United States
Environmental Protection
Agency

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

EPA-450/4-80-001
January 1980

Air

EPA

Assessing the Representativeness of Ozone Monitoring Data

Final Report

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Assessing the Representativeness of Ozone Monitoring Data

Final Report

by

F.L. Ludwig and E. Shelar

Atmospheric Science Center
SRI International
Menlo Park, California 94025

Contract No. 68-02-2548
SRI Project 7863

EPA Project Officer: Warren P. Freas

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

January 1980

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Publication No. EPA-450/4-80-001

ABSTRACT

This project has been directed toward defining the extent to which existing ozone monitoring data can be used to represent conditions outside the area immediately surrounding a monitoring station. The most important concern has been with the National Ambient Air Quality Standard (NAAQS) for ozone, seeking relationships between observed second-maximum hour-average ozone concentrations and the area within which it is possible to state with reasonable probability that NAAQS have or have not been exceeded.

Areas within which the National Ambient Air Quality Standard (NAAQS) for ozone is likely to have been exceeded are shown to be related to the observed annual second-maximum hourly ozone concentrations. All pairs of SAROAD stations separated by 500 km or less that had nearly complete annual data sets were considered for the years 1974 to 1977 to determine the probability that the NAAQS would be exceeded at one station of the pair, given the observed second-maximum hourly ozone concentration at the other and their separation. Applying this relationship to current SAROAD data for 1977 and 1978, circles were drawn around each SAROAD monitoring site to show the area within which it is 95 percent probable that the 120 ppb NAAQS has been exceeded during 1977 or 1978.

The report describes meteorological situations and seasons during which high ozone concentrations are most likely in various parts of the country, so that special monitoring studies can be designed to supplement existing data. An aircraft monitoring protocol is given that will provide ozone observations that are representative of ground-level conditions.

This report was submitted in fulfillment of Contract 68-02-2548 by SRI International under the sponsorship of the Environmental Protection Agency.

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ACKNOWLEDGMENTS

Many people and organizations have been helpful during this study. We are especially indebted to the Project Officer, Mr. Warren P. Freas, for his useful suggestions. At SRI, R. Trudeau, S. Webster, A. Smith, and J.H.S. Kealoha assisted in various phases of the project. The efforts of the publications group of the SRI Advanced Development Division are gratefully acknowledged.

EXECUTIVE SUMMARY

Introduction and Objectives

This project has been directed toward defining the extent to which existing ozone monitoring data can be used to represent conditions outside the area immediately surrounding a monitoring station. The most important concern has been with the National Ambient Air Quality Standard (NAAQS) for ozone, seeking relationships between observed second-maximum hour-average ozone concentrations and the area within which it is possible to state with reasonable probability that NAAQS have or have not been exceeded.

Another important objective has been to identify site characteristics that make data unrepresentative of surrounding areas. The meteorological conditions associated with high ozone concentrations in different parts of the country have also been investigated. Finally, all the information has been combined to specify areas where further monitoring may be needed, and to define methods by which special monitoring programs can be used to meet those needs.

The approach taken during this study has used only existing data. The emphasis has been on information available from the system for Storage and Retrieval of Aerometric Data (SAROAD). Some data from special studies have also been incorporated, especially to determine conditions under which aircraft measurements can be used to estimate ground ozone concentrations.

Relationships Among Ozone Observations at Separate Sites

The focus of this study has been on exceedance of the NAAQS for ozone. To this end, a list of observed second-maximum hourly ozone (hereafter referred to as the second-maximum) concentrations was compiled for all stations and years for which more than 7,000 hours of data are available. By taking all possible pairs of such stations that were within 500 km of one another, it was possible to determine the probability that the NAAQS would be exceeded at one station of the pair, given the observed second-maximum ozone concentration at the other and their separation. Figure S-1 shows the probability that the annual second-maximum ozone concentration would exceed 120 ppb within 50 km of a station, given the observed value for that station. Similar presentations were prepared for other station separations. The curve in Figure S-1 has the expected characteristics. It shows that at very low observed annual second-maximum ozone concentrations, the probability of observing an exceedance of the NAAQS is quite small, but as expected, the probabilities increase within increasing observed annual second-maximum ozone concentrations. For locations within 50 km of an observing station, it becomes virtually certain that an exceedance of the standard will be found if the station observed a sufficiently large second-maximum ozone concentration. Figure S-1 shows that the probabilities reach 90 percent at a little less than 150 ppb, 95 percent at about 175 ppb and 99 percent at 275 ppb. These statistics are heavily influenced by data collected in urban areas

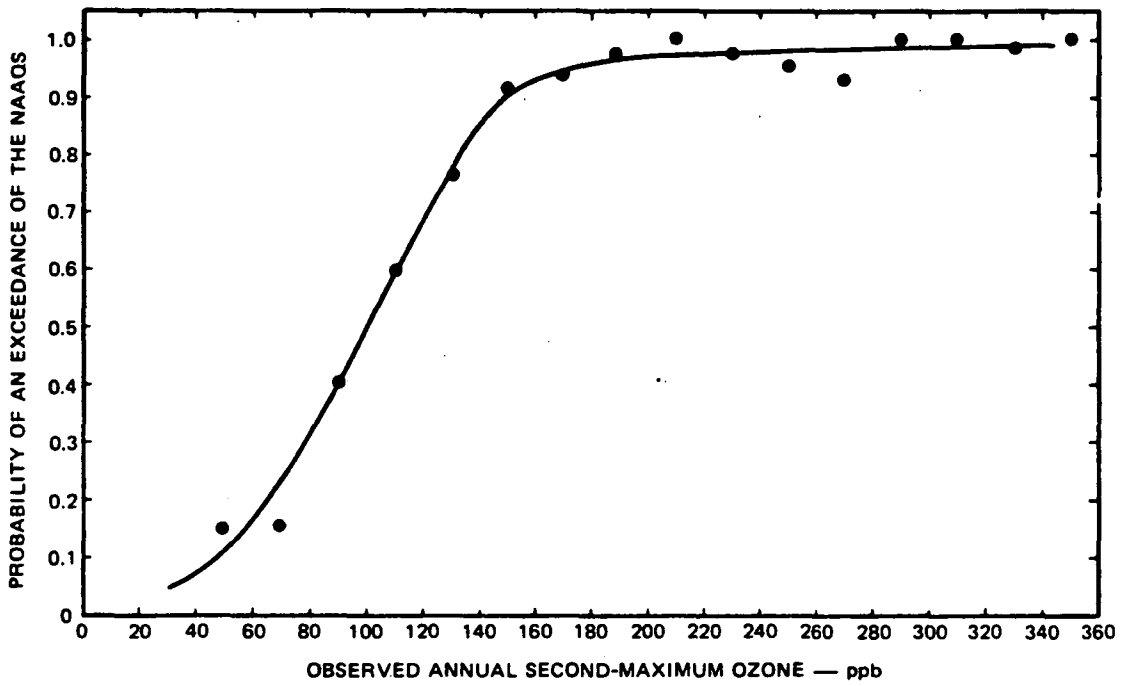


Figure S-1. Probability that the annual second-maximum ozone concentration exceeds 120 ppb within 50 km of a station, given the observed value for that station.

where ozone gradients are apt to be greater than in more remote locations. Therefore, the probabilities of observing an NAAQS exceedance are expected to be greater in a remote area, for any given observed second-maximum ozone concentration, than in the urban areas.

There is a relationship between the annual second-maximum ozone concentration observed at a location and the distance from the station at which the probability of observing an exceedance of the NAAQS for ozone falls below a specified level. Figure S-2 shows the relationships that were found for three different specified probabilities as derived from plots of data such as that presented in Figure S-1. Qualitatively, the relationship shown in Figure S-2 is as expected. For example, if the concentration of 120 ppb is observed, it provides little guarantee that the NAAQS will be equalled or exceeded anywhere but at the station itself. As the observed value increases so does the distance within which it is likely that the standard will be exceeded. However, it is not possible to achieve the higher probabilities beyond some cutoff distance, regardless of how great the observed second-maximum ozone concentration might be because the physical and statistical relationship between observations separated by great distances are exceedingly tenous. This is discussed in Section 2-A-3. Thus, the distance within which one might assume a 95 percent probability of an exceedance should not be more than 175 to 200 km regardless of the observed second-maximum ozone concentration. With a 90 percent probability, the cutoff is about 225 to 250 km.

Areas of Probable Exceedance of the NAAQS for Ozone

It is obvious that curves like those in Figure S-2 can be used in combination with observed values of maximum ozone concentrations to define areas within which exceedances of the NAAQS for ozone are likely to have occurred. Figure S-3 is a map of the United States that indicates those areas where it is 95 percent probable, on the basis of observed annual maximum ozone concentrations, that the NAAQS for ozone has been exceeded during 1977 or 1978. The annual maximum was selected as the design value for the data set based on the procedures described by Curran (1979). Figure S-3 is based not only on data from those stations with nearly complete data sets, but also on data from sites that had fewer than 7,000 hours per year. Even though a data set is not complete, only one observation in excess of 120 ppb may be sufficient to define an area within which exceedances are likely. In general the area defined by an incomplete data set will be smaller (it can not be larger) than it would be if derived from a complete data set. In Figure S-3, the symbol 'L' is used to mark locations where the observed maximum concentration was less than 120 ppb.

Data from special studies, or data not otherwise archived in the SAROAD, could be used to characterize additional areas in Figure S-3 in regard to exceedance of the NAAQS. One of the recommendations of this project is that an intensive search for such data be undertaken before any special monitoring programs are planned. A search for, and use of, existing data would be considerably more cost-effective than field monitoring projects.

Meteorological Factors Associated with High Ozone Concentrations

If special monitoring programs are required, they can be planned more effectively if the meteorological conditions associated with high ozone concentrations and exceedances of the

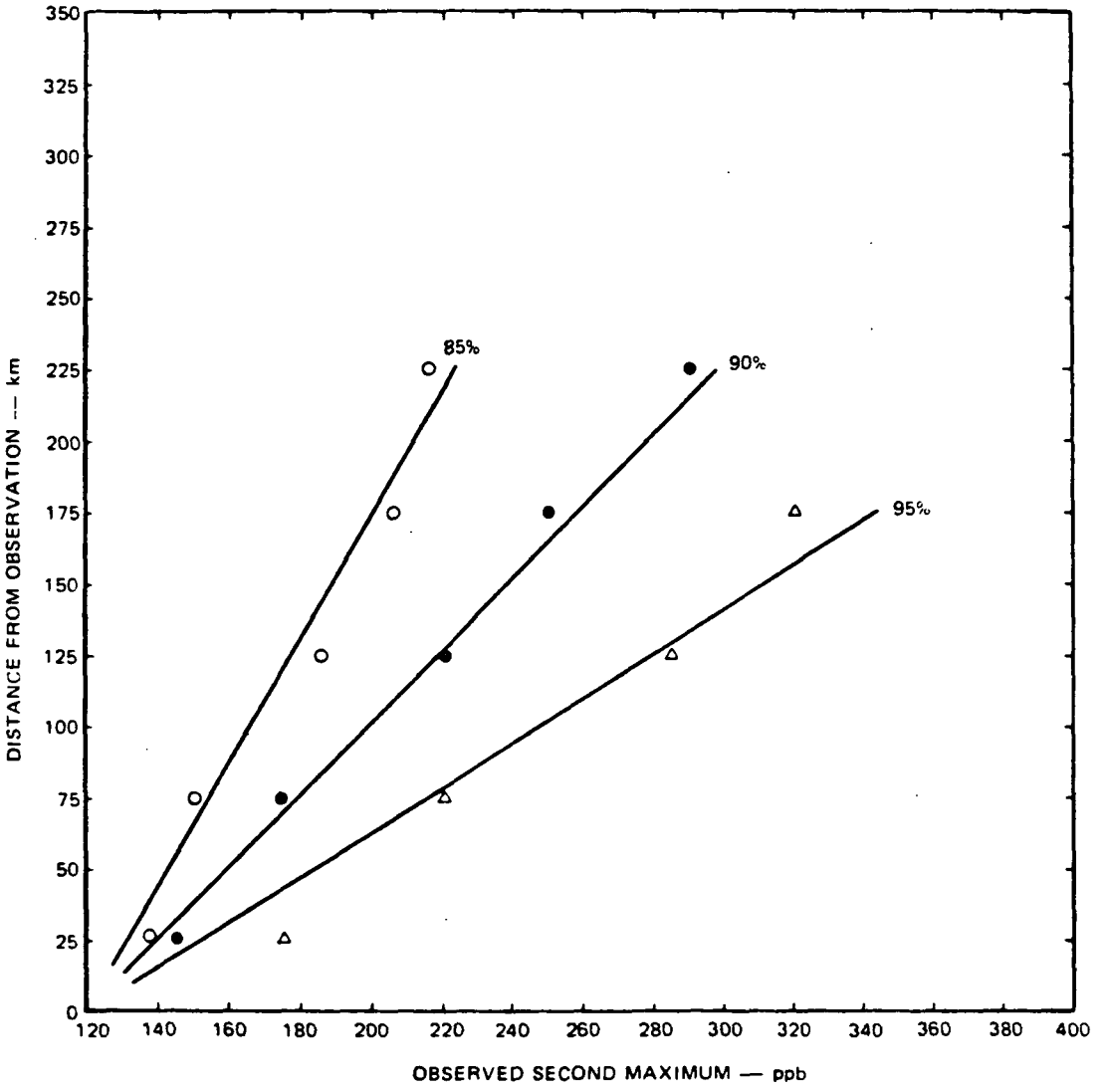


Figure S-2. Probability of observing an exceedance of the NAAQS for ozone as a function of observed second-maximum ozone concentration and distance.

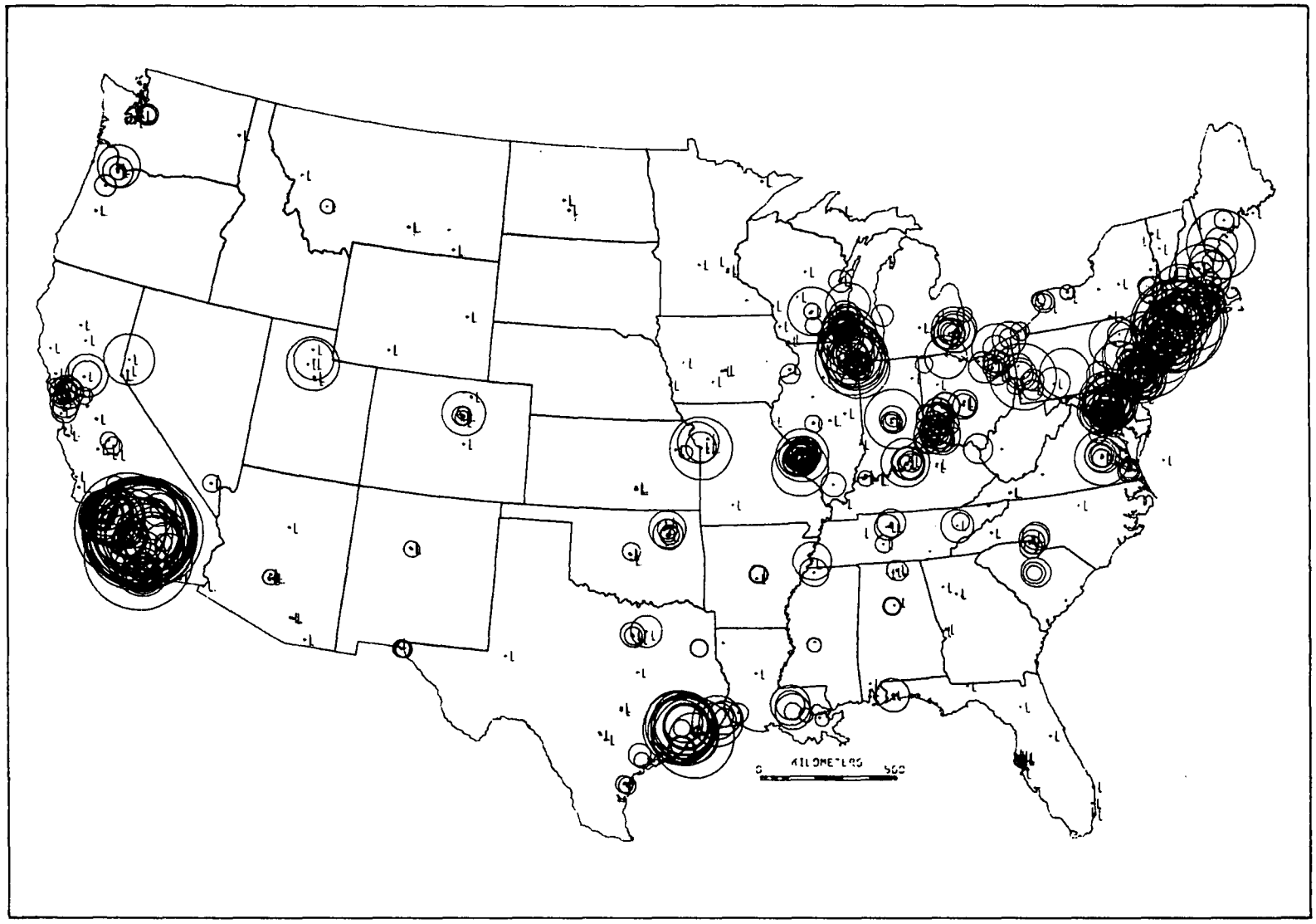


Figure S-3. Areas where it is 95-percent probable that hourly ozone concentrations in excess of 120 ppb occurred during 1977 or 1978.

NAAQS are defined. It has been found during the course of this project that although there are similarities in the relationships between synoptic-scale meteorological features and areas where ozone concentrations are high from one region of the country to another, there are also important differences. In most regions of the country, high ozone concentrations are frequently associated with high-pressure systems, but the segment of the high-pressure system where concentrations are highest tends to vary from one region to another. For example, the northern part of high-pressure systems are most frequently associated with episodes of high concentration in the northeast part of the United States. In the central and northern Midwest, the northwestern quadrant is most common. Along the Gulf Coast and in the Southeast, it is the southwestern quadrant of high-pressure systems that is most frequently associated with high ozone concentrations. In Southern California, the photochemical season is associated with the presence of the semipermanent Pacific high-pressure system; Southern California is located near the eastern margin of this system. However, the thermal low over the interior valleys and deserts is the most persistent feature of the weather patterns observed on the highest ozone days in Southern California.

Except in Southern California, the warm air in the vicinity of frontal systems also provides a frequent site for ozone "episodes." Such areas could also be frequently classified as being on the periphery of a high-pressure system, but it seems worthwhile to classify them separately. There is a common tendency to think that frontal systems and air pollution episodes are incompatible, but the prevailing conditions here are frequently atypical of high-pressure systems, with greater wind speeds.

Just as there are geographical differences with regard to the synoptic-scale weather features that are associated with high ozone concentrations, there are also some geographical differences in seasonal effects. Throughout most of the country, the summer months have the highest ozone concentrations. In New England and in the southern Great Plains, high ozone concentrations appear to be frequent from May through September. However, in the Ohio River Valley and the area south of the Great Lakes, the months of most frequent high ozone concentrations are July and August. Further to the south, along the Gulf Coast from Texas to Florida, June and July are the months of most frequent high ozone concentrations. In the northern High Plains, some of the highest ozone concentrations occur in the Spring, however, anthropogenic sources of precursor emissions, found in the northern Great Plains or the Great Basin, extend the season of highest ozone from spring through summer.

Station Characteristics Likely to Result in Unrepresentative Readings

The second-maximum ozone readings available from SAROAD were used as one basis for identifying stations that appeared to have unrepresentative data. Readings from stations within 25 km of one another were compared, and those pairs whose readings differed by more than 100 ppb were identified. Maps like the one shown in Figure S-3 were also examined for stations reporting compliances with the standard near the center of areas that had a high probability of exceeding the standard. The characteristics of the stations identified were examined; the most frequent contributors to unrepresentative readings were NO sources. If a station is located close to an arterial with high traffic density, the NO from that traffic can react with the ozone to remove most of it. Thus, the presence of nearby NO sources can reduce ozone concentrations from rather high levels to a few tens of ppb or less. Even more common are stations that are not close to any single NO source, but are located within a general area of high

emissions. Data from St. Louis, Denver, Washington, among other cities, suggest that the scavenging effects of NO may reduce ambient ozone levels by several tens of ppb in heavily urbanized areas.

An analysis of available information suggests that well-operated, well-calibrated ozone monitors should provide data that are accurate to within 15 pbb or less when the new ultra-violet assay calibration techniques are used. Gas phase titration calibration techniques provide similar accuracies. Some older methods of calibrating the instruments can introduce errors of several tens of ppb.

Recommendations

Methods for Obtaining Additional Data

The most efficient means to obtain data to characterize the NAAQS status of additional areas would begin with a survey of non-SAROAD data sources. Data may be available from EPA regional offices, local agencies, and industrial sources, or from special studies conducted in the different regions, especially those where current monitoring is sparse. Presumably, such a survey would reduce the number of areas that may need further monitoring.

The availability of such data might also provide a basis for better determination of the degree to which areas that are in compliance can be specified from observations already available. The present data base seems to contain too few data from remote and rural locations to be used to develop methods analogous to those used here to specify areas of exceedance of the NAAQS.

One of the methods investigated for obtaining data from inadequately monitored regions was the use of aircraft surveys. Earlier studies of the characteristics of vertical ozone profiles were used to define the conditions under which aircraft data could be used to specify ground-level concentrations. In general, aircraft observations can probably be used to specify ground level ozone concentrations when the measurements are made under sunny conditions, between about 1100 and 1600 local standard time (LST), in areas well away from cities. This should present few or no problems, because the greatest interest will be in those situations likely to produce the highest ozone concentrations, and these tend to coincide with the conditions necessary to obtain aircraft data that will be useful for specifying ground-level conditions. High ozone concentrations occur outside cities during the late-morning and afternoon hours of sunny days.

The aircraft monitoring protocol that is described in this report specifies that the observations should be conducted during the seasons with the highest probability of ozone standards exceedances, in the appropriate segments of weather systems, and during the appropriate periods of the day. As further insurance that the aircraft data are in fact representative of ground-level conditions, it is also specified that periodic vertical soundings be made to measure ozone, temperature, dew point and aerosol concentration. These measurements can be interpreted on board the aircraft, if suitable on-board display capabilities are available, to assure that the measurements are being made within a well-mixed layer and that the vertical gradient of ozone concentration is small.

SECTION 1
INTRODUCTION

A. *Purposes of the Research*

The study described in this report was undertaken primarily to determine the degree to which existing historical data could be used to define areas where the National Ambient Air Quality Standard (NAAQS) for ozone was either met or exceeded. Three corollary purposes accompanied this major purpose. First, we sought to determine those factors that affect representativeness of the ozone monitoring data: meteorological factors, the siting of the monitoring stations and the methods of measurement have been examined. The study also defines areas where additional ozone monitoring may be necessary to provide information on existing ozone levels. Finally, the characteristics of an air/ground monitoring program that can be used to characterize the United States with regard to areas of compliance with the NAAQS for ozone are described.

B. *Approach to the Study*

It should be understood that this was a "paper study," and only existing data were used. The major source of data has been SAROAD (Storage and Retrieval Of Aerometric Data). Data from SAROAD have been examined for agreement between observations at one site and those from other sites at varying distances. The data have also been used to identify times of widespread high ozone concentrations, so that the meteorological conditions associated with such events could be identified. We have also used the data base to attempt to identify a few stations that are in disagreement with their neighbors, to see if they exhibit common siting characteristics.

The results of these analyses have been used to define geographical areas where monitoring is not now adequate to determine whether the NAAQS for ozone is exceeded. The results with regard to characteristics of nonrepresentative monitoring sites should be useful in the future in siting monitors that will provide more widely usable data. The studies of the meteorological conditions associated with widespread exceedances of the ozone standard have been incorporated into some recommended strategies for surveying areas to determine whether the standard is exceeded.

C. *Organization of the Report*

The next section of this report provides an extended summary of the major findings and includes only enough background information so that the findings will be intelligible. The remainder of the supporting material, from which the findings were derived, is discussed in the third section of the report. The last section presents recommendations that have been derived from the analysis.

The authors hope that the organization used for this report will make it easier for a reader to digest the conclusions as a whole. With the conclusions already stated, it should be easier for a reader to interpret the supporting material. Furthermore, if only certain parts of the study are of interest, it should be easier to identify the related supporting material.

SECTION 2
MAJOR FINDINGS

A. *Relationships Among Ozone Observations at Separate Sites*

1. *Background*

If ozone concentrations are spatially continuous, two locations that are geographically proximate should have similar ozone concentrations, whether the ozone concentration under consideration is for a particular hour, the highest hour-averaged concentration for a particular day or the second-maximum hour-averaged ozone concentration for the year, so long as the field for the type of observation is spatially continuous and relatively smooth. With this reasoning in mind, some important questions can be asked regarding the concept of representativeness. For example, one could examine the average difference between readings at separate stations, and determine how that difference varies as a function of the distance between stations.

For the purposes of this study, it is more important to know how well exceedances of the NAAQS for ozone can be determined from existing data. For example: If a particular concentration of ozone has been observed at one location, can that observation be used reliably to determine whether or not the NAAQS is exceeded at some other, nearby location? The answer to that question depends in large part on:

- The type of ozone concentration being considered—for example, the answer may be different for same day comparisons than for comparisons on an annual basis.
- The magnitude of the observed ozone concentration—the observation of a very high ozone concentration indicates that the standards are more likely to be exceeded at nearby locations. Similarly, very low concentrations are more likely to be associated with compliance nearby.
- Separation between the point for which an observation is available and the point of interest in determining whether or not the standards are exceeded.
- Location and siting factors—a station that is strongly affected by local and anomolous effects can seldom be used reliably to estimate conditions in surrounding areas.

The effects of the first three factors listed above have been quantified by analyzing ozone observations from pairs of stations. The details of the analyses are described in greater detail later. Briefly, they included stratification according to the distance separating the two stations of a pair (e.g. 0-50 km, 50-100 km, etc.). The subsets of data were then analyzed to determine the average absolute difference between ozone observations at the two stations, for example, and the conditional probability that the NAAQS was, or was not, exceeded at one of the stations of a pair, given the observed ozone concentration at the other.

2. *Average Difference Between Observed Ozone Concentrations as a Function of Separation Between Stations*

In order to study the possibility that there are differences in the relationships among observations at different sites from one geographical region of the country to another, some analyses have been performed on subsets of data from different regions of the country. The four regions considered were:

- The Northeast
  - Connecticut
  - Massachusetts
  - Rhode Island
  - New Jersey
  - New York
  - Pennsylvania
- The Midwest
  - Kentucky
  - Illinois
  - Indiana
  - Iowa
  - Missouri
  - Ohio
- The Southwest
  - Arkansas
  - Louisiana
  - Oklahoma
  - Texas
- Southern California—California south of latitude 34° 22' (roughly south of Santa Barbara).

Figures 1 through 4 show scattergrams relating the distance between stations to the absolute value of the difference between their annual hourly second-maximum ozone concentration (hereafter referred to as the second-maximum). Only stations where more than 7,000 hours of data had been collected during the year were included in the samples. In these figures, each asterisk indicates one case of that particular combination of station-separation and absolute difference between observed second-maximum ozone concentrations. Numerals less than nine indicate that a corresponding number of cases had occurred with that particular difference in reading and spatial separation; the numeral 9 indicates nine or more such cases. Tables 1 through 4 are cross-tabulations of the data shown in the corresponding figures.

