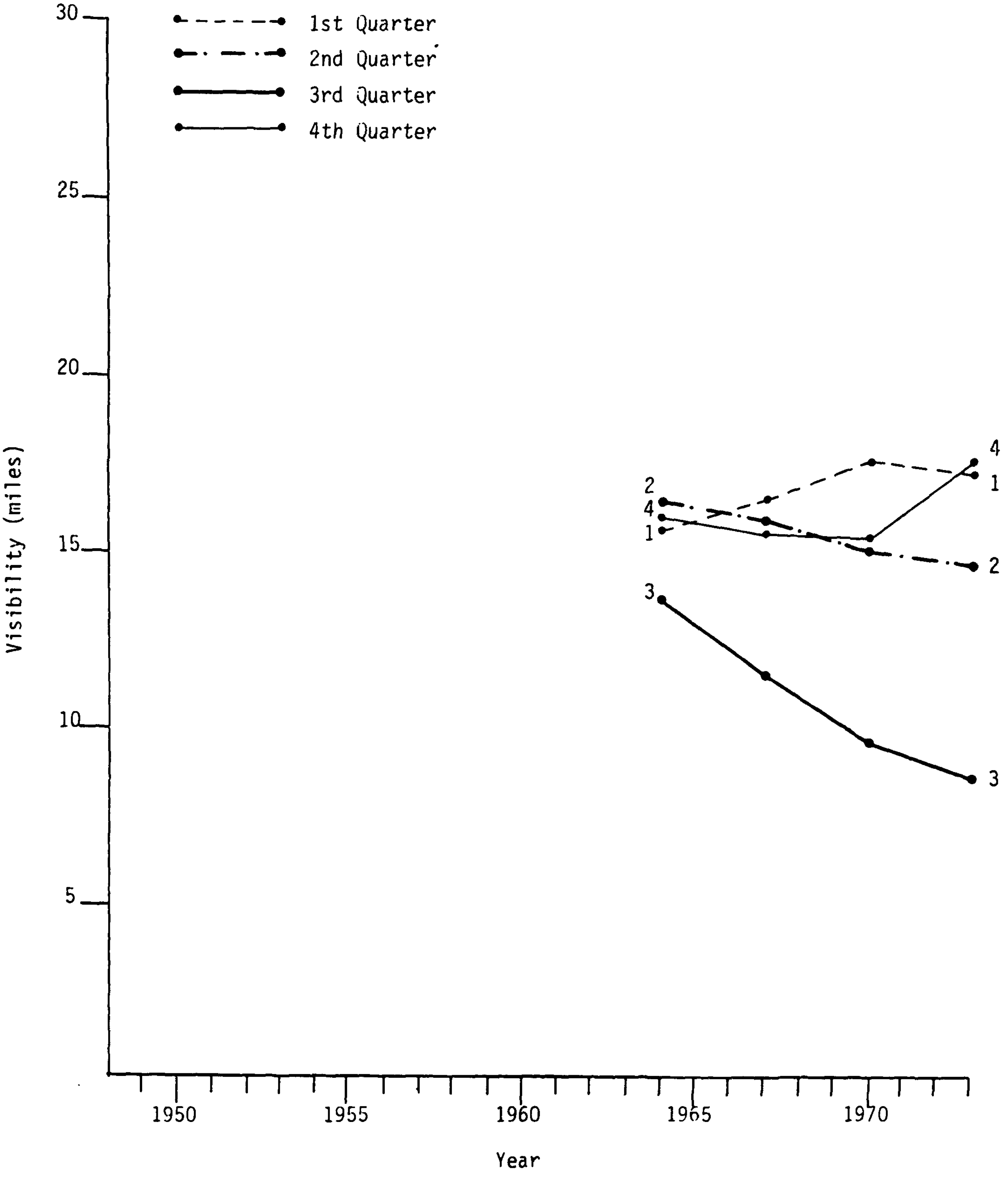

Figure 31. Seasonal visibility trends at Dulles (median levels, 3 year averages).

