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FINAL REPORT

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TECHNICAL REPORT

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A B S T R A C T

Distributions of temperature and ozone aloft were determined during a ten-day observational program involving an instrumented light aircraft flying between Los Angeles and Ventura county.

Ozone layers were commonly detected above the base of the sub-tropical subsidence inversion.

Concurrent winds aloft measurements made at intervals throughout the day and night provided data from which streamline air flow maps were prepared for heights associated with the high ozone values. From these maps trajectories were constructed which indicated that the measured ozone aloft over coastal Ventura county came from the Los Angeles Basin.

This report was submitted in fulfillment of Contract No. ARB 4-1126, by Metro Monitoring Services under the sponsorship of the California Air Resources Board. Work was completed as of August 25, 1975.

TABLE OF CONTENTS

APPENDICES

Note: Appendices B - E are contained in Volume II, Supplement Volume

I SUMMARY

A ten-day program designed to detect the flow of photochemical pollutants aloft from the coastal edge of the Los Angeles Basin to the Ventura county coasts was conducted during June and July, 1975.

Aircraft soundings and traverses between Santa Monica and Oxnard provided temperature and ozone measurements six times per 24-hour day, while winds aloft were measured at three locations on a similar time schedule.

The ozone, temperature structure and wind data were plotted on cross-sections for each observational period.

Ozone-rich layers were detected aloft over the entire study area. The most persistant layer was found just above the base of the subsidence inversion characteristic of the southern California summer season.

A second layer, usually near 1.07 km, was also frequently present. It was generally associated with the stable air near the top of the inversion layer.

For each of the study days, the layer of air above Oxnard containing the highest ozone concentration was used to determine the level at which trajectory computations would be made. These trajectories represented the paths taken by the ozone-rich parcels prior to their arrival at Oxnard. As such, they represent a history of the parcels, and give evidence as to their prior whereabouts and thus an indication of the origin of the ozone.

All but one of the trajectories showed that the

air parcels originated over the Los Angeles Basin. A special trajectory was constructed for the time when the highest ozone was measured at Oxnard. This trajectory, too, gave evidence that the air parcel came from the Los Angeles Basin.

The results of this study suggest that over-water transport of ozone aloft from the Los Angeles Basin to Ventura county is a rather common occurrence; however, additional measurements of this type are required before the frequency of occurrence of this over-water transport phenomenon can be quantified.

II INTRODUCTION

Ozone concentrations in the Ventura county portion of the South Coast Air Basin (SCAB) above the California standard (0.10 ppm for 1 hour) have caused concern and raised questions about the source(s) of this pollutant problem. (c.f. Tubbs, 1975). In addition, the recent request by the Ventura County Board of Supervisors in January 1975 that the State Air Resources Board (ARB) change the air basin boundary lines so as to remove Ventura county from the SCAB and place it into the South Central Coast Air Basin has given considerable impetus to the study of the magnitude and frequency of occurrence of long range transport of ozone and ozone precursors from the Los Angeles to the Ventura area. Obviously, if the high ozone concentrations in Ventura county are due primarily to the long range transport of ozone and ozone precursors from the Los Angeles area, then Ventura county's efforts to <u>prevent</u> severe ozone air pollution are highly dependent on Los Angeles' efforts to <u>control</u> severe ozone air pollution.

In the past, the causes of high ozone concentrations in Ventura county have generally been attributed to the Ventura county "area source" and/or the "over land intrusion" of the Los Angeles smog plume through the San Fernando valley. However, these two transport mechanisms fail to explain the relatively high ozone concentrations recorded in the coastal areas of Ventura county during periods when surface wind reports show only westerly winds. These relatively high ozone concentrations do not appear to be due to the Ventura county "area source" since many of the air mass trajectories reconstructed from surface winds indicate that the air parcels did not pass over any significant primary pollutant emission sources as they moved from the sea to the air quality monitoring stations. Recently, more detailed analyses of ozone episode cases in Ventura county (c.f. Sklarew and Chaplin, 1975) have suggested the importance of ozone transport aloft and subsequent fumigation to the ground as a causative mechanism. However, these analyses have been seriously hampered by the lack of vertical wind, temperature, and ozone profiles in Ventura county and air mass trajectories of high ozone concentration parcels aloft leaving the Los Angeles area. Very recently, studies of wind and temperature soundings and power plant plumes in the Los Angeles coastal area near the Los Angeles International Airport have shown that the wind aloft within the inversion layer often blows from the east, transporting pollutants trapped in the inversion westward out to sea, even when the westerly sea breeze is already developed at the surface and the gradient flow aloft is westerly. This easterly flow in the inversion layer is thought to be due to the return flow of the sea breeze circulation or sub-synoptic scale eddy effects which are not completely understood. The pollutants in the inversion layer are thought to be transported there by such mechanisms as penetrative convection, sea breeze undercutting, sea breeze stagnation, entrainment from transport up heated slopes, and convergence zones. In addition, some other mechanisms suggested specifically for the frequently observed high ozone concentrations in the Southern California inversion layer are: injection above by large scale subsidence from the stratosphere, photochemical production (aging) within the layer, destruction below the layer, or differential advection and diffusion. The extent to which the possible aforementioned mechanisms contribute to high ozone concentrations in the inversion layer at various locations and times is not well understood and is beyond the scope of this project.

