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# THE RELATIONSHIP BETWEEN OZONE CONCENTRATIONS AND AIR TRANSPORT OVER WESTERN ARIZONA

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# The Relationship Between Ozone Concentrations and Air Transport Over Western Arizona

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ABSTRACT. The high concentrations(>100 ppbv) of $O_3$ measured near the surface in Yuma, Arizona, are primarily the result of the transport of $O_3$ and its precursors from the heavily populated southern California coastal region extending from Oxnard to San Diego. The highest $O_3$ concentrations are measured when the wind speeds are low, resulting in transport times of 36 to 48 hours for the distance from the coastal regions to the vicinity of Yuma. High daytime $O_3$ concentrations are associated with low nighttime concentrations (<10 ppbv) caused by the destruction of $O_3$ by NO, most of which is added to the atmosphere from vehicular traffic near the $O_3$ monitoring station. The continuous record shows a sharp decline in $O_3$ concentrations that coincides with the morning rush hour and vehicular activity in an adjacent parking lot. The least diurnal variability in $O_3$ concentrations, i. e., the lowest incidence of atmospheric pollutants, usually occurred during conditions of brisk wind, when the transport time to the Yuma area from the southern California coastline was 12 hours or less. However, the same condition of relatively little diurnal variability of $O_3$ was observed when transport was rapid from the Baja California or inland desert regions. Analysis of the relationship between $O_3$ concentrations measured in the Yuma area and air mass back trajectories showed that the most common wind direction for both polluted and nonpolluted times in Yuma was westerly. During the polluted times, transport was across the heavily populated southern California coastal regions. During nonpolluted times, air mass transport was commonly from Pacific Ocean areas across Baja California. Wind speed, as a regulator of the degree of air mass dilution during transport, was sometimes a determining factor in the occurrence of high $O_3$ concentrations at Yuma. Analysis of air mass back trajectories indicated that the central and northern parts of the western Arizona border are also subject to the impact of pollution from southern California.

## 1. INTRODUCTION

Monitoring, by the Arizona Department of Environmental Quality (ADEQ), of the concentrations of ozone ($O_3$) in the atmosphere of Yuma, Arizona, has shown that the National Ambient Air Quality Standard of 120 ppbv is occasionally reached or exceeded (G. Neuroth, ADEQ, private communication). This concentration is comparable to that measured in the metropolitan areas of Phoenix and Tucson, Arizona, and is much higher than would be expected to be generated in the vicinity of a city the size of Yuma (population about 45,000), which is located in the relatively well ventilated "Basin and Range Province" of southeastern California and southwestern Arizona. Since it has been noted that the higher $O_3$ concentrations often occur when the local wind

direction is southwesterly, attention was deflected away from consideration of importation of $O_3$ or its precursor pollutants from the population centers of southern California (J. Guyton, ADEQ, private communication), which are west or northwest from Yuma. The finding of elevated concentrations of $O_3$ in the Yuma atmosphere, without there being an obvious external source, led to the supposition that anthropogenic activity in and near Yuma was, in large measure, responsible. The acceptance of this supposition then led to the conclusion that further economic development of the area must be constrained in order to avoid exacerbation of the pollution problem (G. Neuroth, ADEQ, private communication).

The suggestion that $O_3$ pollution generated by local anthropogenic activity in Yuma could be equal to that found in the much more populous Arizona cities of Phoenix and Tucson is counter-intuitive, and the initial subjective response is that this suggestion would be difficult to support scientifically. Because of the unfortunate consequences of acceptance at face value of the existing circumstantial evidence, the ADEQ is seeking either a viable scientific mechanism supporting the suggestion of local origin, or a defensible explanation for the importation of $O_3$ or its precursors from an identifiable remote source (G. Neuroth, ADEQ, private communication). The purpose of this paper is to report the evaluation of air mass transport information in relation to the monitoring record collected at Yuma, in order to provide a definitive answer to the questions regarding pollutant origin.

## 2. OZONE IN THE ATMOSPHERE

The $O_3$ concentration commonly found in the northern mid-latitude marine boundary layer is on the order of 20 to 30 parts per billion by volume (ppbv); increases in $O_3$ concentrations are usually observed with increasing altitude in the lower troposphere. Thus, in the absence of anthropogenic pollution, air transported from southern California to western Arizona could be expected to contain between 20 and 40 ppbv of $O_3$. Air masses originating from a continental direction can be expected to have a higher $O_3$ content; concentrations of about 40 ppbv are commonly measured in nonpolluted areas (e.g., Logan, 1985; Bohm et al., 1991: Van Valin and Luria, 1988; Van Valin and Pueschel, 1981). The two different air mass source regions, marine or continental, then, establish two general levels from which anthropogenic emissions alter the $O_3$ concentration, either positively or negatively.

Pollutant gases emitted to the atmosphere, i.e., hydrocarbons and the oxides of sulfur and nitrogen, form a chemical mixture that responds strongly to the influence of sunlight. The three basic reactions are as follows (Seinfeld, 1989):

$$NO + O_3 \text{ ---> } NO_2 + O_2 \qquad (1)$$

$$NO_2 + h\nu \text{ ---> } NO + O \qquad (2)$$

$$O + O_2 + M \text{ ---> } O_3 + M \qquad (3)$$

These reactions occur rapidly, maintaining the steady-state $O_3$ concentration. What is needed to continue the photochemical reaction path that converts NO to

$NO_2$ without consuming a molecule of $O_3$ is to circumvent reaction (1). This is accomplished by the photochemical oxidation of hydrocarbons to form organic peroxy radicals, $RO_2$, which react with NO to form $NO_2$. Reactions (2) and (3) result in net $O_3$ formation.

The formation of $RO_2$ depends upon the attack of the hydroxyl radical (OH) on hydrocarbons. The OH is formed by the photochemical dissociation of $O_3$, carbonyl compounds (RCHO), or nitrous acid (HONO). HONO is itself formed during the night in polluted atmospheres, reaching its maximum concentration just before sunrise. In the presence of sunlight it has a lifetime of only a few minutes, dissociating to form OH and NO. The NO that is formed is then available for reaction with $O_3$, and can be partly responsible for the slight decrease in $O_3$ concentrations commonly seen in polluted atmospheres just after sunrise. The usual morning rush-hour traffic increase also injects NO into the atmosphere, contributing to a further decrease in $O_3$ concentrations.

## 3. WINDS IN THE YUMA AREA

The shortest straight-line distance from Yuma to the Pacific Ocean at the Baja California Norte coast is only about 230 km to the west-southwest; the distance to the Los Angeles County coast is 400 km to the west-northwest. The distance from the Los Angeles County coast to the area of Needles, California, Topock, Arizona, and Lake Havasu, Arizona, is also about 400 km, whereas the distance to the Lake Mead and northwestern Arizona area is about 500 km. Polluted boundary layer air above the Southern California megalopolis may be lifted to 900-950 m above sea level (ASL) to pass over the geological barrier of the low mountains and passes of the peninsular ranges. From there it is ducted in a southeastward direction, toward Yuma, by the Salton Trough and by the northwest-southeast-oriented ranges of the Basin and Range Province of southeastern California and southwestern Arizona. The geological barrier to transport from the southern California coast to the central and northern parts of western Arizona is only slightly more effective; air transported in an easterly or northeasterly direction would not receive the topographical ducting effect, but the highest terrain encountered would be that of the San Gabriel Mountains of elevation similar to that of the peninsular ranges.

During the winter season the air flow in the Yuma area is northerly or northwesterly at the 1000 mb (surface), 850 mb (about 1530 m ASL), and 700 mb (about 3160 m ASL) levels. During the summer, the 850 and 700 mb flows are influenced by the subequatorial easterly winds, although the surface winds rarely reflect this influence. In connection with the changes in zonal flow, and under the influence of the surface heating, a localized low-pressure system (a "heat low") sets up over southwestern Arizona and southeastern California. The counterclockwise flow around this low imparts a southerly component to the measurements at Yuma, where, in reality, the air at the surface and 850 mb is usually of northeastern Pacific origin. Typically, the surface air is advected southeastward along the Pacific coast and moves inland over southern California or the extreme north of Baja California to reach Yuma from the west or west-southwest. Air at 850 mb typically follows a similar path over the ocean, but is carried farther south before being captured by the desert heat low and being advected to Yuma from the southwest or south. Air

at 700 mb is more likely to originate from the south or southeast.

The calculation of air trajectories to yield the path an air parcel may have followed to arrive at some defined location is a basic meteorological technique described in texts such as that of Hess (1959). For this work, we used a numerical back trajectory method developed by Harris (1982) to produce isobaric trajectories to endpoints at Yuma (32.7°N, 114.6°W), Needles (34.7°N, 114.5°W), and Lake Mead (36.7°N, 114.0°W), from April 1, 1990, through September 30, 1991.

The isobaric back trajectories were computed from analyzed winds along the constant pressure surfaces of 1000, 850, and 700 mb. The analyzed winds consist of gridded wind components at standard pressure levels, and are produced by the National Meteorological Center (NMC) global atmospheric model, using rawinsonde wind observations supplemented by aircraft reports and satellite data. The resolution of the NMC grid is 2.5° of latitude and longitude, and grids are produced every 12 hours at 0000 Universal Time (UT, same as Greenwich Mean Time)(1700 local time, LT) and 1200 UT (0500 LT).

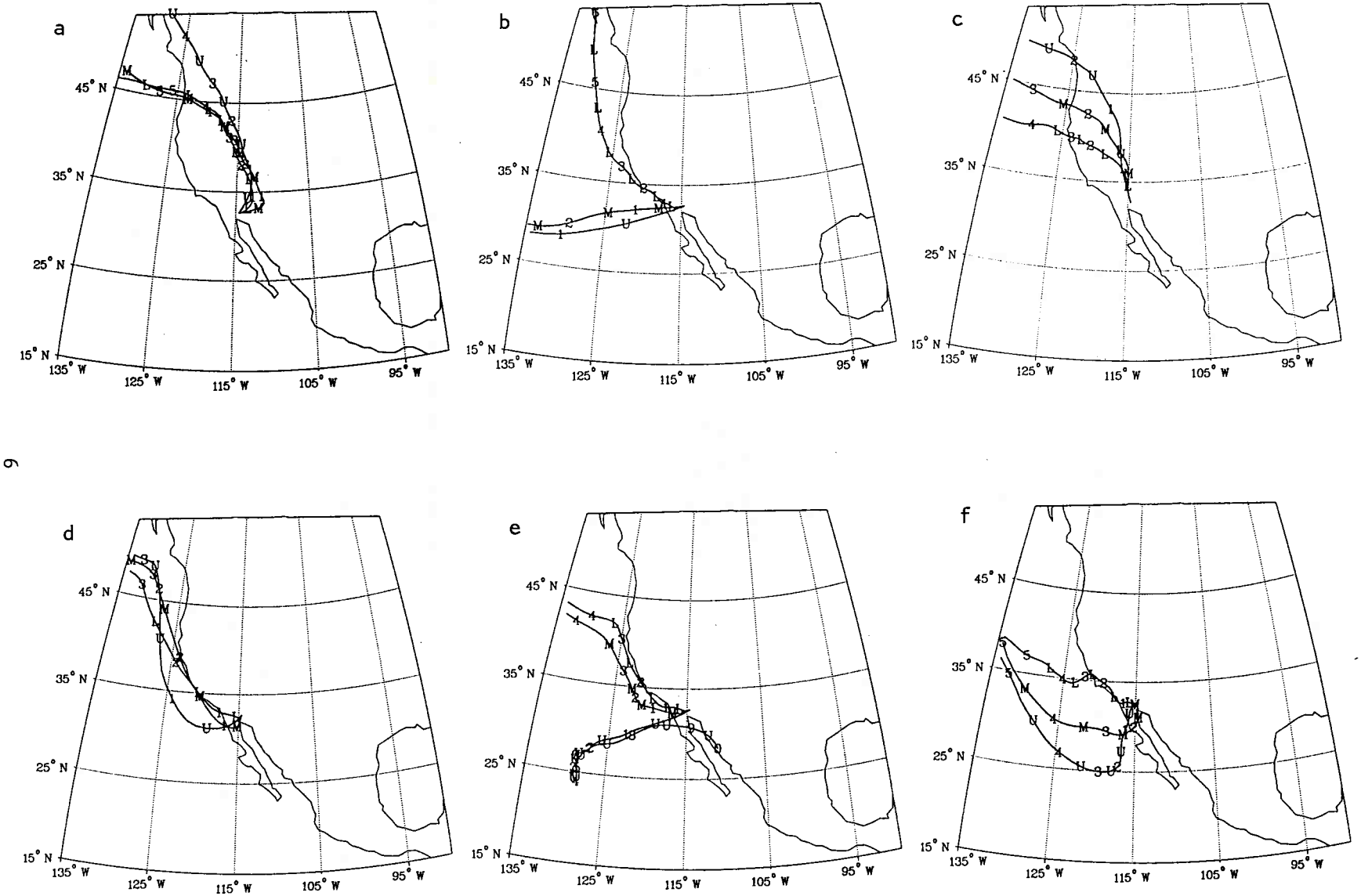
A 10-day trajectory consists of 80 individually computed 3-hour segments placed end to end; each segment is produced by an iterative approximation technique involving bilinear interpolation to the midpoint of each 3-hour period. The NMC model computes the gridded wind components for grid points, even where the surface pressure is less than the stated pressure, by extrapolating downward (Harris, 1982).