TABLE 8. NET PERCENT CHANGES IN VISIBILITY BY SEASON, 1953-1955 TO 1970-1972

LOCATION	CHANGES IN THREE-YEAR AVERAGES OF MEDIAN VISIBILITY, 1954-1971				
	Jan.- Mar.	Apr.-June	July - Sept.	Oct.- Dec.	Entire Year
METROPOLITAN					
Washington, DC	+11%	-6%	-27%	-2%	-8%
Chicago, IL	+18%	-13%	-22%	-7%	-6%
Newark, NJ	+28%	+10%	-4%	+25%	+14%
Cleveland, OH	-3%	-8%	-23%	-8%	-10%
Average for Metropolitan Sites	+14%	-4%	-19%	+2%	-2%
URBAN/SUBURBAN					
Lexington, KY	-25%	-49%	-59%	-32%	-41%
Charlotte*, NC	-7%	-39%	-55%	-22%	-33%
Columbus, OH	+6%	-15%	-30%	-4%	-11%
Dayton, OH	+9%	-11%	-48%	-2%	-9%
Average for Urban/Suburban Sites	-4%	-28%	-48%	-15%	-23%
NONURBAN					
Williamsport, PA	-3%	+10%	-25%	-6%	-9%
Dulles*, VA	+29%	-19%	-52%	-15%	-25%
Average for Nonurban Sites	+13%	-4%	-38%	-10%	-17%

*Trends for these two locations are extrapolated to cover the period 1954-1971.

TABLE 9. NET PERCENT CHANGES IN EXTRA EXTINCTION BY SEASON, 1953-1955 TO 1970-1972

LOCATION	CHANGES IN THREE-YEAR AVERAGES OF MEDIAN EXTRA EXTINCTION, 1954 to 1971				
	Jan.- Mar.	Apr.- June	July - Sept.	Oct.- Dec.	Entire Year
METROPOLITAN					
Washington, DC	-10%	+6%	+41%	+2%	+9%
Chicago, IL	-16%	+16%	+31%	+8%	+7%
Newark, NJ	-23%	-10%	+4%	-21%	-13%
Cleveland, OH	+3%	+10%	+33%	+9%	+12%
Average for Metropolitan Sites	-11%	+5%	+27%	0%	+4%
URBAN/SUBURBAN					
Lexington, KY	+37%	+112%	+161%	+52%	+79%
Charlotte*, NC	+8%	+71%	+136%	+31%	+55%
Columbus, OH	-6%	+20%	+47%	+4%	+12%
Dayton, OH	-9%	+13%	+102%	+3%	+11%
Average for Urban/Suburban Sites	+7%	+54%	+111%	+22%	+39%
NONURBAN					
Williamsport, PA	+4%	-10%	+36%	+7%	+11%
Dulles*, VA	-25%	+28%	+120%	+20%	+37%
Average for Nonurban Sites	-10%	+9%	+78%	+13%	+24%

*Trends for these two locations are extrapolated to cover the period 1954-1971.

DISCUSSION OF VISIBILITY PATTERNS AND TRENDS

A natural question to pose at this point is "What caused the historical visibility changes in the Northeast?" Because the results of our visibility/pollutant regressions (Chapter 5) indicate that sulfate aerosol is the major contributor to haze in the Northeast, one might hypothesize that the visibility changes were related to sulfate changes. Indeed, this hypothesis becomes very plausible if one considers the following similarities between sulfate patterns and visibility patterns:

- From the early 1960's to the early 1970's, sulfate concentrations did not change greatly at most urban sites in the Northeast, but increased substantially at nonurban sites (EPA 1975; Trijonis 1975; Frank and Posseil 1976). Visibility has changed very little at metropolitan locations, but has decreased substantially at urban/suburban and nonurban locations.

- By the early 1970's, nonurban sulfate concentrations in the Northeast (averaging ~10 $\mu g/m^3$) were nearly as great as urban sulfate concentrations (averaging ~14 $\mu g/m^3$) (EPA 1975; Frank and Posseil 1976). Visibility in nonurban areas tended to be only slightly better than visibility in metropolitan areas.*

- From the middle 1960's to the early 1970's sulfate concentrations in the Northeast increased substantially during the third calendar quarter relative to sulfate concentrations in other seasons (Frank and Posseil 1976). By the early 1970's, these trends had produced a distinct third quarter maximum in the seasonal pattern for sulfates. Likewise, the decreasing trend in visibility was especially pronounced during the third quarter. By the early 1970's, the seasonal pattern for visibility exhibited a distinct minimum in the third quarter.