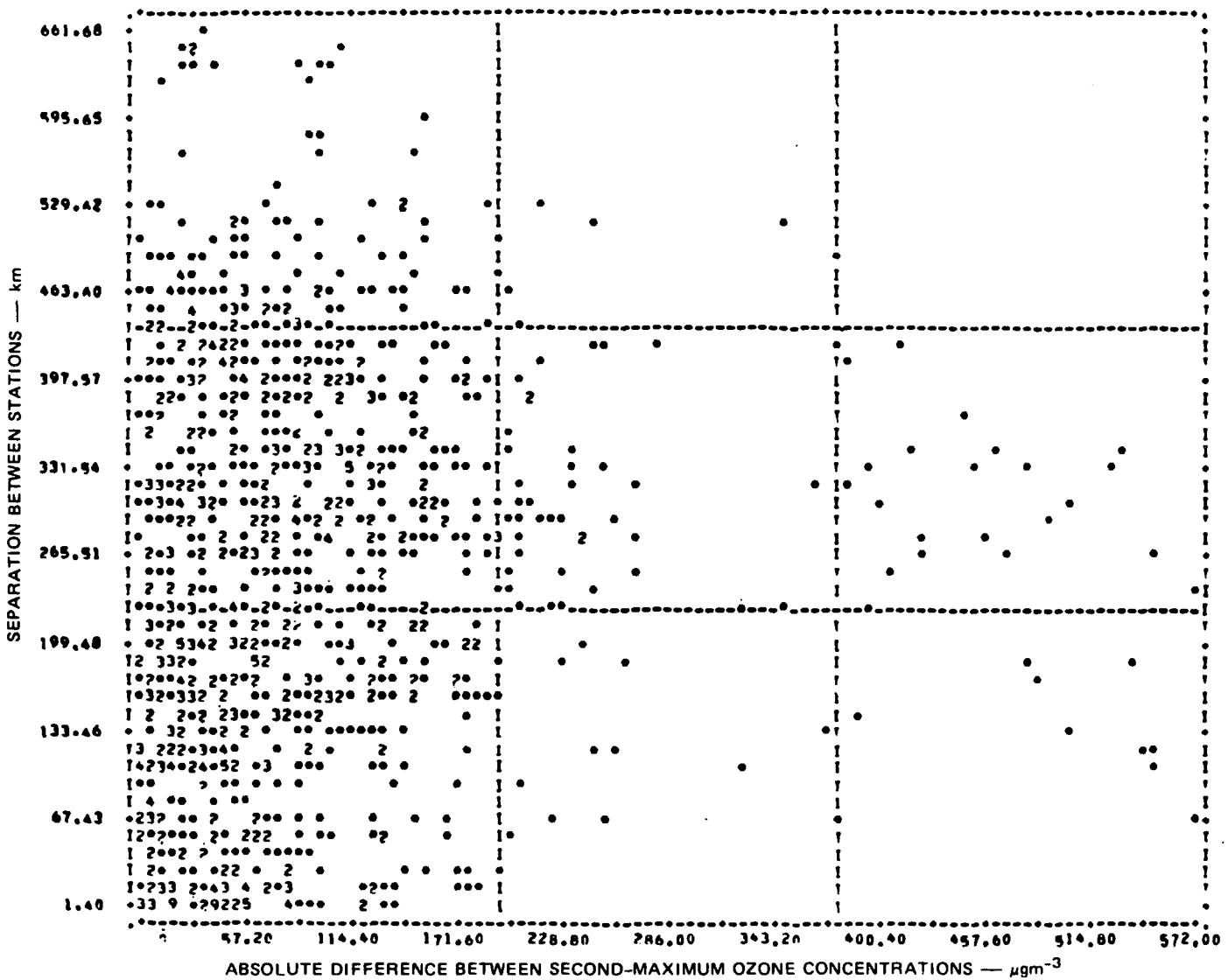


Figure 1. Scattergram of the distance between monitoring stations and the absolute difference between the second-maximum ozone concentrations for stations in the Northeast states.

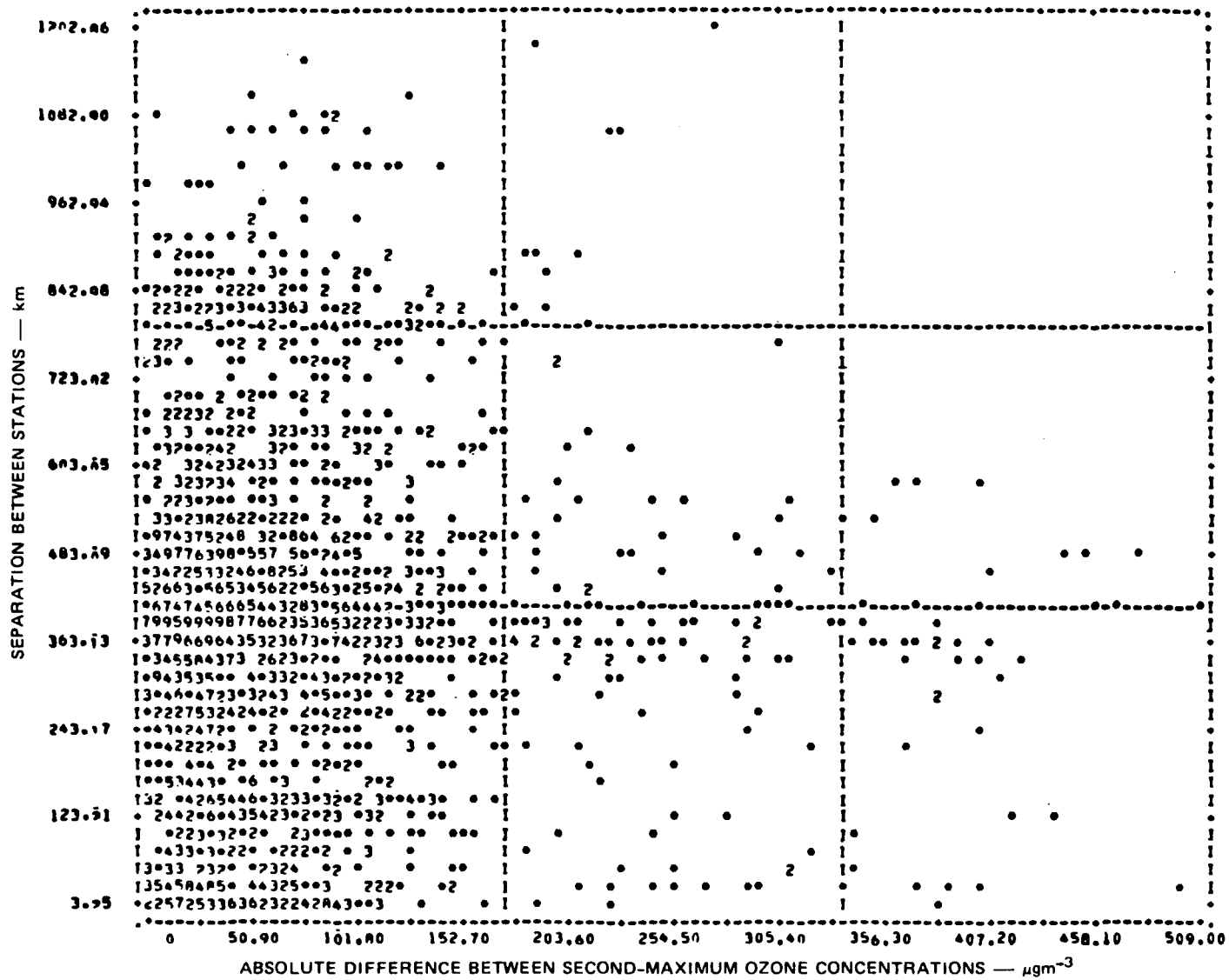


Figure 2. Scattergram of the distance between monitoring stations and the absolute difference between the second-maximum ozone concentrations for stations in the Midwest states.

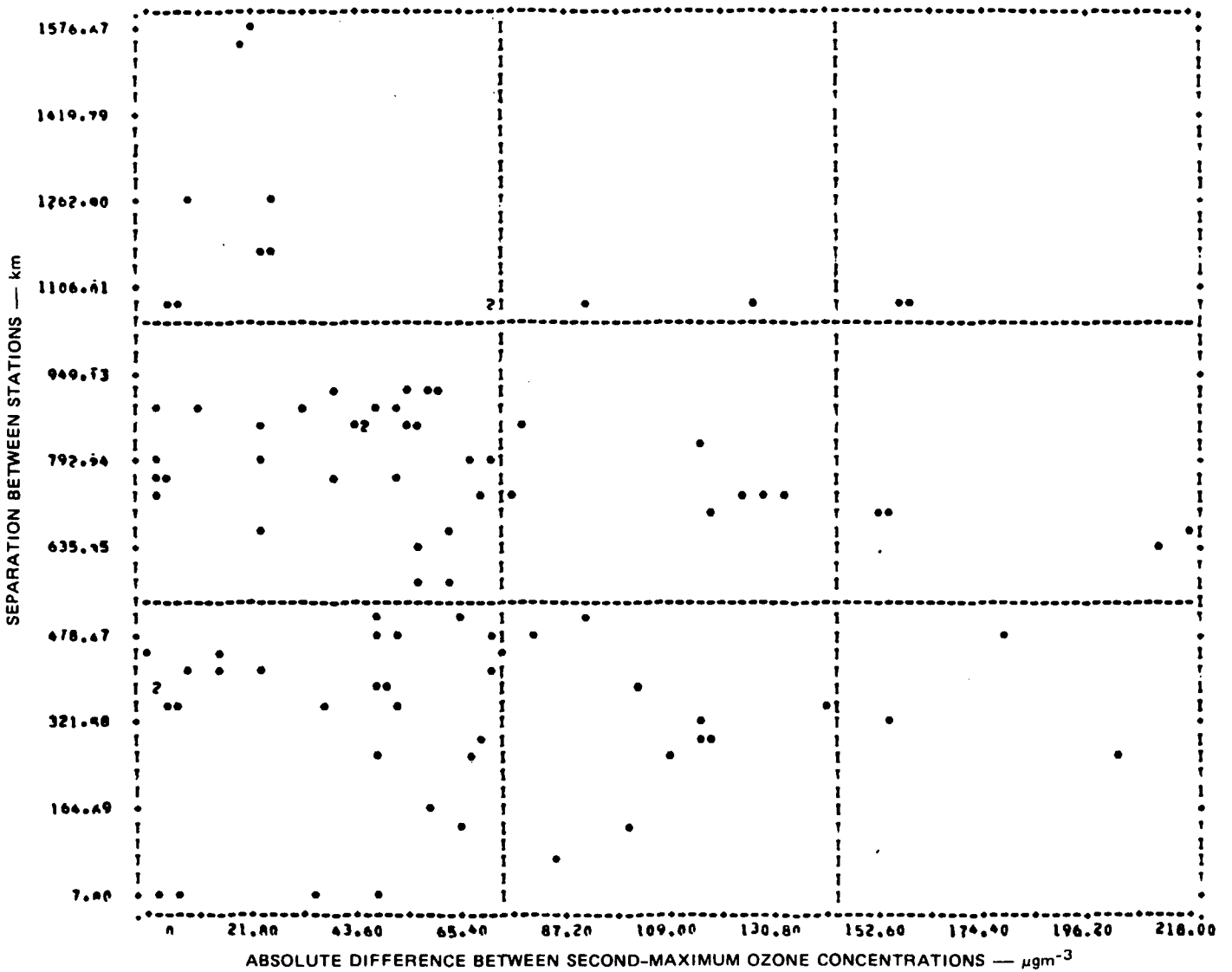


Figure 3. Scattergram of the distance between monitoring stations and the absolute difference between the second-maximum ozone concentrations for stations in the Southwest states.

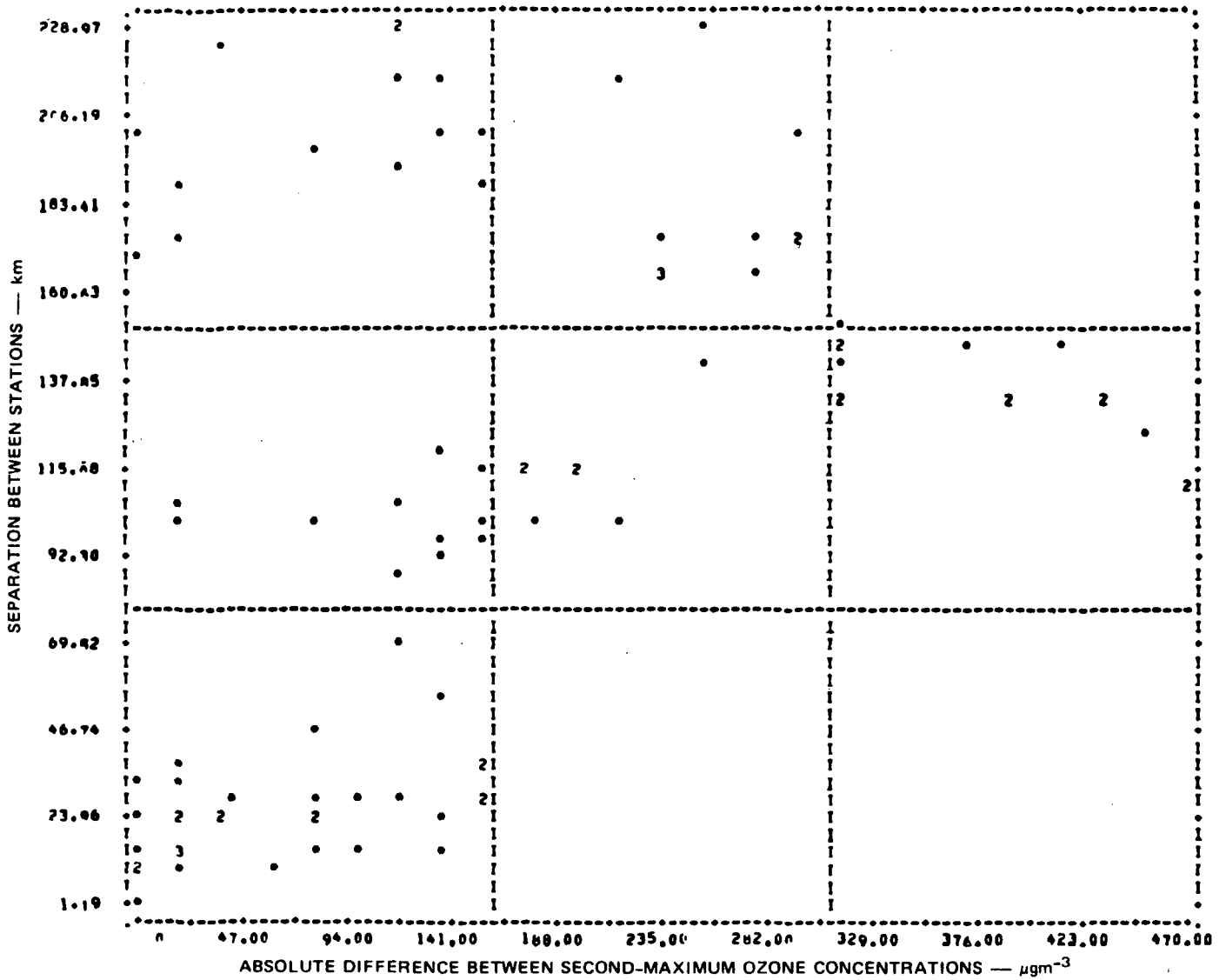


Figure 4. Scattergram of the distance between monitoring stations and the absolute difference between the second-maximum ozone concentrations for stations in Southern California.

TABLE 1 CROSS-TABULATION OF DISTANCE AND THE ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS FOR THE NORTHEAST STATES

ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS — ppb

SEPARATION BETWEEN STATIONS — km	COUNT / ROW PCT / COL PCT / TOT PCT	1-20PPB 1.	21-40PPB 2.	41-60PPB 3.	61-80PPB 4.	81-100PPB 5.	101-120PPB 6.	121-140PPB 7.	161-180PPB 9.	ABOVE 180PPB 10.	ROW TOTAL
0-50KM	1.	55	37	10	8	6	0	0	0	0	116
		47.4	31.9	8.6	6.9	5.2	0	0	0	0	10.5
		15.1	13.7	5.2	6.3	9.0	0	0	0	0	
		5.0	3.4	.9	.7	.5	0	0	0	0	
51-100KM	2.	29	17	6	5	3	3	1	0	2	66
		43.9	25.8	9.1	7.6	4.5	4.5	1.5	0	3.0	6.0
		8.0	6.3	3.1	4.0	4.5	10.0	6.7	0	5.6	
		2.6	1.5	.5	.5	.3	.3	.1	0	.2	
101-150KM	3.	45	27	12	9	1	0	2	1	5	102
		44.1	26.5	11.8	8.8	1.0	0	2.0	1.0	4.9	9.2
		12.4	10.0	6.3	7.1	1.5	0	13.3	25.0	13.9	
		4.1	2.4	1.1	.8	.1	0	.2	.1	.5	
151-200KM	4.	47	28	25	17	10	1	1	0	4	133
		35.3	21.1	18.8	12.8	7.5	.8	.8	0	3.0	12.1
		12.9	10.4	13.1	13.5	14.9	3.3	6.7	0	11.1	
		4.3	2.5	2.3	1.5	.9	.1	.1	0	.4	
201-250KM	5.	42	27	22	15	8	4	1	2	2	123
		34.1	22.0	17.9	12.2	6.5	3.3	.8	1.6	1.6	11.2
		11.5	10.0	11.5	11.9	11.9	13.3	6.7	50.0	5.6	
		3.8	2.4	2.0	1.4	.7	.4	.1	.2	.2	
251-300KM	6.	19	27	20	17	11	6	4	0	6	110
		17.3	24.5	18.2	15.5	10.0	5.5	3.6	0	5.5	10.0
		5.2	10.0	10.5	13.5	16.4	20.0	26.7	0	16.7	
		1.7	2.4	1.8	1.5	1.0	.5	.4	0	.5	
301-350KM	7.	39	23	27	20	10	9	2	0	10	140
		27.9	16.4	19.3	14.3	7.1	6.4	1.4	0	7.1	12.7
		10.7	8.5	14.1	15.9	14.9	30.0	13.3	0	27.8	
		3.5	2.1	2.4	1.8	.9	.8	.2	0	.9	
351-400KM	8.	20	22	22	13	7	2	0	0	3	89
		22.5	24.7	24.7	14.6	7.9	2.2	0	0	3.4	8.1
		5.5	8.1	11.5	10.3	10.4	6.7	0	0	8.3	
		1.8	2.0	2.0	1.2	.6	.2	0	0	.3	
401-450KM	9.	28	32	26	8	6	3	3	0	3	109
		25.7	29.4	23.9	7.3	5.5	2.8	2.8	0	2.8	9.9
		7.7	11.9	13.6	6.3	9.0	10.0	20.0	0	8.3	
		2.5	2.9	2.4	.7	.5	.3	.3	0	.3	
ABOVE 450KM	10.	40	30	21	14	5	2	1	1	1	115
		34.8	26.1	18.3	12.2	4.3	1.7	.9	.9	.9	10.4
		11.0	11.1	11.0	11.1	7.5	6.7	6.7	25.0	2.8	
		3.6	2.7	1.9	1.3	.5	.2	.1	.1	.1	
	COLUMN TOTAL	364	270	191	126	67	30	15	4	36	1103
		33.0	24.5	17.3	11.4	6.1	2.7	1.4	.4	3.3	100.0

TABLE 2 CROSS-TABULATION OF DISTANCE AND THE ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS FOR THE MIDWEST STATES

ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS — ppb

SEPARATION BETWEEN STATIONS — km	COUNT / ROW PCT / COL PCT / TOT PCT	1-20PPB 1.	21-40PPB 2.	41-60PPB 3.	61-80PPB 4.	81-100PPB 5.	101-120PPB 6.	121-140PPB 7.	141-160PPB 8.	161-180PPB 9.	ABOVE 180 PPB 10.	ROW TOTAL
0-50KM	1.	73	45	31	4	2	3	3	2	1	5	169
		43.2	26.6	18.3	2.4	1.2	1.8	1.8	1.2	.6	3.0	7.4
		8.2	7.1	7.9	2.4	2.9	7.5	13.6	7.4	6.3	14.7	
		3.2	2.0	1.4	.2	.1	.1	.1	.1	.0	.2	
51-100KM	2.	35	25	11	5	1	1	1	2	2	0	83
		42.2	30.1	13.3	6.0	1.2	1.2	1.2	2.4	2.4	0	3.6
		4.0	3.9	2.8	3.0	1.5	2.5	4.5	7.4	12.5	0	
		1.5	1.1	.5	.2	.0	.0	.0	.1	.1	0	
101-150KM	3.	38	33	19	9	1	0	3	0	1	2	106
		35.8	31.1	17.9	8.5	.9	0	2.8	0	.9	1.9	4.6
		4.3	5.2	4.9	5.5	1.5	0	13.6	0	6.3	5.9	
		1.7	1.4	.8	.4	.0	0	.1	0	.0	.1	
151-200KM	4.	44	37	17	10	1	1	0	0	0	0	110
		40.0	33.6	15.5	9.1	.9	.9	0	0	0	0	4.8
		5.0	5.8	4.4	6.1	1.5	2.5	0	0	0	0	
		1.9	1.6	.7	.4	.0	.0	0	0	0	0	
201-250KM	5.	44	14	10	8	3	2	1	0	1	1	84
		52.4	16.7	11.9	9.5	3.6	2.4	1.2	0	1.2	1.2	3.7
		5.	2.2	2.6	4.8	4.4	5.0	4.5	0	6.3	2.9	
		1.9	.6	.4	.4	.1	.1	.0	0	.0	.0	
251-300KM	6.	51	28	24	7	4	1	0	2	0	2	111
		45.9	18.0	21.6	6.3	3.6	.9	0	1.8	0	1.8	4.9
		5.8	3.2	6.2	4.2	5.9	2.5	0	7.4	0	5.9	
		2.2	.9	1.1	.3	.2	.0	0	.1	0	.1	
301-350KM	7.	61	41	29	9	7	5	1	4	0	4	161
		37.9	25.5	18.0	5.6	4.3	3.1	.6	2.5	0	2.5	7.1
		6.9	6.5	7.4	5.5	10.3	12.5	4.5	14.8	0	11.8	
		2.7	1.8	1.3	.4	.3	.2	.0	.2	0	.2	
351-400KM	8.	122	74	39	25	11	8	6	4	5	8	302
		40.4	24.5	12.9	8.3	3.6	2.6	2.0	1.3	1.7	2.6	13.2
		13.8	11.7	10.0	15.2	16.2	20.0	27.3	14.8	31.3	23.5	
		5.3	3.2	1.7	1.1	.5	.4	.3	.2	.2	.4	
401-450KM	9.	101	77	60	22	9	8	2	7	2	6	294
		34.4	26.2	20.4	7.5	3.1	2.7	.7	2.4	.7	2.0	12.9
		11.4	12.1	15.4	13.3	13.2	20.0	9.1	25.9	12.5	17.6	
		4.4	3.4	2.6	1.0	.4	.4	.1	.3	.1	.3	
ABOVE 450KM	10.	317	268	150	66	29	11	5	6	4	6	862
		36.8	31.1	17.4	7.7	3.4	1.3	.6	.7	.5	.7	37.8
		35.4	42.3	38.5	40.0	42.6	27.5	22.7	22.2	25.0	17.6	
		13.9	11.7	6.6	2.9	1.3	.5	.2	.3	.2	.3	
COLUMN TOTAL		888	634	390	165	68	40	22	27	16	34	2287
		38.8	27.8	17.1	7.2	3.0	1.8	1.0	1.2	.7	1.5	100.0

TABLE 3 CROSS-TABULATION OF DISTANCE AND THE ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS FOR THE SOUTHWEST STATES

ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS — ppb

SEPARATION BETWEEN STATIONS — km	10-20PPB 1.	21-40PPB 2.	41-60PPB 3.	61-80PPB 4.	81-100PPB 5.	101-120PPB 6.	ROW TOTAL
0-50KM	3 75.0 9.1 3.1	1 25.0 2.6 1.0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	4 4.1
51-100KM	0 0 0 0	0 0 0 0	1 100.0 8.3 1.0	0 0 0 0	0 0 0 0	0 0 0 0	1 1.0
101-150KM	0 0 0 0	0 0 0 0	1 100.0 8.3 1.0	0 0 0 0	0 0 0 0	0 0 0 0	1 1.0
151-200KM	0 0 0 0	2 100.0 5.3 2.1	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	2 2.1
251-300KM	0 0 0 0	2 40.0 5.3 2.1	2 40.0 16.7 2.1	0 0 0 0	0 0 0 0	1 20.0 33.3 1.0	5 5.2
301-350KM	0 0 0 0	1 25.0 2.6 1.0	2 50.0 16.7 2.1	1 25.0 10.0 1.0	0 0 0 0	0 0 0 0	4 4.1
351-400KM	5 50.0 15.2 5.2	3 30.0 7.9 3.1	1 10.0 8.3 1.0	1 10.0 10.0 1.0	0 0 0 0	0 0 0 0	10 10.3
401-450KM	4 66.7 12.1 4.1	2 33.3 5.3 2.1	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	6 6.2
ABOVE 450KM	21 32.8 63.6 21.6	27 42.2 71.1 27.8	5 7.8 41.7 5.2	8 12.5 80.0 8.2	1 1.6 100.0 1.0	2 3.1 66.7 2.1	64 66.0
COLUMN TOTAL	33 34.0	38 39.2	12 12.4	10 10.3	1 1.0	3 3.1	97 100.0

TABLE 4 CROSS-TABULATION OF DISTANCE AND THE ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS FOR SOUTHERN CALIFORNIA

ABSOLUTE DIFFERENCE BETWEEN SECOND-MAXIMUM OZONE CONCENTRATIONS — ppb

SEPARATION BETWEEN STATIONS — km	COUNT / ROW PCT / COL PCT / TOT PCT	1-20PPB 1.1	21-40PPB 2.1	41-60PPB 3.1	61-80PPB 4.1	81-100PPB 5.1	101-120PPB 6.1	121-140PPB 7.1	141-160PPB 8.1	ABOVE 160 PPB 10.1	ROW TOTAL
0-50KM	1.	17	6	3	6	0	0	0	0	0	32
		53.1	18.8	9.4	18.8	0	0	0	0	0	34.8
		70.8	75.0	30.0	35.3	0	0	0	0	0	
		18.5	6.5	3.3	6.5	0	0	0	0	0	
51-100KM	2.	0	0	2	4	0	0	0	0	0	6
		0	0	33.3	66.7	0	0	0	0	0	6.5
			0	20.0	23.5	0	0	0	0	0	
		0	0	2.2	4.3	0	0	0	0	0	
101-150KM	3.	2	1	1	3	5	1	1	5	9	28
		7.1	3.6	3.6	10.7	17.9	3.6	3.6	17.9	32.1	30.4
		8.3	12.5	10.0	17.6	100.0	16.7	25.0	55.6	100.0	
		2.2	1.1	1.1	3.3	5.4	1.1	1.1	5.4	9.8	
151-200KM	4.	3	1	1	1	0	4	2	3	0	15
		20.0	6.7	6.7	6.7	0	26.7	13.3	20.0	0	16.3
		12.5	12.5	10.0	5.9	0	66.7	50.0	33.3	0	
		3.3	1.1	1.1	1.1	0	4.3	2.2	3.3	0	
201-250KM	5.	2	0	3	3	0	1	1	1	0	11
		18.2	0	27.3	27.3	0	9.1	9.1	9.1	0	12.0
		8.3	0	30.0	17.6	0	16.7	25.0	11.1	0	
		2.2	0	3.3	3.3	0	1.1	1.1	1.1	0	
	COLUMN TOTAL	24	8	10	17	5	6	4	9	9	92
		26.1	8.7	10.9	18.5	5.4	6.5	4.3	9.8	9.8	100.0

It is evident from the figures and the tables that very large differences in the observed hourly second-maximum concentrations have occurred even at stations that are separated by only a few kilometers. Surprisingly, differences in readings appear to be greatest for locations that are separated by distances of a few hundred kilometers and less for greater separations. This may be an artifact, however, reflecting that more pairs of stations in each data set are separated by distances of a few hundred kilometers than are separated by somewhat greater or lesser distances. Tables 1 (Northeast states) and 4 (Southern California) show a tendency for greater representation of the intermediate distances.

The contingency tables (or cross-tabulations) have four numbers within each square; the absolute number of cases that meet the two criteria that define the square is given by the first figure. The second figure within each square defines the percentage of the total number of cases in that row that falls within that particular column; the third figure shows the percentage of the total number of cases in that column that falls in that particular row. The last figure shows the percentage of the total data set that falls within that square. For instance, the upper-left square of Table 1 shows:

- There were 55 instances when the absolute difference between second-maximum readings was 0-20 ppb and the station separation was less than 50 km.
- 47.4 percent of all stations separated by less than 50 km had second-maximum readings that differed by less than 21 ppb.

- 15.1 percent of the instances when the second-maximum values differed by less than 21 ppb were associated with stations separated by less than 50 km.

- 5.0 percent of all cases had second-maximum values that differed by less than 21 ppb and were separated by less than 50 km.

Row and column totals of absolute and percentage frequencies are shown at the ends of the rows and the bottoms of the columns.

The tables indicate that most differences in second-maximum observations are less than 40 ppb, except in the Southern California data set, where more than half the differences exceed 60 ppb. The larger differences associated with the Southern California data reflect the effect of the Southern California summer weather, which changes little from day to day and which results in strong, persistent pollutant gradients in the Los Angeles basin.

Figures 5 and 6 show how the average differences between second-maximum ozone readings vary with the separation between stations. These figures were compiled from the same data used to prepare Figures 1 and 2. The data were stratified according to separation between stations using 50-km bins. The absolute values of differences in the second-maximum readings were transformed by adding 0.5 ppb and then determining the geometric mean and the standard geometric deviation for each data subset. The geometric means (reduced by 0.5 ppb) and the range indicated by the standard geometric deviations have been plotted in Figures 5 and 6: The transformations avoid the problems associated with determining geometric means for data sets that include zero values. The data were too few to prepare diagrams of this type for the Southwest or Southern California regions.