The existence of ozone and ozone precursors in significant concentrations in the inversion layer with easterly wind flow suggests it is certainly possible that some of the Los Angeles Basin smog plume can be transported westerly aloft, over-water, to the ocean off the Ventura county coast, and subsequently transported inland when the depth of the sea breeze increases to the levels where the high ozone concentrations are present and eventually reach the ground by fumigation in the transition zone from over-water to over-land flow or on the more elevated terrain inland.

The purpose of this project is to investigate the feasibility and extent of the over-water transport mechanism for delivering high ozone concentrations from the Los Angeles area to the Ventura county area. The scope of this project included frequent vertical wind, temperature and ozone profiles on a nearly round-the-clock basis at three locations along the coast between Los Angeles and Ventura counties during three periods for a total of 10 days in June to July 1975, and analysis of the generated data. The second over-water measurement period, from July 9-11, 1975, was an ARB episode condition and was coordinated with the episode sounding program at the Burbank airport, also being conducted by Metro Monitoring Services for the ARB.

The report contains a description of the measurement equipment and techniques including calibration procedures, detailed analyses of the data using vertical profiles, cross-sections, and air mass trajectories, selected color photographs of interesting visual observations, and conclusions and recommendations. All the basic data and analyses from the program are contained in a data supplement volume.

III BACKGROUND

The purpose of this section is to briefly review the history of ozone or oxidant measurements aloft as they apply to this project and other relevant meteorological and air quality studies.

Apparently, the first program of ozone measurements aloft in the Southern California area was that performed by Stanford Research Institute (SRI) (1954) which consisted of several sampling flights by airplane over the Los Angeles Basin and concluded that, "The ozone (probably oxidant) concentration remained roughly constant below and through the inversion layer and dropped off sharply above it." Next, Neiburger, et al (1955) reported the results of oxidant measurements from 15 blimp flights over the Los Angeles Basin and found, "...a maximum concentration of oxidant at the base of the inversion layer itself, and usually a distinct decrease in concentration above it". Their data suggested that, "...gaseous pollutants are largely confined to the volume of atmosphere under the inversion layer".

It appears that Lea (1968b) was the first to note the existence of a definite and consistent ozone concentration maximum within the inversion layer and at a considerable distance from the Los Angeles Basin (Pt. Mugu , 80.5 km west of downtown Los Angeles). Lea (1968b) concluded that the balloon-borne chemiluminescent ozonesonde measurements made at Point Mugu in 1965 gave valid data and that the ozone concentrations aloft were significant in comparison with surface ozone concentrations. Lea (1968b) concluded that, "a possible explanation might involve lifting of Los Angeles pollutant into the inversion by convection and orography, followed by modification en-route to Pt. Mugu by differential erosion and differential advection. From the persistence of observed ozone maxima in the soundings, the semi-permanent temperature inversion over coastal southern California appears to be an effective reservoir for atmospheric ozone. It seems likely that ozone stored therein can at times reach the surface and contribute to localized pollution." In a follow-up investigation at Pt. Mugu in 1967, Lea (1968a) made a comparison between ozone soundings at Pt. Mugu and Pasadena and found the ozone maximum was again above the inversion base at Pt. Mugu, and in some instances layers of ozone were observed within the inversion above Pasadena. Finally, a recent summary of ozonesonde measurements at Pt. Mugu during three periods between 1965 and 1972 (108 soundings total) has been provided by de Violini (1974) which shows "often a strong peak at low altitudes, generally below 3 kilometers", in all months of the year with "a tendency for very high concentrations of ozone to occur within the lowest kilometer of the atmosphere in May at Point Mugu."

The next major study of the distribution of ozone aloft in the Southern California area appears to be that of Edinger, et al (1972) and Edinger (1973) consisting of two light aircraft, instrumented to measure total oxidant, temperature, dewpoint, and pressure. Each aircraft flew three times a day (0900, 1200, and 1600 PST), one along a generally east-west route from Santa Monica to Riverside and the other along a generally north-south route from Riverside to the northern side of the San Bernardino mountains, during a three day period in June 1970. The aircraft made ascents and descents along the routes to provide "slant soundings" and the meteorological conditions in the vicinity of the San Bernardino mountains were measured by rawinsondes and double-theodolite pilot balloons (pibals). Edinger, et al (1972) concluded that some oxidant is vented up the slopes of the San Gabriel and San Bernardino mountains during the day and subsequently advected back over the Los Angeles basin to the south within the inversion layer and some oxidant is trapped in the inversion layer when the nighttime surface cooling lowers the base of the inversion through the polluted air brought in by the sea breeze during the day. Edinger (1973) gives a more detailed analysis of the data along the Santa Monica to Riverside route, "confirms Lea's (1968) earlier findings and further illuminates the pattern from the coast inland to the basin's mountainous perimeter." In addition, Edinger (1973) results show that the vertical distribution of oxidant is nearly uniform in the mixing layer with the concentrations usually higher near the tops of the layer than at the ground due mainly to scavenging of ozone by nitric oxide emitted at ground level.

Another important study of the distribution of pollutants aloft was that of Gloria, et al (1974) which involved use of an instrumented twin engine aircraft to measure a number of pollutants, as well as meteorological variables, over a considerable altitude (about 18,000 feet) and area of California including the South Coast Air Basin, the San Francisco Bay area, the Salinas valley, and the Pacific ocean within 200 miles of the coast. The data from flights on seven days from 1971 to 1973 showed among other things the existence of relatively large ozone concentration fluctuations at higher altitudes like those observed previously within the inversion layer with dimensions of about 1 mile horizontally or less than 200 feet vertically.