- In the middle 1960's, the area of greatest sulfate concentrations centered around the Ohio Valley. By the early 1970's, the area of greatest sulfate concentrations had expanded in a southeasterly direction (Frank and Posseil 1976). The largest decreasing trends in visibility were observed in the southeasterly part of the Northeast quadrant (i.e. at Lexington and Charlotte).

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*Actually, the urban/nonurban difference in visibility is even smaller than the urban/nonurban difference in sulfates. This may be explained, in part, by the fact that visibility observations represent integrals over several miles, while sulfate data are point measurements.

- An area of decreasing sulfate trends existed in New York State, and the New York City, northern New Jersey metropolitan area extending to Philadelphia (Frank and Posseil 1976). This was the only area where we found an increasing trend in visibility, (i.e. at Newark).

A companion report to this project (Husar and Patterson 1978) provides data on historical SO_x emission trends, by source type and by season. The patterns in these emission trends lead us to propose the following hypotheses as explanations for the sulfate and visibility trends:

- The increases in sulfates (ana decreases in visibility) at nonurban locations in the Northeast are related to the substantial increase that occurred in SO_x emissions from nonurban, tall-stack sources (power plants).

- In most metropolitan areas, sulfates (and visibility) have remained approximately constant because the increase in background sulfates was negated by the effect of reduced local SO_x emissions from residential, commercial, and industrial sources.

- Sulfates (and visibility) did not show strong trends in the winter because the power plant emission increase was not as large in the winter as in the summer and because most of the SO_x reduction from commercial and residential sources occurred in the winter.

- Sulfates rose (and visibility fell) dramatically during the summer because the growth in power plant SO_x was especially pronounced during the summer and because there was little SO_x reduction from other sources during the summer. The increase in summertime sulfate may also have been related to increases in photochemical smog, from hydrocarbon and NO_x emission growth, which would promote more rapid and complete oxidation of SO_2.

CHAPTER 5

VISIBILITY/POLLUTANT RELATIONSHIPS

Before control strategies can be planned for maintaining or improving visibility in the Northeast, the atmospheric components that contribute to visibility reduction must be identified. This chapter relates airport visibility measurements to Hi-Vol particulate measurements in order to gain insight as to the causes of haze in the Northeast. The analysis is based on regression equations relating daily estimates of extinction coefficient to TSP, sulfate, nitrate, and relative humidity. The statistical methods and their limitations are discussed in detail in Chapter 2.

DATA OVERVIEW

In this report, visibility/pollutant regression studies are conducted for three metropolitan locations (Chicago, Newark, and Cleveland) and three urban/suburban locations (Lexington, Charlotte, and Columbus). The data base, summarized in Table 3 (page 21), consists of daytime visibility and relative humidity measurements taken at airports, combined with daily TSP, sulfate and nitrate measurements taken at nearby NASN monitoring sites (from 2 to 10 km away from the airports). All days of NASN sampling for the years 1966 through 1972 are included, eliminating only those days when precipitation was reported at the airport.*

Table 10 lists the number of data points and the average values for the pertinent variables at each location under study. The definitions of the variables, total extinction (B), relative humidity (RH), SULFATE (S), NITRATE (N), and remainder of TSP (T), are discussed at length in Chapter 2.

Table 11 summarizes the linear correlation coefficients among the variables at each location. Only two pairs of variables correlate signifi-

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*Out of the remaining data (over 700 days), we eliminated one day: July 8, 1972 at Lexington. Visibility was very good that day, but the NASN readings for TSP and sulfate were higher than for any other day at Lexington. The NASN recordings appeared to be invalidated by a measurement taken on the same day and at the same location by the Kentucky Division of Air Pollution Control which resulted in a TSP value less than one-fourth of the NASN value.

TABLE 10. SUMMARY STATISTICS FOR LOCATIONS INCLUDED IN VISIBILITY/POLLUTANT STUDIES

LOCATION	NUMBER OF DATA POINTS*	AVERAGE VALUES FOR KEY PARAMETERS: B = 24.3/V $(10^4 m)^{-1}$	RH (%)	$S = 1.3\ SO_4^=$ (μg/m3)	$N = 1.3\ NO_3^-$ (μg/m3)	T = TSP - S - N (μg/m3)
<u>METROPOLITAN</u>						
Chicago	131	2.96	58.7	19.4	3.8	103.1
Newark	134	2.91	53.9	17.9	3.1	68.8
Cleveland	102	3.10	62.6	21.0	3.4	112.3
<u>URBAN/SUBURBAN</u>						
Lexington	86	3.10	62.8	12.4	3.4	62.6
Charlotte	131	2.82	59.5	11.6	2.4	91.8
Columbus (OH)	130	3.56	63.7	15.7	3.9	83.7

*Days of NASN sampling from 1966 through 1972, with days of precipitation deleted.