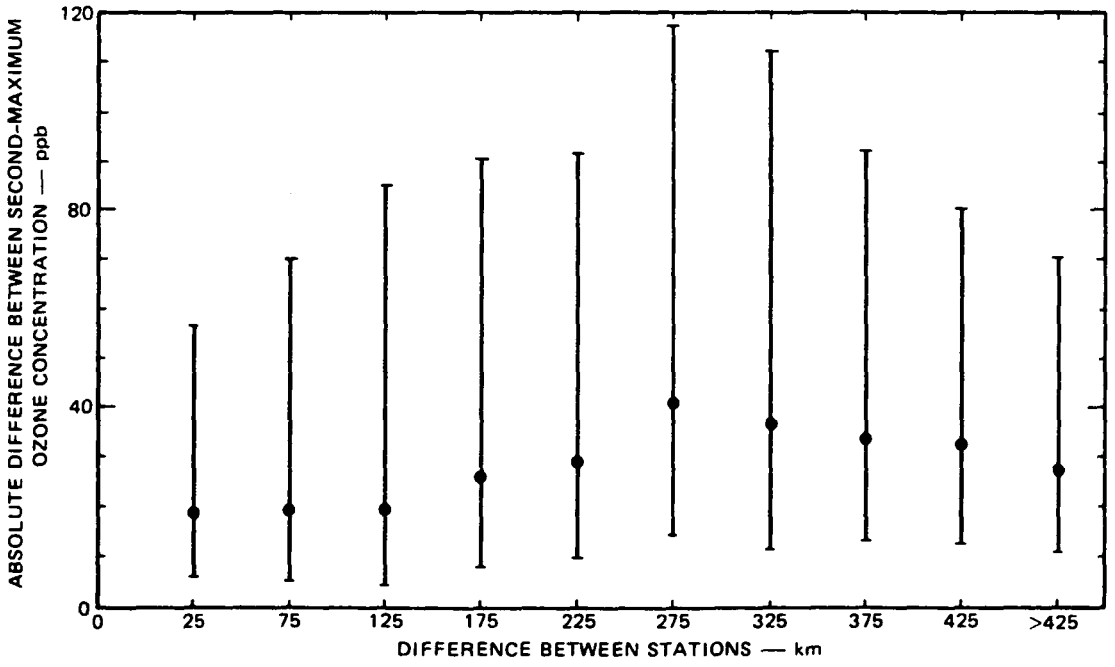


Figure 5. Geometric means of difference in second-maximum ozone concentration for the Northeast.

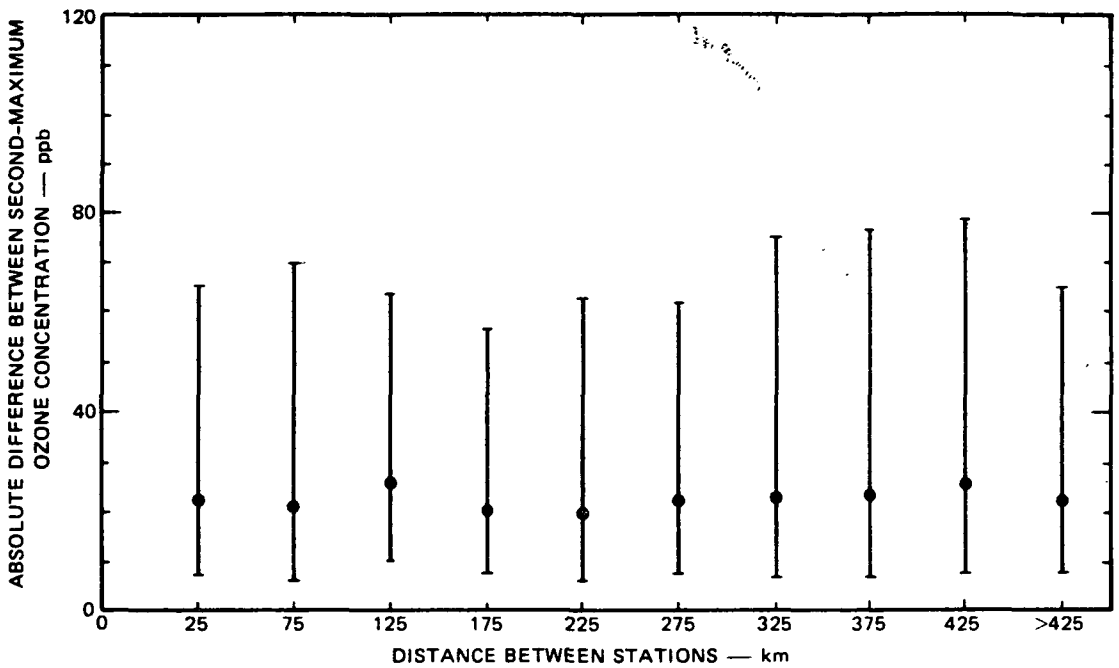


Figure 6. Geometric means of difference in second-maximum ozone concentration for the Midwest.

There is an obvious relationship between station separations and differences in the observed second-maximum ozone concentrations. In the Northeast, there is a slight tendency for the absolute values of the differences to increase with separation out to about 250 km, and then to actually decrease with greater separations. However, even if this apparent tendency is not an artifact, it is too weak to be useful. The data from the Midwest in Figure 6 show virtually no change with station separation in the average difference between observed second-maximum ozone readings. Figures 1 through 6 suggest that other types of relationships must be sought in order to determine the degree to which existing data can be used to characterize those areas where the NAAQS is met or exceeded.

3. *Conditional Probabilities of Observing Exceedances of the NAAQS*

As noted in the preceding section, the average difference between second-maximum concentrations observed at two stations is not closely enough related to station separation to be used to determine areas of noncompliance with the standards. For this reason, another approach is needed. The approach described in this section is based on the following question: "How does the probability of observing an exceedance of the NAAQS vary with distance from a station where a given concentration has been measured?" If that question can be answered for a variety of observed second-maximum ozone concentrations, then it should be possible to define an area around each existing station where the probability of observing an exceedance of the NAAQS is either very high or very low (and that area is reasonably certain to be in exceedance or in compliance).

The question of whether or not the standards are exceeded within an area can be asked for a given day, but that is not the question of greatest interest for this particular study. In essence, the form of the question to be addressed here is whether or not a particular location can be reliably designated in exceedance of the standards on an annual basis. The annual second-maximum hourly concentrations were selected as the appropriate design values. The reader is directed to Section 3-A for a more detailed discussion on this selection.

Figure 7 shows the conditional probabilities that the NAAQS was exceeded more than once during a year at different distances from a location where the second-maximum ozone concentration exceeded different thresholds. There is considerable scatter evidenced in the data, because many of the subsets representing certain increments of station separation had sparse data, but the major features of the expected behavior are apparent. For example, the curves do converge at the smaller separation distances, as is to be expected—any threshold above 120 ppb is certain to be associated with an exceedance when the location for which the probabilities are being estimated is coincidental with the observing station, i.e. zero separation distance. At the other extreme, when the location for which the probabilities are being estimated is very distant from the observation site, one might expect the two to be unrelated. Thus, the probability of finding a second-maximum ozone concentration above the NAAQS is independent of the observed value and equal to the probability of finding such an exceedance at a location selected randomly from the total data set. In this instance, 72.5 percent of the stations had second-maximum ozone concentrations in excess of 120 ppb. Thus, it is not surprising that at distances greater than about 250 km, the probability of observing an exceedance of the NAAQS is about 72 percent regardless of the threshold.

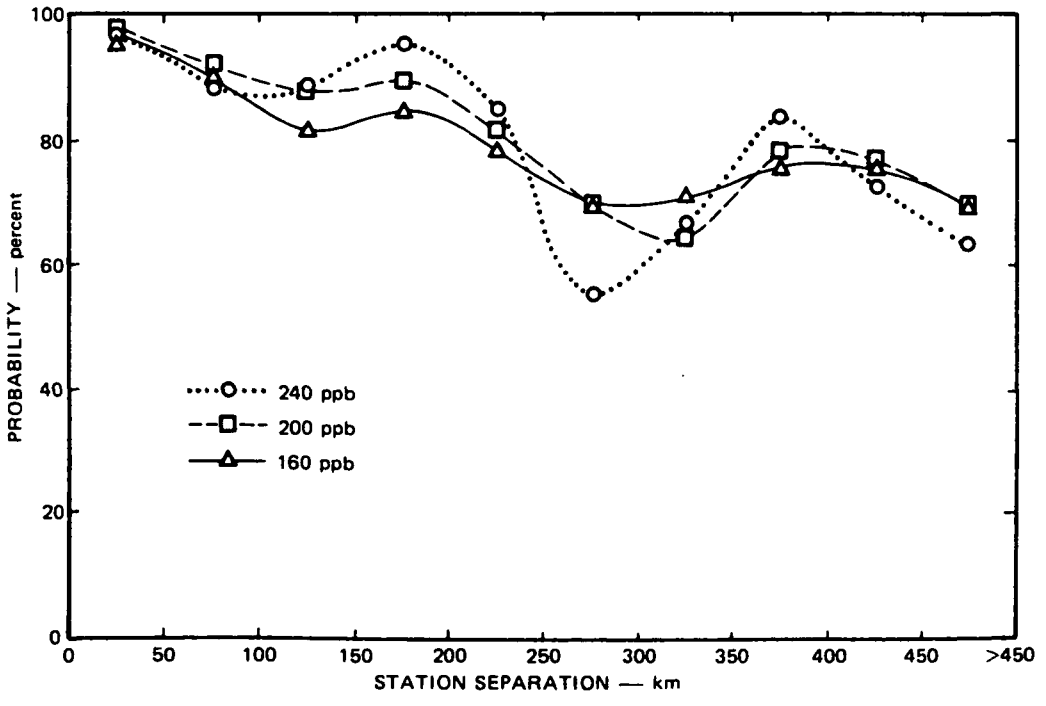


Figure 7. Probability as a function of distance between stations that ozone will exceed 120 ppb if the annual second-maximum ozone concentration has been observed to exceed specified thresholds for all U.S. monitoring sites for 1977.

4. *Identification of Areas Where Exceedances of the NAAQS for Ozone are Probable*

The probability that a station will have exceeded the NAAQS for ozone, given that it is within a certain distance from a station where some threshold ozone concentration has been exceeded, has already been discussed. These conditional probabilities can be expressed as a function of the distance between the observing stations and the threshold that was exceeded. If the probability is fixed, then it should be possible to express—as a function of observed annual second-maximum, hour-averaged ozone concentration—the radius of the area for probable NAAQS exceedances. Each station in the United States that has observed an exceedance of the NAAQS for ozone can then be used to define an area within which such exceedances were probable. Those areas can be considered to have an established status, with regard to the NAAQS for ozone. In principal, a similar approach could be used to establish areas of probable compliance with the standards, however, the present data are not sufficient to establish such a relationship. The status of other areas within the country might then be considered undefined, so these areas would be candidates for the establishment of some sort of monitoring.

Contingency tables like Table 5 show the relative frequency at which the standards were exceeded at the second station of a pair, given that some concentration had been observed at the first station. For example, Table 5 shows that for station pairs separated by 50 km or less, there were 20 instances when the second-maximum ozone concentration was between 40 and 60 ppb at one of the stations. Of those 20 instances, a second-maximum ozone concentration in excess of 120 ppb was observed on only three occasions at the other station of the pair. Thus, there was only about a 15-percent likelihood that two or more exceedances would be found within 50 km of a station whose second-maximum ozone concentration for the year was between 40 and 60 ppb. As another example, Table 5 shows 28 instances with second-maximum concentrations between 260 and 280 ppb at one of the stations in the pair. Of those 28, the observed second-maximum at the other station exceeded 120 ppb in 26 cases. Thus, the annual probability of exceeding the ozone standard twice or more within 50 km of a station where the second-maximum was observed to be between 260 and 280 ppb was about 93 percent. Similar probabilities can be determined for each of the concentration intervals shown in Table 5.

Contingency tables were prepared showing the number of cases of exceedances and nonexceedances versus observed second-maximum ozone values in 40 ppb bins. Tables were prepared for station separations of 0 to 50 km, 50 to 100 km, and so forth. The Chi-square test showed significant relationships at better than the 1-percent level for stations separated by as much as 250 km. The tables for stations separated by 250 to 350 km were also significant at the 1 percent level, but most of the relationships were opposite to the expected, i.e., there were fewer than the expected number of exceedances associated with the higher second-maximum observations. This is further evidence of the anomolous relationships discussed earlier in connection with Figures 5 and 6. At separations greater than 350 km, the relationships are not significant at the 1 percent level.

Figure 8 shows the empirical probabilities associated with the annual second-maximum ozone concentrations at stations separated by less than 50 km. A smooth line has been drawn approximating the trends of the points. The curve in Figure 8 has the expected characteristics: At very low observed annual second-maximum ozone concentrations, the probability of observing an exceedance of NAAQS within 50 km of a station is quite small, and the probabilities increase with increasing observed annual second-maximum ozone concentrations. For locations within 50 km of an observing station, it becomes virtually certain that an exceedance of a

TABLE 5 JOINT FREQUENCY OF OCCURRENCE OF ANNUAL SECOND-MAXIMUM OZONE CONCENTRATIONS AT STATIONS SEPARATED BY LESS THAN 50 km

Second-Maximum Ozone Concentration (ppb)	Second-Maximum Ozone Concentration (ppb)																				
	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	160-180	180-200	200-220	220-240	240-260	260-280	280-300	300-320	320-340	340-360	360-380	380-400	Row Total
0-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20-40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40-60	0	0	2	3	4	8	3	0	0	0	0	0	0	0	0	0	0	0	0	0	20
60-80	0	0	3	0	5	9	2	1	0	0	0	0	0	0	0	0	0	0	0	0	20
80-100	0	0	4	5	6	13	8	6	2	1	0	0	1	0	0	0	1	0	0	0	47
100-120	0	0	8	9	13	22	44	15	11	3	0	1	0	2	0	0	0	0	0	0	128
120-140	0	0	3	2	8	44	58	45	40	22	4	4	4	3	1	0	2	0	0	0	240
140-160	0	0	0	1	6	15	45	66	52	38	8	6	5	4	2	2	3	1	0	0	254
160-180	0	0	0	0	2	11	40	52	64	28	13	4	4	3	0	0	0	0	0	0	221
180-200	0	0	0	0	1	3	22	38	28	28	14	10	1	3	1	2	3	2	0	0	156
200-220	0	0	0	0	0	0	4	8	13	14	20	2	1	0	0	0	0	0	0	0	62
220-240	0	0	0	0	0	1	4	6	4	10	2	2	2	0	1	1	3	1	0	0	37
240-260	0	0	0	0	1	0	4	5	4	1	1	2	0	0	2	0	2	0	0	0	22
260-280	0	0	0	0	0	2	3	4	3	3	0	0	0	2	1	4	2	1	1	2	28
280-300	0	0	0	0	0	0	1	2	0	1	0	1	2	1	0	2	6	1	0	0	17
300-320	0	0	0	0	0	0	0	2	0	2	0	1	0	4	2	2	8	3	2	4	30
320-340	0	0	0	0	1	0	2	3	0	3	0	3	2	2	6	8	20	6	1	2	59
340-360	0	0	0	0	0	0	0	1	0	2	0	1	0	1	1	3	6	0	1	2	18
360-380	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	1	1	0	2	7
380-400	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	4	2	2	2	2	14
Column Total	0	0	20	20	47	128	240	254	221	156	62	37	22	28	17	30	59	18	7	14	1380

standard will be found if the station observes a sufficiently large second-maximum ozone concentration. Figure 8 shows that the probabilities reach 90 percent at a little less than 150 ppb, 95 percent at about 175 ppb, and about 99 percent at 275 ppb.

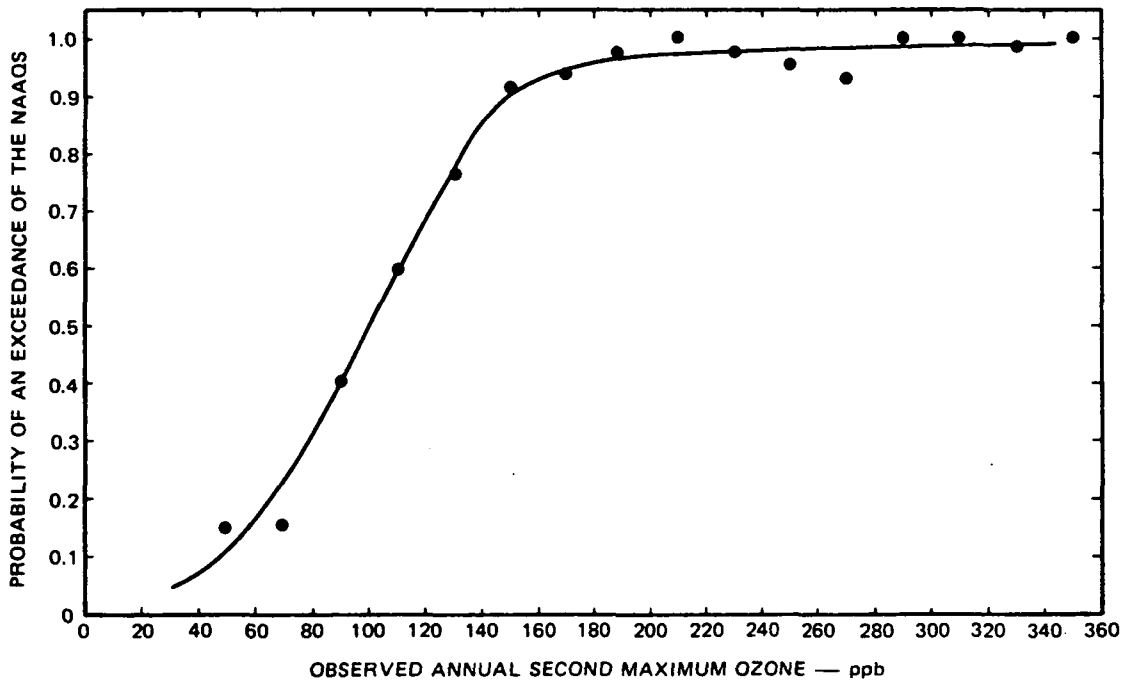


Figure 8. Probability that the annual second-maximum ozone concentration exceeds 120 ppb within 50 km of a station, given the observed value for that station.

One would expect that at sufficiently large distances from a station, the likelihood of observing an exceedance of the NAAQS twice or more during the year (based on the observed second-maximum ozone concentrations at that station) would not reach such high levels, regardless of the observed ozone concentrations because the physical factors that cause the relationships are generally limited in spatial scale. This expectation is generally confirmed by the data. Figure 9 shows the conditional probabilities calculated for data from pairs of stations separated by other distances. While there is considerable scatter, it is still possible to draw reasonable curves to approximate the trends indicated by the points. At the greatest separations, the probabilities of observing an exceedance of the NAAQS (given an observed second-maximum ozone concentration) do not generally reach 99 percent. Furthermore, as expected, the observed concentration required for a specified probability level increases with increasing separation. For example, when stations are separated by 50 to 100 km, an annual second-maximum ozone concentration of 175 ppb or greater must be observed at one of them before the probability of observing an exceedance of the NAAQS at the other exceeds 90 percent. When the stations are separated by 100 to 150 km, the required concentration climbs to about 235 ppb before the probability that second-maximum ozone concentration will exceed 120 ppb reaches 90 percent. Finally, for stations separated by 200 to 250 km, an observation of around 290 ppb is required.

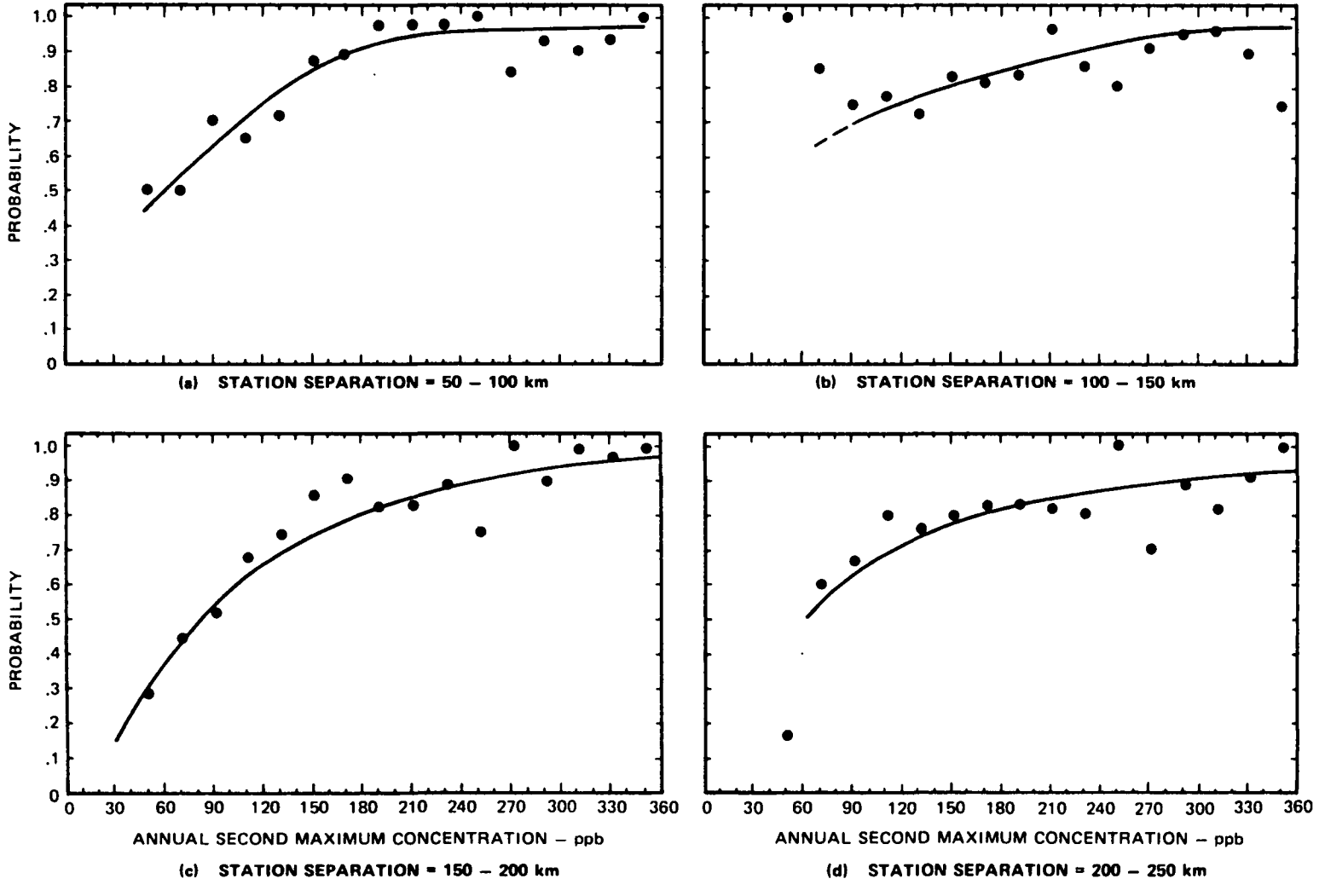


Figure 9. Observed probabilities of an exceedance of the ozone standard for the different station separations as a function of the second-maximum ozone value.

There is an obvious relationship between the annual second-maximum ozone concentration observed at a location and the distance from that station at which the probability of observing an exceedance of the NAAQS falls below a specified level. Figure 10 shows the relationships for three different, specified probabilities as derived from the data presented in Figures 8 and 9. Qualitatively, the relationship is as expected. For example, an observed concentration (annual second-maximum) of 120 ppb provides little guarantee that the NAAQS will be equaled or exceeded twice or more anywhere but at that station. As the observed value increases, so does the distance range for likely exceedance of the standard. As noted before, it is not possible to achieve the higher probabilities beyond some cut-off distance, regardless of how great the observed second-maximum ozone concentration might be. Thus, the distance range for a 95 percent probability of exceedance is unlikely ever to be more than 175 to 200 km, regardless of the observed second-maximum ozone concentration. For 90 percent probabilities, this cutoff is 225 to 250 km, and the 85 percent threshold can be achieved to distances around 250 to 275 km.

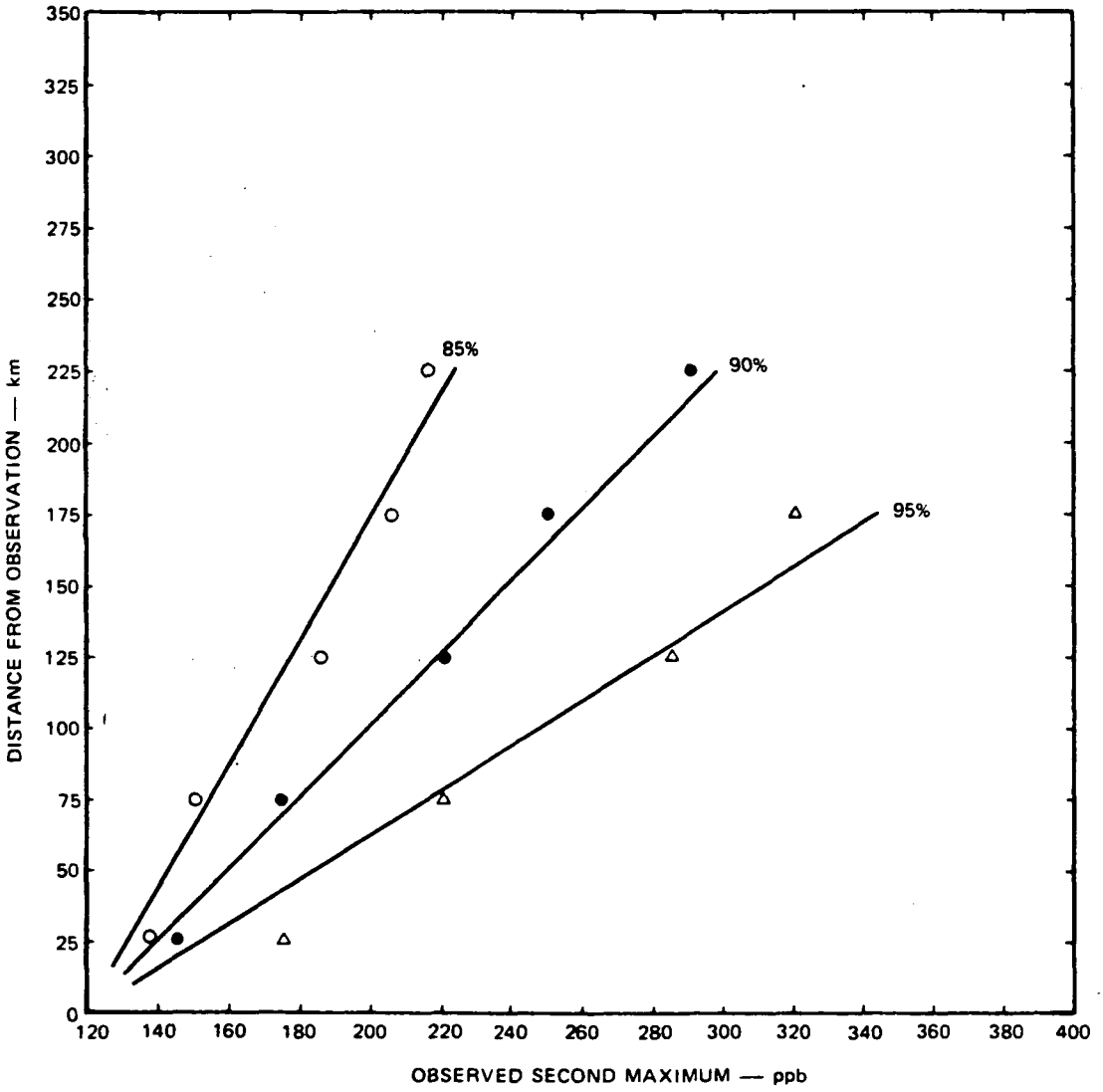


Figure 10. Probability of observing an exceedance of the NAAQS for ozone as a function of observed second-maximum ozone concentration and distance.

It is obvious that the curves in Figure 10 can be used in combination with observed values of second-maximum ozone concentrations to define areas within which exceedances of the NAAQS for ozone have probably occurred twice or more during a year. Figure 11 is a map of the United States that shows those areas where it is 95 percent probable, based on the relationship shown by the straight line in Figure 10 and on the observed annual maximum ozone concentrations, that the NAAQS for ozone has been exceeded once or more during years 1977 or 1978. The annual maximum ozone concentrations for each year and station for which more than 7,000 hours of data were available were considered. Stations with more than 7,000 hours per year with observed concentrations less than 120 ppb are marked with the symbol "L". The largest radius used was 200 km, and the smallest, for graphical reasons, was 4 km. The appropriate size circles were drawn centered on the location of the various observing sites, resulting in Figure 11.

It is obvious from the figure that available data are sufficient to characterize much of the country as exceeding the ozone standards. However, many large areas have not been conclusively identified as exceeding or being less than the standard on the basis of data in the SAROAD.