The largest study of the 3-dimensional distribution of pollutants in California was that supported by the ARB during 1972 to 1974 using two highly instrumented aircraft flying coordinated patterns in the South Coast (Los Angeles portion), San Joaquin valley, and San Francisco Bay Air Basins in conjunction with ground-level sampling on 59 different days (242 sampling flights). The 3-D program also included special studies of 2 power plant plumes, roadways, and one 24-hour sampling period to measure ozone characteristics at night. An initial analysis of this extensive data base has been made by Blumenthal, et al (1974) and additional analyses are being made under ARB sponsorship and by other researchers. Blumenthal, et al (1974) shows a detailed picture of the mixing layer structure and ventilation processes in the Los Angeles basin during typical smog conditions and during one episode condition along with the long range transport and aging of aerosol and gaseous pollutants which are similar to the results of other more recent studies and confirms many previous assumptions and speculations. However, the analysis and application of the 3-D Program data to the development of models and control strategies is hampered by the lack of vertical wind data along the air mass trajectories, of around-the-clock sampling, and of obtaining data for more than one episode.

A major study of the three-dimensional distribution of pollutants following an air parcel (trajectory approach to air pollution measurement and modeling) in the Los Angeles Basin was conducted during the fall of 1973 under the sponsorship of the Coordinating Research Council (CRC) and the Environmental Protection Agency (EPA). The Los Angeles Reactive Pollutant Program (LARPP), as it was called, has been described by Perkins (1974) at a recent symposium where initial results were presented and the data archive was described for interested researchers. The LARPP involved use of two highly instrumented heliocopters flying a "drifting box pattern" about an air parcel marked by three tetroons and a tracer material, with coordinated meteorological observations, including radiation, mobile air quality van, and radar tracking measurements on 35 days covering a range of smog conditions from light to heavy ozone (greater than 30 pphm). The data base from the LARPP appears to be generally good, although there were some problems with the heliocopter air quality and tracer data. Preliminary analyses of the data by Eschenroeder (1974) show relatively large fluctuations in pollutant concentrations, especially ozone and nitric oxide, during horizontal traverses and vertical soundings, which are thought to be due to the effect of inhomogeneous turbulent mixing of reactants on photochemical reactions. One of the objectives of LARPP is to determine the reaction rates of various species following an air parcel in the real atmosphere. In particular, it is of interest to see from the LARPP data if the predictions of photochemical quasi-equilibrium theory that for the reactions

$$[NO_2] + h\nu \xrightarrow{k_1} [NO] + [O] \qquad (1)$$

$$[NO] + [O_3] \xrightarrow{k_3} [NO_2] + [O_2] \qquad (2)$$

the ratio

$$\frac{k_1 \; [NO_2]}{k_3 \; [NO] \, [O_3]} \doteq 1 \qquad (3)$$

or is different from 1 due to, say, the case of fresh NO being introduced into an atmosphere high in ozone, but no reaction taking place until these are intimately mixed.

Very recently, the ARB and California Department of Transportation (Cal Trans) have placed emphasis on obtaining vertical temperature and ozone profiles during episode conditions for forecast support and air-shed model validation purposes, respectively. Metro Monitoring Services is currently under ARB contract to provide 60 sounding flights (20 days or less) from the Burbank airport on relatively short notice around the time of episodes. So far, only one episode period has been called, July 9-11, 1975. During this period, Burbank soundings were coordinated with the over-water flights in this project. Cal Trans (Ranzieri and Grissinger, 1975) have also made some airborne soundings in the South Coast Air Basin in June and during July 10-11, 1975, and plan to make additional soundings under episode conditions including those with an EPA aircraft in late September-early October, all as part of their air shed model validation program in five California areas. However, it appears that the results reported here are the first involving nearly around-the-clock airborne measurements with coordinated pibal measurements along a Los Angeles smog transport route which has not been previously investigated in detail.

There are results on ozone measurements aloft at other locations in California outside the South Coast Air Basin which are appropriate to include in this brief historical review with applications to this project. Lovill and Miller (1968) and Miller and Ahrens (1970) found by means of balloon soundings and aircraft, respectively, high levels of oxidant formed from photochemical smog over the San Francisco Bay area. Miller and Ahrens (1970) suggest that "the maxima (in oxidant concentration) just above the base of the inversion, west of the coastline, could have been injected westward within internal waves that break toward the upstream direction, somewhat in the manner shown by laboratory experiments of Thorpe (1968) and others." However, a more plausible explanation would seem to be the "terrain lifting and return flow injection" mechanism shown in Edinger, et al (1972) which is supported by the easterly winds aloft in the Miller and Ahrens (1970) case studies.

In the San Joaquin Valley of California, Miller, et al (1972) obtained evidence that oxidant (or its precursors) is transported eastward from the population centers of the Valley to the higher elevation valleys in the Sierra Nevadas. Miller's, et al (1972) evidence was based on 11 days of ground level oxidant, temperature and wind measurements and 2 days of airborne oxidant and temperature measurements during August 1970, and they conclude that "many more meteorological and air pollution measurements are needed to fully characterize the San Joaquin Valley pollution and its transport to the west slope of the Sierras".