TABLE 11. CORRELATIONS AMONG VARIABLES USED IN THE VISIBILITY/POLLUTANT ANALYSIS

CHICAGO

	B	RH	S	N	T
B	1.00	**.38**	**.34**	-.01	-.04
RH		1.00	.12	-.09	-.32
S			1.00	**.43**	**.50**
N				1.00	**.40**
T					1.00

LEXINGTON

	B	RH	S	N	T
B	1.00	**.61**	**.42**	-.04	.00
RH		1.00	.20	.06	-.12
S			1.00	-.11	.20
N				1.00	.03
T					1.00

NEWARK

	B	RH	S	N	T
B	1.00	**.56**	**.43**	.02	**.37**
RH		1.00	**.28**	-.07	.02
S			1.00	.15	**.60**
N				1.00	**.31**
T					1.00

CHARLOTTE

	B	RH	S	N	T
B	1.00	**.58**	**.39**	**-.22**	-.02
RH		1.00	.09	**-.20**	-.15
S			1.00	.10	**.27**
N				1.00	**.44**
T					1.00

CLEVELAND

	B	RH	S	N	T
B	1.00	**.32**	**.61**	-.03	.09
RH		1.00	.03	.08	-.21
S			1.00	**.26**	**.40**
N				1.00	**.42**
T					1.00

COLUMBUS, OH

	B	RH	S	N	T
B	1.00	**.60**	**.61**	**.18**	.12
RH		1.00	.11	.03	**-.22**
S			1.00	.10	**.29**
N				1.00	**.18**
T					1.00

○ = Significant from zero at 95% confidence level cantly at all six locations; these pairs, both exhibiting linear correlations from approximately 0.3 to 0.6, are extinction vs. relative humidity and extinction vs. sulfates. Two other pairs of variables (remainder of TSP vs. sulfates, and remainder of TSP vs. nitrates) correlate significantly at five of the six locations.

MULTIVARIATE REGRESSION

Stepwise multiple linear regressions relating daily extinction coefficient to the other four variables are conducted according to Equation (6), page 23. The results of these regressions, retaining only those coefficients that are greater than zero at a 95% confidence level, are presented in Table 12. The total correlation coefficients are 0.48 at Chicago, 0.81 at Columbus, and 0.67 to 0.70 at the other four locations. At the 95% confidence level, the multiple linear regressions retain relative humidity at all six locations, SULFATE at five of the locations, and NITRATE and the remainder of TSP at only one location each. As will be demonstrated in later discussions, the coefficients in the regression equations (extinction coefficients per unit mass for the pollutant variables) are consistent with basic principles and with other published values.

As evidenced by the total correlation coefficients, the results of the regression analysis are considerably weaker at Chicago than at the other five locations. The explanation most likely lies in air mass differences between the airport (Chicago/Midway) and the NASN location (Herman 1977).*

Stepwise multiple regressions are also conducted using the nonlinear RH regression model, Equation (7), page 23. The results of these regressions, again retaining only those coefficients that are greater than zero at a 95% confidence level, are presented in Table 13. For each location the nonlinear RH model attains a higher total correlation coefficient than the linear model even though there is one less free parameter in the nonlinear RH regression

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*When we originally decided to include Chicago in the visibility/pollutant analyses, we thought that the Chicago NASN site wa: within 3 km of the visibility observation site (Midway airport). We later discovered that the latitude/longitude information contained in the Chicago NASN site file was wrong and that the site is actually located nearly 20 km from the airport.