It should be noted that the approach taken above can also be used to define areas that are not likely to have exceeded the standards. Such classifications are more limited in area. For example, Figure 8 indicates that an observed annual second-maximum ozone concentration less than about 50 ppb is required before the probability of an exceedance within 50 km is reduced to 10 percent or less (corresponding to a probability of compliance of 90 percent or more). The kind of analysis used here does not appear to be very sensitive for determining compliance with the standard; it does not appear possible to establish compliance with the standards to distances greater than about 50 km from an observing site. There are some regions of the United States shown in Figure 11 where the standards have not been exceeded at any of the sites from which data are available and it is probable that the ozone standards have not been exceeded anywhere within those general areas. However, this cannot be quantified from presently available information.

Figure 11 shows some inconsistencies. For instance, a circle centered on Denver encompasses an "L" symbol denoting compliance. Such inconsistencies have been used to identify some stations whose characteristics were studied for common traits related to unrepresentativeness. These have been discussed in a technical memorandum prepared as part of this project (Ludwig and Shelar, 1979).

Figure 11 shows the areas that can be characterized with regard to probable exceedance of the NAAQS for ozone on the basis of reasonably complete data from the SAROAD, i.e., data sets of more than 7,000 hours per year. The characterized areas can be expanded when less complete data sets are included; only one or more observations in excess of 120 ppb are needed to be reasonably certain that an area is one within which exceedances are likely. In general, the area defined by an incomplete data set will be smaller (it cannot be larger) than would be obtained from a complete data set, but the inclusion of incomplete data sets can reduce the area that is uncharacterized as shown in Figure 12.

Presumably, data from special studies or data not otherwise archived in the SAROAD could be used to reduce the area uncharacterized with regard to compliance or exceedance of the NAAQS. An intensive search for such data sources was beyond the scope of this project. However, a search for existing data that could be used to characterize some of the regions left blank in Figure 12 would probably be much more cost effective than special monitoring of some kind. (This will be discussed further in Section 4.)

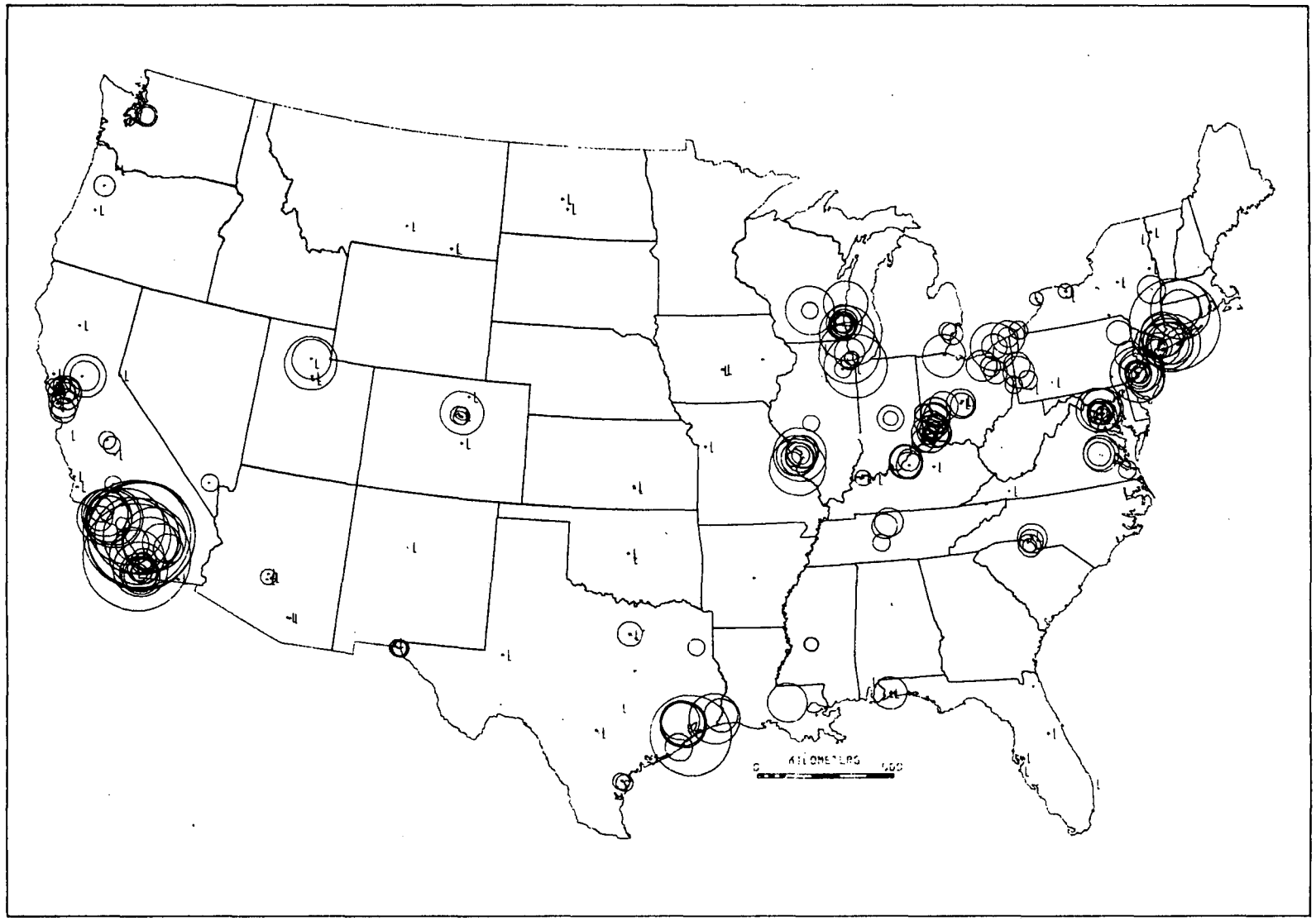


Figure 11. Areas where it is 95-percent probable that the NAAQS for ozone has been exceeded based on SAROAD stations with more than 7000 hours per year for the years 1977 and 1978.

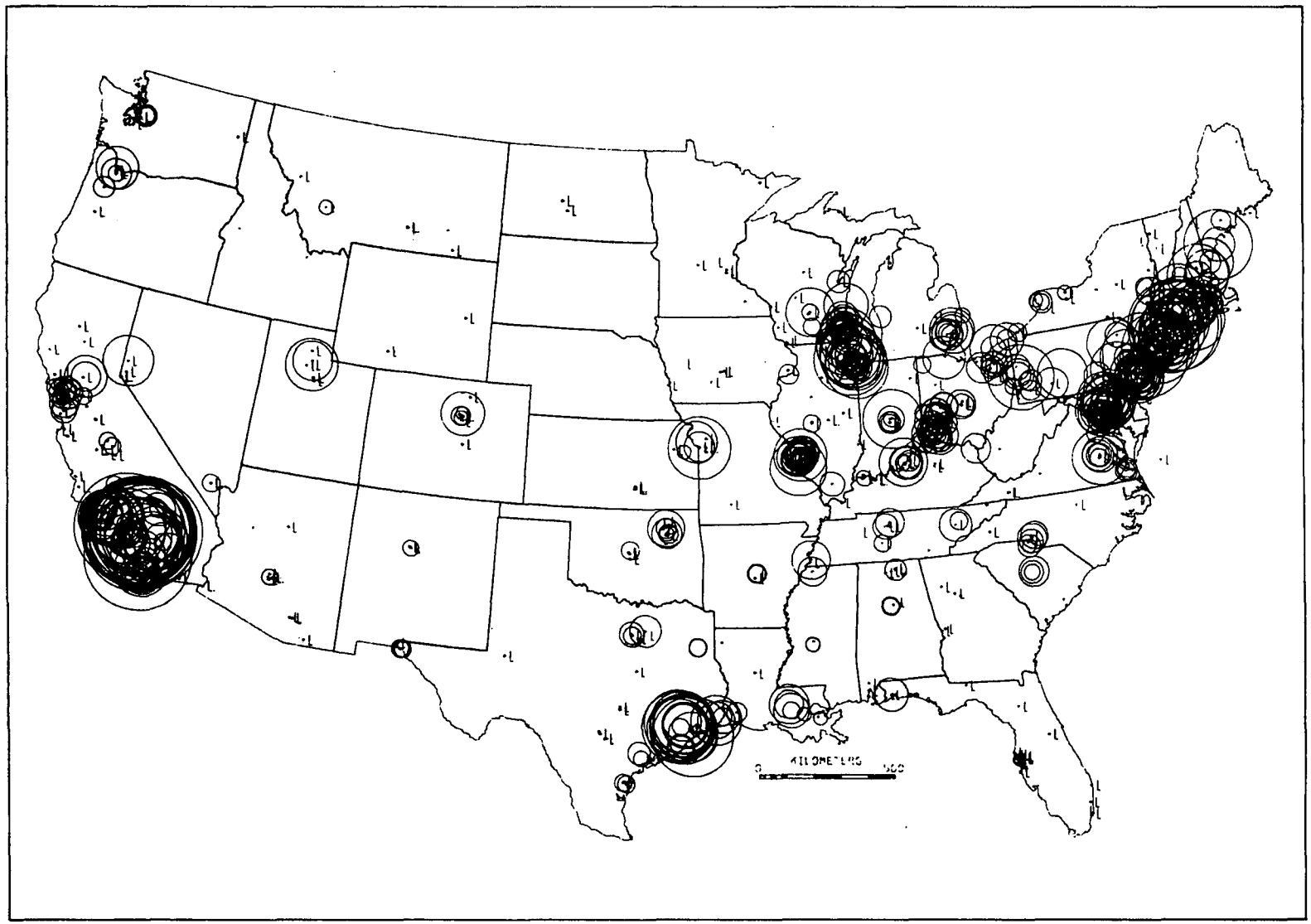


Figure 12. Areas where it is 95-percent probable that the NAAQS for ozone has been exceeded based on all SAROAD data for 1977 and 1978.

5. *Factors Accompanying Widespread Exceedances of the NAAQS*

a. *General*

For practical reasons, it is important to be able to recognize those situations where exceedances of the NAAQS are most likely to occur. The essential ingredients for the buildup of high ozone concentrations are: an accumulation of precursor emissions, sunshine, and relatively little ozone removal at the surface or by chemical reactions. The first two items depend largely on meteorological conditions. The last item depends more on location.

Sunshine is not usually measured and reported but is closely related to temperature: It is not surprising that ozone concentrations have been found to be closely related to temperatures. An examination of the analyses of ozone concentrations prepared by Ludwig, Simmon et al. (1977) for each day of 1974 shows that there were no instances in the eastern United States when ozone concentrations exceeded 120 ppb on a day when the maximum temperatures did not exceed 70°F (21°C). Meyer et al. (1976) and Ludwig, Reiter et al. (1977) provided further evidence of the importance of temperature in determining ozone concentration. Both groups found significant correlations between observed ozone concentrations and ambient temperatures measured in the air parcel during the preceding several hours. Ludwig and Martinez (1979) recently found in an examination of 1977 summer data from Houston that ozone concentrations in excess of 120 ppb were not observed with temperatures less than 75°F (24°C).

TABLE 6 NUMBER OF DAYS PER MONTH IN 1977 WITH DAILY MAXIMUM OZONE IN EXCESS OF 120 ppb IN SELECTED REGIONS OF THE U.S.

Month	Region			
	Northeast	Midwest	Texas-Louisiana Gulf Coast	Southern California
January	0	1	2	0
February	0	4	2	10
March	1	3	3	4
April	5	10	8	16
May	14	22	11	8
June	15	19	9	27
July	17	26	15	30
August	17	13	13	29
September	3	8	8	25
October	0	0	13	22
November	0	0	0	12
December	0	0	0	10

Data source: SAROAD

b. *Seasonal Effects in Different Geographical Areas*

With the dependence on temperature described above, it is not surprising that there are strong seasonal variations in the incidence of exceedances of the ozone standard. The SAROAD data for 1977 from the selected regions were examined to see how the frequencies of occurrence of ozone standard exceedances changed from month to month and from region to region during 1977. The results are shown in Table 6. A similar tabulation was prepared from 1974 data for the eastern U.S. by Ludwig, Reiter et al. (1977) using the old NAAQS of 80 ppb. That tabulation also showed summer and fall to be the seasons when high ozone concentrations are most probable. There are differences in probability from one part of the country to another and there are also some differences in the seasonal distribution of ozone exceedances from place to place.

6. *Effects of Large-Scale Weather Systems in Different Geographical Areas*

Several authors have pointed out that relatively high ozone concentrations are frequently found in association with high-pressure systems (e.g. Bach, King and Vukovich, 1976; Ludwig, Reiter et al., 1977; Wolff, Ferman, and Monson, 1979). It is usually stated that the preferred part of the high-pressure system is the "backside" or western part. Ludwig, Reiter et al. (1977) examined the frequency that high ozone concentrations (in excess 80 ppb) were observed in association with different meteorological features in the eastern United States during 1974. They found that the higher ozone concentrations occurred most frequently in the western parts of high-pressure systems. If cases that they classified as being in the warm air near a front—an area usually located at the western extreme of a high-pressure system—are added to those cases that they classified as being in the western parts of anticyclones, then, the high ozone concentrations were found in the western half of high-pressure systems in sightly more than half of the cases. About 25 percent of the time, the high ozone concentrations were associated with the central or eastern parts of a high-pressure cell.

Ludwig, Reiter et al. (1977) presented another table which hinted that the meteorological features associated with high ozone concentrations may differ from one part of the country to another. That table related the winds reported on the morning weather map to areas where relatively high peak-hour ozone concentrations (in excess of 80 ppb) occurred during the day for the months June through August. The differences in the wind direction that they found from one geographical region to another suggest different locations relative to the high-pressure system. Since winds are calm in the center of the anticyclone and spiral clockwise outward, the different winds can be interpreted as being associated with different parts of the anticyclone. Based on the tabulations of wind direction associated with relatively high ozone concentrations given by Ludwig, Reiter eta l. (1977), the Texas-Louisiana Gulf Coast is most frequently in the center or southwestern part of a high-pressure system when the relatively high ozone concentrations occur, while in New England the more northerly parts of a high-pressure systems are more often involved. The analyses of Ludwig, Simmon et al. (1977) were used to prepare Table 7, which shows a breakdown of the occurrence of exceedances of the 120 ppb NAAQS in the eastern U.S. during 1974 according to geographical area and meteorological feature.

TABLE 7 OZONE CONCENTRATIONS IN EXCESS OF 120 ppb AND ASSOCIATED WEATHER FEATURES IN VARIOUS PARTS OF THE EASTERN UNITED STATES DURING 1974

Synoptic-Scale Weather Feature	Region			
	Texas/ Louisiana Oklahoma	Northeast	Southeast	Midwest
Near a front				
Cold air	1	6	1	1
Warm air	9	11	6	13
High-pressure system				
Northwest	1	8	1	9
Southwest	18	4	6	6
Southeast	1	2	2	2
Northeast	0	5	2	1
Center	1	2	2	2
Other	8	5	2	3

Table 8 was prepared from analysis of 1977 ozone data from the four geographical regions that served as a focus of this study. Threshold ozone concentrations were selected for each area such that observed ozone concentrations, averaged over the area, exceeded the threshold on ten to fifteen days during the year. In this way, cases of widespread, high ozone concentrations were identified for each of the geographical areas. A computer analysis of the ozone pattern was prepared for each selected case and compared with the corresponding morning weather map (Nat. Oceanic and Atmos. Admin., 1977).

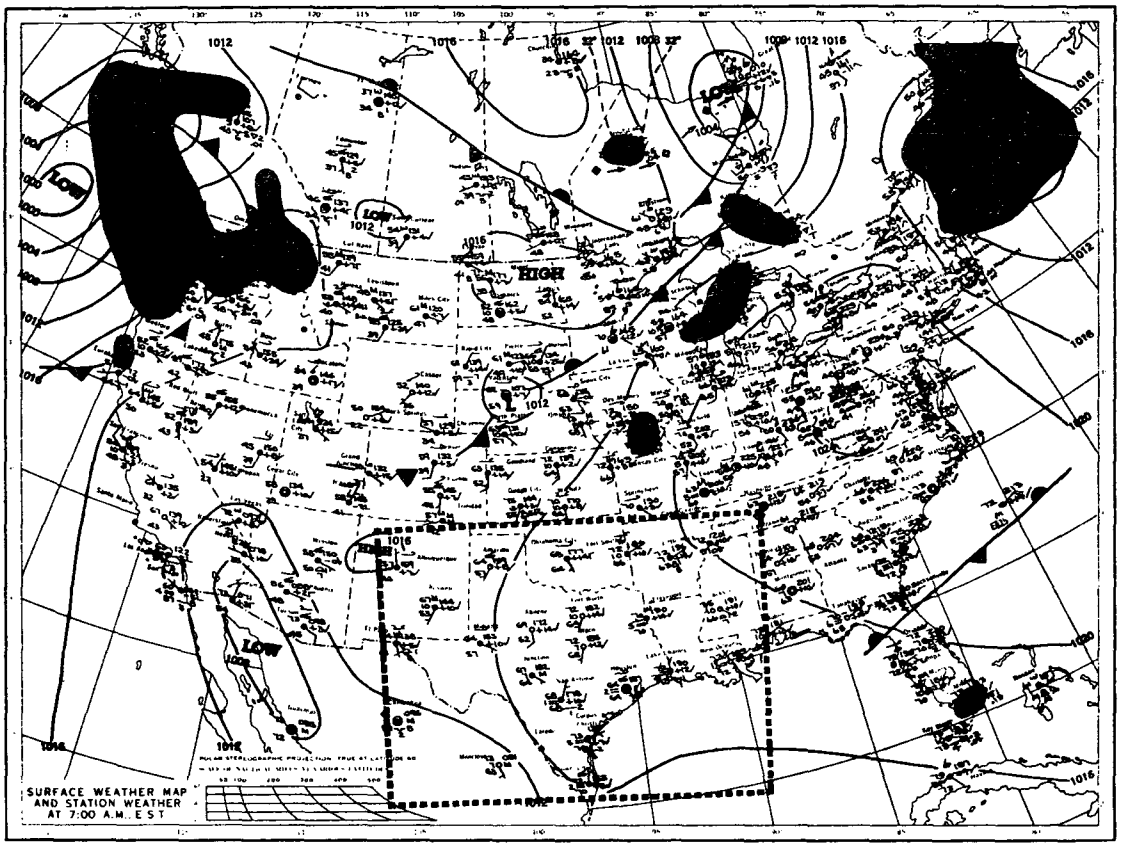
Table 9 summarizes the nature of the meteorological conditions associated with those widespread, high ozone-concentration cases. It is apparent from Tables 7 and 9 that incidents of high ozone concentration are associated with somewhat different meteorological features in different parts of the country. Both Tables 7 and 9 show that high ozone concentrations in the Texas-Louisiana Gulf Coast area are most frequently associated with the southwestern quadrant of a high-pressure system. Figure 13 gives an example—4 June 1977—of such a system. The pressure gradients cause light airflow onshore, or nearly parallel to the shore. This, in turn, allows an accumulation of precursors, with subsequent ozone formation.

Ludwig and Shelar (1977) pointed out that the accumulations of precursors and ozone occur in the northeastern part of the United States when the airflow parallels the alignment of the urban areas in that region. In contrast to the Texas Gulf area, such airflow in the northeastern U.S. tends to be associated with the northwestern quadrant of high-pressure systems. Tables 7 and 9 reflect this fact. An example of such a situation is shown in Figure 11 for 4 July 1977. The example shows that the high concentration area was in the northern part of the high. This is not unusual; in fact, as Table 7 shows, the high concentrations sometimes fall in the northeast quadrant of a high-pressure cell.

TABLE 8 SELECTED DAYS WITH WIDESPREAD HIGH OZONE CONCENTRATIONS IN DIFFERENT REGIONS DURING 1977

Northeast		Midwest		Texas/Louisiana/ Arkansas		Southern California	
Date	Regional Average Ozone Concentration (ppb)	Date	Regional Average Ozone Concentration (ppb)	Date	Regional Average Ozone Concentration (ppb)	Date	Regional Average Ozone Concentration (ppb)
17 May	119	16 May	91	26 Apr	93	4 Jun	157
4 Jul	111	24 May	94	11 May	91	25 Jun	146
15 Jul	112	25 May	95	12 May	99	26 Jun	157
16 Jul	152	27 May	95	31 May	111	11 Aug	148
17 Jul	150	28 May	110	1 Jun	98	4 Sep	146
19 Jul	108	4 Jun	94	2 Jun	144	5 Sep	155
20 Jul	123	15 Jun	95	4 Jun	103	6 Sep	162
21 Jul	132	14 Jul	94	5 Jun	111	7 Sep	178
4 Aug	111	15 Jul	98	6 Jun	99	11 Oct	154
5 Aug	105	28 Jul	93	9 Jun	108	14 Oct	166
		30 Jul	91	16 Jul	92	15 Oct	164
				23 Jul	98	17 Oct	154
				26 Jul	93	18 Oct	154
				27 Jul	94		

Data source: SAROAD



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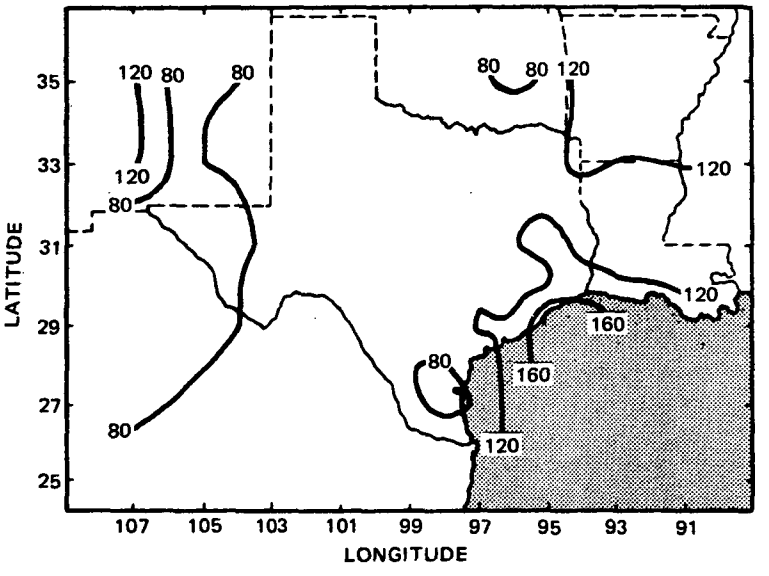


(b) PEAK-HOUR OZONE CONCENTRATIONS

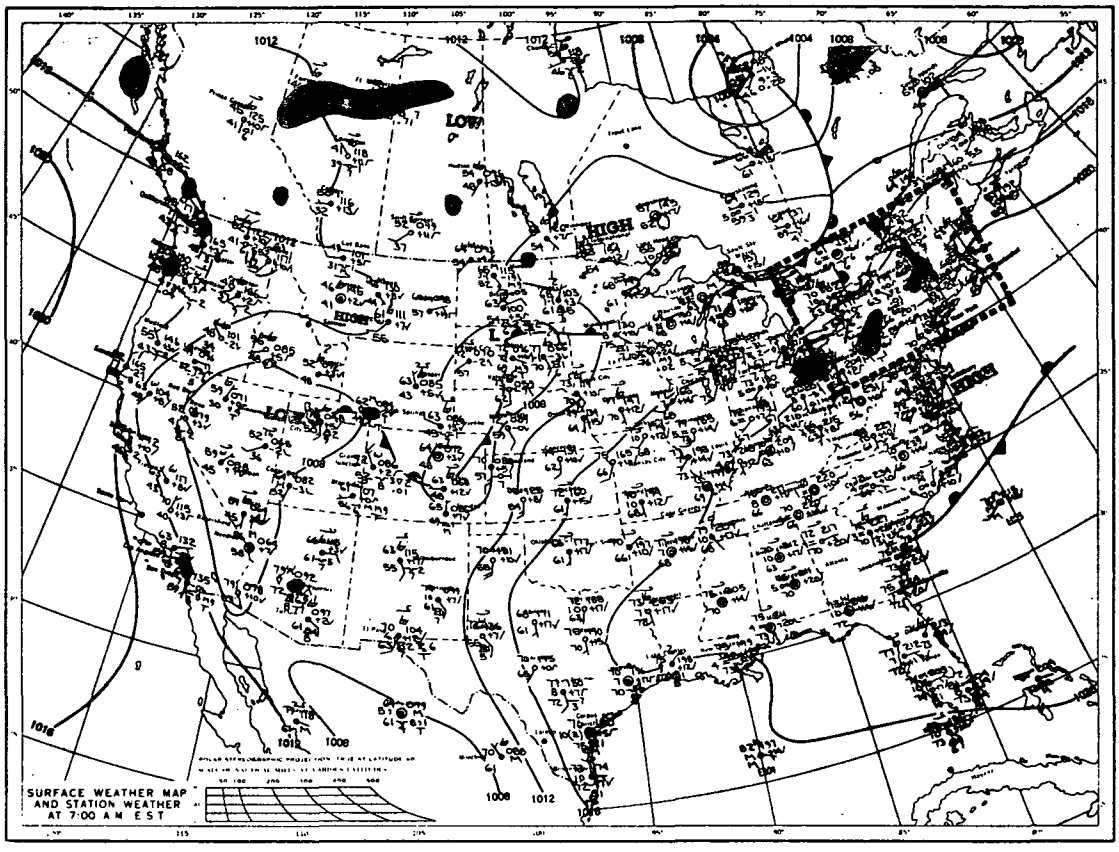
Figure 13. Example of high ozone concentrations associated with the southwest quadrant of a high-pressure system over the Texas-Louisiana Gulf Coast area, 4 June 1977.

TABLE 9 WEATHER FEATURES ASSOCIATED WITH WIDESPREAD HIGH OZONE CONCENTRATIONS IN SELECTED REGIONS OF THE UNITED STATES DURING 1977

Synoptic-Scale Weather Feature	Region			
	Texas/ Louisiana	Northeast	Midwest	Southern California
Warm air near a front	4	3	4	0
High-pressure system				
Northwest	0	7	3	0
Southwest	7	0	2	0
Southeast	1	0	0	0
Northwest	0	0	0	0
Center	0	0	0	0
Other	2	0	1	13 (see text)

Ludwig and Shelar (1977) also noted that the orientation of fronts in the northeastern United States is frequently such that the airflow ahead of them parallels the alignment of urban areas and allows the accumulation of precursors. The importance of this mechanism is indicated by Tables 7 and 9, which show an appreciable number of cases of high ozone concentrations in the warm air near fronts. Figure 15 shows an example that occurred on 16 July 1977. Tables 7 and 9 suggest that this same meteorological feature is also frequently associated with high ozone concentrations in Texas and Louisiana. Figure 16, for 31 May 1977, provides an example of one such instance for that area. Unlike the Northeast, where there is usually well-organized air flow over a succession of urban emission areas in such synoptic situations, warm air ahead of a front in Texas is frequently rather stagnant, allowing an accumulation of precursors and ozone to occur. Certainly, as can be seen from the example shown in Figure 16, the air behind the front tends to be cleaner. (This is also true in the Northeast.)

Tables 7 and 9 show that the northwest quadrant of a high-pressure system is the favored location for episodes of high ozone concentrations in the Midwest, but the southwest quadrant is also a frequent site of such events. Other parts of the high-pressure system are less frequently associated with high ozone concentrations. Figures 17 and 18 provide examples of instances when the areas of high ozone concentrations in the Midwest were associated with the northwest and southwest quadrants of high-pressure areas, respectively. Tables 7 and 9 also suggest that the warm air near fronts is a not-infrequent locale for high ozone concentrations in the Midwest. Figure 19—25 May 1977—shows an example where the warm air just ahead of an advancing cold front contains rather high concentrations of ozone.