A good example of a more extensive study of the meteorology and ozone concentrations in a rural California coastal valley is that of Baboolal, et al (1975) based on a year-long program of special measurements in the Santa Ynez Valley which is about 160 km northwest of Los Angeles and about 56 km east of the Pacific Ocean. This program consisted of continuous year-long measurements (surface winds at 3 locations), continuous selected season measurements (surface winds at 3 other locations and acoustic radar and turbulence), and discrete spot measurements (vertical profiles of temperature and ozone twice a day on 15 days spread over the year). These vertical profiles usually showed relatively high ozone concentrations aloft within the inversion layer which were attributed to "the rural valley as the unlikely source". In addition, about half of all the soundings obtained with a Dasibi O_3 Analyzer showed relatively large fluctuations in ozone concentrations at the same altitude between the up and down soundings usually separated by only several minutes in time and between the Santa Ynez and Vandenberg soundings separated by 48 km and about 15 minutes in time. It should also be noted that about one-fourth of the soundings showed no ozone at all apparently due to instrument or recording problems. Baboolal, et al (1975) indicate that "as the program unfolded it was apparent that a good deal of the ozone problem was due to pollutants already in the air mass when it entered the valley. Since the field program was not designed to answer this larger transport question, the important question as to the exact source of this air mass remains unanswered." It is certainly conceivable that the Los Angeles smog plume is transported aloft as far west as Santa Ynez and this is consistent with the range of transport to the east found by Blumenthal and White (1975) to be discussed later.

Finally, Egami, et al (1974) have measured very small ozone concentrations aloft in the vicinity of a major coalfired power plant in the Three Corners area (California, Nevada, and Arizona). In fact, they found essentially zero ozone concentrations in the power plant plume itself due to the intense quenching by the nitric oxide in the plume during conversion to nitrogen dioxide and that the "ozone deficit" provides a good means of long range plume tracking.

Except for Point Mugu ozonesonde results of Lea (1968) and the very limited aircraft tracking of the Ormond Beach Power Plant plume by Blumenthal et al (1974) which also showed an "ozone deficit" in the plume close to the plant, there appears to be no real analysis of the transport and diffusion of ozone aloft over Ventura county prior to this project. A statistical analysis of all the ground level oxidant air quality data available for Ventura county for the 1965-1974 period has recently been made by Tubbs (1975) which concludes among other things:

> "Because of the complexity of the emissions and transport situation, and the relatively young state-of-the-art of scientific research done on the subject, the question of how much of our oxidant problem is caused by our own emissions and how much is transported from other areas is not presently known. These unanswered questions are important for the purpose of control and public interest. Efforts are continuing by environmental researchers, including APCD, in scientific studies to find the quantitative answers to these questions. The consensus of opinion at this time, at least qualitatively, is that Ventura county is definitely affected by other areas, but is largely the source of its own problems."

It is important to point out that the last sentence of the above conclusion has been added since the first edition of the Tubb's study appeared in November 1973 and that the results of one scientific study supported by Ventura county on the causes and nature of oxidant transport before and during episodes (oxidant concentrations greater than or equal to 0.20 ppm) has recently become available. Sklarew and Chaplin (1975) conclude that 3 of the 4 main episode transport regimes identified suggest transport of ozone or ozone precursors from either offshore or the Los Angeles Basin, and that the 4 regimes classify over 50% of the 52 episode days studied for 1973. In addition, they stated the following:

> "Possible high levels of ozone within the Southern California inversion thus provides one possible explanation of the observed ozone levels. The late morning flow from the east in the inversion would not be inconsistent with transport of ozone (or ozone precursors) from the Los Angeles Basin into eastern Ventura county. Winds aloft and inversion height as well as ozone levels in the inversion would help greatly in understanding Ventura county ozone levels."

Finally, it is important to briefly review some other relevant meteorological and air quality studies and data with applications to this project. Lea (1968b) found that "winds (aloft) from the southeast through northeast generally accompany the strong ozone maxima (aloft) at Point Mugu, "and this differs considerably from the climatic mean in which westerly and northerly (surface) winds predominate". In addition, Lea (1968b) concludes that, "it is seldom possible to construct definitive trajectories of ozone-rich air reaching Point Mugu due to confusion introduced by sub-synoptic scale effects and the paucity of supporting observations". de Violini (1974 and 1975) has provided a statistical summary of upper air observations for Point Mugu and a description of the Range weather network, including the Laguna Peak station, which unfortunately does not include the frequency distribution of winds aloft at either Point Mugu or Laguna Peak to provide an estimate of the frequency of the easterly flow condition which favors over-water transport of ozone aloft from the Los Angeles Basin.