Back trajectory examples are shown in Figures 1a-1i. Figure 1a is an example of northerly flow in response to high pressure centered over Utah. This situation occurs more frequently during the cooler months than during the summer. The expected $O_3$ concentration would be typical of relatively unpolluted continental regions. Figure 1b shows that surface air was transported at modest velocity along the California coast and across the southern California regions, while the air at 850 and 700 mb was moving at high velocity from the west. A surface low-pressure area was centered over the ocean west of San Luis Obispo, and an upper-level low was situated over Wyoming and Utah. This system produced an $O_3$ concentration range at the observing station in Yuma of 49-61 ppbv from 1200 through 1800 LT. Figure 1c is another example of air from a northerly source region with fairly high transport velocities for several days across the continent, in response to a prominent midcontinent low-pressure system. The 1200-1800 LT $O_3$ range at Yuma was 54-57 ppbv. In the example of Figure 1d, the surface air was transported from the Los Angeles area in about 24 hours, while air at 850 and 700 mb was transported southeastward parallel to the coast, and came inland to Yuma across Baja California. At that time a cold front extended from northwestern Mexico to Wyoming with associated low pressure; an upper-level low was centered over northern Nevada. Trajectory velocities were high at all levels, but the surface $O_3$ range at Yuma during 1200-1800 LT was 61-71 ppbv. In Figure 1e the surface air was transported from southern California in approximately 24 hours, while the 700 mb air appears to have been considerably influenced by easterly flow a short distance to the south. Transport was dominated by a secondary low centered over southwestern Arizona; an occluded front was situated from central California across Nevada and Utah. $O_3$

concentrations measured in Yuma from 1200 through 1800 LT were from 59 to 69 ppbv. Figure 1f depicts a situation that commonly recurs. A surface low-pressure zone was centered over Yuma, and surface air was transported slowly across the southern California populated regions to the endpoint at Yuma. The 850 and 700 mb air made a larger counterclockwise loop over the ocean before moving swiftly from the oceanic source across Baja California. The Yuma $O_3$ analysis range at 1200-1800 LT was 74-81 ppbv. Figure 1g is an example of surface and 850 mb air being transported parallel to the coast, then inland from the southwest across Baja California in response to the persistent "hot months" low-pressure zone over southwestern Arizona-southeastern California. The $O_3$ concentration range from 1200 through 1800 LT was 46-61 ppbv. In Figure 1h the heat low caused the surface air, of northern Pacific origin, to hug the California coast before being transported across the southern California region in about 24 hours. An upper-level, diffuse high-pressure system over northern Mexico and Texas brought 850 and 700 mb air in from the south or southeast along a meandering transport path. The 1200-1800 LT $O_3$ range at Yuma was 56-74 ppbv. Figure 1i depicts the transport of northern Pacific air to the Yuma region in response to the heat low over southwestern Arizona, coupled with an upper-level low over Utah and Colorado, and high pressure over the Pacific Ocean. The 850 and 700 mb air approached Yuma from the south on counterclockwise circulation, while surface air tracked across southern California. $O_3$ concentrations at Yuma were only in the 40-44 ppbv range.

Figures 2a-21 (monthly for July 1990-June 1991) show the directions from Yuma of the surface, 850 mb, and 700 mb air masses 72 hours before they arrived at Yuma. The frequency at which the air masses resided in each octant (0-45°, 45-90°, 90-135°, ... 315-360°) at that time is expressed as a percentage of the total time during the month in question. This figure illustrates the differences in source direction of the three levels with respect to season. For example, the surface and 850 mb air masses were in the 270-315° octant 40 and 27% of the time in July, 49 and 27% in August, and 48 and 40% in September. Surface air masses continued to be strongly represented by this octant during most months of the year, but the 700 mb winds reflected the seasonal shift of zonal flow; the easterly-southeasterly direction was relatively more probable during July-September, and the westerly-southwesterly direction more probable during winter.

Figures 3a-31 and Figures 4a-41 (monthly for July 1990-June 1991) present similar information for source directions of air masses arriving at the Needles-Topock-Lake Havasu (Needles) and the Lake Mead-Northwestern Arizona (Lake Mead) regions. Comparisons between air mass source regions in corresponding months for Yuma and Needles show that westerly zonal flow at Needles occurs relatively less frequently than at Yuma (Figure 2). Although the 270-315° octant continues to dominate the wind pattern at the surface, the southerly and southwesterly quadrants are relatively more frequently represented at all levels. Relative to the air mass source areas for Yuma and Needles, depicted in Figures 2 and 3, the 225-270° octant at Lake Mead (Figure 4) was more frequently represented for the surface flow, and the 270-315° octant less frequently represented during July, August and September, 1990, and March through June, 1991.


a
b
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25° N
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125° W
115° W
105° W
95° W

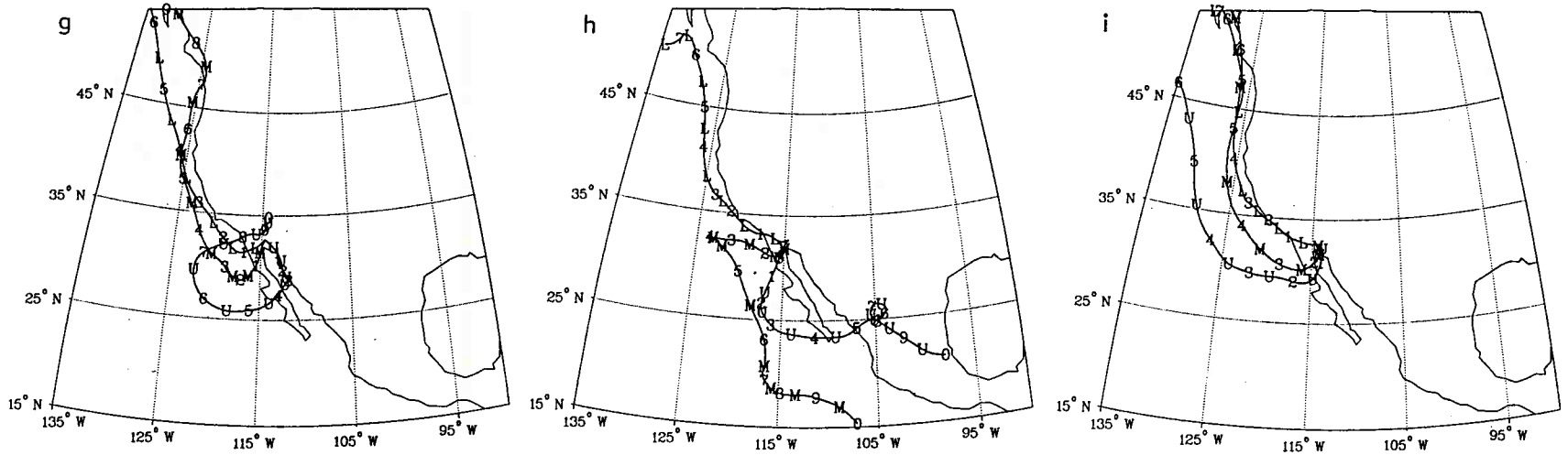



Figure 1 (a-l).--Examples of air mass back trajectories to an endpoint at Yuma (32.7°N, 114.6°W) at 0000 UT (1700 local time) at three isobaric pressure levels. The letters "L", "M", and "U" represent the 1000, 850, and 700 mb (hPa) levels; they appear the first time at a point 12 hours away from the endpoint, and at 24-hour increments thereafter. The numbers 1 through 0 represent 24-hour increments back from the endpoint. The significance of each trajectory is explained in the text. (a) October 10, 1990; (b) April 21, 1991; (c) April 29, 1991; (d) May 20, 1991; (e) June 20, 1991; (f) July 2, 1991; (g) July 14, 1991; (h) August 18, 1991; (i) September 14, 1991.

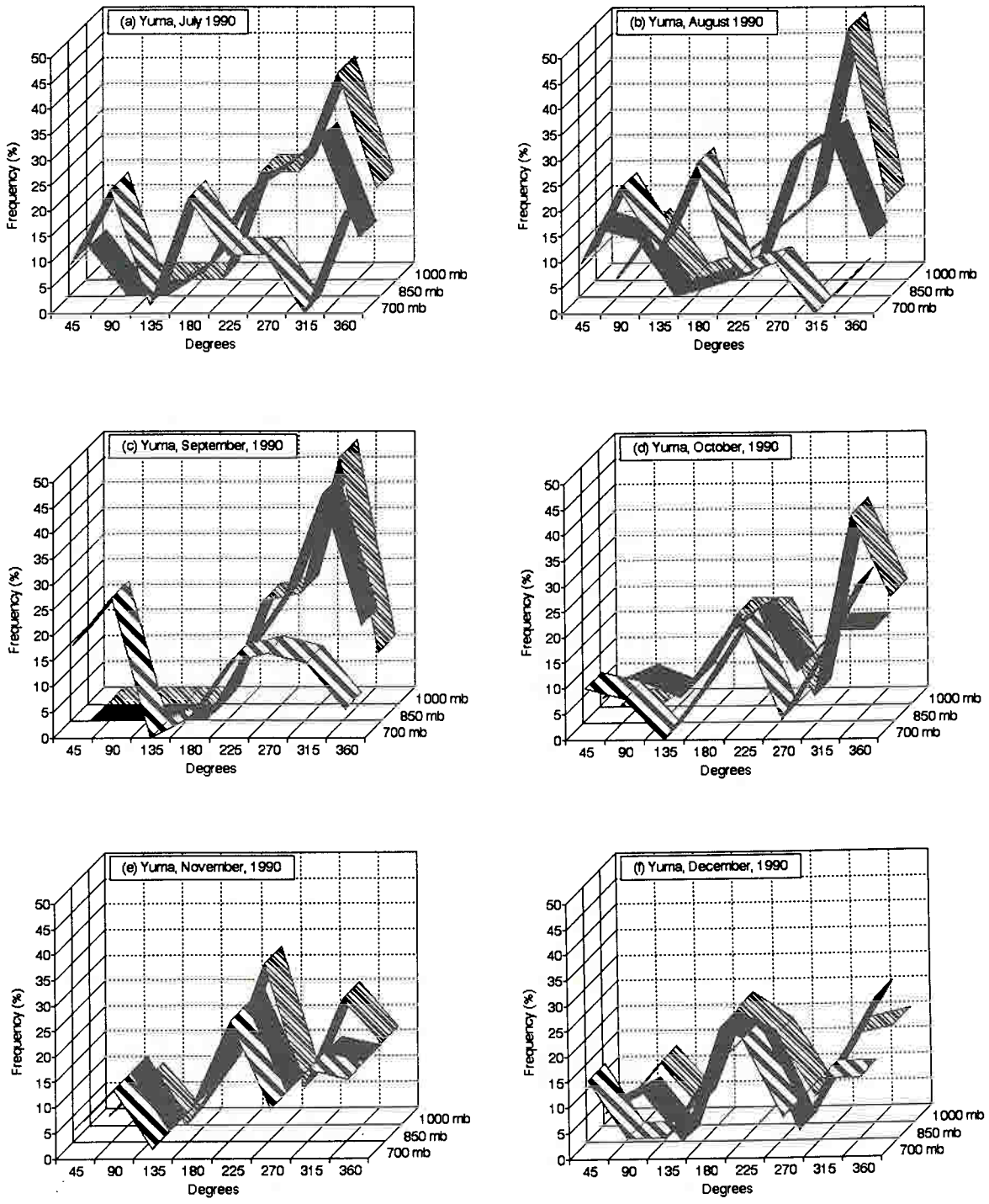



Figure 2.--Average monthly directions from Yuma (32.7°N, 114.6°W) of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Yuma for (a) July 1990 through (f) December 1990, expressed as a percentage of the total time of representation of that direction.