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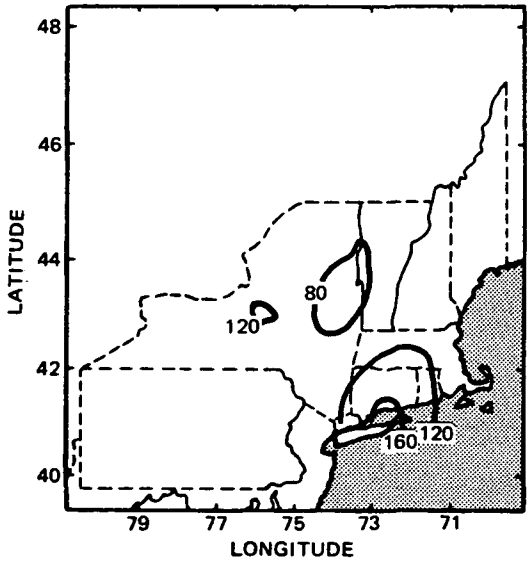
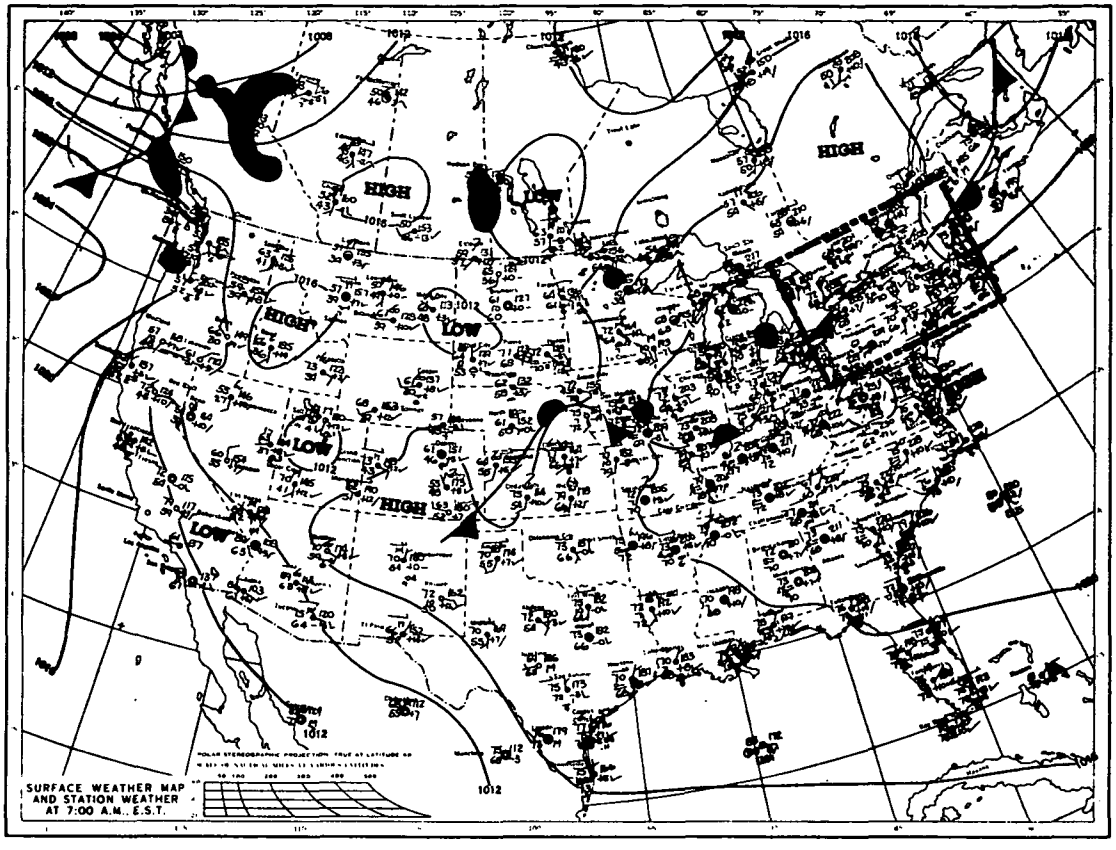


(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 14. Example of high ozone concentrations associated with the northern part of a high-pressure system in the northeastern U.S., 4 July 1977.



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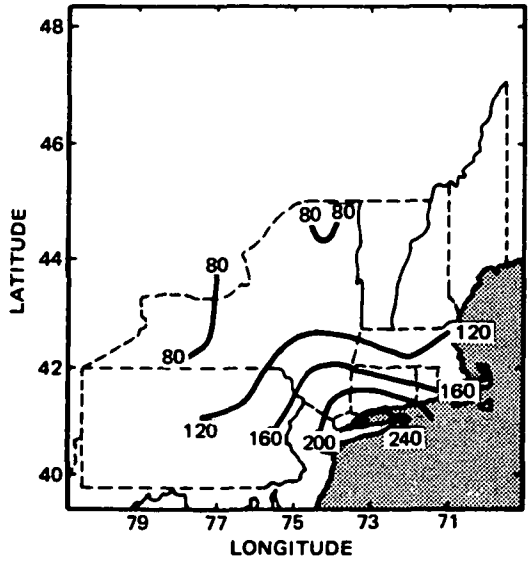
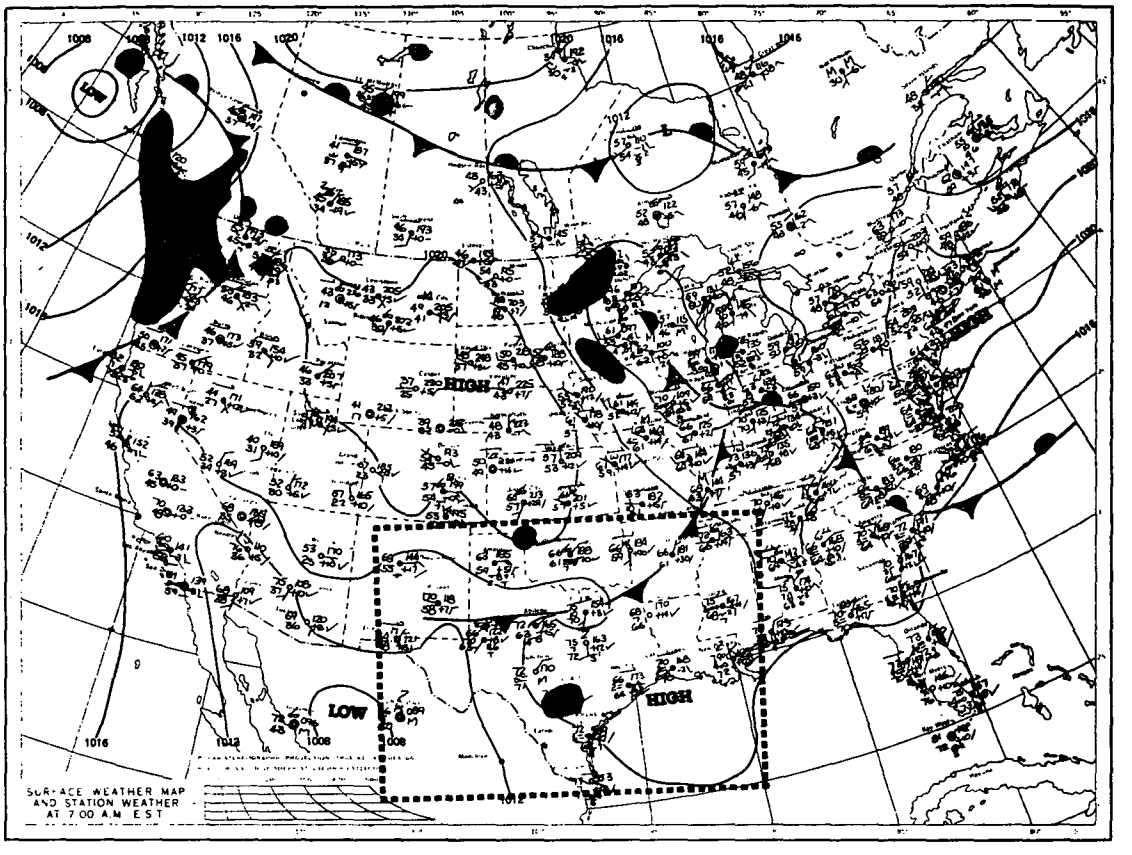


(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 15. Example of high ozone concentrations in warm air near a weather front in the northeastern U.S., 16 July 1977.



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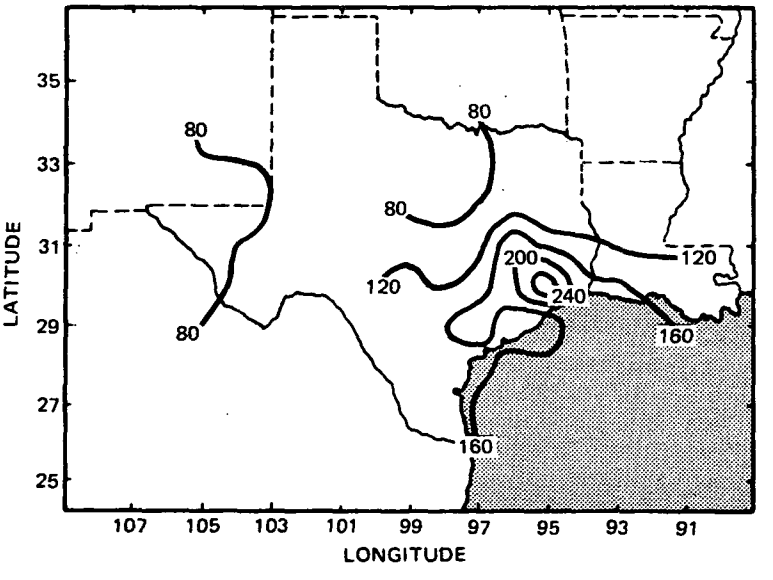
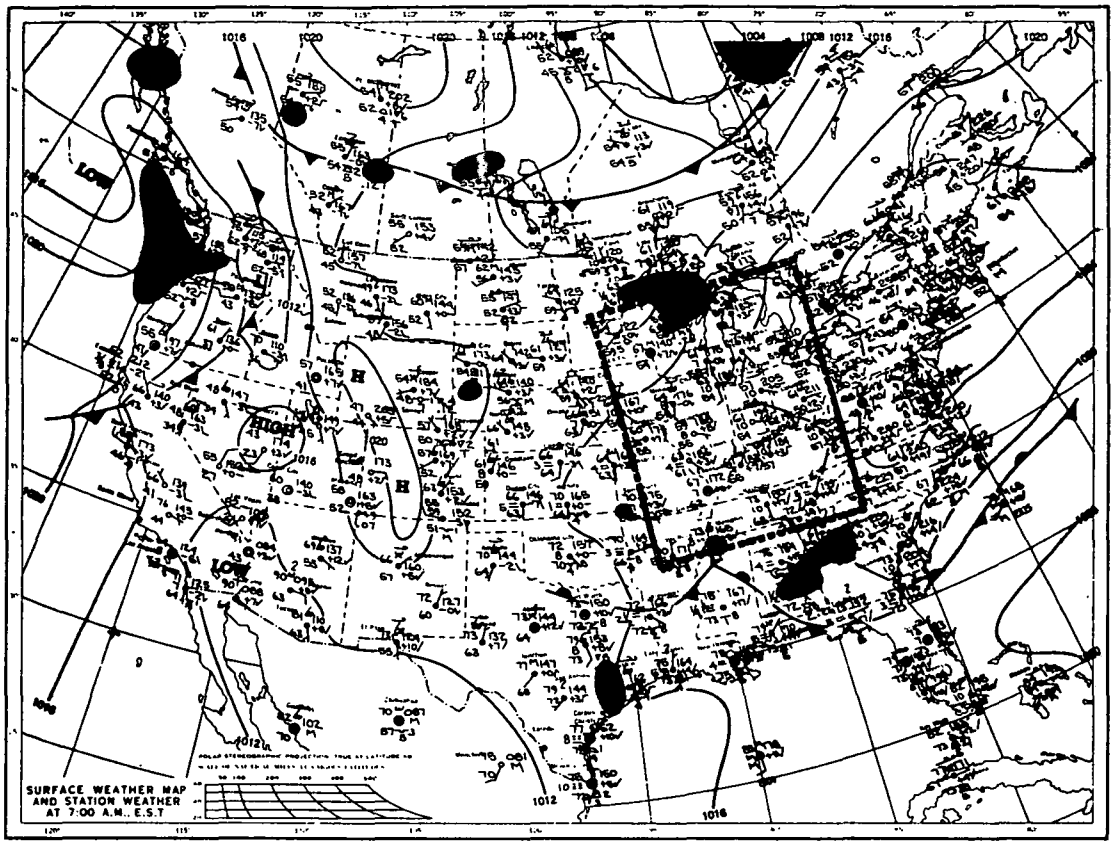


(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 16. Example of high ozone concentrations in warm air near a weather front in Texas, 31 May 1977.



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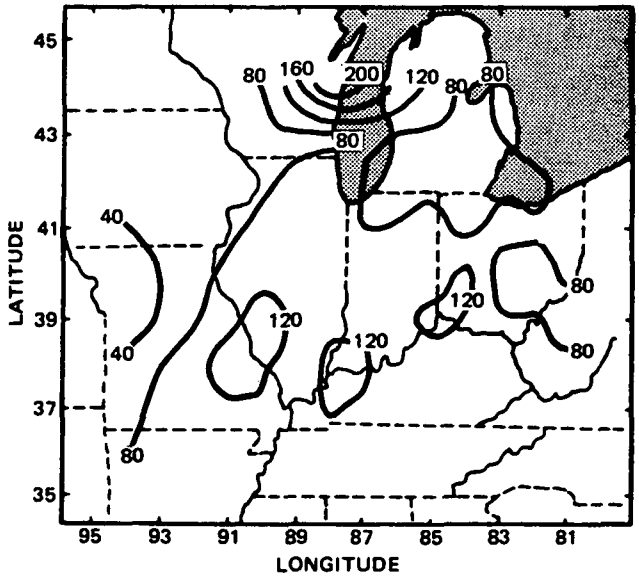
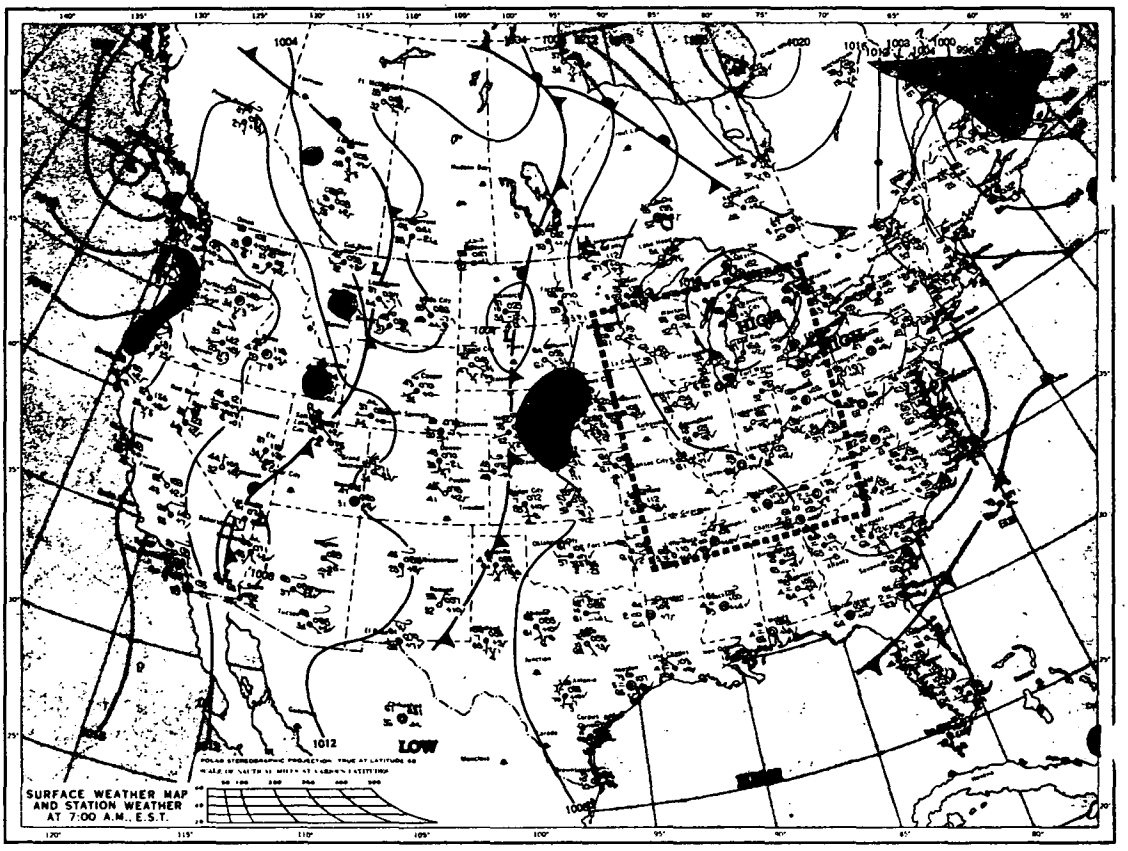
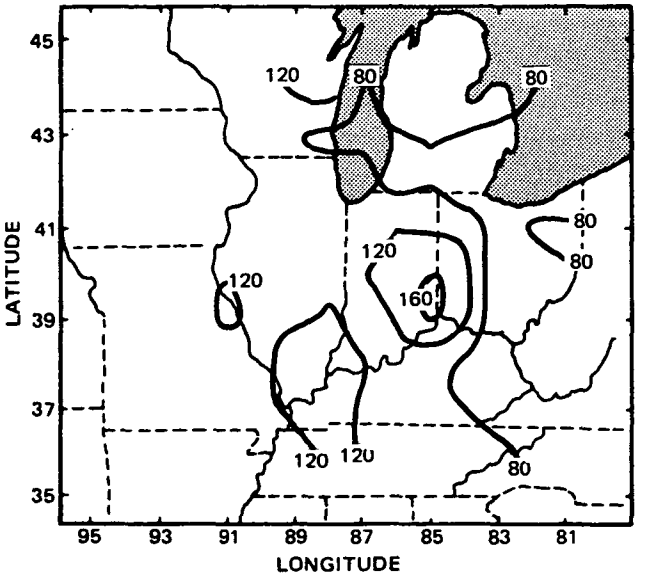


(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 17. Example of high ozone concentrations in the northwest quadrant of a high pressure system in the Midwest, 28 July 1977.

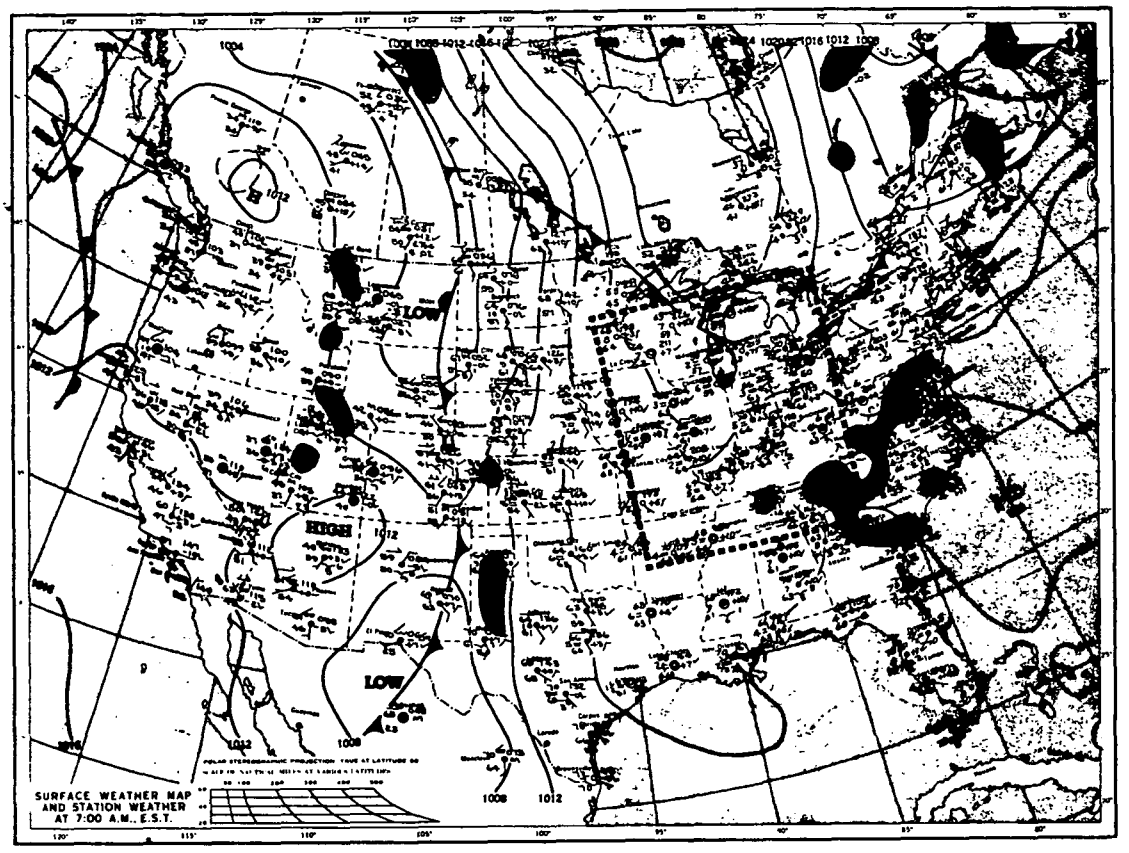


(a) SURFACE WEATHER

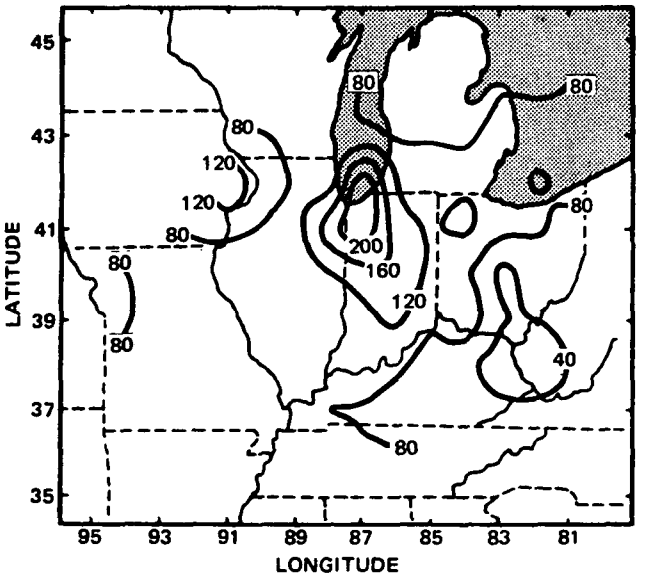


(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 18. Example of high ozone concentrations in the southwest quadrant of a high pressure system in the Midwest, 27 May 1977.



(a) SURFACE WEATHER



(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 19. Example of high ozone concentrations in warm air near a weather front in the Midwest, 25 May 1977.

The 1974 analyses of Ludwig, Simmon et al. (1977) were used to provide some estimate of where the highest ozone concentrations were found in the southeastern United States, because this area has been mentioned as being potentially in need of supplemental monitoring. However, the need for supplemental monitoring of itself makes the analyses less reliable. Nevertheless, interpolation between the few data points available for the region has given some indication of the weather features that are associated with high ozone concentrations there. Table 7 shows that concentrations in excess of 120 ppb were less frequently observed in the Southeast than in the Texas-Louisiana area, but the relative distribution with regard to location in high-pressure systems is similar. The southwest quadrant of the high-pressure system is the most frequent location of the high ozone concentrations. Next, as in the Texas-Louisiana region, comes the warm air near a weather front. This information should provide some guidance for planning field programs.

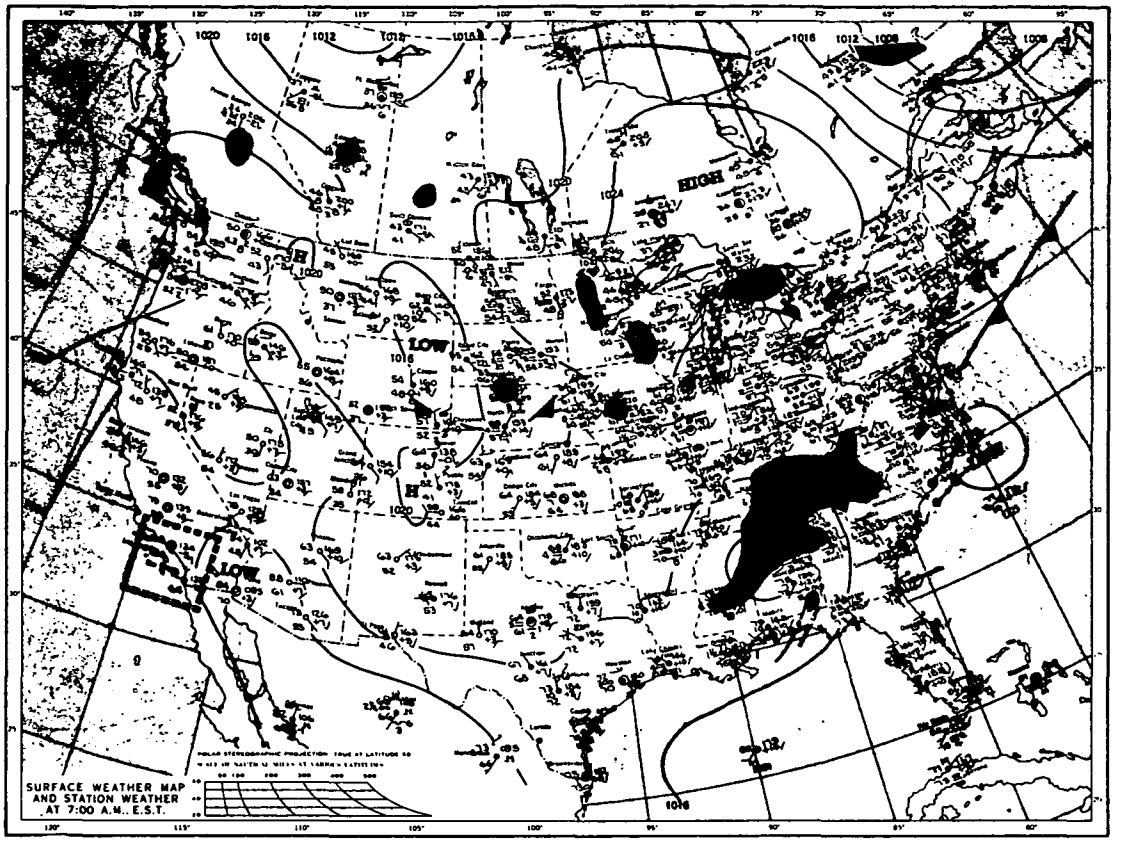
The classification of weather systems shown in Tables 7 and 9 was derived from the work of Ludwig, Reiter et al. (1977) which focused only on the conditions in the eastern United States. This classification system does not fit the conditions in Southern California very well, and all the cases selected for study in that region are in the "other" category. Figure 20 is an example of the pressure pattern that prevailed in all the selected Southern California cases. Basically, the semipermanent Pacific high-pressure system is located well to the west of the California coast. In that sense, Southern California was in one of the eastern quadrants. However, this large-scale pattern was consistently modified by the presence of a thermal low-pressure trough over the interior deserts and the Central Valley of California. A trough was found over the interior in all cases, but in one instance (17 October 1977) the Daily Weather Map analysis showed a cold front through the southeast part of California and Nevada. Otherwise, the pressure patterns all look very much like that shown in Figure 20, except that at the hour of the analysis (0400 PST), stratus clouds or fog were frequently present along the coast; the coastal clear skies in Figure 20 at this hour of the morning are rather unusual.

The low pressure over the interior, combined with the high pressure offshore, produces onshore flow in Southern California, transporting the precursors and the resulting ozone eastward and southeastward, following the lower-altitude paths through the topography. The areas of high ozone concentration can be seen in Figure 20 to stretch out along paths that parallel the airflow.

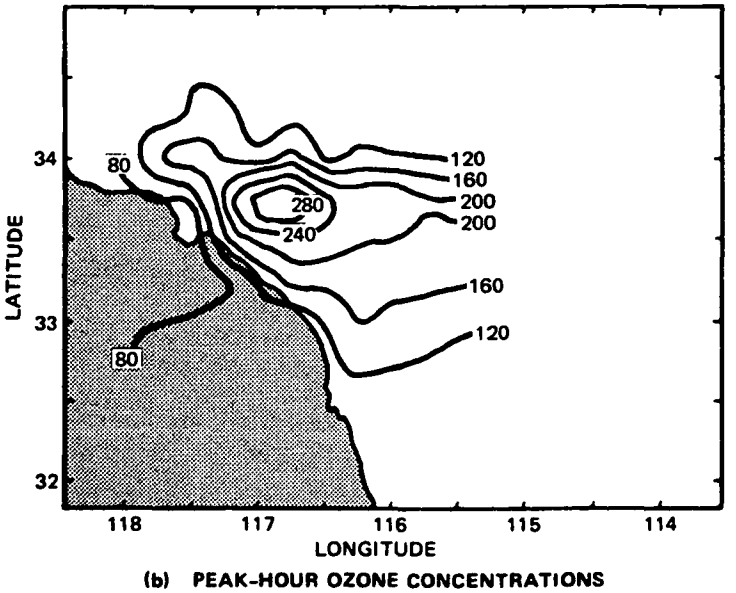
B. *Factors Causing Observed Ozone Concentrations To Be Unrepresentative*

1. *Local Siting Effects*

The most serious errors in the measurement of ozone concentrations that are caused by improper siting generally arise from the destruction of ozone by nitric oxide. Ludwig and Shelar (1978) have used a very simple model to describe the destruction of ozone in the vicinity of roadways: The change in ozone concentration caused by traffic interference is estimated to be about numerically equal to the locally added NO_x when the added NO_x is less than about 50 ppb. Figure 21 provides estimates of the maximum interference likely at different distances from roadways of differing average daily traffic (ADT). Of course, this maximum, which is based on light (1 m/s) winds paralleling the roadway at rush hour in a relatively stable atmosphere (Paquill-Gifford Class E), will not commonly occur. Furthermore, the effects are limited by the ambient ozone and NO concentrations. Obviously, the amount of ozone removed by NO cannot be greater than the amount of ozone already present. Therefore, the effects tend to be asymptotically limited by the total amount of ozone present. Also the effects tend to be less for the



(a) SURFACE WEATHER



(b) PEAK-HOUR OZONE CONCENTRATIONS

Figure 20. Example of a typical pressure pattern associated with high ozone concentrations in Southern California, 7 September 1977.

higher ambient NO concentrations. Figure 21 is based on Ludwig and Shelar's (1977) diagrams, using the assumptions shown in the figure. The K_1/K_2 ratio refers to the ratio of the reaction rate for the photolytic decomposition of NO_2 to the reaction rate of NO with O_3 to form NO_2.