There is very little information on the meteorology of the coastal region between Los Angeles and Ventura county as it relates to transport and dispersion of pollutants aloft. Pack and Angell (1963) tracked 25 constant-volume balloon (tetroon) flights released from Point Dume and Corral Beach (about 5 miles east-northeast of Point Dume) at a height of about 500 ft.(0.15km)and characterize the observed trajectories as "milling around" associated with very light air transport and converging air flows. Kao (1960) has shown that the Southern California inversion aloft virtually acts as a boundary surface which separates the planetary boundary layer into a lower layer where the flow is primarily thermally driven (sea breeze) and an upper layer where the flow is more or less the Ekman Spiral. Kao's (1960) simple model does not treat the return flow in the inversion layer itself, but his average vertical wind distribution from 39 rawin soundings during July and August 1968 at Santa Monica Airport show a transition from westerly to easterly flow between about 3000 feet and 4500 feet(0.9-1.4 km) at 1600 PST. Edinger and Wurtele (1971) have made a rather intensive study of the offshore marine layer characteristics during July 1967 consisting of 18 aircraft flights with 315 slant soundings between four locations (Point Mugu, Topanga canyon, Santa Barbara island, and Catalina island). They found from a search for relationships in individual case studies that, "only a general fall during the day in height over the area, stands out as significant, a characteristic of marine layer behavior along the Los Angeles coastline previously noted". Edinger and Wurtele (1971) concluded from a statistical analysis of all the cases the following:

> "It is apparent that the interface or transisition zone between the marine layer and the inversion layer is affected by the Santa Monica Mountains. In their vicinity this zone is closer to the sea surface and has irregularities of greater vertical extent in it. Furthermore the transition from marine layer to inversion layer is less abrupt there and harder to delineate with the marine layer tending to be more stable and the lower part of the inversion less stable. It's as if heat from the slopes is most effectively injected throughout a height interval that includes both the top of the marine layer and the bottom of the inversion layer. It appears also that all this takes place while at least the marine layer and perhaps the lower part of the inversion layer is undergoing subsidence."

The above suggests the intriguing possibility that some occurrences of high ozone concentrations at inland locations in Ventura county like Thousand Oaks and Simi valley could be due to entrainment of ozone and ozone precursors from the Los Angeles Basin into the inversion layer along the Santa Monica mountains and subsequent transport inland and fumigation down to the ground.

Finally, some information on the transport and diffusion of elevated pollutant sources in the Ventura county coastal area extending to the inland valleys is available from the special plume tracking and downwind sampling studies at the Ormond Beach Power Plant near Point Mugu. Giroux, et al (1973) concluded from a time series of early morning pibal winds at Point Mugu during the August 1973 tracer program that, "the southeasterlies are a permanent feature of the winds aloft above the surface layer at Point Mugu, and appear to penetrate to the ground level on the western edge of the plain almost every morning. Although one would normally anticipate a weak southeasterly flow as the land breeze veers to a sea breeze, the strength of this flow remains surprising. Forecasters familiar with the local area indicate that this is the usual, though undocumented, situation in the morning over Oxnard in the summer." Giroux, et al (1974) found the summer season tracer program coincided with a period high ground level ozone concentrations in the Ventura county area and especially in the Simi valley (0.39 ppm record high) and that the air quality impact of this elevated source (power plant) extended to considerable distances from the coast including to most of the inland valleys. The vertical soundings of plume tracer concentrations indicated the plume generally remained within the mixing layer with some entrainment into the inversion layer aloft especially in the vicinity of heated slopes. The air quality impact area of this source in the summer season was found to be located generally northwest and southeast of the plant along the coast during the early morning and late evening hours, respectively, and to northeast extending inland to Camarillo during the midday. These results would appear to be consistent with the hypothesis of over-water transport of ozone and ozone precursors aloft from Los Angeles to Ventura county and subsequent transport inland and fumigation down to the ground as the primary mechanism for the high concentrations observed. More results which bear on this problem will hopefully be obtained during the forthcoming plume tracer study at the Ormond Beach Plant, the goal of which is to obtain definitive data on the air quality impact from the plant under very limited mixing conditions, when the plume may be imbedded entirely within the inversion layer, and on the air quality impact on elevated terrain inland (Mirabella, 1975).

Concluding the review of other relevant studies, it is important to mention results on "hangover", long range transport, production downwind of power plants, and slowing of reactions by incomplete mixing of ozone, as well as some recent mathematical modeling work. Duckworth and McMullen (1975) have shown that the oxidant "hangover" aloft can be considerable from a comparison of the Burbank (0.18 km, 598 ft. above sea level) and the Mt. Lee (6.4 km south of Burbank, 0.51 km, 1680 ft. above sea level) data for an 11 day period in June 1974. The mean diurnal oxidant concentrations for the two locations were quite similar during the daytime, but quite dissimilar during the nighttime, with the Mt. Lee oxidant generally above 0.09 ppm and the Burbank oxidant generally near zero. In addition, they found that "the effect of this oxidant hangover burden is enhanced by a tendency for the burden to increase on successive nights within a smog episode" and, "thus the air which was mixed downward from this hangover layer during the daytime brought less and less "relief" as the episode developed" Seinfeld, et al (1973) has concluded among other things, that data on nighttime pollutant concentrations aloft, like ozone, are very important to advances in understanding and modeling.

As mentioned previously, Blumenthal and White (1975) have analyzed the stability and long range transport of ozone or ozone precursors downwind (east) of the Los Angeles Basin using data obtained in the ARB 3-Dimensional Pollutant Gradient Study. They found from detailed analysis of one episode day that ozone precursors accumulated in the western part of the Los Angeles Basin during the stagnant night and early morning hours, and then were transported eastward with the onset of the sea breeze to the eastern part of the basin and "aged" enroute. In addition, Blumenthal and White (1975) demonstrated the stability of high ozone concentrations aloft from one period of midnight measurements, but they did not analyze the contribution of transport and fumigation of ozone or ozone precursors within the inversion layer to ground level ozone concentrations at long range. Such an analysis is very important to determining the full impact of ozone or ozone precursors at long range.