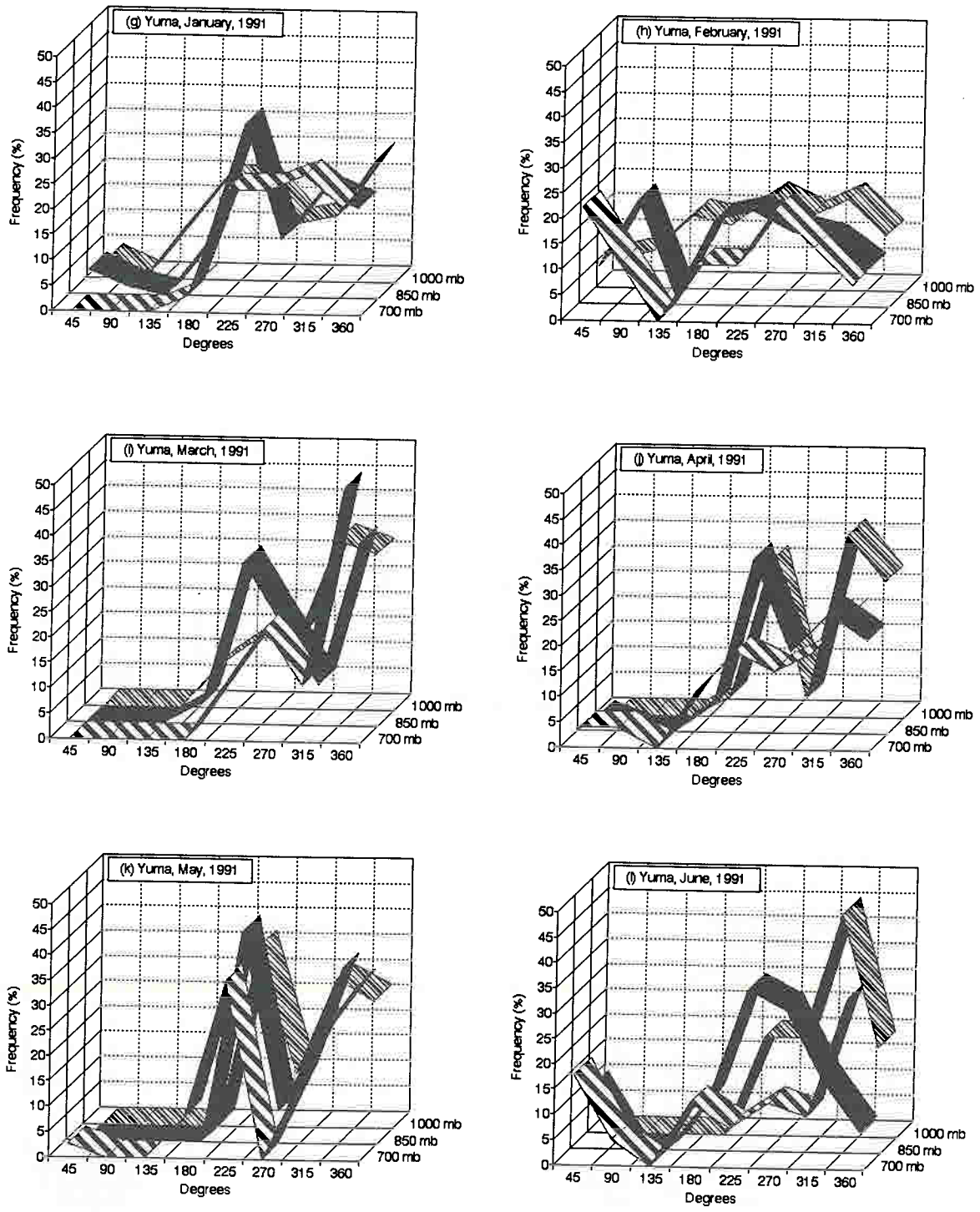



Figure 2 (cont'd.).--Average monthly directions from Yuma (32.7°N, 114.6°W) of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Yuma for (g) January 1991 through (l) June 1991, expressed as a percentage of the total time of representation of that direction.

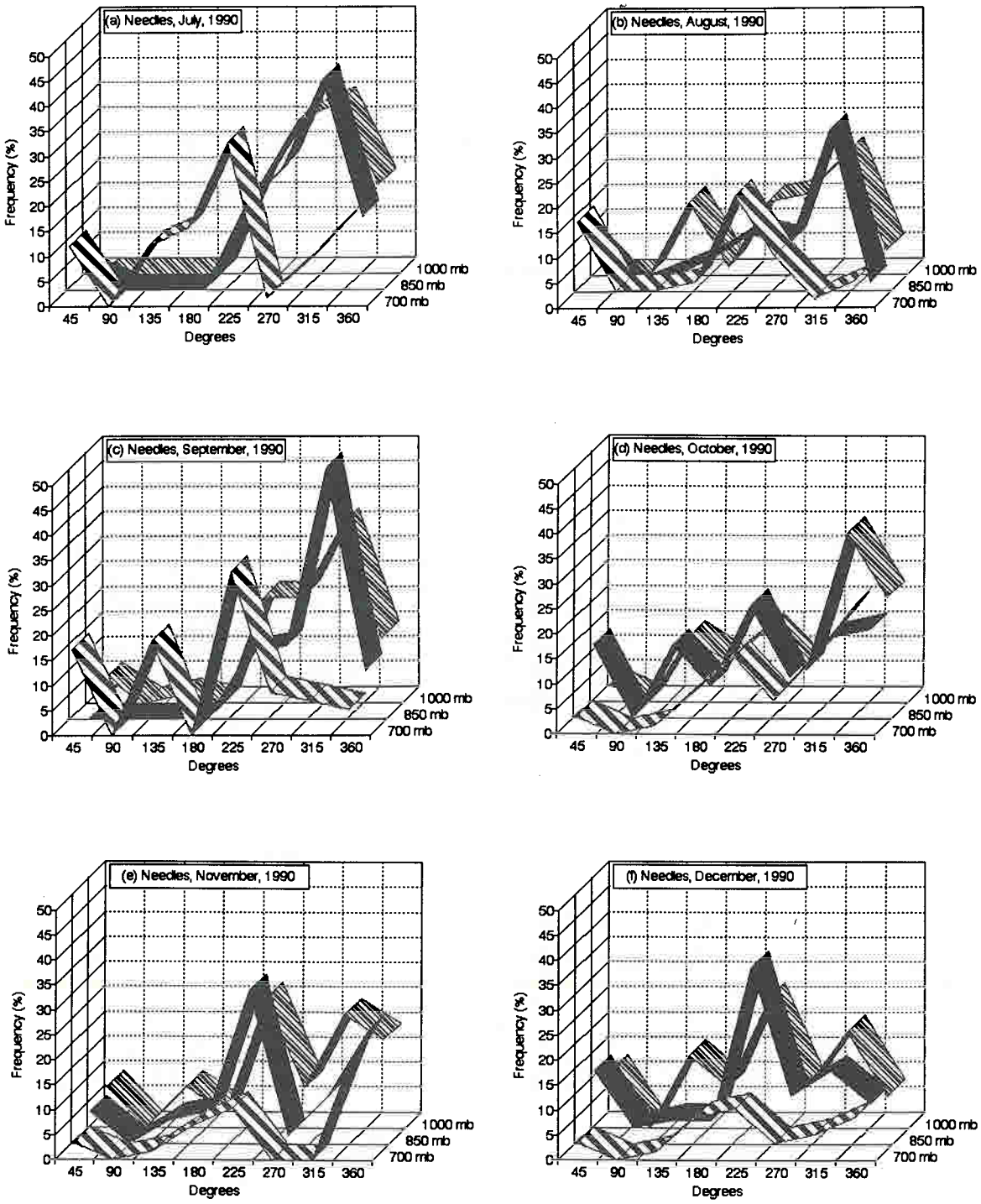



Figure 3.--Average monthly directions from the area of Needles, California, and Topock and Lake Havasu, Arizona (Needles)(34.7°N, 114.5°W), of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Needles, for (a) July 1990 through (f) December 1990, expressed as a percentage of the total time of representation of that direction.

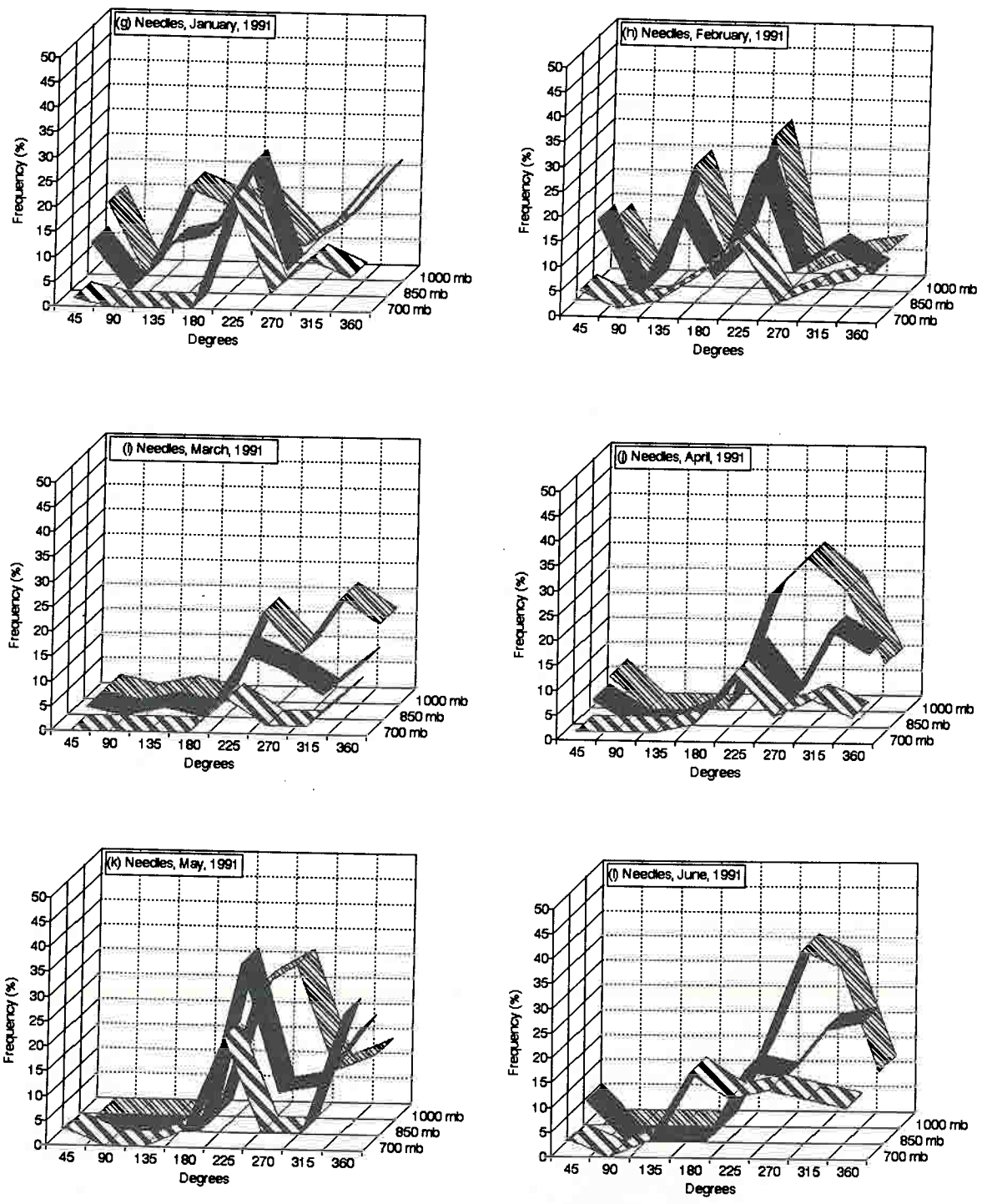



Figure 3 (cont'd.).--Average monthly directions from the area of Needles, California, and Topock and Lake Havasu, Arizona (Needles) (34.7°N, 114.5°W), of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Needles, for (g) January 1991 through (l) June 1991, expressed as a percentage of the total time of representation of that direction.

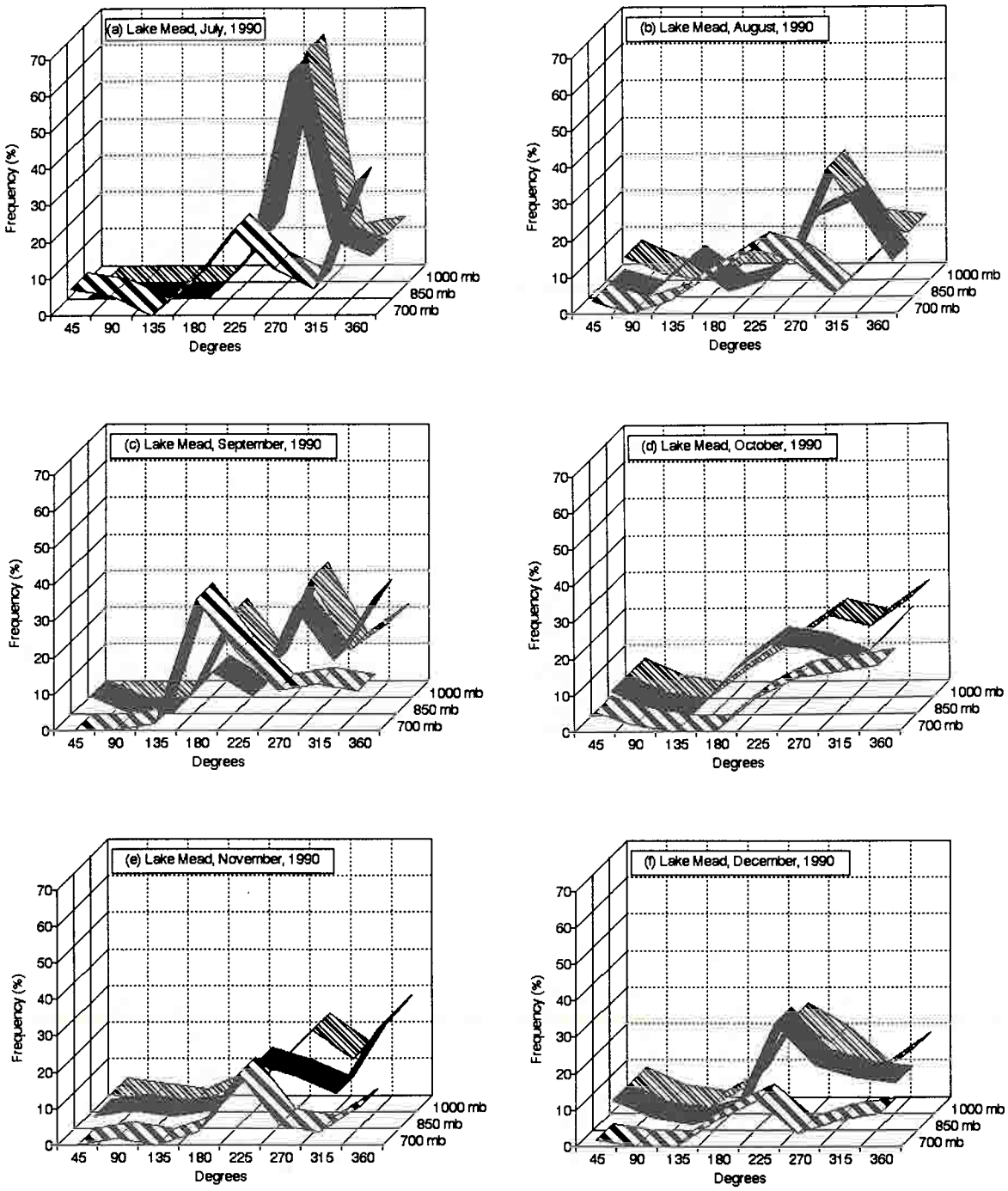



Figure 4.--Average monthly directions from the Lake Mead and Northwestern Arizona area (Lake Mead)(36.6°N, 114.0°W) of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Lake Mead, for (a) July 1990 through (f) December 1990, expressed as a percentage of the total time of representation of that direction.