According to Ludwig and Shelar (1978) the worst effects can be kept below about 40 to 50 ppb by staying more than about 20 m from small streets (about 1000 ADT) and about 250 m from larger streets (10,000 ADT). Under more nearly ordinary circumstances, the effects can be kept to the same magnitude even when the probes are much nearer to the street, as reflected in recent regulations promulgated by EPA (Federal Register, 1979b). Those regulations specify that the minimum distance to roadways from ozone monitors should be from 10 m (for 10,000 ADT) to 250 m (100,000 ADT).

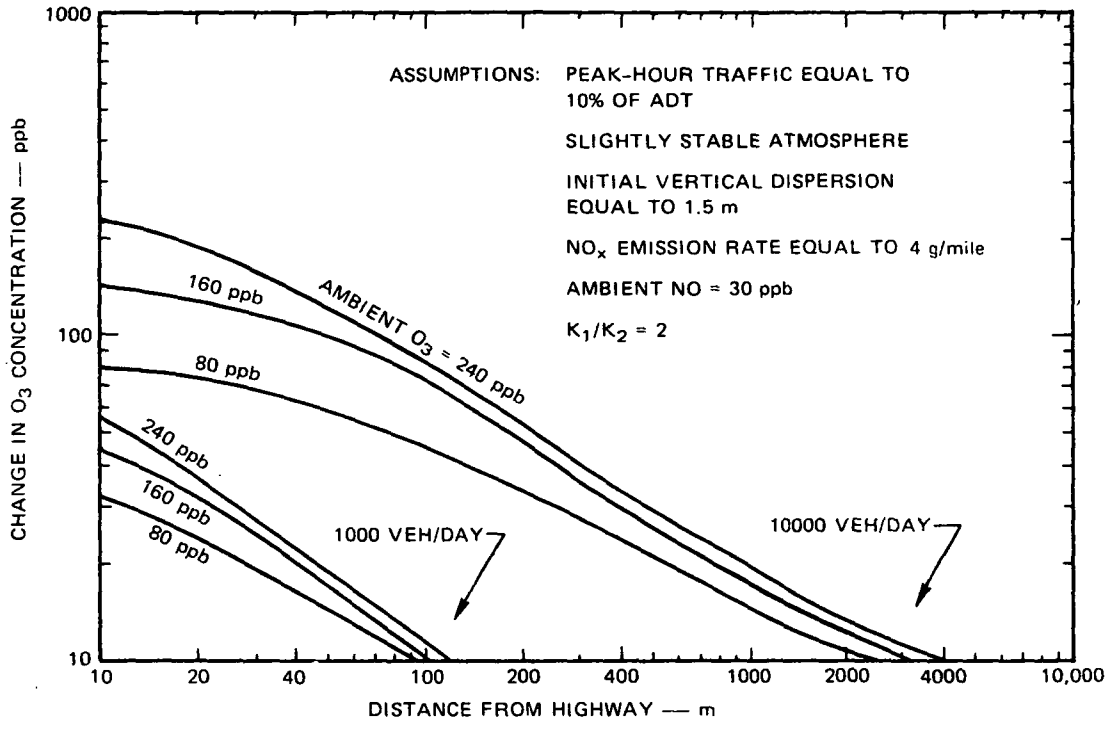
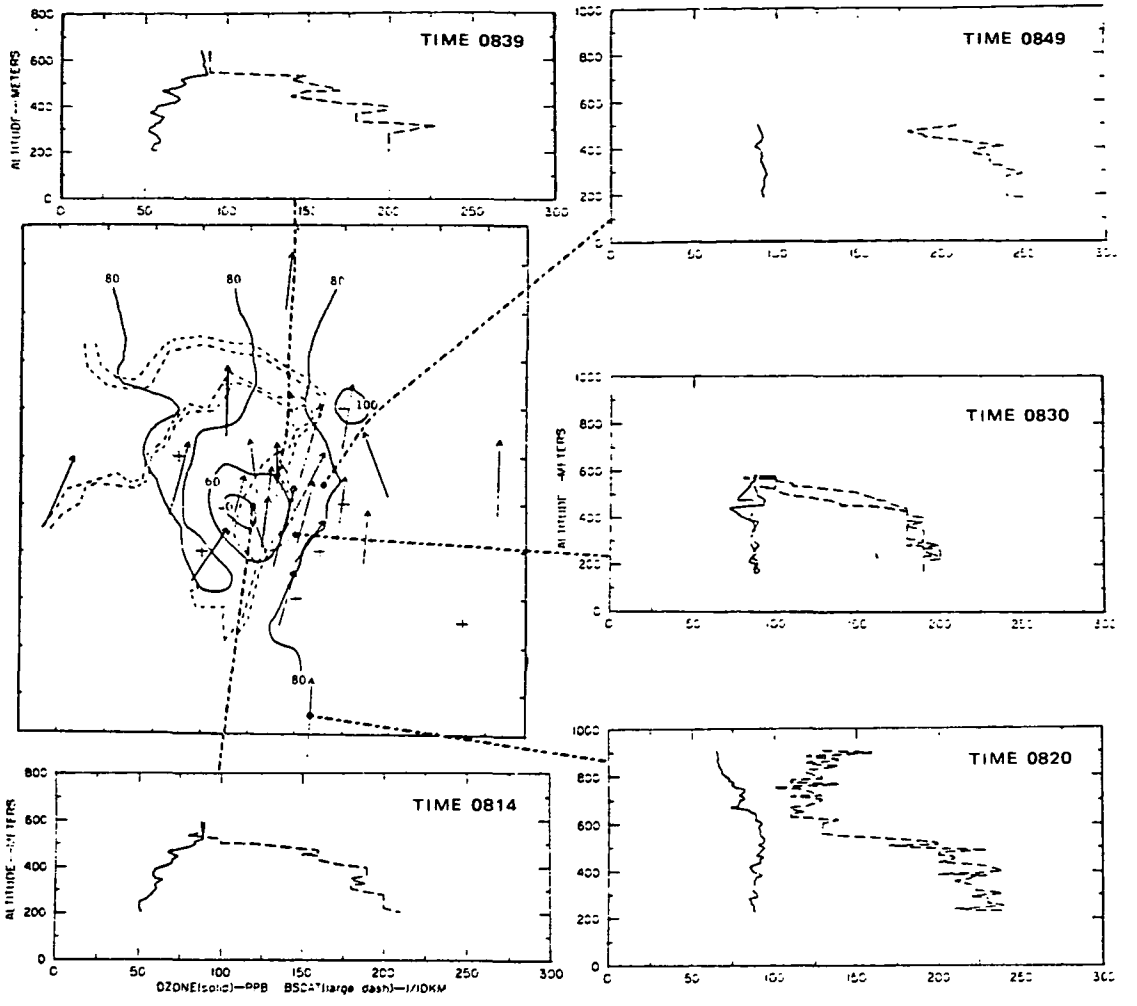


Figure 21. *Estimated ozone depletion at distances from a roadway.*

2. *Urban Area Siting Effects*

The effects of a city's NO emissions are not limited to points that are within the immediate vicinity of NO sources, although the effects are greatest at such locations. In general the highest concentrations of ozone in an area will be away from areas of greatest NO emissions. Figure 22 shows how the NO emissions in St. Louis on the morning of 19 July 1976 reduced ozone concentrations by about 40 to 50 ppb. The map in the figure shows the Mississippi and Missouri River; the urbanized area of St. Louis is outlined by the dashed line that runs through the center of the closed 40-ppb isopleth near the center of the map. Vertical ozone profiles measured during the same hour around the area are also shown along with nephelometer readings. Arrows indicate surface wind direction; their length equals one hour's travel distance at the observed speed.

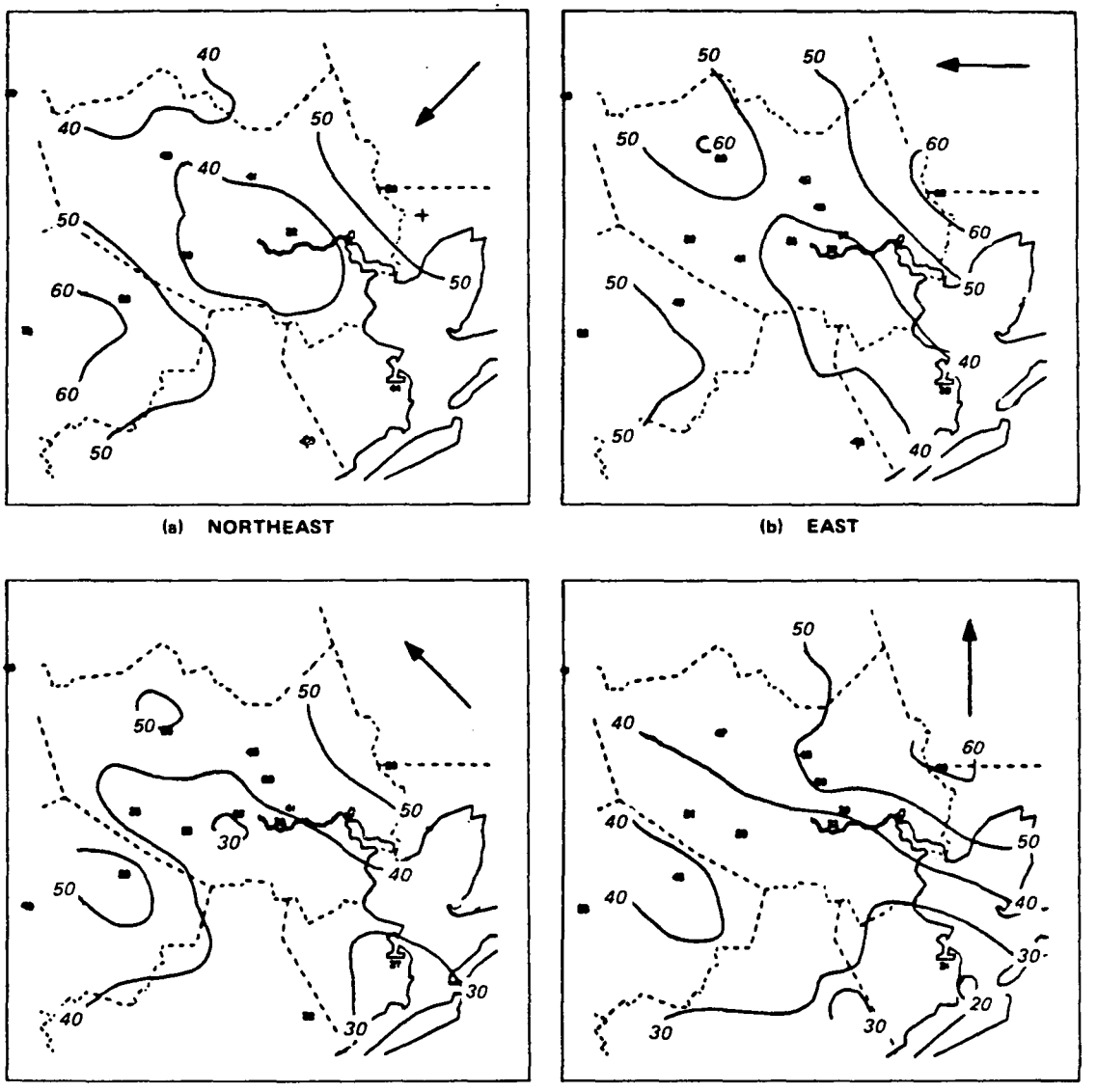


SOURCE: LUDWIG, 1979

Figure 22. St. Louis ozone concentrations on the morning of 19 July 1976.

The vertical profiles taken outside the city (along the right side of Figure 22) show nearly uniform concentrations of about 80 ppb for the first several hundred meters. The profile taken over the center of the city shows the same concentrations aloft, but near-surface concentrations were reduced by NO emissions to about 40 ppb. The vertical profile at the top of the figure shows similar conditions at the northern edge of town, but the reduction of ozone by NO was somewhat less—only 20 to 30 ppb.

Figure 23 from Ludwig and Martinez (1979) shows average August 1977 afternoon ozone concentrations classified according to wind direction observed at a site north of Houston. (The Houston urban area is in the middle of the map.) For most of the wind directions, the average urban concentrations were 10 to 20 ppb less than concentrations outside the urban area. It appears that the presence of a relatively large city can reduce ozone concentrations over fairly large areas by a few tens of ppb or more. In general, the highest ozone concentrations in an area will be outside the city limits (Ludwig and Shelar, 1977). Specific siting examples, identified during the analysis of SAROAD data undertaken as part of this project, tend to confirm this conclusion. Those cases are discussed in a technical memo (Ludwig and Shelar, 1979).



SOURCE: LUDWIG AND MARTINEZ, 1979

Figure 23. Average August 1977 afternoon ozone concentrations (ppb) in Houston.

3. *Instrumental and Operational Factors*

Miller (1978) has pointed out at least five possible sources of error in an overall monitoring system, including the error caused by unrepresentativeness of the site, errors arising when samples are randomly collected, and errors arising in data handling. Neither of the latter two errors will be addressed here, but errors due to measurement method and calibration must be discussed to some extent, if the importance of unrepresentativeness is to be kept in perspective.

The calibration procedure for ozone monitoring has been described in the Federal Register (1979a). Basically, a stable ozone concentration must be generated, and that concentration determined by ultraviolet (UV) photometry. According to the regulations the photometer must have a precision within 5 ppb or 3 percent of the concentration, whichever is greater. Thus, the uncertainty arising from currently prescribed calibration procedures must lie between about 5 and 10 ppb, depending on concentration. Similar errors might be expected to arise from the use of a UV instrument for monitoring; in fact, the monitoring errors might be somewhat larger, because of the special care and maintenance prescribed by the regulations for the instrument used in establishing the standard concentrations. Assuming that the errors add as the square root of the sum of their squares, the total uncertainty in this type of measurement is 7 to 15 ppb.

Judging by manufacturers' specifications (Lawrence Berkeley Laboratory, 1973) chemiluminescent ozone monitors have a noise level of 1 or 2 ppb, reproducibility of 5 or 10 ppb, and similar uncertainties in linearity. Thus, an overall uncertainty of 10 ppb for carefully operated chemiluminescent instruments does not seem to be an unreasonable estimate. In combination with the recommended calibration procedures, a well-operated chemiluminescent instrument should be able to measure ozone concentrations within 10 to 20 ppb.

Before 1979, calibration procedures other than the UV assay technique were used. Beard (1978) found that one of these procedures, gas phase titration of excess ozone with nitric oxide, tended to indicate higher ozone concentrations, by 2 to 7 percent, than were obtained by UV photometry. Hogeson (1976) found "excellent agreement between O_3 determination of UV or GPTE" (gas phase titration). Methods that used iodometric procedures to determine ozone concentrations for calibration purposes, however, did not generally agree well with the UV procedures according to Hogeson (1976), and the different variations of the iodometric procedure did not agree well with each other.

Hogeson (1978) compared three different iodometric techniques and gas phase titration with ozone concentrations determined by UV calibration. The three iodometric techniques were: the EPA technique using 1 percent neutral-buffered potassium iodide reagent, the California Air Resources Board method using 2 percent neutral-buffered potassium iodide, and the Los Angeles Air Pollution Control District method using 2 percent unbuffered potassium iodide.

The data were compared with the UV measurements and linear expressions derived by regression as follows:

- Gas phase titration (GPT):

$$[O_3]_{GPT} = 1.09[O_3]_{UV} - 3\text{ppb} \quad .$$

- California Air Resources Board (CARB):

$$[O_3]_{CARB} = 1.29[O_3]_{UV} - 5\text{ppb} \quad .$$

- EPA:

$$[O_3]_{EPA} = 1.24[O_3]_{UV} - 35\text{ppb} \quad .$$

- Los Angeles Air Pollution Control District (LAAPCD):

$$[O_3]_{LAAPCD} = 0.96[O_3]_{UV} - 32ppb \quad .$$

The above results were obtained with air humidified to 50 percent relative humidity. Hogeson (1976) concluded that the neutral buffered potassium iodide procedures (i.e., CARB and EPA) indicated ozone concentrations that were 18 to 30 percent higher than those observed by UV procedures in the presence of moist air. Thus, there appears to have been a systematic bias toward higher readings with the older calibration procedures. This can be corrected for, but a residual uncertainty might amount to 5 to 30 ppb, depending on concentration. It appears that older data, obtained using iodometric calibration procedures, might be subject to uncertainties of a few tens of ppb.

C. *Relationships of Ground-Level Ozone Concentrations to Those Aloft*

1. *Background.*

A monitoring network may not be adequate to determine whether or not the NAAQS are exceeded everywhere in the country: It may be necessary to supplement existing data. The aircraft-survey, approach requires a knowledge of the conditions under which aircraft measurements can be used to estimate ground-level observations. This section addresses that problem; recommendations are given in Section 4 for incorporating the results described here into an aircraft monitoring program to obtain data quickly and efficiently over a large areas.

Most of the analysis required to relate ozone concentrations aloft with those of the surface has been performed by Ludwig (1979). Effort on this project has been directed toward adapting his findings to the design of aircraft monitoring programs. Ludwig examined 268 ozone profiles measured in different parts of the country and classified them according to their shape. This kind of analysis is obviously useful to the solution of the problem of estimating surface concentrations from data measured aloft. Aircraft measurements can be easily used to estimate surface concentrations whenever the vertical ozone-concentration profile is characterized by small vertical gradients. The problem is knowing when it can be reliably assumed that such vertical profiles of ozone concentrations are present.

An other factor that needs to be considered is the compatibility of the aircraft data with the hour-averaged surface measurements. At typical wind speeds of a few meters per second, an hour-average ozone value is derived from air that has traveled about 10 km. In an aircraft traveling about 50 m/s, this distance will be covered in about 3 minutes. The response time of an ozone monitor will generally be measured in seconds, so the aircraft measurements will tend to provide somewhat finer spatial/temporal detail than the ground measurements. However, in practice the aircraft data are reported with separations of a few kilometers between observations (see e.g., Westberg et al., 1977). When such data are analyzed, the result is a spatial smoothing comparable to that for one-hour averaging.

The remainder of this section describes the classification system developed by Ludwig (1979), identifies the types of profile suitable for aircraft-survey determinations of surface concentrations, and describes the conditions under which those profiles are most likely to be found.

2. *Types of Vertical Profiles of Ozone Concentration*

The reader will better understand the classification system used for vertical ozone profiles, especially the later discussions of the conditions under which those profiles are most likely to be observed, after a brief discussion of factors governing the three-dimensional distribution of ozone in the atmosphere. Basically, the distribution of ozone is determined by the chemical processes that lead to its formation and destruction and by the meteorological processes that encourage or inhibit vertical mixing.

The chemical processes that cause the formation of ozone from the primary emissions of hydrocarbons and oxides of nitrogen operate only during the daylight hours. A substantial period of time (hours) is usually necessary before the resultant ozone is produced. However, destruction of ozone can occur at any time and generally proceeds rather rapidly. The most rapid process for destroying ozone is its reaction with nitric oxide; ozone can also be destroyed by contact with surfaces. Destruction proceeds more slowly in the free atmosphere. Significantly, most destruction of ozone occurs near the ground.

The other important governor of ozone distribution in the lower atmosphere is mixing. Atmospheric mixing determines the depth to which precursors (which are usually emitted near ground level) are mixed, during or before the ozone-formation process. Atmospheric mixing also governs the amount of pre-existing ozone that is mixed downward to replace ozone destroyed at, or near, the surface. Most vertical profiles result from combinations of these processes and fall into a limited number of categories. These categories and their causes are discussed below.

Ludwig's work categorizing ozone profiles (1979) evolved from earlier work by Johnson and Singh (1977a) and from the analysis of a large amount of data collected by others in the following geographical areas: St. Louis area (Mage et al., 1978), the northeastern United States (Environmental Monitoring and Support Laboratory, 1975; Spicer et al., 1976; Washington State University, 1976 and Wolff et al., 1975), Washington D.C. (Fitzsimmons et al., 1978), Houston (Westberg et al., 1977), Los Angeles (Blumenthal et al., 1974; Johnson and Singh, 1977b), Indianapolis (Lovelace et al., 1975), and Toronto (Weibe et al., 1975).

Figure 24 shows the six commonly found ozone profile types. The height and concentration scales shown in the diagram are used for illustrative purposes only; observed conditions frequently differ substantially. It is obvious that measurements made anywhere within the boundary layer will do a good job of characterizing surface concentrations when the profiles fall in either the A or D categories.

Figure 25 shows the relationship between the hour-average concentration measured at the surface and the average concentration through the mixing layer as derived from observed aircraft profiles that were classified either as Type A or Type D. The unit slope and essentially zero intercept of the least-squares regression line (correlation = 0.98) allows the assumption of equality between mixed layer and surface values to be made with considerable confidence. The close agreement should not be surprising, since one of the criteria for classifying a profile as either a Type A or Type D is that the vertical gradient of concentration within the mixing layer be small. Nevertheless, the findings are quite useful because they demonstrate that such conditions are frequently found.

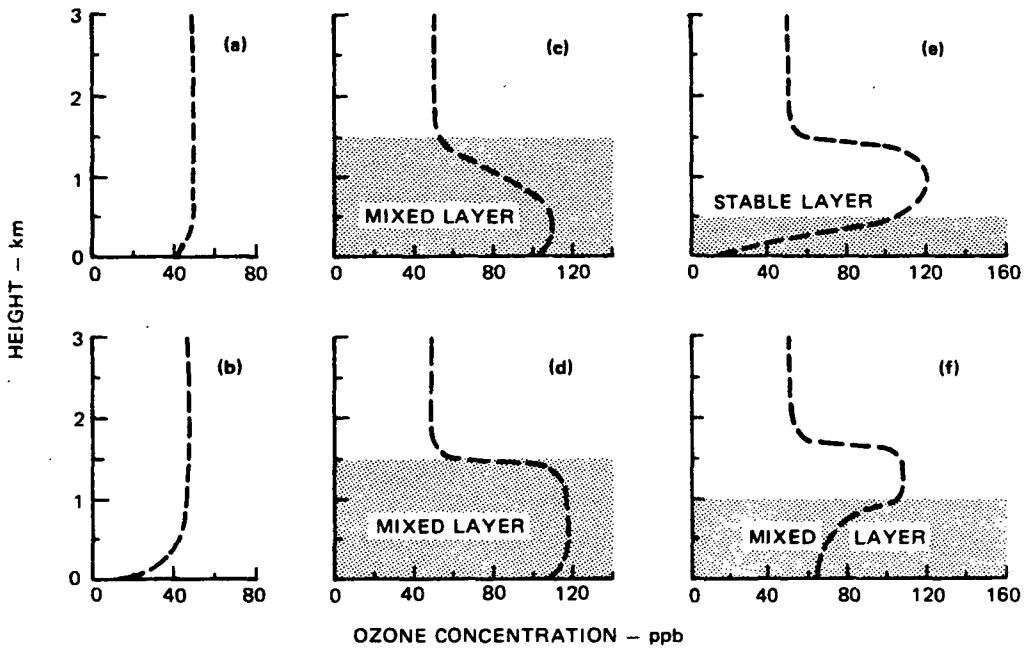


Figure 24. Six types of vertical profile.

Section 3 discusses the times of day, locations relative to urban areas and meteorological condition that have been found to be associated with Types A and D profiles. The application of these findings to the design of an aircraft sampling program is discussed in Section 4.

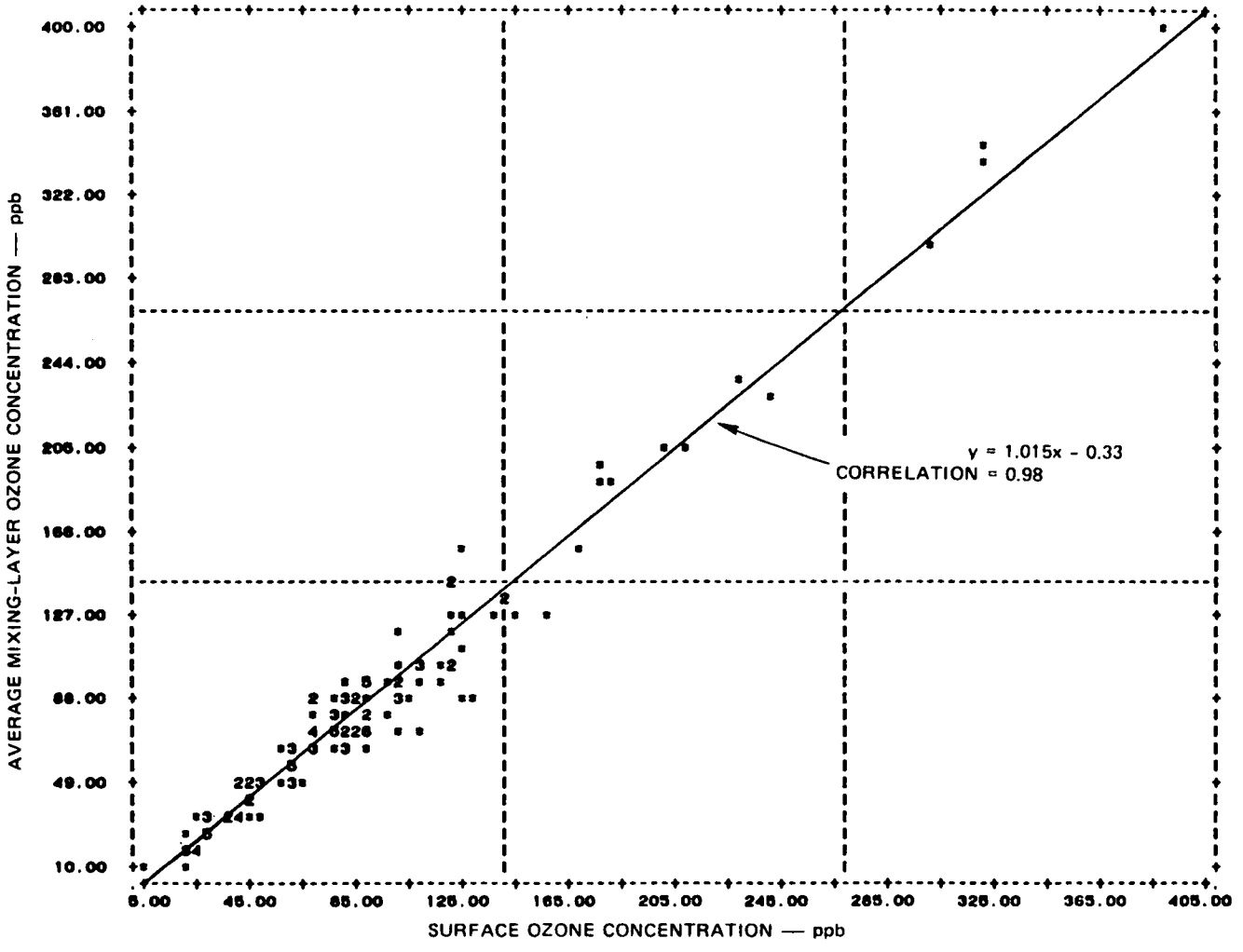


Figure 25. Scattergram of average mixing-layer ozone concentrations as a function of surface concentrations for profiles A and D.

SECTION 3

SUPPORTING MATERIAL

The preceding section contained a discussion of the findings that were most relevant to the project objectives and certain supporting material necessary for an understanding of these findings. Some results from the project did not lead to any major conclusions (e.g., some of the analyses of the relationships among daily peak-hour ozone readings at different stations) or were not necessary to the understanding of those major findings presented earlier (e.g., the decisions and logic that went into the selection of data to be used for detailed studies and for the selection of case studies). This section is provided for the sake of completeness. It includes some discussion of the logic underlying decisions and some of the less conclusive results.

A. *Data Survey and Selection*

The project specified that the data from at least four geographical areas be used for the statistical analysis. These regions were to have surface-monitoring data sufficiently extensive that statistical comparisons among sites would be possible. It was also important that the chosen geographical areas cover a variety of climatological conditions. With these considerations in mind, four areas were selected in consultation with the Project Officer. The four areas that were chosen are shown in Figures 26 through 29. (The locations from which data were available through the SAROAD for the year 1977 are also shown in the figures.) The four areas include:

- The Northeastern states—Pennsylvania, New York, New Jersey, Connecticut, Rhode Island, and Massachusetts.
- The Midwestern states—Iowa, Illinois, Missouri, Indiana, Kentucky, and Ohio.
- Texas and the adjacent states of Oklahoma, Arkansas, and Louisiana.
- Southern California stations, south of the Tehachapi Mountains.