With regard to possible production of ozone downwind of power plants, Davis, et al (1974) concluded from airborne measurements at several isolated power plants near Washington, D. C. that, "depletion of ambient ozone levels in the path of the plume was typically observed out to distances of 24 km from the plant; but of even greater significance was the fact that in nearly all cases during daylight hours (summer months) net ozone formation was seen beyond this point". Davis, et al (1974) "propose that ozone is depleted primarily in the conversion of NO to NO_2, and that the ozone bulge at large distances is due to photochemically initiated free radical chemistry involving OH free radicals..." On the other hand, airborne plume tracking at the Alamitos and Haynes Power Plants in the Los Angeles Basin has apparently shown only an ozone deficit in the plume at long range (Mirabella, 1975). The ozone concentrations in the Ormond Beach Power Plant plume in Ventura county will be measured at long range during the forthcoming tracer study (Mirabella, 1975).

The possible slowing of photochemical reactions like those involved in ozone formation during incomplete mixing has been discussed by Eschenroeder, et al (1973) and others. The full significance and consequences of this phenomenon have yet to be developed, but it may be responsible for the large fluctuations in ozone concentrations observed aloft within short distances (horizontally and vertically) and short time periods at the same location.

It is well known that the structure of atmospheric turbulence is very intermittant in time and space, outside the well mixed surface layer, in stable and inversion layers aloft. In addition, it is conceivable that high ozone concentrations aloft may not show up completely until the fumigation process starts and the associated turbulence completely mixes the ozone precursors in the inversion layer. Eschenroeder, et al (1973) suggest that the degree of incomplete mixing on ozone formation can be checked by computing the ratio in equation (3) presented previously, and this indicates the importance of measuring NO, NO_2 and turbulence simultaneously with O_3 in future studies of vertical profiles and layers of high ozone concentrations aloft.

With regard to mathematical modeling studies, Liu, et al (1974) have described a major program of photochemical model development and initial validation for the Los Angeles Basin. This "grid type" model predicts, among other things, that the vertical profiles and of ozone concentrations often increase with height below the inversion layer which is in qualitative agreement with measurements and with the simple steady state relationship derived from kinetic mechanisms in equation (3). However, it appears that the vertical distribution of ozone in the inversion layer, its change with time, and its role in ground level concentrations via fumigation has not been modeled. Liu, et al (1974) concluded that, "understanding of the overnight carryover processes must be achieved if multi-day episodes are to be simulated". Graedel, et al (1974) have modeled the effects of variations in bulk meteorological parameters like advection, mixing height, and solar radiation on ozone concentrations in Essex county, New Jersey for summer workdays. Their results show the relative contributions to the overall diurnal variation in ozone concentrations from variations in these bulk meteorological parameters differ widely at different times of the day and for different degrees of cloud cover. Graedel, et al (1974) found that the ozone maxima decrease with increasing cloud cover (decreased solar radiation), photochemical production of ozone is more important than that due to changes in mixing depth and advection during most of the day with full sun, the advection term can override the influences of both destructive chemistry and increasing mixing height in the afternoon with full sun, and the mixing height always acts as a dampening effect on ozone production and is particularly effective in limiting the magnitude of the midmorning peak in the total ozone concentration rate of change. Finally, Graedel, et al (1974) conclude as expected that on cloudy days the chemical production of ozone is small and concentration variations result principally from meteorological influences like advection and mixing height, and that temperature has an effect on ozone production independent of mixing height and advection. The above modeling results certainly indicate the need for the type of nearly round-the-clock horizontal and vertical ozone concentration profiles, during episode and light smog conditons obtained in this project, to permit advances in model development and validation.

IV METEOROLOGICAL SETTING

The field work was accomplished during two periods representative of typical summer conditions along the southern California coast.

The first series began on June 2, 1975 and lasted to June 4, 1975. During this period a relatively deep marine layer was dominating the weather picture, with a well-developed thermal low lying over the lower Colorado River area between California and Arizona. The upper air pattern was one with a trough aloft affecting southern California, (Appendix B presents the daily weather patterns at the surface and aloft, as presented by the U. S. National Weather Service.)

On June 4, 1975 the trough aloft deepened, and became a closed low, resulting in a general deepening of the marine layer. Operations were suspended at this point, to await a more pollution-prone situation.

On July 9, 1975, the field operations were reinstituted, to cover a period of high air pollution potential. Generally low inversions were the rule through the three-day period from the 9th to the 11th. The weak pressure gradients at the surface were a reflection of a high pressure cell aloft centered over the southwestern U.S. This episode ended with an approaching trough aloft which began intruding from the northwest as the existing ridge began to dissipate.

Conditions from July 13 to July 18, 1975 were those associated with a moderately deep marine layer, with a weak frontal passage detected aloft on the morning of July 16th. This introduced air with a much lower background level of ozone than had previously been found, but by July 18, 1975, when the field program came to an end, the ozone values were again increasing aloft, coincident with an upper ridge building over California.

V EQUIPMENT

A. Airborne

The aircraft used in this project was a Piper Cherokee (PA28-140) low wing monoplane. The temperature sensor and ozone sampling intake was located on the left side of the fuselage, away from the engine exhaust outlet.