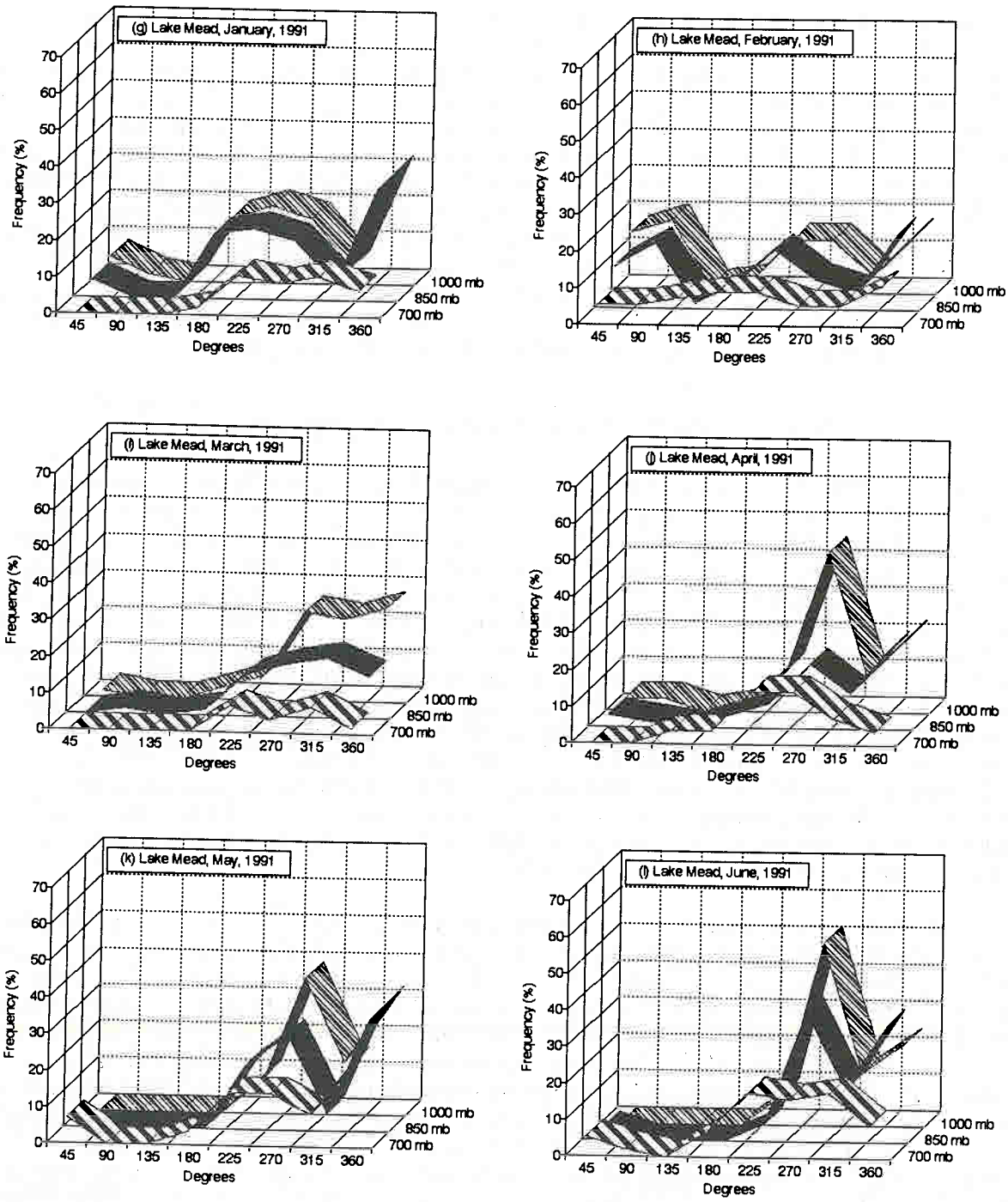


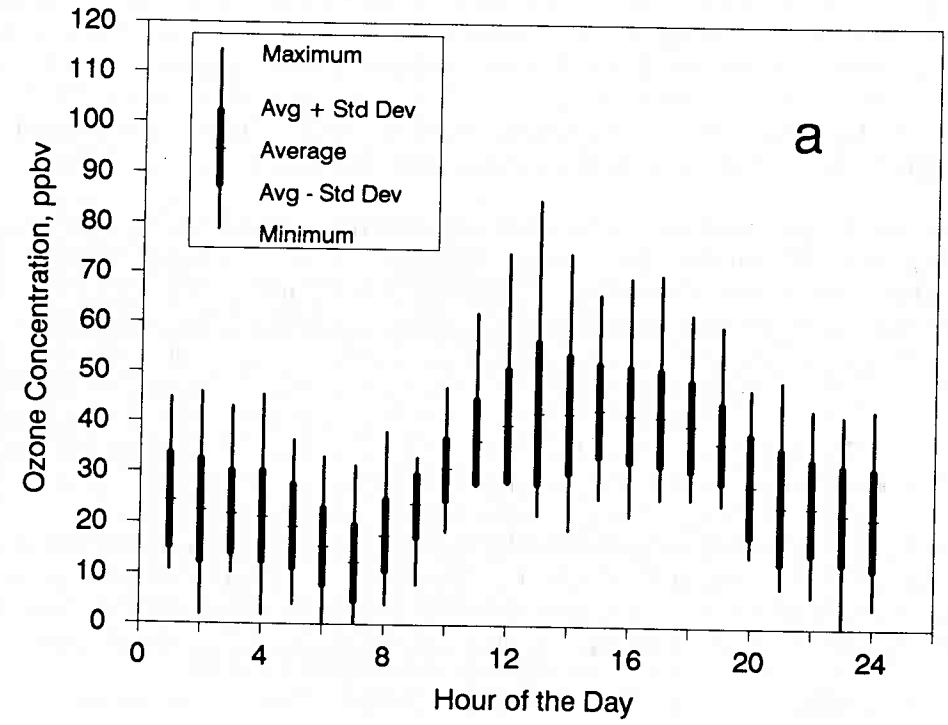

Figure 4 (cont'd.).--Average monthly directions from the Lake Mead and Northwestern Arizona area (Lake Mead)(36.6°N, 114.0°W) of the 1000 (surface), 850, and 700 mb air masses 72 hours prior to arrival at Lake Mead, for (g) January 1991 through (l) June 1991, expressed as a percentage of the total time of representation of that direction.

Although a considerable number of similarities are apparent in the positions of the respective air masses 72 hours prior to arrival at their endpoints, the differences are significant and instructive. For the surface (1000 mb) and 850 mb levels, the 72-hour source regions for Yuma and Needles during the months April through September were predominantly in the 270-315° octant, the 225-270° octant being a secondary source region; for Lake Mead the most common source regions were in the 225-270° octant. For Yuma, northerly air flow at the 1000 mb and 850 mb levels, with 72-hour air mass source regions to the north, was relatively uncommon during any month. For Needles northerly or northeasterly air flow (72-hour source regions in the 0-90° quadrant) in these levels was observed 10-20% of the time during the winter. The airflow observations at Lake Mead were similar, but for February 1991, northerly flow to this area was observed 20-30% of the time.

## 4. OZONE MEASUREMENTS IN THE YUMA AREA

An $O_3$ monitor sited at the City of Yuma Maintenance Yard is operated continuously 6 months a year, from April through September. Some of the characteristics of the $O_3$ concentration variations shown by the data record, such as a prominent diurnal cycle, are indicative of urban areas. The hourly averages, 1-$\sigma$ standard deviations, and extreme values related to this cycle are shown in Figure 5a for August 1990 and Figure 5b for May 1991; within the available record, these months represent the least and the greatest average monthly $O_3$ values. Figure 6 presents the averages of all $O_3$ data collected for the years 1989, 1990, and 1991 for the hours of midnight (0000), 6 AM (0600), Noon (1200), and 6 PM (1800). All times shown in Figures 5 and 6 are local time (LT). A prominent minimum consistently recorded at 0700 LT (Figure 5) is due primarily to local vehicular traffic; this factor is discussed in Section 5. Minor random variations are seen from year to year, but the diurnal cycle, as shown in hourly detail in Figure 5, is demonstrated by Figure 6 to be robust and reproducible.

Numerous measurements in the Northern hemisphere within several hundred kilometers of populated areas (e.g., Logan et al., 1981) have shown a seasonal cycle in the $O_3$ concentrations, with a broad maximum in summer. The monthly averages of the 0000, 0600, 1200, and 1800 LT readings from the Yuma record from 1989, 1990, and 1991 (Figure 7), however, demonstrate a much different cycle. The lowest average concentrations were recorded in August; the other months, in ascending order of average $O_3$ concentration, were July, September, June, April, and May. It is evident from Figure 5, however, that the lower monthly average $O_3$ concentrations during the summer are the consequence of a greater number of days with low $O_3$ concentrations, rather than lower measured concentrations on all days; the highest concentrations recorded during August equal the highest concentrations recorded during May, but there were more days during August when the concentrations were consistent with oceanic and clean continental values. This is evidently the result of a greater frequency of surface wind from the 180-270° quadrant during summer, compared with spring (Figures 2, 3, and 4), i.e., from the ocean with transport across sparsely populated Baja California. During the winter, and to nearly as great an extent during the spring and fall, the predominant wind direction is westerly or west-northwesterly, i.e., from the heavily populated, and polluted, areas



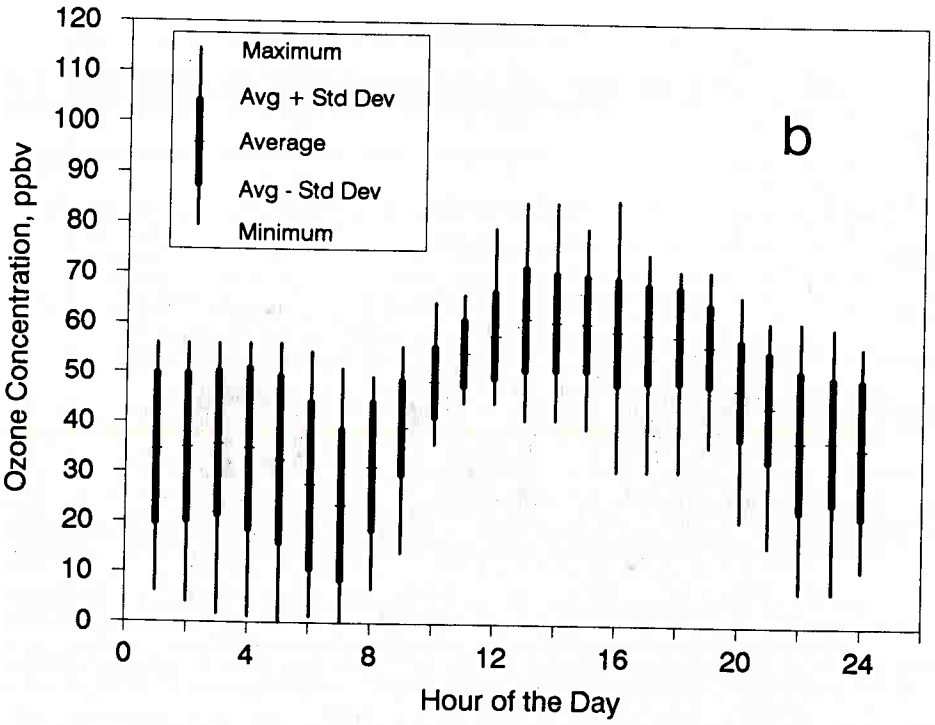




Figure 5.--$O_3$ concentration averages (-) at Yuma, plus or minus 1-$\sigma$ standard deviation (ends of broad line), and maximum and minimum values (ends of narrow line), by hour of the day for (a) August 1990 and (b) May 1991.

of California. The annual cycle observed in southern California, with maximum $O_3$ concentrations being recorded in summer, seems to manifest itself in Yuma with sporadic occurrences of high 1-hour values. The highest hourly average during the 3-year period shown in Figure 7 was observed in June 1989, and the average of the highest monthly readings during June, July, and August was slightly higher than that for April, May, and September.