TABLE 12. SUMMARY OF LINEAR VISIBILITY/POLLUTANT REGRESSIONS

LOCATION	TOTAL CORRELATION COEFFICIENT	REGRESSION EQUATION
METROPOLITAN		
Chicago	.48	$B = 2.18 + .047(RH - \overline{RH}) + .040$ SULFATE
Newark	.67	$B = 1.14 + .096(RH - \overline{RH}) + .026$(TSP - SULFATE - NITRATE)
Cleveland	.70	$B = 1.42 + .044(RH - \overline{RH}) + .081$ SULFATE
URBAN/SUBURBAN		
Lexington	.68	$B = 2.35 + .084(RH - \overline{RH}) + .062$ SULFATE
Charlotte	.67	$B = 1.56 + .059(RH - \overline{RH}) + .108$ SULFATE
Columbus	.81	$B = 1.33 + .089(RH - \overline{RH}) + .120$ SULFATE + .091 NITRATE

TABLE 13. SUMMARY OF NONLINEAR RH VISIBILITY/POLLUTANT REGRESSIONS

LOCATION	TOTAL CORRELATION COEFFICIENT	REGRESSION EQUATION
<u>METROPOLITAN</u>		
Chicago	.52	B = 2.22 + .014 SULFATE/(1 - .01RH)
Newark	.71	B = 0.70 + .026 SULFATE/(1 - .01RH) + .0064(TSP - S - N)/(1 - .01RH)
Cleveland	.72	B = 1.49 + .026 SULFATE/(1 - .01RH)
<u>URBAN/SUBURBAN</u>		
Lexington	.72	B = 0.86 + .024 SULFATE/(1 - .01RH) + .0069(TSP - S - N)/(1 - .01RH)
Charlotte	.73	B = 1.24 + .046 SULFATE/(1 - .01RH)
Columbus	.90	B = 0.98 + .046 SULFATE/(1 - .01RH) + .022 NITRATE/(1 - .01RH)

equation. The total correlation coefficients are now 0.52 for Chicago, 0.90 for Columbus, and 0.71 to 0.73 for the other four locations.

The SULFATE/(1 - .01RH) variable appears in the equations for all six locations and is the most significant variable (according to an F-test or t-test) at all six locations. The partial correlation coefficients between extinction and SULFATE/(1 - .01RH) alone are 0.52 for Chicago, 0.89 for Columbus, and 0.65 to 0.73 for the other four locations. At two of the sites (Newark and Lexington), the variable (TSP - S - N)/(1 - .01RH) is significant, and at one site (Columbus), NITRATE/(1 - .01RH) is significant. As demonstrated later, the regression coefficients (extinction coefficients per unit mass adjusted for relative humidity) are again very reasonable according to fundamental principles and other published values.

EXTINCTION BUDGETS

As explained in Chapter 2, the regression equations can be used to derive extinction budgets which indicate the fraction of haze, on the average, that is attributable to each pollutant species. Table 14 presents extinction budgets for the six locations under study. In computing those extinction budgets, we have used the nonlinear RH regression models rather than the linear regression models because the form of the nonlinear RH models is more reasonable on physical grounds and because the nonlinear RH models attain a better fit to the data at all six locations.

Table 14 indicates that the extinction budgets based on the nonlinear RH models account for the majority of extinction at each location except Chicago. The "unaccounted for" fraction is 69% at Chicago and ranges from 19% to 43% among the other five locations. It should be stressed that the "unaccounted for" category may represent errors in the data base (e.g. visibility and pollutants measured at different locations, visibility and pollutants not measured during identical portions of the day, measurement errors, etc.) as well as extinction contributions from atmospheric constituents omitted from the analysis. Thus, some of the "unaccounted for" category (especially in Chicago) may, in fact, be attributable to sulfates, nitrates, and/or remainder of TSP.

From the extinction budget, it is obvious that sulfates tend to be the

TABLE 14. EXTINCTION BUDGETS FOR LOCATIONS IN THE NORTHEAST UNITED STATES

LOCATION	CONTRIBUTIONS TO TOTAL EXTINCTION				
	Blue-Sky Scatter	Sulfates	Nitrates	Remainder of TSP	Unaccounted for
<u>METROPOLITAN</u>					
Chicago	5%	26%	0%	0%	69%
Newark	5%	40%	0%	36%	19%
Cleveland	5%	52%	0%	0%	43%
<u>URBAN/SUBURBAN</u>					
Lexington	5%	30%	0%	42%	23%
Charlotte	5%	56%	0%	0%	39%
Columbus	4%	65%	8%	0%	23%

dominant atmospheric component related to visibility loss in the Northeast. The estimated contributions to haze range from 26% to 65% for sulfates, 0% to 8% for nitrates, 0% to 42% for the remainder of TSP, and 4% to 5% for blue-sky scatter by air molecules. If we take an aggregate view and average the results for the five non-Chicago locations, we obtain the following:

Component	Contribution to Total Extinction
Blue-Sky Scatter	5%
Sulfates	49%
Nitrates	2%
Remainder of TSP	16%
Unaccounted for	28%

Because the problem of colinearity between variables may distort the regression results for some of the sites (e.g. by sometimes overemphasizing the sulfate term, sometimes overemphasizing the remainder of TSP term), we tend to have more confidence in the aggregate conclusions than we have in the results for individual locations.