These states encompass a variety of climatic regions, and the figures show that they have reasonably dense air quality monitoring networks.

After the study areas were selected and the data obtained from the Project Officer, the hourly data was processed to make it more manageable for further analysis. The hourly SAROAD data were processed to extract the daily maximum-hourly concentrations, using the following approach:

- All units were transformed to parts per billion (ppb). Daily maxima were selected from the hourly values whenever there were at least 16 observations for the same day and at least 9 observations from the period 0800 to 1800 local standard time (LST).
- Peak-hour values of zero were deleted.
- Excessively high values (greater than 300 ppb in the winter or greater than 500 ppb in the summer) were deleted.

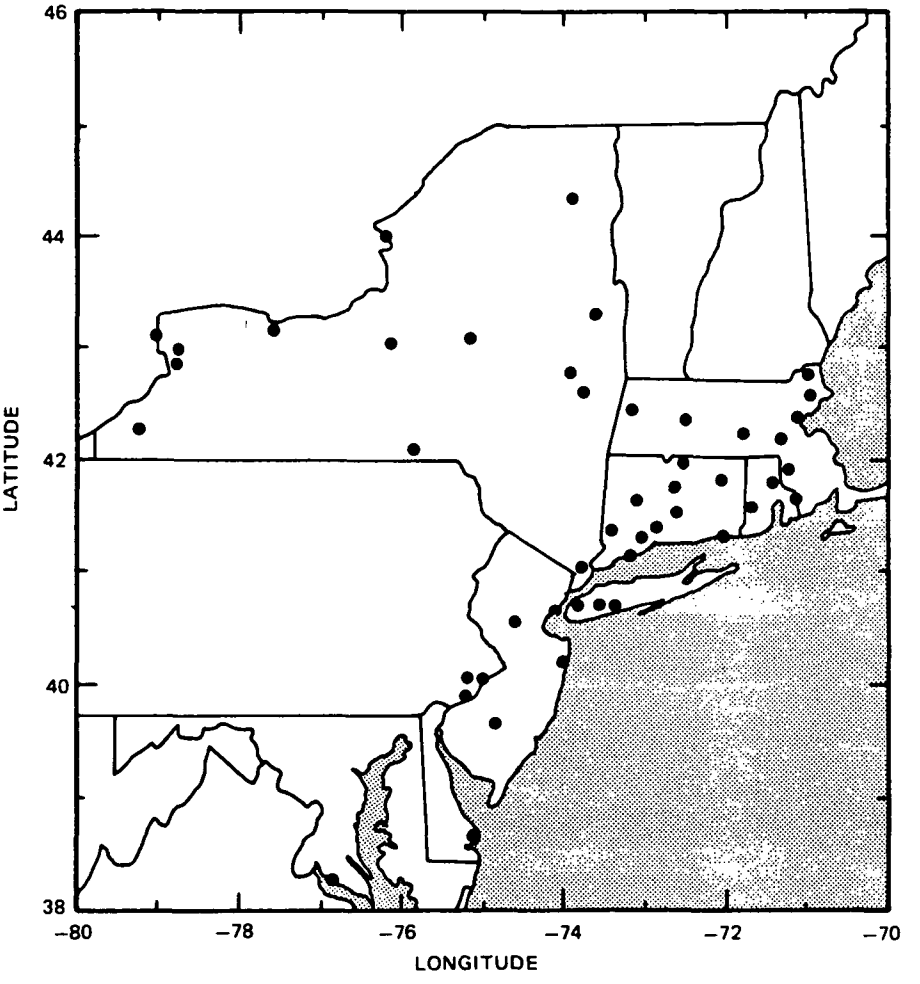


Figure 26. Locations of SAROAD Northeast ozone monitoring stations for 1977.

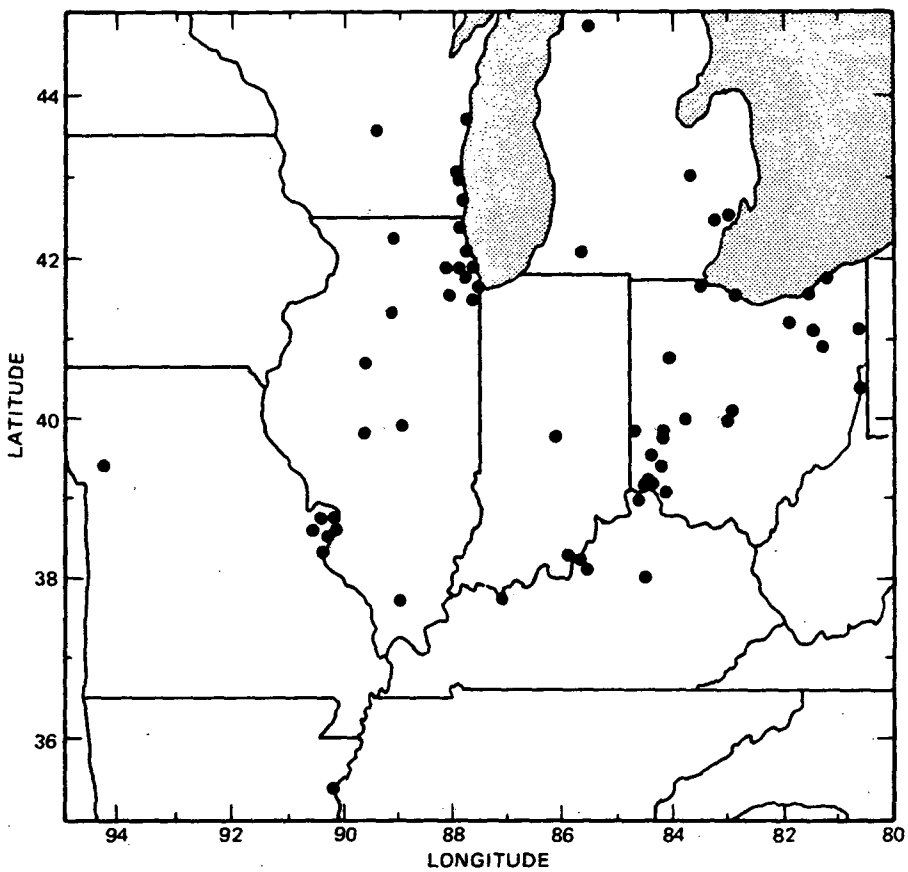


Figure 27. Locations of SAROAD Midwest ozone monitoring stations for 1977.

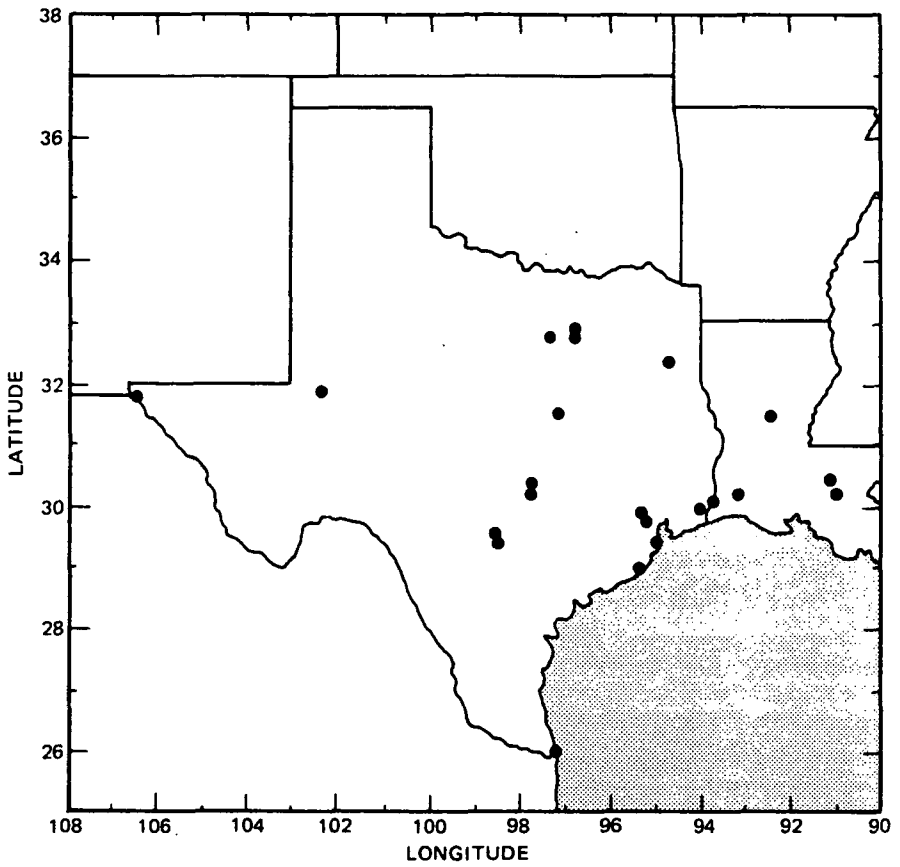


Figure 28. Locations of SAROAD Southwest ozone monitoring stations for 1977.

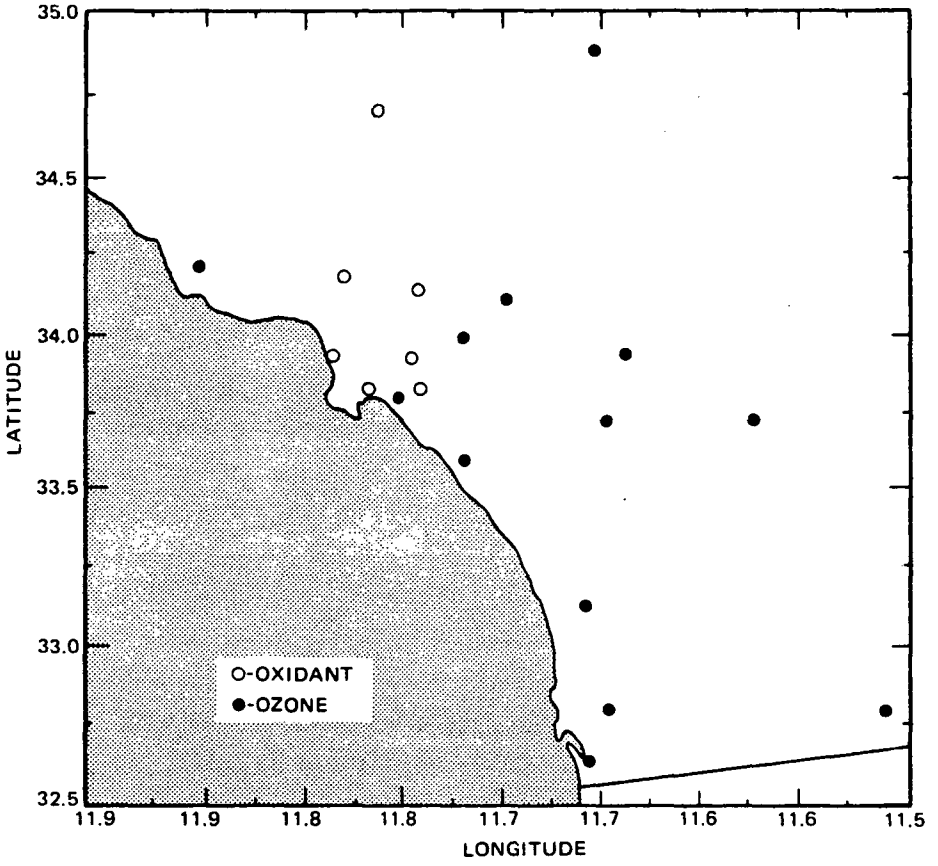


Figure 29. Locations of SAROAD ozone and oxidant monitoring stations in Southern California for 1977.

The result of this processing was a computer tape that contained the peak-hour values for all the stations and for all the suitable days of the years 1975, 1976, and 1977. With the data in computer-compatible form, cross-tabulations of observed peak-hour ozone concentrations were prepared for various station-separation intervals.

In addition to the hourly data from the four selected geographical regions, the Project Officer also supplied a data tape of the maximum and second-maximum observed hourly ozone concentrations for all the stations available from the SAROAD for the years 1974 through 1977. This data tape also contained information regarding the number of hours of observations from which the maximum and second-maximum values were determined. This data base was constructed prior to promulgation of the new statistical form of the ozone standard (Federal Register, 1979a), so estimated values in terms of the daily form of the standard were not readily available from SAROAD. Procedures for determining compliance with the new standard and for estimating design values have been published by EPA (Curran, 1979). The daily form is only slightly less stringent (Federal Register, 1979a) than the originally specified interpretation.

B. *Identification of Conditions Associated with Widespread Exceedances of the Ozone Standard*

The 1977 daily peak-hour ozone data from the four different geographical regions were used as the basis for selecting a limited number of "episode days," when high ozone concentrations were widespread in the areas. Each of the four geographical regions was considered separately. The goal was to identify about a dozen days for each region and to examine those days to determine the shared meteorological characteristics. Those characteristics were then compared, from region to region and with earlier studies, particularly those of Ludwig, Reiter, et al. (1977). The results of these comparisons were discussed in Section 2. Recommendations derived from the analyses are presented in Section 4.

For each day of 1977 all the observed peak-hour ozone concentrations were averaged for each region. A threshold was selected, against which the spatially averaged peak-hour concentrations could be compared, such that ten to fifteen days during the year of 1977 exceeded the threshold in that particular region. Table 10 shows the threshold used for each region and the number of days when the spatially averaged peak-hour ozone concentrations in the corresponding geographical area exceeded that threshold. Table 10 shows the selected dates for each region and the corresponding regional average peak-hour ozone concentrations.

TABLE 10 THRESHOLD OF SPATIALLY AVERAGED PEAK-HOUR OZONE CONCENTRATIONS USED TO SELECT DATES FOR CASE STUDIES

Region	Threshold (ppb)	Number of Days Over the Threshold
Northeast	104	10
Midwest	90	11
Texas/Louisiana	90	14
Southern California	145	13

In addition to the selected cases from 1977 discussed above, the daily weather maps and peak-hour ozone concentration analyses for 1974 that were presented by Ludwig, Simmon et al. (1977) were reexamined. These same analyses were used as the basis for an earlier study (Ludwig, Reiter et al., 1977), where the areas with ozone concentrations in excess of 80 ppb (the NAAQS in effect at the time the analyses were prepared) were examined to determine what kinds of weather features were associated with such high concentration areas in the eastern United States. These earlier analyses made no attempt to determine if the areas of high ozone concentration were associated with different meteorological features from region to region.

The reexamination of the earlier analyses undertaken as part of this project focused on geographical areas where ozone concentrations were in excess of the higher, newer NAAQS of 120 ppb. Furthermore, an attempt was made to determine whether these high concentrations were associated with different meteorological features in the Northeast states, the Midwest states, and the Texas-Louisiana-Arkansas area and the Southeast states. The Southern California area was not included in this reinterpretation, because it falls outside the area covered by the maps prepared by Ludwig, Simmon et al. (1977). The results of the analyses were summarized in Table 7.

It should be noted that the automated analysis procedures that were used to prepare the ozone analyses introduce considerable smoothing into the field. The methodology is discussed in detail by Ludwig, Simmon et al. (1977). Basically, the method of analysis begins by deriving ozone concentrations for a number of grid points. These values are based on weighted averages of peak-hour ozone concentrations observed in the vicinity. The weighting of the observations is an inverse function of the distance from the grid point. In essence, if there are a number of observations close together, the analysis is drawn as though their average was used. An extrapolation algorithm is also employed to extend the analysis beyond the area from which observations are available.

C. *Analysis of the Conditions Associated with the Different Ozone Profile Types*

Practical consideration in the design of an aircraft monitoring program requires that the experimenter be able to identify when the aircraft measurements are suitable for representing ground-level ozone concentrations. This is tantamount to requiring a knowledge of when the vertical profile will be of either Type A or D (see Figure 24). It will also be necessary to determine when the aircraft is within a well-mixed layer with small vertical gradient concentrations. This will be discussed at greater length when recommendations are given for the design of an aircraft monitoring program.

The profile studies of Ludwig (1979) provide the necessary guidance for recognizing when the profiles are apt to be Type A or Type D. As a general rule, Type A profiles evolve from Type B profiles during the morning hours as the nocturnal surface inversion is destroyed by heating and mixing. Usually, the transition is complete by about 1000 LST. Type D profiles sometimes evolve from Type E profiles in a similar way, but the establishment of the Type D profiles in such cases may not occur until the mixing layer reaches its maximum height for the day. The Type D profiles also evolve from Type C profiles on occasion, after the air has traveled farther from the city. The evolution of a Type D profile from a Type C requires that there be enough time for the precursors emitted near ground level (and the ozone formed from them) to mix uniformly through the depth of the boundary layer. It should be apparent from the preceding discussion that the establishment of Type A or Type D profiles, with their relatively uniform distribution of ozone through the mixing layer, requires fairly strong vertical mixing. Vertical mixing depends on atmospheric stability, which in turn depends on time of day, cloud cover, and wind speed (Turner, 1964).

The objectives of this study are such that not all locations and conditions are of equal interest. Thus, when an attempt is made to determine what conditions are associated with the occurrence of Type A or Type D profiles, not all cases are of equal interest. The following considerations are of greatest importance:

- Conditions most likely to cause exceedances of the federal ozone standards.
- Regions without an adequate ground-level monitoring network.
- Areas away from cities (where ground-based monitoring would be most difficult to support).

Thus, it is necessary to identify Type A and D profiles in areas away from cities during periods conducive to the occurrence of high ozone concentrations, i.e., in strong sunshine and light winds. Strong sunshine and light winds are also associated with unstable atmospheric conditions (see, for example, Pasquill, 1961 or Gifford, 1961) and vigorous mixing. Furthermore, destructive processes that cause strong concentration gradients are generally more pronounced in the urban areas, with their nitric oxide sources, than in the more remote areas. Thus, the conditions and locations of greatest interest to this study are those that are frequently associated with the occurrence of Type A and D ozone-concentration profiles.

1. *Relative Frequency of Different Profile Types at Different Times of Day*

Table 11 is a contingency table showing the frequency of combination of profile type and time of day in the data analyzed by Ludwig (1979). The first number in each square is the number of cases having the combination of profile and time of day represented by the square. The second number shows the percentage of the total number of cases in that row (time interval) that had the characteristics of that column (profile). The third figure in the square shows the percentage of the total cases in that column (profile) that occurred with the characteristics represented by that row (time interval). Finally, the last number in a square shows the percentage of the total cases that have the combination of characteristics represented by the square. For example, the square at the second row and second column of Table 11 shows that the sample contained 12 Type A profiles that occured between 0600 and 0900 LST. This represented 20.7 percent of all the data collected between 0600 and 0900 and 15.0 percent of all the Type A profiles. Finally, 4.5 percent of all the observations were both taken between 0600 and 0900 and of Type A. The first column of the table shows that the sample includes one case whose profile classification was uncertain.

Table 11 shows that the A and D profiles were very uncommon during the nighttime hours, and represented less than one quarter of the observations between 0600 and 0900 LST. The frequency of Types A and D increased to nearly 60 percent of the cases between 0900 and 1200 and to more than two-thirds of the afternoon cases. Thus, the chances of encountering conditions where aircraft measurements could be used to estimate ground-level ozone concentrations are quite good during the late-morning and afternoon hours.

TABLE 11 FREQUENCY OF OCCURRENCE OF DIFFERENT PROFILE TYPES AT DIFFERENT TIMES OF DAY

TIME INTERVAL — local standard time	COUNT / ROW PCT / COL PCT / TOT PCT	PROFILE TYPE: UNCERTAIN	A	B	C	D	E	F	ROW TOTAL
BEFORE 600	1.	0	0	2	0	0	2	0	4
		0	0	50.0	0	0	50.0	0	1.5
		0	0	15.4	0	0	6.3	0	
		0	0	.7	0	0	.7	0	
600-900	2.	0	12	6	0	2	10	28	58
		0	20.7	10.3	0	3.4	17.2	48.3	21.6
		0	15.0	46.2	0	2.9	31.3	51.9	
		0	4.5	2.2	0	.7	3.7	10.4	
900-1200	3.	0	35	4	4	10	9	15	77
		0	45.5	5.2	5.2	13.0	11.7	19.5	28.6
		0	43.8	30.8	19.0	14.7	28.1	27.8	
		0	13.0	1.5	1.5	3.7	3.3	5.6	
1200-1500	4.	0	25	0	9	27	8	5	74
		0	33.8	0	12.2	36.5	10.8	6.8	27.5
		0	31.3	0	42.9	39.7	25.0	9.3	
		0	9.3	0	3.3	10.0	3.0	1.9	
1500-1800	5.	1	7	0	7	27	3	6	51
		2.0	13.7	0	13.7	52.9	5.9	11.8	19.0
		100.0	8.8	0	33.3	39.7	9.4	11.1	
		.4	2.6	0	2.6	10.0	1.1	2.2	
1800-2100	6.	0	0	0	1	2	0	0	3
		0	0	0	33.3	66.7	0	0	1.1
		0	0	0	4.8	2.9	0	0	
		0	0	0	.4	.7	0	0	
2100-2400	7.	0	1	1	0	0	0	0	2
		0	50.0	50.0	0	0	0	0	.7
		0	1.2	7.7	0	0	0	0	
		0	.4	.4	0	0	0	0	
	COLUMN TOTAL	1	80	13	21	68	32	54	269
		.4	29.7	4.8	7.8	25.3	11.9	20.1	100.0

TABLE 12 FREQUENCY OF OCCURRENCE OF DIFFERENT PROFILE TYPES AT DIFFERENT LOCATIONS RELATIVE TO THE CITY

LOCATION RELATIVE TO THE CITY	COUNT ROW PCT COL PCT TOT PCT	PROFILE TYPE UNCERTAIN	A	E	C	D	E	F	ROW TOTAL
UPWIND OR TO ONE SIDE		1 .8 100.0 .4	51 38.3 63.8 19.0	5 3.8 38.5 1.9	9 6.8 42.9 3.3	24 18.0 35.3 8.9	19 14.3 59.4 7.1	24 18.0 44.4 8.9	133 49.4
ABOVE CITY		0 0 0 0	14 20.9 17.5 5.2	4 6.0 30.8 1.5	1 1.5 4.8 .4	19 28.4 27.9 7.1	9 13.4 28.1 3.3	20 29.9 37.0 7.4	67 24.9
DOWNWIND		0 0 0 0	9 17.6 11.2 3.3	4 7.8 30.8 1.5	9 17.6 42.9 3.3	19 37.3 27.9 7.1	4 7.8 12.5 1.5	6 11.8 11.1 2.2	51 19.0
UNCERTAIN		0 0 0 0	6 33.3 7.5 2.2	0 0 0 0	2 11.1 9.5 .7	6 33.3 8.8 2.2	0 0 0 0	4 22.2 7.4 1.5	18 6.7
COLUMN TOTAL		1 .4	80 29.7	13 4.8	21 7.8	68 25.3	32 11.9	54 20.1	269 100.0

2. *Relative Frequencies of Different Profile Types in the Environs of Urban Areas*

Table 12 shows the relative frequency of occurrence of the different profile types in different locations relative to the nearest city. The key to the entries is analogous to that discussed for Table 11. For example, the entries in the second column of the first row show that there were 51 observations of Type A profiles taken upwind or to one side of urban areas, representing 38.3 percent of all the observations that were made upwind or to one side of the city and 63.8 percent of all Type A profile observations. The first row of Table 12 shows that over half the observations made upwind or to one side of the city revealed a profile of Type A or Type D. Downwind of cities the total frequency of Type A or Type D is about the same as upwind, but their relative proportions are reversed. That is, Type D profiles are found about twice as frequently downwind of cities as Type A. The frequency of occurrence of Types A and D profiles above cities is somewhat less than in areas outside the city.

3. *Relationship Between Surface Ozone Concentrations and Those Aloft for Different Stability Classes*

It should be apparent from the above discussion that the vigor of atmospheric mixing plays a large part in determining the nature of the ozone profile. Thus, the most unstable atmospheric conditions should be associated with the most nearly uniform vertical distributions of ozone. Figure 30 gives strong indications that this is true. For those measurements taken during extremely unstable conditions (A stability), the ratios of the surface to mixed-layer ozone concentrations cluster around one, and the differences between mixed-layer and surface concentrations cluster around zero. The stability increases toward Class D (neutral stability), as does the frequency of ratios that are much greater and much smaller than one. Large negative and larger positive differences also are more common under the less unstable conditions.

Table 13 presents information similar to that given in Figure 30; it shows the averages and the standard deviations for the differences and ratios as stratified according to the stability class that prevailed when the measurements were made. The average ratio of surface to mixed-layer concentrations varies with stability class, but the standard deviation shows a monotonic increase from the most unstable (A) to the neutral (D) conditions. Similar, but much less pronounced, tendencies appear in the tabulation of average differences according to stability class.

TABLE 13 COMPARISON OF OZONE CONCENTRATIONS AT THE SURFACE AND ALOFT BY STABILITY CLASS

Stability Class*	Number of Cases	Difference† (ppb)		Ratio‡	
		Average	Standard Deviation	Average	Standard Deviation
A	27	6.5	12.5	0.92	0.18
B	81	-1.1	16.0	0.99	0.24
C	68	10.1	19.4	0.86	0.25
D	50	3.5	16.5	0.90	0.31

*A = extremely unstable; B = moderately unstable; C = slightly unstable; and D = neutral.

†Mixing layer concentration − surface concentration.

‡Surface concentration/mixing-layer concentration.

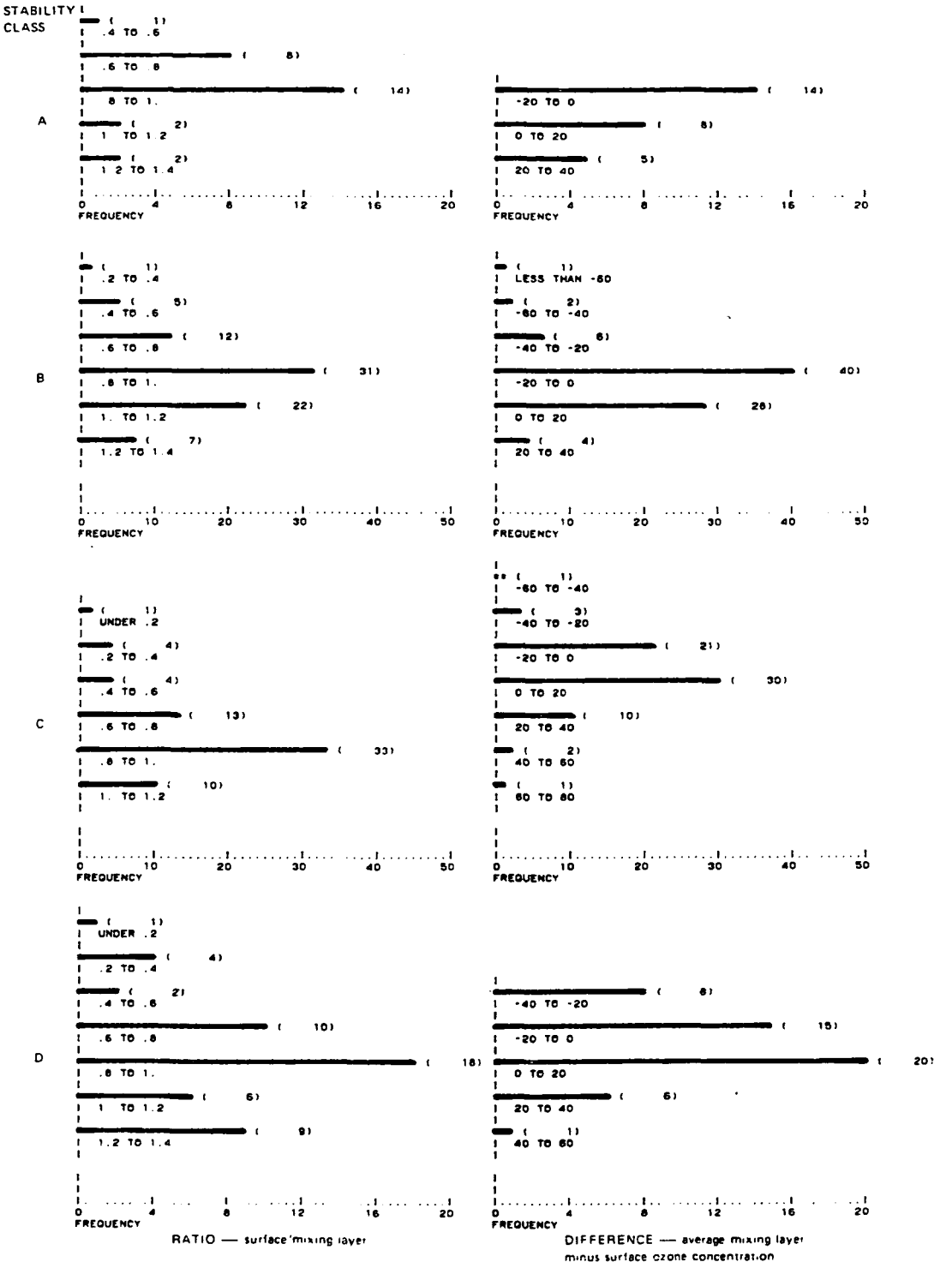


Figure 30. Histograms of ratios and differences between surface and mixing-layer ozone concentrations for different atmospheric stability classes.