Another well-documented cycle that manifests itself in urban atmospheres is the weekly one, in which the Monday through Friday diurnal cycles are more pronounced than those for Saturday and Sunday. However, in the Yuma data set, the differences between the weekday and weekend average $O_3$ values are small and not conclusive (Figures 8, 9a, and 9b). The Sunday and Saturday 0600, 1200 and 1800 LT $O_3$ averages are slightly greater than the corresponding weekday values. This circumstance tends to support the thesis that pollution in Yuma is largely imported but that NO emissions by local traffic near the Yuma sampling station depress the ambient $O_3$ concentration.

The logical explanation for the lack of a prominent weekday-weekend difference is that the pollutant chemicals going through the photochemical cycle in the Yuma area were transported in from a distant source and that the variability in the rate of transport obscures, in a statistical sense, the

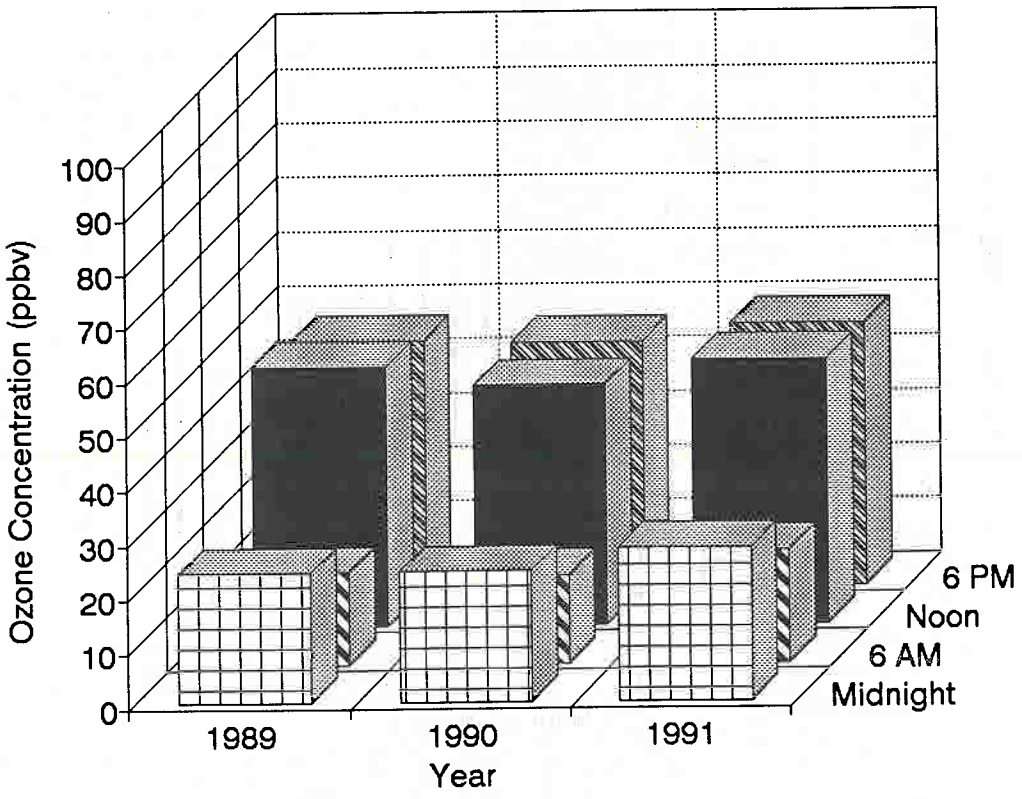



Figure 6.--Average $O_3$ concentrations at Yuma at 0000, 0600, 1200, and 1800 LT, as recorded during the April through September periods in 1989, 1990, and 1991.

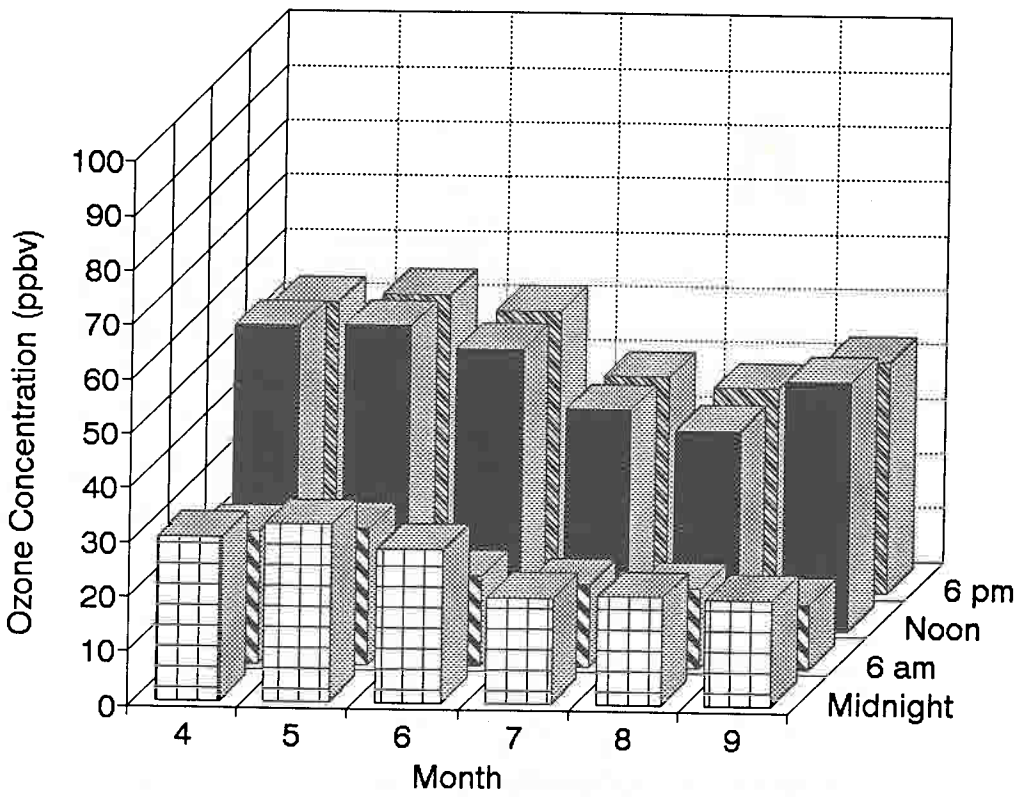



Figure 7.--Average $O_3$ concentrations at Yuma by month (April through September of 1989, 1990, and 1991) for 0000, 0600, 1200, and 1800 LT.

signature of weekdays versus weekends. If it can be considered to be meaningful, the slightly higher $O_3$ concentration measured on weekends can be taken as evidence that the lessened local weekend traffic emits less NO to destroy ambient $O_3$.

## 5. LOCATION OF THE OZONE ANALYZER IN YUMA

The $O_3$ analyzer in Yuma is sited in the southwest corner of the City Maintenance Yard at 1485 South Second Avenue. This is one block north of 16th Street, which is an east-west arterial and is one of the Yuma access routes to I-8. It is one (long) block east of Fourth Avenue, which is the I-8 Business route through Yuma, formerly designated as route U.S. 80. The air intake of the analyzer is about 4 m above ground, is about 10 m from the traffic lanes of Second Avenue, which is a moderately busy commercial street, and is about 10 m from the entrance to the City and Police Department employees parking lot. It is appropriate to note, relative to the pronounced minimum in $O_3$ recorded for the hour ending at 0700, that Police Department personnel arrive at and depart from work at fixed times that do not vary with regard to weekends, holidays, or season; the morning shift change occurs at 0700 LT.

Photographs of the area (courtesy of J. Guyton, ADEQ) taken on a normal

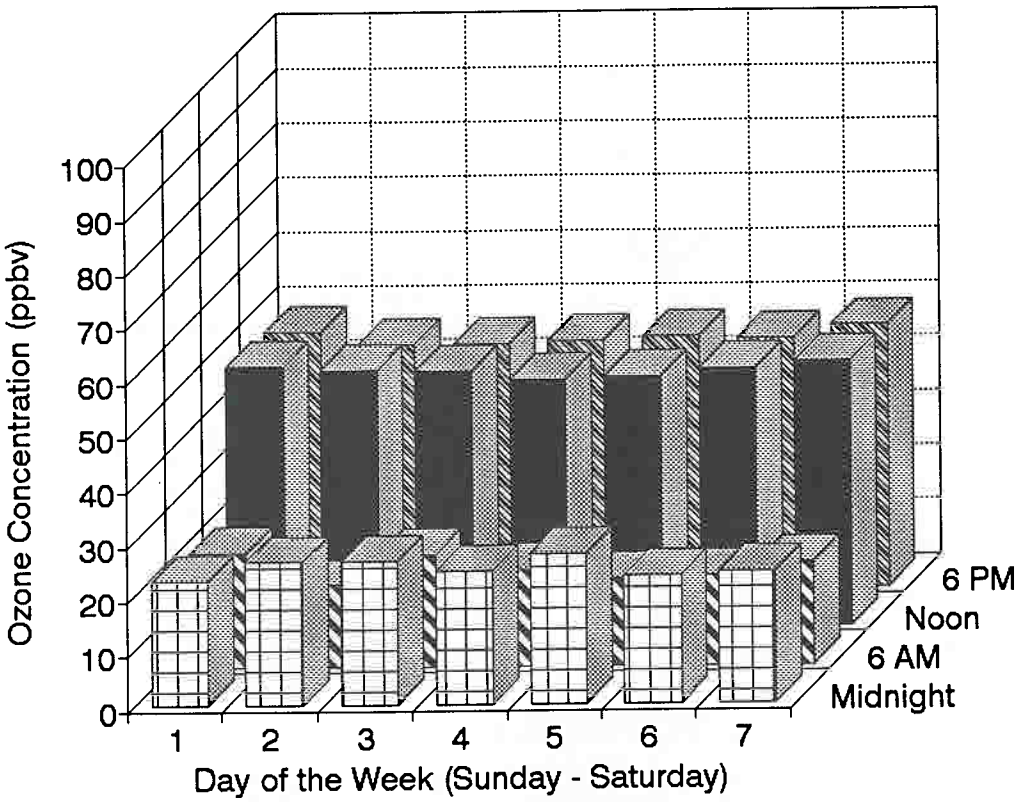



Figure 8.--Average $O_3$ concentrations at Yuma by day of the week (April through September of 1989, 1990, and 1991) for 0000, 0600, 1200, and 1800 LT.

workday, show about 40 vehicles parked in the City employees parking lot, and perhaps another 50 vehicles parked within a one-block radius on Second Avenue, on 15th Street, and in other parking lots. Some cars are shown driving past on Second Avenue. Numerous businesses are shown within a one-block radius, including a refrigeration service, an auto repair and parts company, an air conditioning and sheet metal business, a bar, a food store, a gas station, and a bank in an office building. The Police Department building is adjacent to the employees parking lot.

It is our judgement that the location of the $O_3$ analyzer at the Yuma Maintenance Yard results in a strong negative bias in the $O_3$ record. This presumed negative bias may be equalled in other parts of the Yuma area, but it is not likely to be exceeded. The reason for the negative bias is that this location is in the midst of Yuma's greatest concentration of vehicular traffic. The reaction of NO, emitted from motor vehicle engines, with $O_3$ [Reaction (1)] is relatively rapid, and the copious amounts of NO emitted by local traffic and by cars exiting the employees' parking lot (where a full stop must be obeyed not more than 10 m from the $O_3$ analyzer air intake) unavoidably leads to destruction of $O_3$ in the ambient atmosphere. The alternative $O_3$ monitoring sites that have been used from time to time in the past (i.e., the County Health Department at Second Street and Second Avenue,