DISCUSSION OF RESULTS

Considering the potential errors in the data bases, the regression studies for the Northeast have been quite encouraging. At all sites but Chicago, total correlation coefficients exceeding 0.7 have been obtained using the nonlinear RH regression model relating extinction to pollutants. At Columbus, a total correlation of 0.9 was attained.

The results of the regressions indicate that the main contributor to haze in the Northeast is sulfate, which typically accounts for approximately 50% of total extinction.* This conclusion is not surprising in light of known principles of aerosol physics. Sulfates are secondary aerosols and tend to occur in the particle size range of 0.1 to 1 micron. In fact, field

*Actually, the fractional contribution of sulfates to haze could be somewhat larger than 50% if some of the "unaccounted for" category represents sulfates. Alternatively, the fractional contribution of sulfates to haze could be somewhat smaller if sulfates are acting in part as surrogates for other pollutants omitted from the analysis, or if sulfates have been overemphasized in the regressions due to statistical problems of colinearity.

experiments in Missouri, Arkansas, and Michigan (Charlson et al. 1974; Weiss et al. 1977) indicate that sulfates constitute the dominant particulate fraction (i.e. 1/2 or more) in the 0.1 to 1 micron size range at those locations. As shown in Figure 32, light scattering per unit mass of aerosol exhibits a pronounced peak in the 0.1 to 1 micron size range, around the wavelength of visible light. Because sulfates tend to reside in the particle size range that is optically most important, it is not unreasonable for sulfates to account for 50% or more of visibility reduction even though they typically constitute only 15% of total aerosol mass in the Northeast.

Further confidence is placed in these conclusions if we compare the extinction coefficients per unit mass based on our regressions to other results published in the literature. Table 15 indicates basic agreement that the extinction coefficients per unit mass are approximately .04 to .11 $(10^4 m)^{-1}/(\mu g/m^3)$ for sulfates, .03 to .09 $(10^4 m)^{-1}/(\mu g/m^3)$ for nitrates*, and .001 to .015 $(10^4 m)^{-1}/(\mu g/m^3)$ for the remainder of TSP. These values for extinction coefficients are also consistent with Figure 32. Figure 32 indicates that secondary aerosols (such as sulfates or nitrates) residing in the .1 to 1 micron size range should exhibit average extinction coefficients per unit mass on the order of .06 $(10^4 m)^{-1}/(\mu g/m^3)$. The remainder of TSP, residing mostly in the size range above 3 microns, should exhibit an average extinction coefficient per unit mass that is one order of magnitude lower.

It should be remarked that the average extinction coefficients per unit mass for sulfates that are determined by the regression models are often slightly higher than would be expected according to Figure 32. The likely explanation is that the recorded mass of sulfate aerosol is lower than the ambient mass because some of the water associated with the ambient sulfate aerosol is lost during measurement procedures (i.e. filter equilibration). The low estimate of ambient sulfate aerosol mass leads to a slightly high estimate of ex-

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*Actually, at most Northeastern locations we obtained no contribution from nitrates, i.e. extinction coefficients for nitrates were not greater than zero with statistical significance. There are two plausible explanations. First, contributions to extinction from nitrates may be so small in the Northeast that the statistical methods are unable to discern the effect. Second, negative interference by sulfates on nitrate measurements (Harker et al 1977) may have masked the nitrate contributions; in this regard we note that negative correlations were sometimes found between nitrates and extinction.