The sampling line, 0.6cm teflon tubing, was kept as short as possible, to reduce the possibility of wall effects which could act to reduce the amount of ozone detected. Total length of the sampling line was about 1.2 m.

Ozone was measured by a Dasibi 1003 AH ozone sensor, factory modified to provide reading update every 13 seconds.

A 0.5 micron filter was added to the sampling system for operations on the last two days of the program in order to remove any interference effects from particulates, since it was planned to fly through a power plant plume near the study area to observe what the NO_x-rich plume would do to the ozone background.

Output from the Dasibi was recorded on a Hewlett-Packard 680M strip chart recorder, operating at a one inch per minute chart speed.

The ozone sensor, together with the recording system, was calibrated by the Air Resources Board at its El Monte facility. Calibration was first accomplished with the instrument connected to 110 v line; calibration while on inverter power was delayed due to an instrument malfunction. After repair of a timing board, this calibration was performed, resulting in a span deviation from true of -3.5% (instrument reads low by 3.5%).

B. Winds Aloft

The winds aloft measuring stations consisted of optical theodolites (David White M6061), tracking 30 gram pilot balloons. The balloons were inflated to a standard free-lift condition which gave a rate of rise averaging about 600 feet per minute (3 mps) from surface to 5000 ft., (1.5 km).

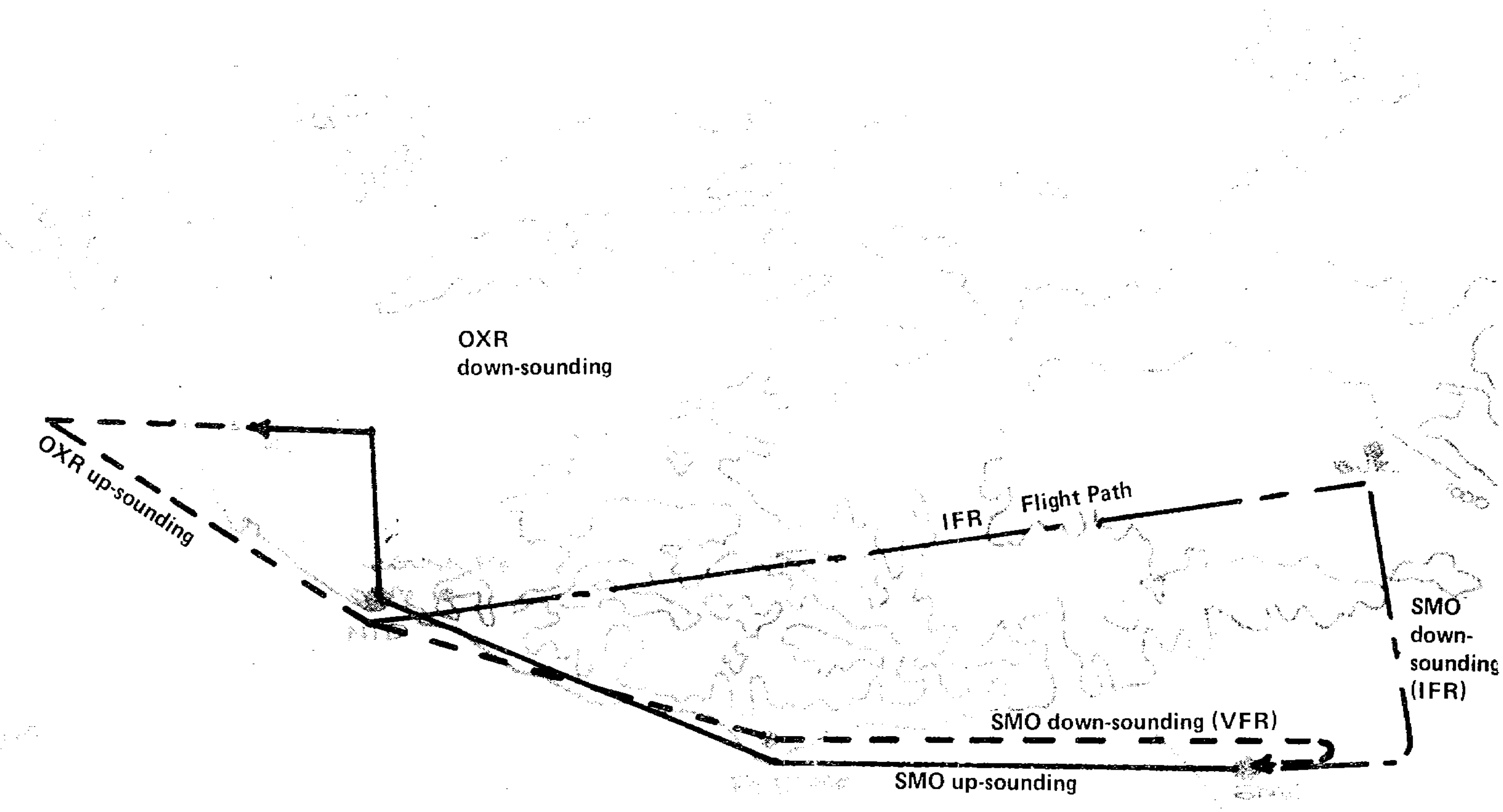

FIG. 1 Aircraft Flight Paths and Station Location Map

VI PROCEDURES

A Aircraft Operations

The study involved the use of an instrumented light aircraft and a network of three winds-aloft observation sites. Flights and simultaneous wind soundings were made every three hours during daylight hours, augmented by flights and balloon runs near midnight.