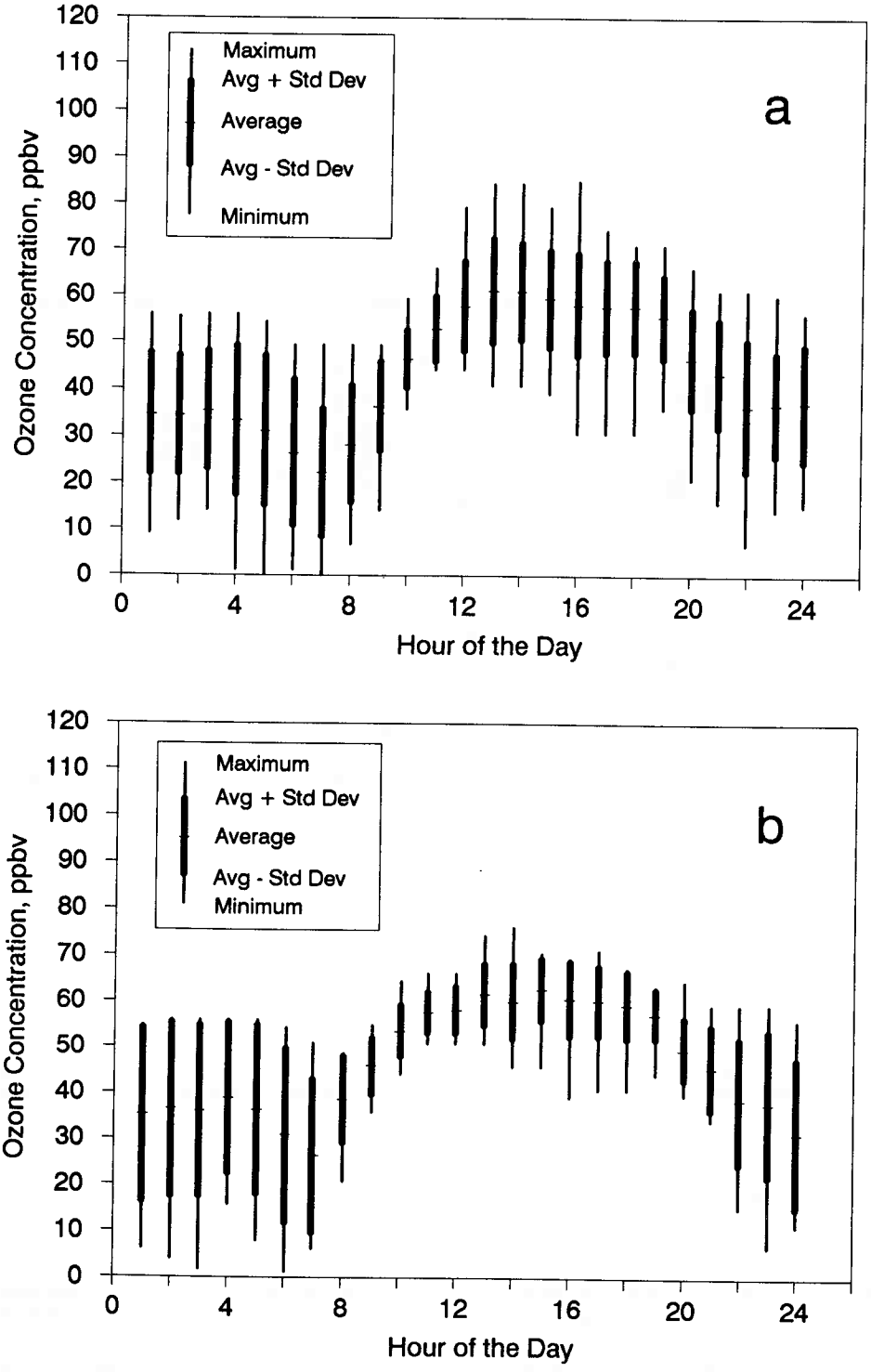



Figure 9.--$O_3$ concentration averages (-) at Yuma, plus or minus 1-$\sigma$ standard deviation (ends of broad line), and maximum and minimum values (ends of narrow line), by hour of the day for (a) weekdays and (b) weekends and holiday, of May 1991 (*cf.* Figure 5b).

or the Yuma Territorial Prison) are also considered to be significantly affected locations.

## 6. POLLUTION SOURCE REGION IDENTIFICATION

In visually examining many back trajectories arriving at a given location over time, one becomes aware of the wind persistence. This awareness, coupled with knowledge of the patterns of pollutant concentrations at the endpoints (in this case, $O_3$ at Yuma), leads one to arrive at certain subjective conclusions regarding the relationship between pollutant concentrations and air mass history. To buttress this subjective understanding with objective evidence, we adapted a technique developed by Poirot and Wishinski (1986). In this procedure, the region surrounding the proposed endpoint is divided into many small areas or squares, and the number of times the trajectories pass through each square and the cumulative residence time of multiple trajectories in each square are tabulated. For this determination, the endpoint of Yuma was placed in the center of a grid 1000 km on a side; each side was divided into 75 parts, with the result that the grid was composed of 5625 squares, each ~13.3 km on a side.

Because, by definition, all trajectories approach the chosen endpoint, the squares close to the endpoint accumulate the greatest number of penetrations and the greatest number of hours of residence time. When this geometric system bias is removed, the normalized pattern of trajectories and air mass residence times indicates the probable source areas for the pollution experienced at the target location. In this way, patterns revealed in the back trajectory data set can be related to the condition of the air parcels that arrive at the endpoint.

For this study, the $O_3$ concentrations measured during the periods April 1 through September 30, 1990, and April 1 through September 30, 1991, were sorted into various intervals, and the corresponding back trajectories were analyzed for normalized residence times in source areas. In Figure 10 the normalized residence times are shown for all days when an hourly $O_3$ average at Yuma was equal to or greater than 80 ppbv; the cumulative residence times in the squares shown by the symbols are expressed as a percentage of the residence time in the most frequently occupied square. In this case, the 100% square and the next highest square (indicated by *) were adjacent in the coastal region northwest of Los Angeles. The two squares whose cumulative residence times represented 60-80% of the maximum (□) were close by in the area northwest of Los Angeles, as were the majority of the squares whose cumulative residence times represented 40-60% of the maximum (◊). The squares whose cumulative residence times were from 20 to 40% of that of the maximum (+) were more scattered, with some distant offshore areas being represented.

Figure 11 displays the locations of the squares representing significant normalized residence times of air parcels that eventually passed through the Yuma area when the highest $O_3$ analyses during the various 24-hour periods were from 70 to 80 ppbv. The square receiving the greatest normalized impact was located on the west edge of the target zone of Yuma. This demonstrates that the path of almost all parcels was to Yuma from the west. The next most

densely affected squares (60-80% of the normalized residence time of the most densely impacted square) were all offshore from Los Angeles, from the Santa Barbara Channel to between San Nicolas and Santa Catalina Islands. Those squares receiving 40-60% of the maximum residence time are arrayed (with the exception of one outlier) from Santa Cruz Island to the western approach to Yuma, and clearly indicate the preferred transport path. The grid squares receiving 20-40% of the normalized residence time of the maximum were also arrayed along this transport path, but in addition suggest that air

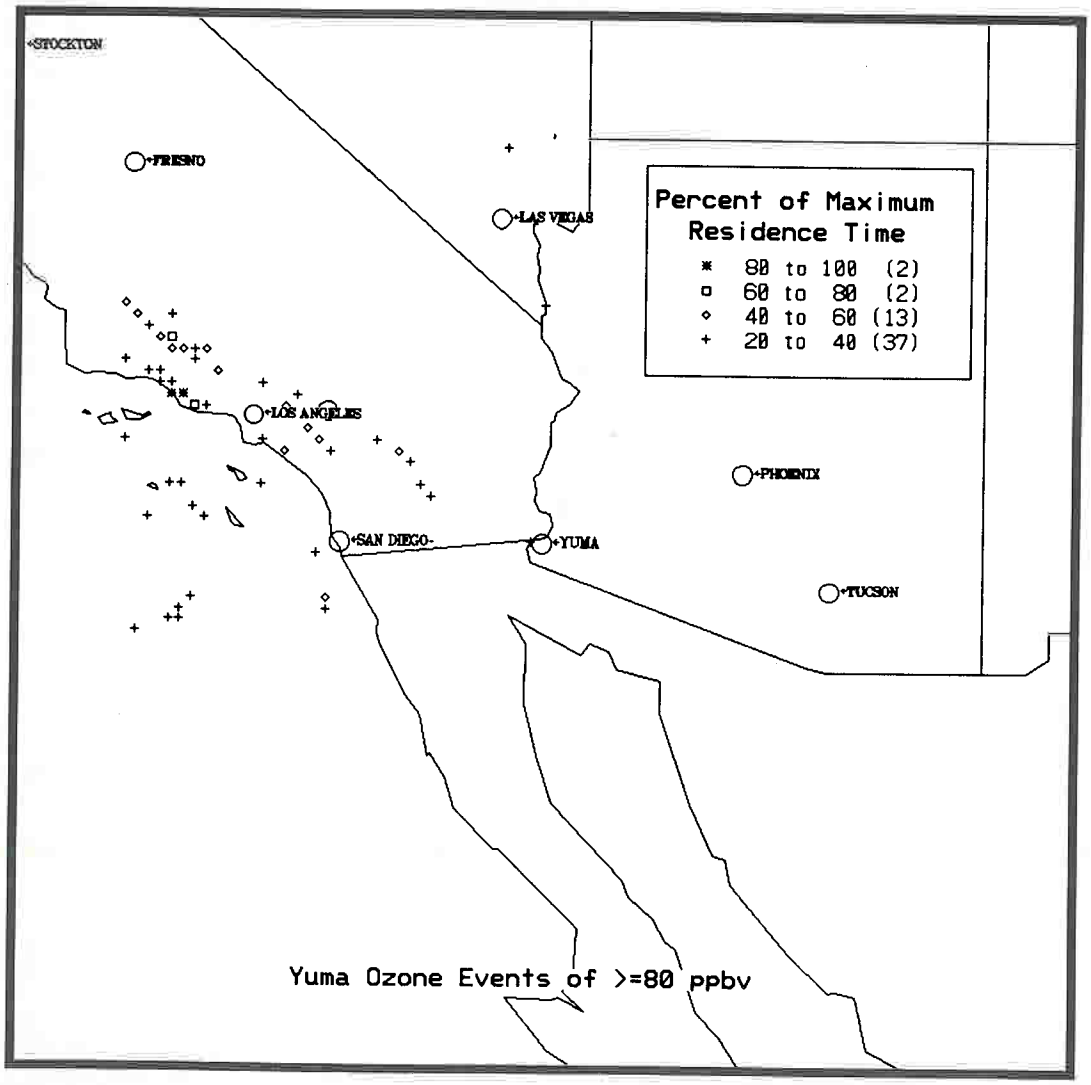



Figure 10.--Grid-square cumulative trajectory residence times. The symbols represent all squares that received at least 20% as much residency as did the highest frequency square, sorted according to 24-hour periods within which a maximum hourly average of 80 ppbv or greater was recorded at Yuma. This tabulation of residency includes both the 0500 and 1700 LT (1200 and 0000 UT) 1000 mb air mass trajectory calculations.

occasionally passed over the San Joaquin Valley en route to Yuma.

Figure 12, showing the residence pattern when the maximum $O_3$ concentration measured during a 24-hour period was from 60 to 70 ppbv, is similar to Figure 11, but suggests that there was a more southerly sweep to the general transport path. In these cases, polluted air from the nocturnal offshore reservoir near the Channel Islands appears to have been advected in a southeasterly direction, coming ashore near San Diego, and being transported along the California-Mexico border toward Yuma.

A diurnal sea-breeze/land-breeze cycle is commonly observed in the California south coast and south-central coast regions whereby air from the coastal lowlands is advected to ocean areas at night, often in a layer from 200 to 500 m ASL that rides over the marine boundary layer air that is in

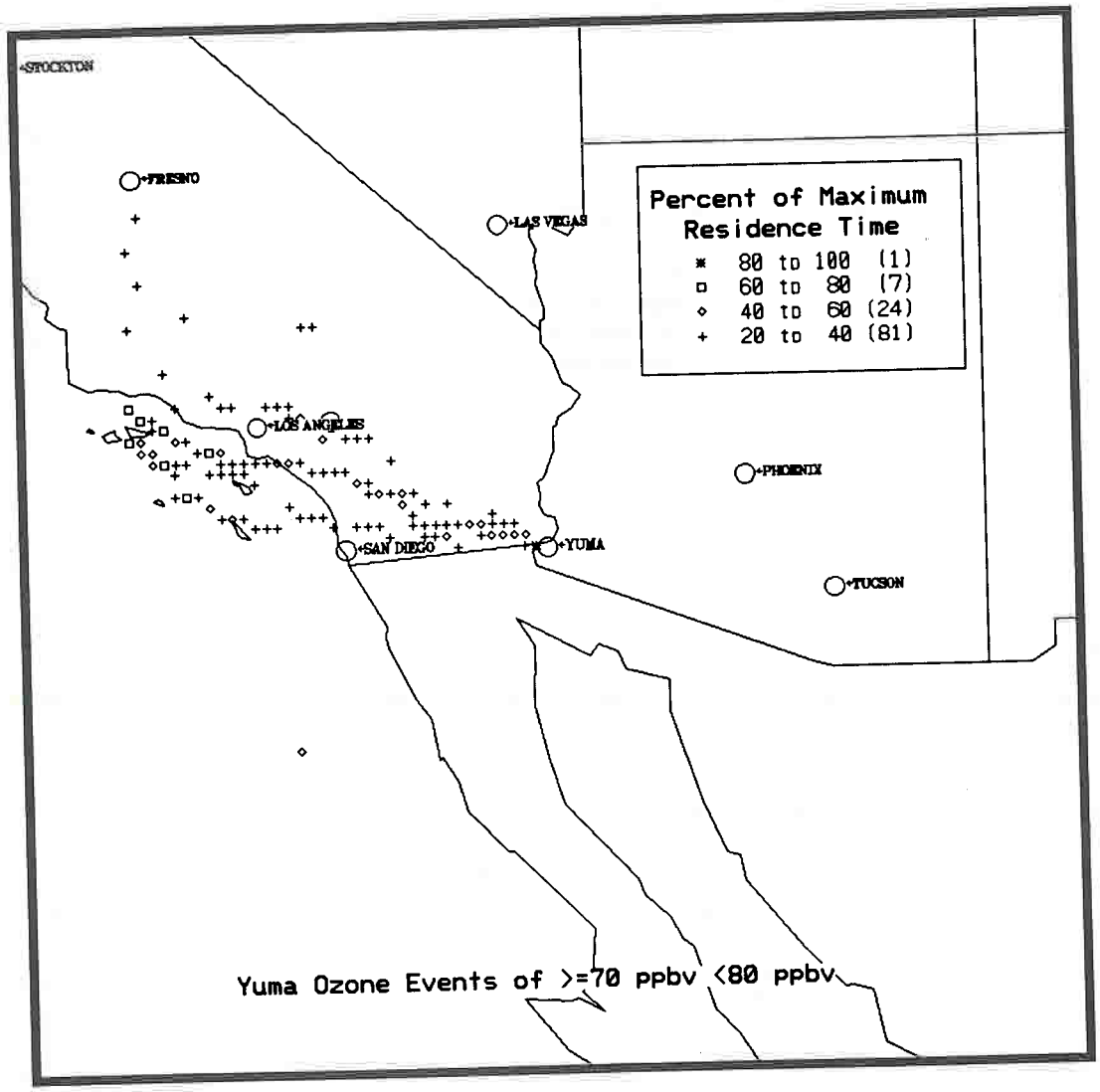



Figure 11.--Same as Figure 10, except that this figure is for 24-hour periods when the maximum hourly average was from 70 to 80 ppbv.

contact with the ocean surface. This air returns to the coastal regions the following morning, where convective activity brings it again into contact with the land surface and mixes it with the resident air volume. In the case of air residing above the Los Angeles Basin, advection has been shown to take place through the inland valleys to the northwest of Los Angeles in addition to the direct path from basin to ocean and return. Through the diurnal cycle, this advection mechanism provides a means for urban pollutants to be stored over the ocean during the night and returned, essentially without dilution, to the continental areas the following morning (Hanna et al., 1991; Douglas and Kessler, 1991; Moore et al., 1991).