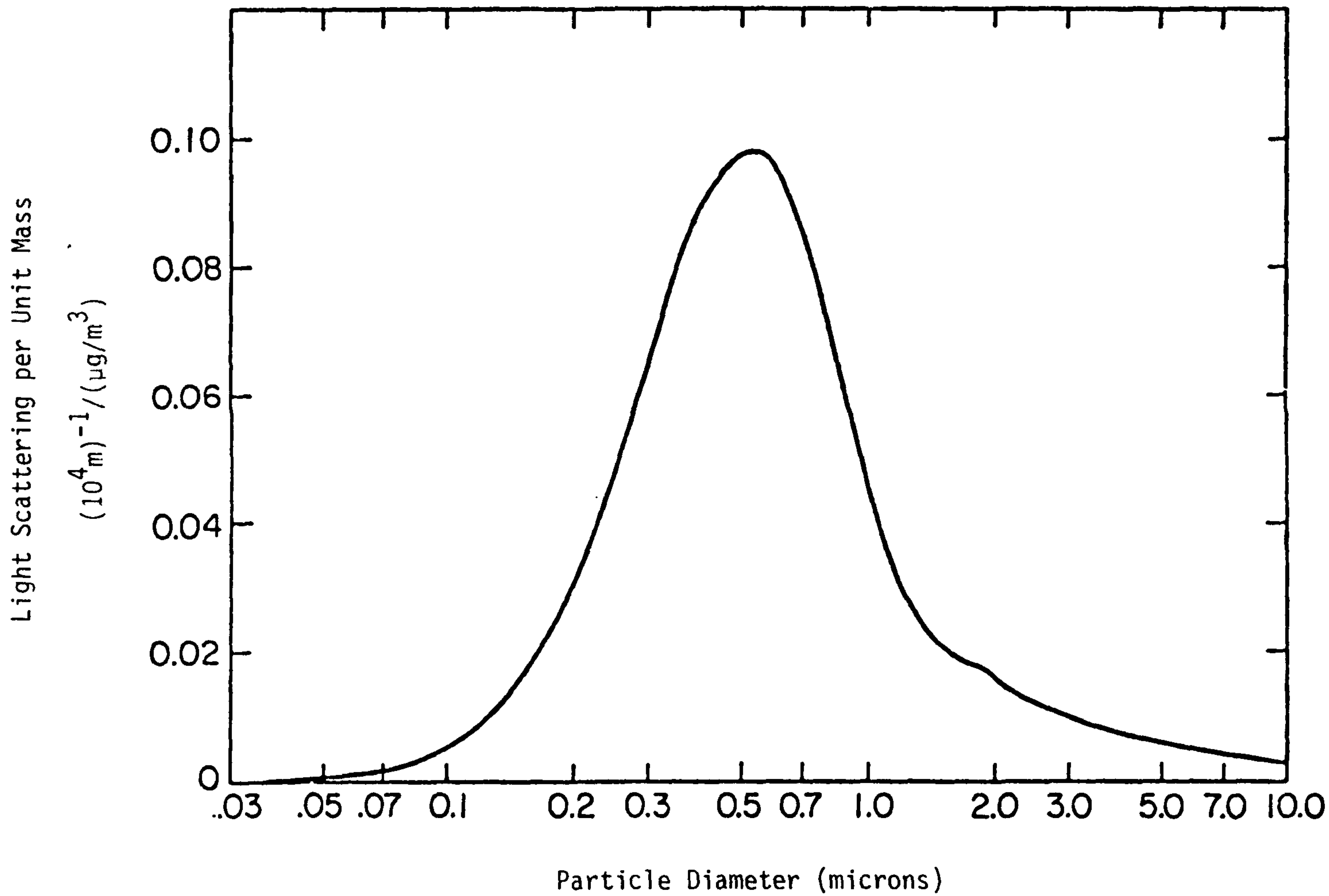

Figure 32. Normalized light scattering by aerosols as a function of particle diameter. Computed for unit density spherical particles of refractive index 1.5 (White and Roberts 1977).

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16. ABSTRACT

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

Visibility in the Northeast is rather poor, median visual range being on the order of 10 miles. Visibility is not now substantially better in nonurban areas than in metropolitan areas of the Northeast. From the middle 1950's to the early 1970's, visibility exhibited only slight trends in large metropolitan areas but decreased on the order of 10 to 40% at suburban and nonurban locations. Over the same period, visual range declined remarkably during the third calendar quarter relative to other seasons, making the summer now the worst season for visibility. The decrease in visibility during the summer was especially notable at suburban and nonurban locations, where atmospheric extinction apparently increased on the order of 50 to 150% during the third calendar quarter.

Regression models based on daily variations in visibility and pollutant concentrations indicate that sulfate aerosol is the single major contributor to haze in the Northeast. Sulfates apparently account for approximately 50% of total extinction.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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