4. *Most Favorable Conditions for Obtaining Aircraft Observations Representative of Ground-Level Ozone Concentrations*

As noted above, the most favorable conditions for Types A and D ozone profiles occur outside urban areas during the late morning and early afternoon when the atmosphere is unstable. Ludwig's (1979) tabulations of ozone profiles were used to determine the frequency of occurrence of the Types A and D profiles under these favorable conditions. Table 14 summarizes the findings. There were 65 instances when ozone profiles were measured outside cities between 1100 and 1600 LST during unstable conditions (Pasquill-Gifford stability classes A, B, or C). The table shows that about 77 percent of such cases are typified by either Type A or D profile.

Table 14 shows that the data analyzed by Ludwig (1979) included an appreciable number of instances where Type C profiles were observed under conditions that are most favorable for the occurrence of Type A or D. This is understandable; in general, the same conditions that produce a Type D profile also produce a Type C. Differences between the two profiles arise from differences in the time elapsed since the precursors left the source area. As noted earlier, a Type D profile is produced when sufficient mixing has taken place to cause ozone and its precursors to be uniformly distributed through the mixing-layer. Before the mixing is complete, the profile will be of Type C, suggesting that Type C profiles are apt to be found closer to the urban areas than Type D. (The need for aircraft monitoring to fill gaps in the existing network is greatest away from the cities, where Type C profiles are less likely to occur.) Table 14 shows the relative frequency of occurrence of the different profile types when Type C occurrences are removed from the list: Nearly 90 percent of such cases are of Type A or D. The percentage would be even higher if we assume that the Type C profiles evolved to Type D at locations farther downwind.

TABLE 14 PROFILES OBSERVED DURING UNSTABLE CONDITIONS OUTSIDE CITIES FROM 1100 AND 1600 LST

Profile Type	Number of Cases	Percentage of All Cases	Percentage of Cases When Type C Profiles are Neglected
A	28	43.1	50.0
B	0	0	0
C	9	13.8	–
D	22	33.8	39.3
E	3	4.6	5.4
F	3	4.6	5.4
Total	65	100	100

D. *Station Characteristics Likely to Result in Unrepresentative Readings*

Two methods were used for identifying cases where the data from stations were likely to be unrepresentative. In one approach, the annual second-maximum values of ozone concentration were examined and compared with values from other nearby stations. All pairs of stations that were separated by 25 km or less and that recorded second-maximum ozone concentrations that differed by 100 ppb or more were identified. The second method used maps similar to Figure 11, but for individual years. A subjective search was made for "L" symbols that were well within circles that defined areas of probable exceedance of the NAAQS for ozone. When the potential cases of unrepresentativeness had been identified, the characteristics of the individual stations were examined after preliminary screening. The preliminary screening included elimination of duplicate pairs—in opposite order or for different years—and obviously spurious data.

Three important factors have been identified in connection with the pairs of sites that were examined. These are:

- Meteorological factors and location relative to the urban center and local wind patterns.
- General urbanization of the surroundings.
- Local traffic effects.

The greatest concentrations are most likely to be observed outside cities in a direction that is downwind during optimum photochemical conditions. The highest concentrations are found a few tens of kilometers from the city. Monitors located in these areas provide data that are representative of the worst conditions. Monitors upwind or within the city can also provide data that are representative of relatively large areas, but these are not the areas that have the highest concentrations and hence, are not of as great interest for purposes of determining compliance with the NAAQS as are the extraurban downwind locations.

The effects of heavy local traffic can cause the data to be totally unrepresentative of larger areas in most instances, although some of the data suggest that high ozone concentrations have been observed at locations with heavy daily traffic under special circumstances. Such special circumstances might include nonpeak traffic hours or wind directions that mitigate effects of the local emissions.

The nature of the air quality standard is such that extreme observations are emphasized, and extreme concentrations tend to be produced by atypical conditions. Thus, factors that influence the representativeness of means or even high quantile values are not always operative when conditions are extreme. Thus, high ozone concentrations can be found near strong NO sources or in the heart of urban areas on occasion, but it is much more probable that they will be observed more frequently elsewhere.

SECTION 4
RECOMMENDATIONS

A. *Areas Where More Data are Required*

Figure 12 can be used as a guide to determine the areas of the country that may not be adequately defined in terms of exceedance of the NAAQS for ozone. It is obvious from the figure that some rather large areas cannot be characterized, using only the ozone concentrations available from the SAROAD. Figure 12 shows that the greatest need for additional information is in the Southeast, the Northern Great Plains, and the Great Basin. Most of the northeastern quadrant of the United States is adequately covered, but there is a conspicuous gap in Maine. However, according to Gordon (1979), a monitoring program now underway should remedy some of the need for additional data. This monitoring is generally limited to those months when photochemical activity is greatest.

Based on an analysis of the nearly complete data sets, as shown in Figure 12, the state of California and parts of the West Coast are covered; coverage in Kansas, Oklahoma, Texas, and along the Gulf Coast tends to be marginal. Our ability to define the air quality status of areas in much of the West from these relatively complete data sets is quite limited.

Numerous data sets were not included in Figure 12 because they were not complete enough for some of the analyses that were performed. For example, the joint frequency analysis used to define probabilities of standards exceedance required that the data sets be comparable and nearly complete. A nearly complete data set is necessary to define an area as "in compliance" because higher values, in excess of the standard, might have occurred during the unmonitored hours. However, an incomplete data set that contains one or more values above the standard can be used to determine that the standard has been exceeded. In such a case the observed second-maximum ozone concentration places a lower bound that can be used to define a radius of probable exceedance which is also a lower bound.

The preceding discussion, which was an extension of earlier arguments, has been included in this recommendation section because it provides a basis for defining geographical areas of the continental United States that should be studied, and because it suggests that greater use of existing data sources would be profitable. For one reason or another, not all monitoring data are archived in the SAROAD, so other sources should be actively explored.

B. *Methods for Obtaining Additional Data*

1. *Survey of Non-SAROAD Data Sources*

As noted above, it should be possible to expand the data base, and enhance the areas that can be characterized with regard to exceedance of the standards for ozone, by obtaining as much non-SAROAD ozone-monitoring data as possible. This should certainly be the first

step, before undertaking any special aircraft- or ground-monitoring program. The expense of special monitoring programs should make them a last resort; acquisition of data already collected could be relatively inexpensive when compared to the cost of large-scale monitoring programs.

Since no single person is likely to be familiar with all the uncataloged ozone data sources in the United States, it would seem most logical to contact many knowledgeable people. The most systematic approach would be to contact EPA Regional Offices to identify known data that had not been entered into the SAROAD. Data from any special studies that had been sponsored by that Region, or that the Region was aware had been undertaken by industries should be obtained if possible. The regional EPA offices might also supply names of knowledgeable individuals in industry, state and local agencies. These sources should be explored, with the focus on those geographical areas of Figure 12 that are largely uncharacterized.

Contacts with various agencies and organizations should result in a catalog of potentially useful ozone data. The catalog, as a minimum, should contain information concerning the dates when the data were collected, the instrumentation and calibration methods used, and at least the general locations of the monitoring sites. Some screening should be done to eliminate unsuitable data. It might also be efficient to eliminate redundant data that would not add significantly to the available coverage. More detailed screening should be undertaken to eliminate unreliable data and to ensure that the monitors were reasonably well-sited.

It should be noted that special aircraft data might prove useful. The relationship between ozone data collected from aircraft and the ground-level concentrations has been discussed at length. That discussion should help decide which aircraft data are suitable. In a subsequent section, a protocol for aircraft sampling that will obtain suitable data is given. That protocol can also help to determine the suitability of aircraft data.

2. *Selecting Times and Areas for Study*

To a large extent, the areas in need of further study will be defined by the analysis of existing data. Areas that cannot be characterized with regard to exceedance of ozone standards must be considered as candidates for special studies. However, not all of those unmonitored areas will be of equal importance: Priority should probably be given to those regions that are suspected of being in exceedance of the standards. It is well established that areas with warm temperatures, plentiful sunshine, and appreciable anthropogenic emissions are candidates for the formation of photochemical ozone. Using these facts as a guide, unmonitored areas in the southern tier of states should probably be given high priority. The northern Great Plains should also be high on the list, followed by the Great Basin states.

Table 6 can serve as a useful guide for deciding what months would be most profitable for conducting special monitoring programs. It is assumed that the months when the highest concentrations are most likely are the months that would be best for monitoring, because they would be most likely to produce decisive evidence of exceedances. Futhermore, that no exceedances were observed during these months, when the probabilities were highest, could be taken as reasonably strong evidence of compliance with the standard.

Ludwig, Reiter et al. (1977) found that relatively high concentrations were most frequently observed in June and July over the Florida Peninsula and along the Texas-Louisiana Gulf

Coast. In the Ohio River Valley, the frequencies were greatest in July and August. This suggests that the month of July would probably be best for a monitoring program in uncharacterized areas in the southeastern United States. Judging by the observed frequencies of relatively high concentrations in 1974 in the Texas-Louisiana Gulf Coast Area and the western parts of Oklahoma, Kansas and Nebraska, monitoring programs in Texas or the southern Great Plains regions could be undertaken almost equally well in June or July; favorable conditions extend into August as well.

Little information is available from the northern High Plains. Singh, Ludwig and Johnson (1977) summarized the seasonal variability of measured ozone concentrations in several remote locations. Their analyses suggest that the highest concentrations are most likely to be found in the late winter and spring months, a fact that suggests non-photochemical sources. Some of the High Plains sites also had relatively high ozone concentrations during summer. It appears that the locations analyzed by Singh, Ludwig and Johnson (1977) in the northwestern High Plains were all subject to influences from stratospheric ozone sources; some of the locations were also subject to occasional influxes of anthropogenic precursors and the consequent photochemical ozone.

In summary, it appears that monitoring in the northern Great Plains and the Great Basin should be done in both the spring and summer months. Data from Great Basin locations in Utah and western Colorado that were analyzed by Singh, Ludwig, and Johnson (1977) showed increases in the average ozone concentrations and daily peak-hour concentrations during the late winter or spring that remained at relatively high levels through July and August.

For purposes of planning more-or-less routine ground-monitoring programs, recommendations for seasonal monitoring are probably sufficient. For less-routine measurement programs, however, especially those involving aircraft, some more detailed specifications of the measurement program would be useful: in particular, the synoptic-scale weather features that were most likely to yield high ozone concentrations. Routine National Weather Service forecast material could thus be used in field planning to identify promising periods for conducting tests.

Tables 7 and 9 show the frequency of association of high ozone concentrations with certain kinds of synoptic meteorological features in various parts of the United States. In interpreting the tables, it should be recalled that high ozone concentrations are associated with plentiful sunshine and are generally positively correlated with temperature. Therefore, field monitoring would best be conducted during periods with clear skies and high temperatures, especially when the area of interest is under the influence of the appropriate synoptic-scale weather system.

In the southeastern United States, the highest ozone concentrations are most likely to be found in the southwestern parts of high-pressure systems. Warm, sunny days when the southern Great Plains are under the influence of the western or southwestern portions of the high-pressure system should have the greatest potential for observing high ozone concentrations. The northern Great Plains and the Great Basin are frequently associated with high ozone concentrations in the northwestern region of high-pressure systems.

According to Tables 7 and 9, nearly all occurrences of high ozone concentrations are associated with warm air masses, rather than with the cold air behind weather fronts. Frequently, high ozone is found on the periphery of the warm air mass, just ahead of a cold front or in the vicinity of a warm front. (For purposes of classification, we have separated these regions from the more central regions of the high-pressure system.) Tables 7 and 9 show that high ozone concentrations can frequently be found in the vicinity of fronts, usually in the warm air, so such regions should not be ignored in planning field-monitoring programs.

3. *Protocol for Aircraft Monitoring*

When the appropriate areas and seasons have been identified, the field project has been mounted, and conditions appropriate for measuring high ozone concentrations are forecast, measurements must be conducted in such a way that they are representative of conditions near ground level. Earlier sections of this report discussed the criteria for identifying situations when concentrations aloft and at ground level were about the same. This section describes a protocol for aircraft monitoring to meet those criteria.

The aircraft observations should be undertaken whenever a Type A or Type D ozone profile (as shown in Figure 24) is likely to exist. In general, the flight should take place after 1000 or 1100 LST and before 1700 or 1800 LST, consistent with the requirement of sampling when ozone concentrations, especially those from photochemical processes, are apt to be greatest. The likelihood of encountering a Type A or Type D profile is further enhanced if conditions are sunny and the atmosphere is unstable. It is assumed that the aircraft monitoring would be conducted during periods and at locations (relative to synoptic weather features) that are most likely to be associated with exceedances of the ozone standard. Furthermore, it is assumed that the region will be without an extensive ground-level monitoring network. Finally, it is also assumed that the areas of greatest interest will be outside cities, where ground-based monitoring is more difficult to support and where higher ozone concentrations are more likely to occur. As noted earlier, conducting the aircraft programs outside cities increases the likelihood of encountering Type A or Type D ozone profiles.

It will be necessary to recognize, while in flight, when the aircraft's ozone measurements represent ground-level conditions. It is therefore essential that the following parameters be measured from the aircraft:

- Ozone concentration
- Temperature
- Dew point
- Altitude or atmospheric pressure.

Nephelometer measurements, to indicate atmospheric aerosol content, would be highly desirable. Other pollutant measurements (e.g., carbon monoxide, oxides of nitrogen, nonmethane hydrocarbons) would be of some use, but by no means essential. Continuous ground monitoring of ozone at one or two locations would be useful.

To determine when the aircraft is within the mixing layer (so that the measurements will be representative of ground-level concentrations), the equipment should have simple, on-board data processing and display capabilities to provide graphical plots of recently measured parameters as a function of altitude or pressure. Subsequent interpretation will require that the data be recorded on board in computer-compatible form. Information must be recorded that can be used to determine the location of the aircraft at any specified time.

Recent aircraft field operations (e.g., Johnson, et al., 1979) have shown that a large field team is unnecessary when only daytime operations are required. Two persons, in addition to a pilot, are required. One of the two team members must be capable of field maintenance of the equipment. The other member of the team must be an experienced air quality meteorologist. Both must be able to operate the equipment and recognize when the aircraft measurements represent ground-level ozone concentrations. While one of the team is flying, the other gathers corollary information (e.g., weather conditions and ground-level air-quality measurements) and interprets data from earlier flights.

Once areas for the monitoring program have been identified, an airport suitable for the operations should be selected and the necessary arrangements made. Satellite airfields or other areas where vertical profiles might be taken should also be selected before operations begin.

To ensure that the aircraft monitoring is conducted when the vertical ozone profile is of Type A or Type D, and that the observations are made in areas of likely high ozone concentrations, a sampling protocol similar to that described below and shown schematically in Figure 31 should be undertaken.

Step 1—Begin sampling operations after the predicted time for breakup of ground-level inversions, probably after 1000 or 1100 LST. An acoustic sounder would be useful to verify that the break-up of the surface inversion had occured; acoustic sounder data would also provide information on the depth of the mixing layer.

Step 2—Fly a vertical spiral near the airport through the top of the mixing layer or to 1.5 km, whichever is the lower. Typically, a vertical spiral to 1.5 km can be flown up-and-down within 7 to 10 minutes in a twin-engine aircraft. During this spiral, the location of the top of the mixing layer should be determined from on-board displays of the vertical profiles of ozone, temperature and dew-point. (Figure 32 shows some profiles taken near Washington, D.C. when the top of the mixing layer was very clearly defined by a temperature inversion and an abrupt drop in pollutant concentrations.) The top of the mixing layer should be identified on board the aircraft, based on the available data displays. This initial vertical profile serves two purposes: It ensures that the ozone profile is of the proper type and that the measurements are being made within the mixing layer.

Step 3—Fly horizontally, at an altitude as far below the top of mixed layer as regulations permit, to a location upwind of the city, and, as shown in Figure 31, fly another vertical spiral. If the study is not focused on a specific city, this step can be omitted, and the flight would proceed to the next step.

Step 4—Fly downwind in a "zig-zag" path, such as that shown in Figure 31. This flight should be at an altitude that is as far below the estimated top of the mixed layer as regulations allow. If a "plume" of ozone is identifiable in the record, the "zig-zag" should be centered on it.

Step 5—Obtain vertical profiles by spiral ascent/descent at 50-100 km intervals, depending on the spacing of suitable locations. These profiles will verify that the measurements are being made within the mixing layer and that the nature of the vertical distribution of ozone is still of Type A or D.

Step 6—Patterns similar to those described in the preceding steps should be flown until late afternoon (about 1600 LST). (Patterns can be flown in alternate directions.) If the study is focused on an individual city, one or two round-trip flights should reach distances of 150 or 200 km downwind. If more than one city is included, the areas 100 to 150 km downwind of all of them should be surveyed. If no urban areas are of interest, a general "search pattern" would be appropriate. In all cases the horizontal flight should be interrupted for periodic determination (50 to 100 km intervals) of the vertical distribution of ozone, temperature, and dew point, preferably near a ground level monitor, if available.

The above description of the required steps is incomplete, as it does not describe preflight and post-flight instrument checks and calibrations, the importance of notebook entries, and other commonly observed practices. Although a detailed discussion of such matters is beyond the scope of this project, it should be understood that good monitoring and measurement practices will be essential.

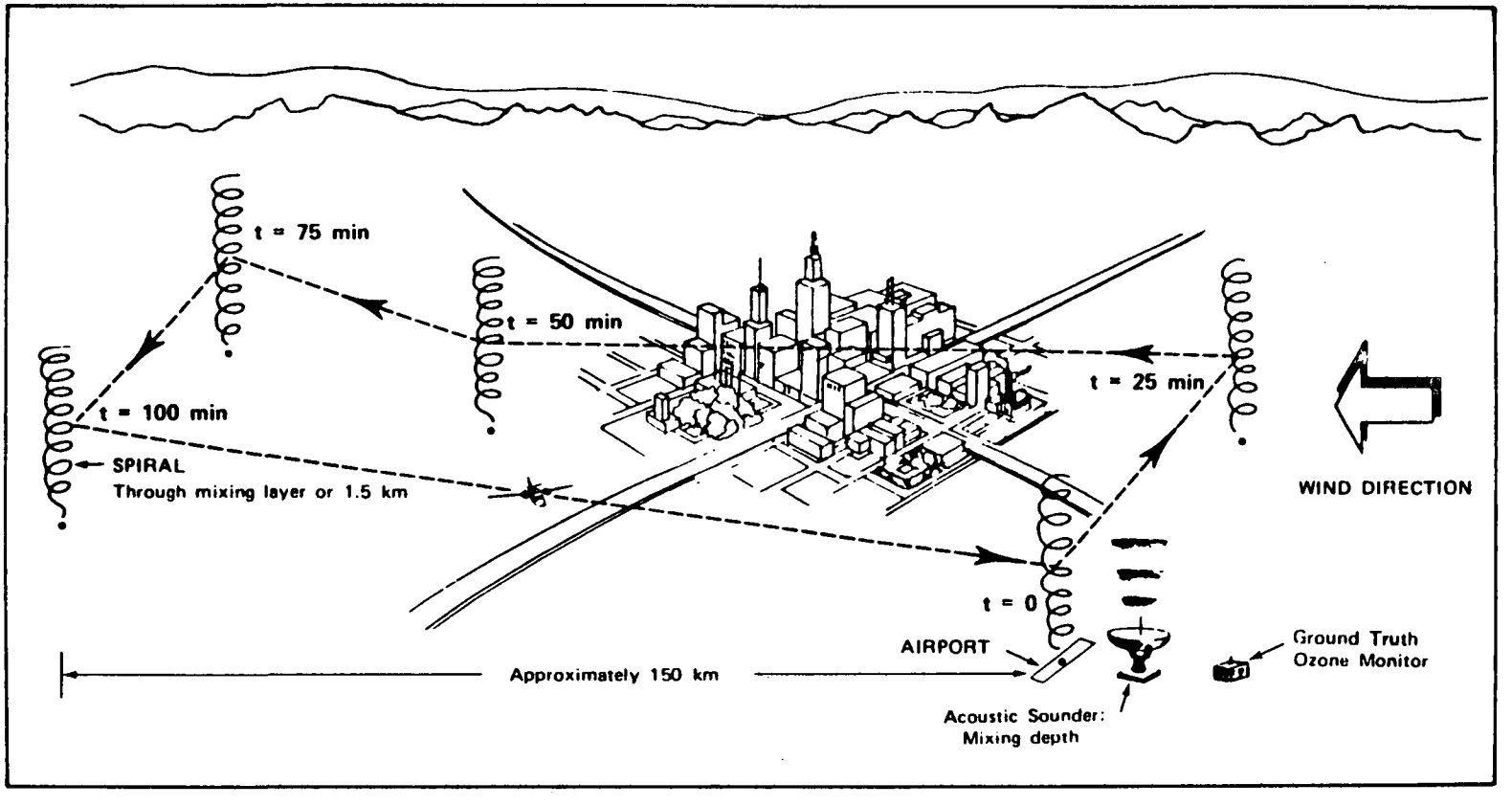


Figure 31. Schematic diagram of aircraft ozone-measurement program designed to estimate ground-level concentrations.

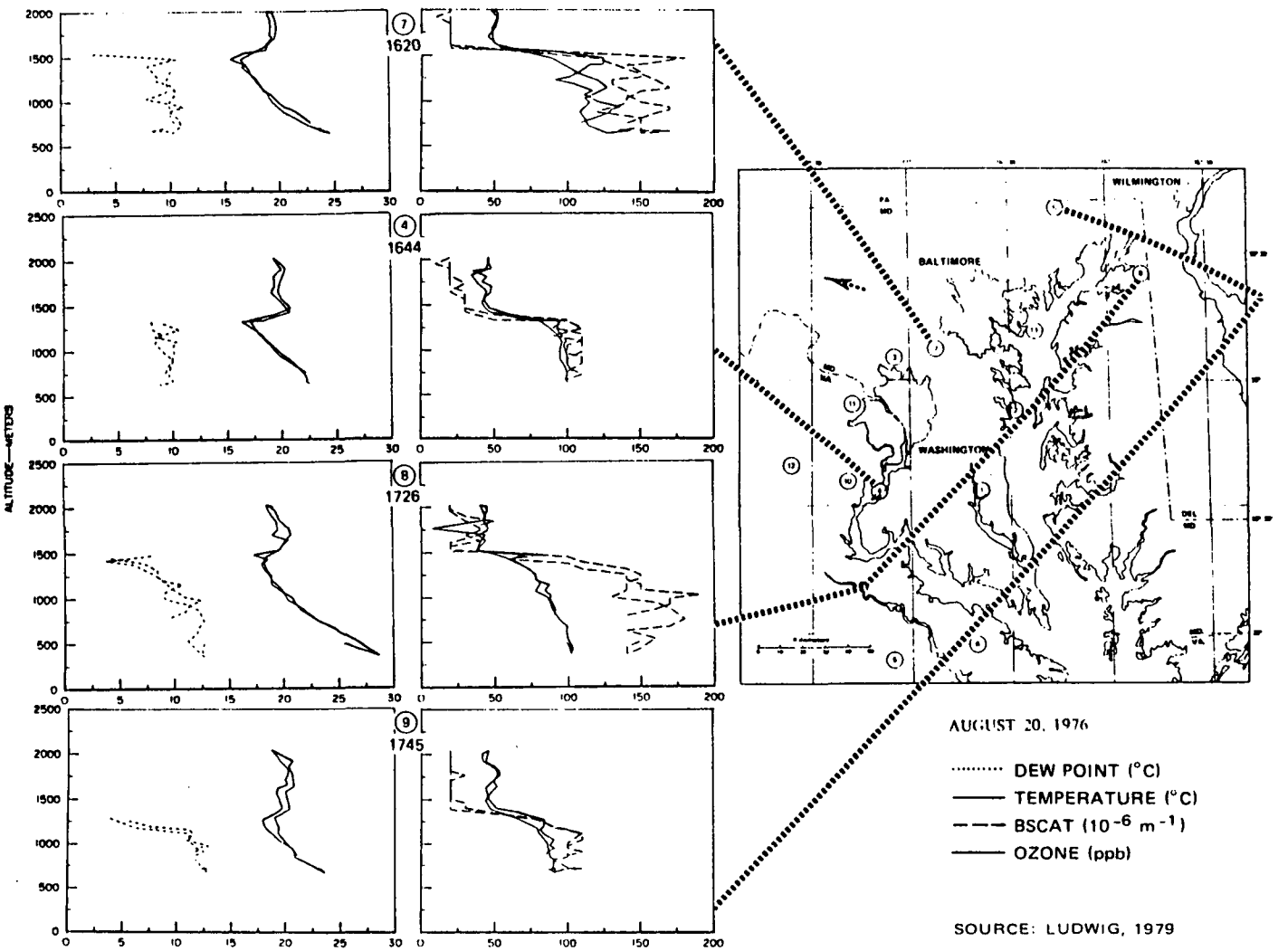


Figure 32. Vertical profiles of ozone, temperature, dew point and BSCAT taken near Washington, D.C.

4. *Ground-Level Monitoring*

Aircraft monitoring has the advantage of covering large areas, but it is expensive and will generally be possible for only a limited time period. Ground monitoring at fixed locations will be limited in spatial scope but can used over extended periods of time. Fixed, ground-based monitors are indicated in locations with data gaps where some identifiable source of precursor emissions is suspected of causing ozone exceedances.

Ludwig and Shelar (1978) give detailed instructions for locating sites where high ozone concentrations are probable. It is recommended that their directions be followed in those instances where identifiable precursor emissions from urban areas have not been adequately monitored in the past. As noted before, special measurements may not be required on a permanent basis: Data collection during a few months when high ozone concentrations are probable should suffice. Table 6 provides information that can be used to identify such months. Ludwig and Shelar (1978) give some guidance for determining the "downwind" direction for instances of probable high ozone concentration. The information concerning locations relative to synoptic-scale weather systems given in Tables 7 and 9 and the information concerning surface-wind direction associated with high ozone concentrations could be used for this purpose.

If a program of monitoring at ground level is undertaken in more remote areas, such as the northern Great Plains, the site selection will be governed more by the character of the entire area than by location relative to specific anthropogenic sources, and sites should be chosen so that their surroundings are characteristic of those of the area. This should not be difficult in the northern Great Plains, but may not be possible in mountainous areas. In relatively flat areas, low-lying ground should be avoided: Singh, Ludwig, and Johnson (1977), among others, found that sites elevated above the surrounding terrain generally give readings characteristic of the lower layers of the atmosphere throughout the day. Low-lying sites tend to be isolated from conditions aloft by cold-air drainage, especially at night. As before, Table 6 provides information concerning the best seasons for monitoring.

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TECHNICAL REPORT DATA
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1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE ASSESSING THE REPRESENTATIVENESS OF OZONE MONITORING DATA		5. REPORT DATE December 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) F.L. Ludwig and Eugene Shelar		8. PERFORMING ORGANIZATION REPORT NO. SRI Project 7863
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI International 333 Ravenswood Avenue Menlo Park, California 94025		10. PROGRAM ELEMENT NO. Task Order 2 11. CONTRACT/GRANT NO. 68-02-2548
12. SPONSORING AGENCY NAME AND ADDRESS Office of Air Quality Planning and Standards Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED FINAL 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Areas within which the National Ambient Air Quality Standard (NAAQS) for ozone is likely to have been exceeded are shown to be related to the observed annual second-maximum ozone concentrations. All pairs of SAROAD stations separated by 500 km or less that had nearly complete annual data sets were considered for the years 1974 to 1977 to determine the probability that the NAAQS would be exceeded at one station of the pair, given the observed second-maximum ozone concentration at the other and their separation. Circles were drawn around each SAROAD monitoring site to show the area within which it is 95 percent probable that the 120 ppb NAAQS has been exceeded for two or more hours during one or more years.

The report describes meteorological situations and seasons during which high ozone concentrations are most likely in various parts of the country, so that special monitoring studies can be designed to supplement existing data. An aircraft monitoring protocol is given that will provide ozone observations that are representative of ground-level conditions. Conditions that cause ozone data to be unrepresentative are described as are uncertainties associated with instrumental and calibration factors.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Standards Ozone Meteorology		

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* U	21. NO. OF PAGES 78
	20. SECURITY CLASS *(This page)* U	22. PRICE

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