In a number of instances, minimum $O_3$ concentrations of less than 30 ppbv were observed. Concentrations in the range 20-30 ppbv are representative of

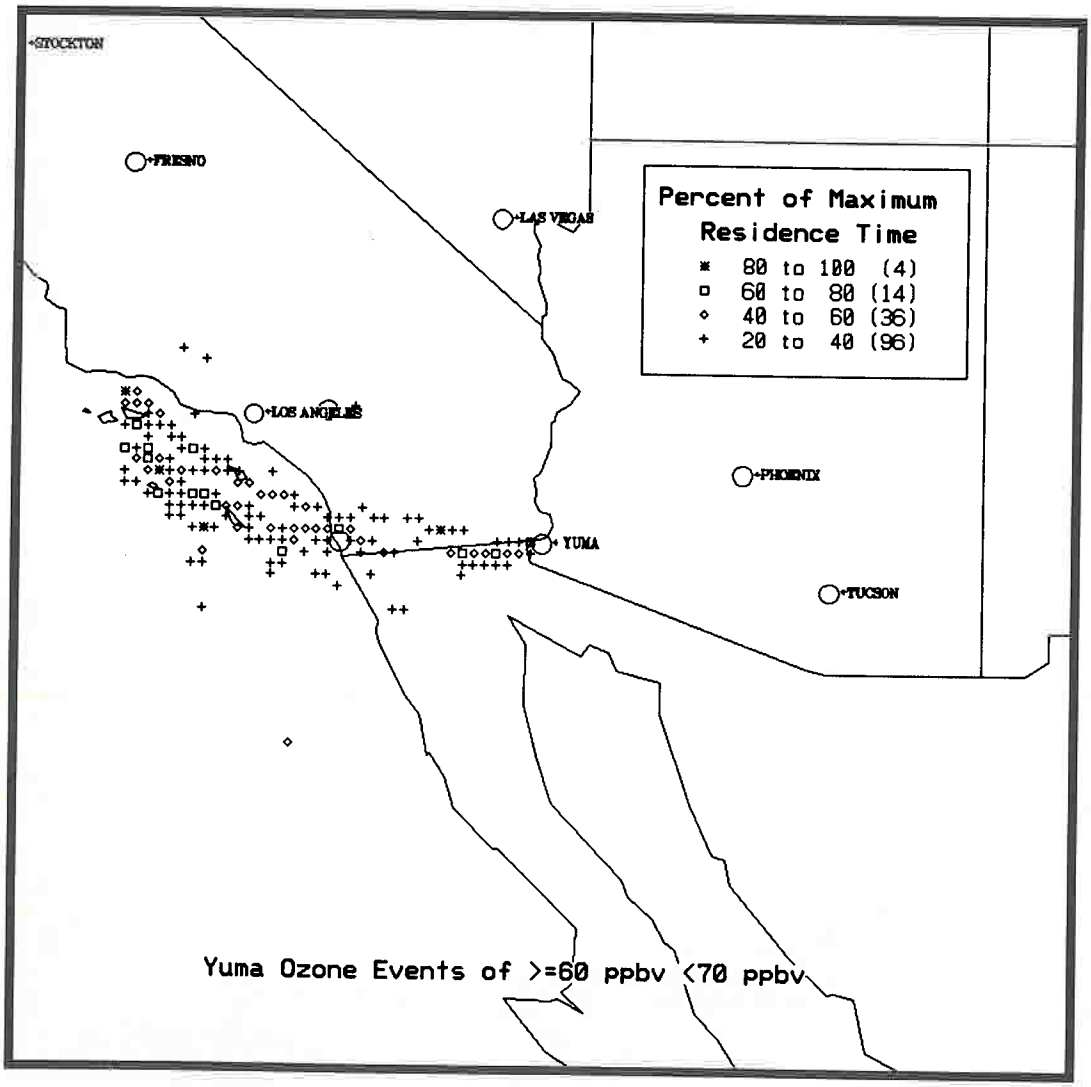



Figure 12.--Same as Figures 10 and 11, except that this figure is for 24-hour periods when the maximum hourly average was from 60 to 70 ppbv.

the relatively undisturbed marine environment, and normalized residence times for this air during tranport to Yuma should be relatively patternless, reflecting only the most common transport paths that avoid high pollution areas. Figure 13 demonstrates that this is the case. Here the square receiving the greatest normalized residence time is along the coast of Baja California approximately 160 km south of the California border; most of the other symbols on this diagram indicate that marine air had been transported to Yuma from the southwest across Baja California (see Figure 1g).

Figures 14 and 15 present normalized residence time data for 24-hour periods when minimum values measured in Yuma were in the range 10-20 ppbv and <10 ppbv, respectively. The $O_3$ concentration range of 10-20 ppbv can represent that found in relatively clean marine air, but can also be typical

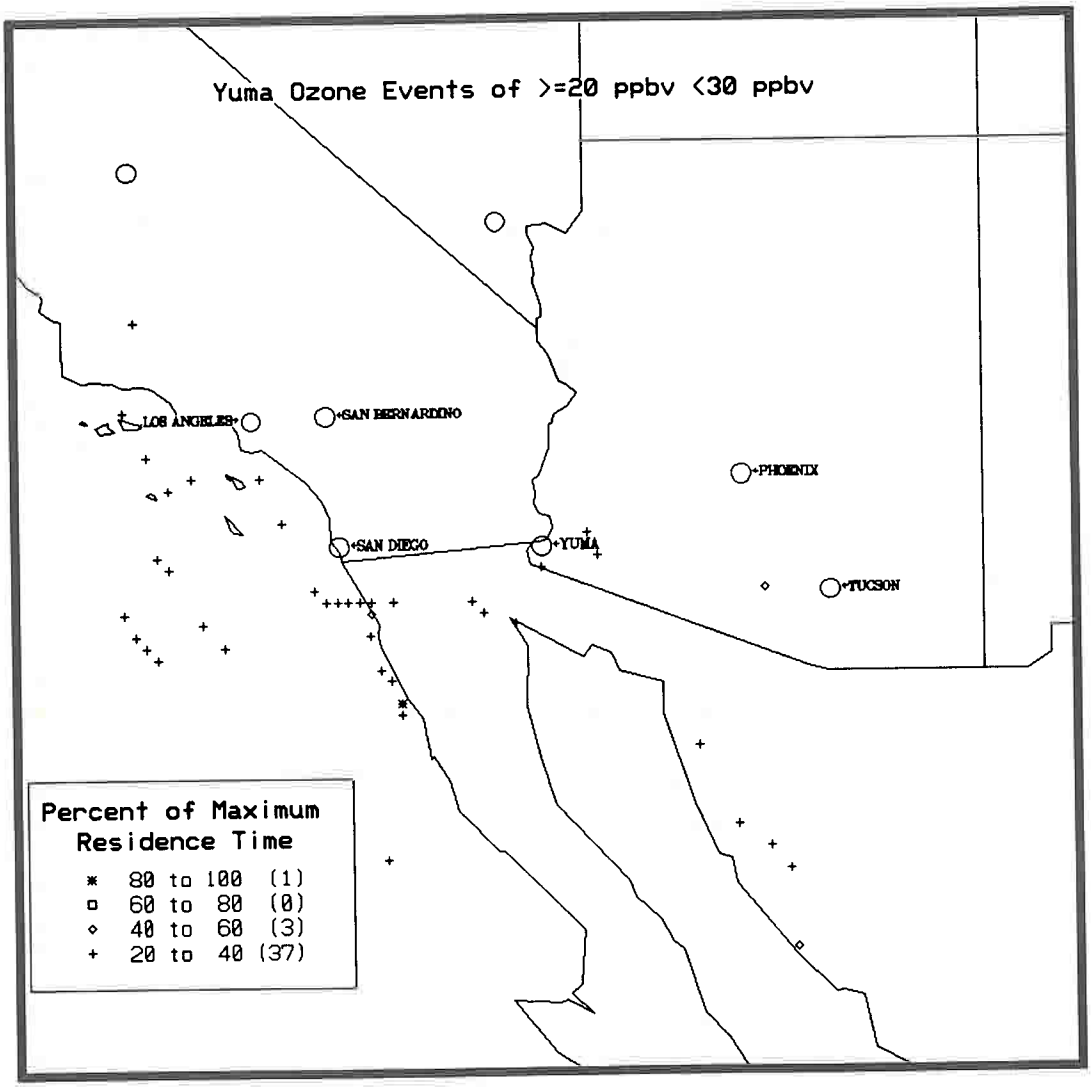



Figure 13.--Same as Figures 10-12, except that this figure is for 24-hour periods when the minimum hourly average was from 20 to 30 ppbv.

of the concentrations found in nighttime polluted air where NO has scavenged $O_3$, but $O_3$ concentrations of <10 ppbv are much more likely to be representative of polluted air than of the natural atmosphere. As seen in Figure 14, the most heavily implicated area is near the Channel Islands, but significant residence times occurred in Baja California and in corresponding offshore areas.

In Figures 13 and 14 there are relatively few data points, corresponding to faster air velocities and lower residence times; this is consistent with $O_3$ concentrations in the range 10-30 ppbv. Figure 15 is somewhat similar to Figure 12, which suggested that polluted air from the nocturnal offshore reservoir areas was advected southeastward toward San Diego and the California-Mexico border en route to Yuma. In Figure 15, the transport path

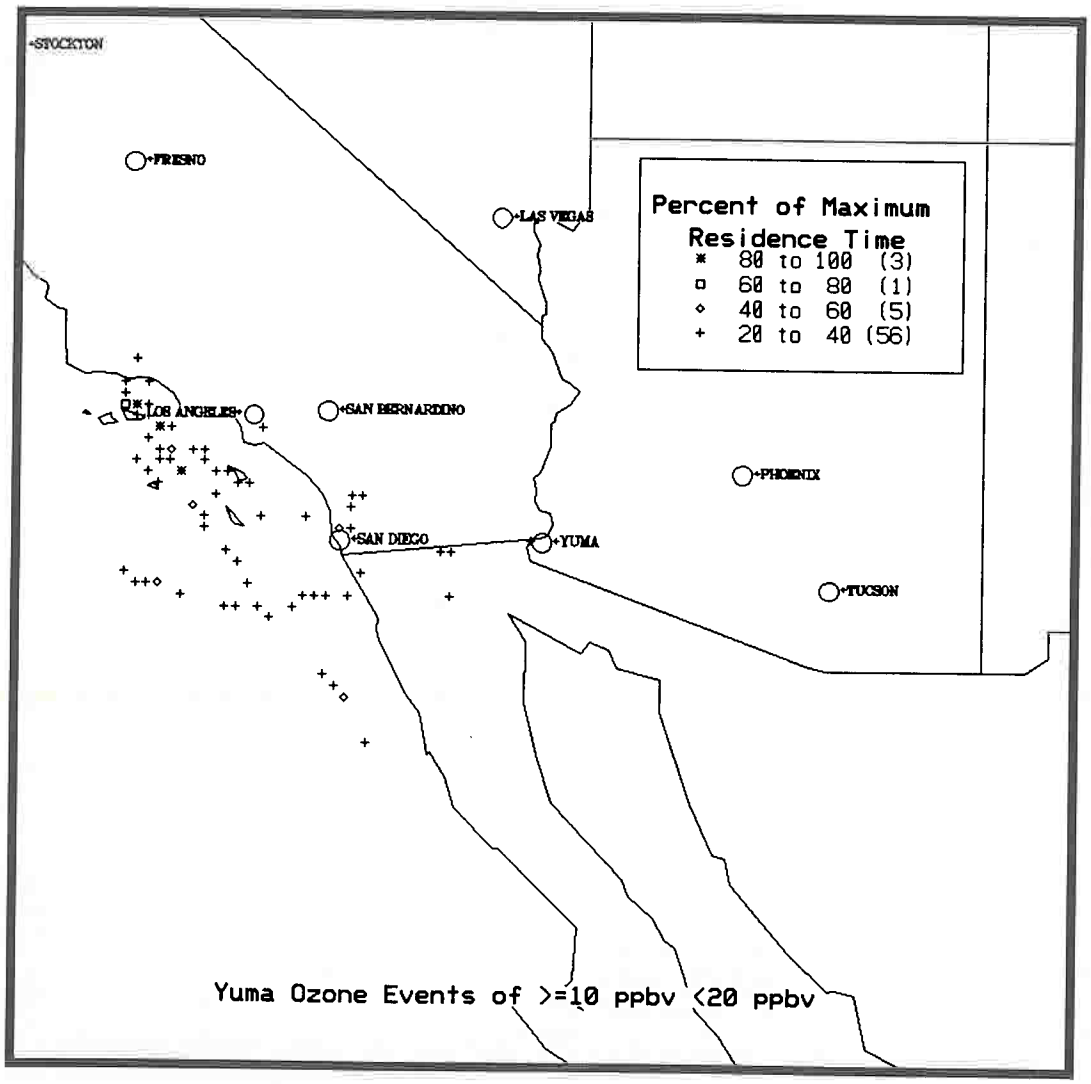



Figure 14.--Same as Figures 10-13, except that this figure is for 24-hour periods when the minimum hourly average was from 10 to 20 ppbv.

is indicated to be slightly more southerly, and therefore moderately polluted air arrived at Yuma during the night or early morning, with the likelihood that vehicular emissions of NO near the measuring station in Yuma further depressed the ambient $O_3$ concentration.

## 7. THE TONOPAH RECORD AS A SUBSTITUTE FOR YUMA

The preceding discussion has been based on $O_3$ measurements taken in a location that was affected by locally produced NO. A consequent disadvantage experienced in attempting a discussion of these measurements is that the degree of the impact of the local NO and the $O_3$ producing capability of the polluted air transported from southern California cannot be known; $O_3$

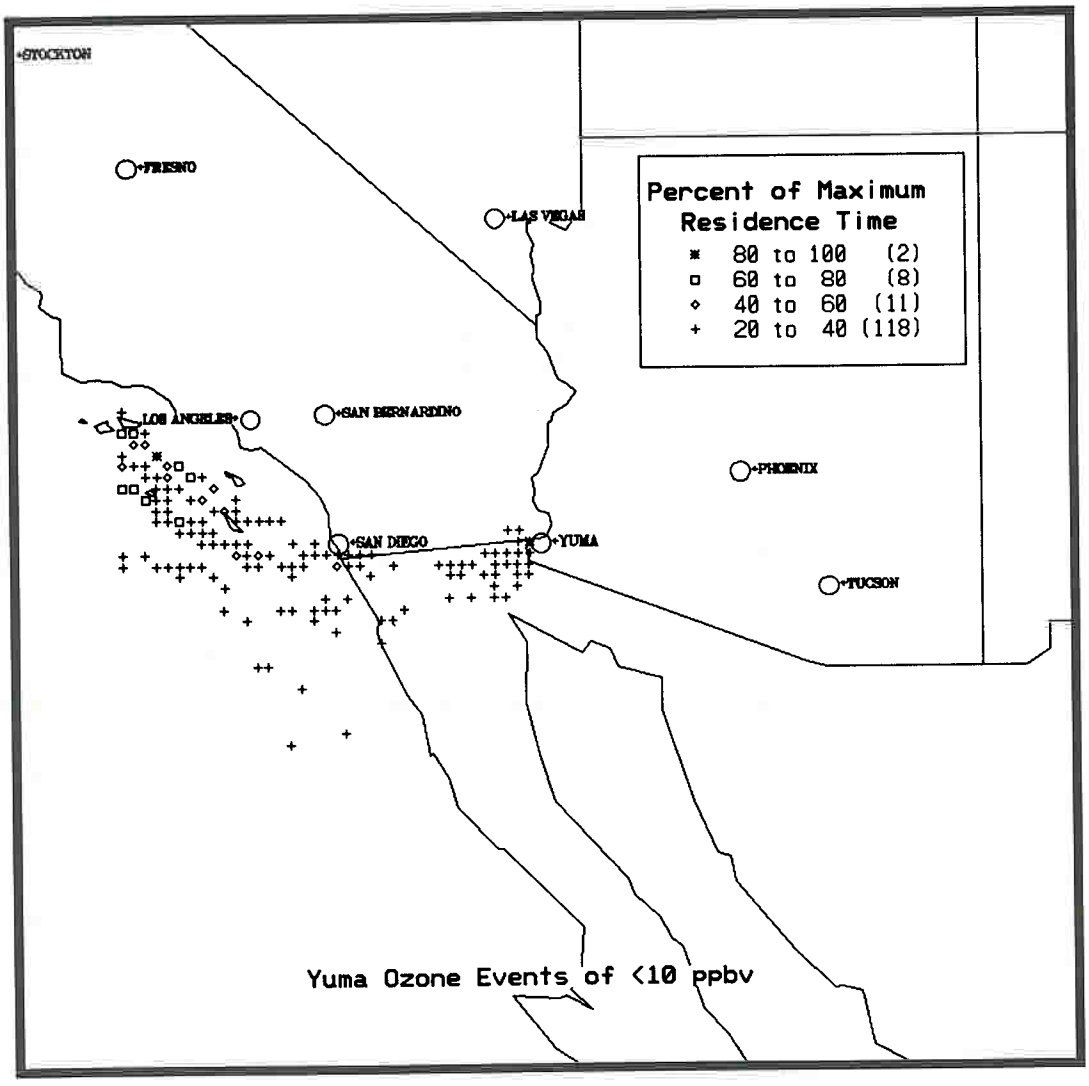



Figure 15.--Same as Figures 10-14, except that this figure is for 24-hour periods when the minimum hourly average was less than 10 ppbv.

measurements have apparently never been made in the Yuma region that were not done in the locally impacted area. A reasonable proxy may exist, however, in the $O_3$ measurements that have been done at Tonopah, Arizona, which can be used to enlighten the discussion about the probable $O_3$ concentrations that could be expected in Yuma if there were no local emissions of NO. The record from Tonopah (J. Guyton, ADEQ, private communication) showed average maximum daily concentrations of 92 ppbv during the month of June, 1989, while at the same time the corresponding value in Yuma was 57 ppbv; the maximum values in both locations occurred in the early afternoon. Tonopah, a rural village, is approximately 75 km west of the Phoenix metropolitan area, 190 km straight-line distance northeast of Yuma, and 500 km straight-line distance east of Los Angeles county. At Tonopah it is very unlikely that the sampling location could have been affected by local pollution, either from the village or from Interstate Highway I-10 a short distance to the north. Pollutant transport from Phoenix is also regarded as improbable because the prevailing wind direction is westerly. The wind and air transport patterns to Yuma shown in Figures 1 and 2 are also expected to be generally applicable to Tonopah. If the Yuma $O_3$ measurements had been obtained in a location that had not been affected by locally emitted NO, the $O_3$ concentrations likely would have been similar to those recorded at Tonopah.

## 8. OZONE AT OTHER WESTERN ARIZONA LOCATIONS

Needles-Topock (Lake Havasu) and Lake Mead-Northwestern Arizona are important recreational areas, and interest properly exists in assessing the impact of pollutants, particularly $O_3$, on these areas. The directions of air masses from the endpoints at Needles-Topock and Lake Mead-Northwestern Arizona, as discussed above and as shown in Figures 3 and 4, indicate that the probability of significant impact from southern California air pollution at these locations is nearly as great as it is at Yuma. The records from Yuma and Tonopah, therefore, can be regarded as proxies, and are necessarily used as the basis for estimating the pollution impact on the Needles-Topock and Lake Mead-Northwestern Arizona areas, since continuous $O_3$ monitoring records are not available. The available evidence indicates that these areas could be receiving sufficient input of pollutant materials from southern California to produce average $O_3$ concentrations similar to the 92 ppbv average recorded in Tonopah. As shown in the Yuma $O_3$ record, typified in Figure 5, the maximum measured values are 20-40 ppbv greater than the average; if this were to hold true at Needles-Topock and Lake Mead-Northwestern Arizona, then the expected maximum values in these areas would approximate the 120 ppbv national standard.

A pollution effect from the Las Vegas, Nevada, metropolitan area, where the population is nearly 250,000, must be assumed. This effect, however, is likely to be minor compared with that from the Southern California megalopolis.

## 9. CONCLUSIONS

1. The air mass back trajectories clearly show that the heavily populated region of southern California is a significant source of the air pollution that produces high $O_3$ concentrations in Yuma.

2. The measured average $O_3$ concentration in Yuma is less than that of the ambient atmosphere because of the input of local NO emissions. Any generation of $O_3$ in the Yuma urban plume will take place at some indeterminate distance downwind of the city. Because of the local topography, Yuma is almost always well ventilated, and any enhancement of the $O_3$ concentrations resulting from local emissions will rarely, if ever, occur in its immediate vicinity.

3. Without the depressing effect of the NO emissions near the sampling site, the measured $O_3$ average midday concentration in Yuma would be about 50% greater than that presently recorded. Concomitantly, 1-hour average $O_3$ values in excess of 120 ppbv could occur.

4. The differing transport patterns of air to Yuma during May and August account for the highest average $O_3$ concentrations being recorded in May and the lowest in August (of the 6 months during which measurements are made at Yuma). During May, the transport path is frequently directly from southern California, whereas in August the path is from the Pacific Ocean, across lightly populated Baja California en route to Yuma.

5. Summertime air mass transport paths to endpoints in the Needles-Topock-Lake Havasu and Lake Mead-Northwestern Arizona areas frequently cross the southern California heavily populated region. As a result, $O_3$ concentrations can be predicted to be greatest in the summer months in both of these areas, with the expected average midday concentrations being about 100 ppbv.

## 10. RECOMMENDATIONS

1. We recommend that an additional $O_3$ monitoring instrument be sited a short distance upwind of the city of Yuma (i.e., west or southwest, due to the prevailing westerly wind direction). This would enable conclusive evaluation of the role of local pollutants in the formation of $O_3$.

2. We recommend that $O_3$ monitoring be extended to all 12 months. Elevated $O_3$ concentrations may be present in the Yuma area during the months October through March, when the air mass transport path is directly from southern California to Yuma.

3. We recommend that additional $O_3$ monitoring instruments be placed in the Topock-Lake Havasu and northwestern Arizona-Lake Mead areas, to determine the impact of southern California pollutants (and those from Las Vegas, as well) on these important recreational resources.

## 11. ACKNOWLEDGEMENT

We thank J. M. Harris, Climate Monitoring and Diagnostics Laboratory, NOAA, for creating the many air mass back trajectory analyses that were used to document the air mass source regions and air flow patterns.

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## 12. REFERENCES


Bohm, M., B. McCune, and T. Vandetta, 1991. Diurnal curves of tropospheric ozone in the western United States. *Atmos. Environ., 25A*, 1577-1590.

Douglas, S. G., and R. C. Kessler, 1991. Analysis of mesoscale airflow patterns in the south-central coast air basin during the SCCCAMP 1985 intensive measurement periods. *J. Appl. Meteor., 30*, 607-631.

Hanna, S. R., D. G. Strimaitis, J. S. Scire, G. E. Moore, and R. C. Kessler, 1991. Overview of results of analysis of data from the South-Central Coast Cooperative Aerometric Monitoring Program (SCCCAMP 1985). *J. Appl. Meteor., 30*, 511-533.

Harris, J. M., 1982. The GMCC atmospheric trajectory program. *NOAA Tech. Memo. ERL ARL-116*, NOAA Air Resources Laboratory, Rockville, MD, 30 pp.

Hess, S. L., 1959. *Introduction to Theoretical Meteorology*. Holt, Rinehart, Winston, New York, 362 pp.

Logan, J. A., 1985. Tropospheric ozone: Seasonal behavior, trends, and anthropogenic influence. *J. Geophys. Res., 90*, 10,463-10,482.

Logan, J. A., M. J. Prather, S. C. Wofsy, and M. B. McElroy, 1981. Tropospheric Chemistry: A global perspective. *J. Geophys. Res., 86*, 7210-7254.

Moore, G. E., S. G. Douglas, R. C. Kessler, and J. P. Killus, 1991. Identification and tracking of polluted air masses in the south-central coast air basin. *J. Appl. Meteor., 30*, 715-732.

Poirot, R. L., and P. R. Wishinski, 1986. Visibility, sulfate and air mass history associated with summertime aerosol in northern Vermont. *Atmos. Environ., 20*, 1457-1469.

Seinfeld, J. H., 1989. Urban air pollution: State of the science. *Science, 243*, 745-752.

Van Valin, C. C., and M. Luria, 1988. $O_3$, CO, hydrocarbons and dimethyl sulfide over the western Atlantic Ocean. *Atmos. Environ., 22*, 2401-2409.

Van Valin, C. C., and R. F. Pueschel, 1981. Fine particle formation and transport in the Colstrip, Montana, powerplant plume. *Atmos. Environ., 15*, 177-189.



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