Figure 1 presents the study area and shows the location of the wind observation points, as well as the aircraft track flown.

The original test plan called for the aircraft to make a sounding of temperature and ozone heading seaward from Santa Monica, leveling off at an elevation where the greatest ozone concentration was noted, and then proceeding offshore at that altitude until reaching the Ventura county coast.

This flight plan was modified when low visibility and Navy missile range safety considerations made it more prudent to climb to 5000 feet (1.5 km) en-route to the Ventura coast, thence descending into the Ventura County Airport at Oxnard, making a touch-and-go landing there and returning to Santa Monica. The June tests were carried on under the initial flight plan procedures, but the July tests followed the latter plan.

The actual aircraft flight path depended on whether or not instrument flight conditions prevailed; when the aircraft was under FAA controller guidance, the flight path on the return leg from Oxnard to Santa Monica followed the route marked by the dashed line on Figure 1, which took the aircraft inland over the

Thousand Oaks - West San Fernando valley area before turning to make an instrument approach to the Santa Monica airport from the east.

The observer recorded the temperature and ozone variation with height during the climbing and descending phases of the flights, with ozone being recorded on a continuous basis throughout.

While the ozone was recorded continuously, the Dasibi ozone sensor operated on a cycling basis, providing an updated reading every 13 seconds. At the aircraft's cruising speed of 120 mph (193 kmph), this is equivalent to a sample every 0.4 miles (0.6 km). During climb and descent, the rate of altitude change was 300 feet per minute (1.5 mps).

Altitude information was derived from the aircraft's altimeter, which was corrected at both ends of the traverse by the altimeter settings reported at each airport.

B Winds Aloft Observations

The 30 gram balloons were tracked to 5000 feet (1.5 km), or until they disappeared into the coastal low clouds. Tracking consisted of obtaining horizontal and vertical angle readings from the theodolites every 30 seconds. The theodolites were first oriented with respect to true north, so that all directional data is given in degrees from true north.

The wind at levels above the ground was obtained by plotting the balloon positions at each 30 second interval, with the wind being obtained graphically from the distance and bearing between successive one-minute balloon positions. This in effect provides an averaging procedure to eliminate variability that could occur if the 30-second positions were considered individually.

Balloon heights were determined from time-height tables for the standard free-lift weighing procedures applicable to 30 gram balloons inflated with helium gas.

At the Los Angeles International Airport site LAX) the National Weather Service's regularly scheduled atmospheric sounding balloon runs were used during the two times per day (0600 PDT and 1200 PDT) they were made. At the other scheduled times, the winds were obtained at LAX as described above.

Since the Weather Services (NWS) balloon data are disseminated as wind readings at 1000 foot (300 m) intervals, rather than the 500 foot (150 m) given by the other stations in the study network, the original NWS records were replotted and the 500 foot (150 m) winds were developed.

The Navy's Pacific Missile Range at Point Mugu (NTD) also makes atmospheric soundings on a semi-routine basis. Winds and temperature data from these soundings were incorporated into data analysis, together with hourly wind data measured at the 1600 foot (0.5 km) summit of Laguna Peak, located just east of Point Mugu.

C. <u>Analytical Procedures</u>

1. Cross-sections

All air sampling, temperature sounding and wind data were placed on cross-sections to present a picture of a slice of the atmosphere as it existed between the Los Angeles Basin and the Ventura coast for each of the traverses.

The cross-sections were analyzed for the ozone layers encountered; the locations of the maxima being indicated by shading. Inversion bases were also noted to establish the relationship between the stable air and the ozone-rich layers.

2. Soundings

Temperature and ozone information has been plotted in terms of height versus degrees F (for temperature) and parts per million (for ozone).

These are for the most part soundings made during ascent phases of the traverses, because they better represent the conditions existing over the coastal waters than the descent soundings, as can be seen by referring to the flight plan shown in Figure 1.

3. Trajectories

To answer the question: "where does the ozone aloft come from?", a series of trajectory maps was prepared.

The trajectory-determination procedure was carried out in the following manner:

a. Using the data as measured at 1200 PDT each day as a starting point, a determination was made of the height at which the ozone maximum occurred over Oxnard.

b. Wind flow maps were prepared for the height noted in the step above. All available data, from the special study network, from the two radiosonde stations at LAX and NTD, and from the Laguna Peak wind recorder, were used as guides to constructing the prevailing streamline pattern existing at each observational time.

c. By extrapolating the high ozone parcel backward in time according to the direction and speed of the air flow as given by the streamline charts, and doing this for successive maps, it is possible to deduce the path that the parcel under study had been following prior to its arrival over Oxnard.

In certain cases, where decided subsidence occurred, the trajectory altitude was changed to keep the air parcel within its environment just above the inversion base. In such cases, the winds at the appropriate levels were used in the trajectory construction process, and the actual height at a particular point is indicated on the trajectory.

This procedure was employed for each day for which data were available.

VII RESULTS

All sounding data representative of the study area are given in Appendix C. These data, together with data from aircraft horizontal traverses and supplemented by data from LAX and NTD have been placed in cross-sectional form (Appendix D).

Inspection of these cross sections show that there is at least one layer of ozone aloft along the Santa Monica to Oxnard route. The lower layer is just above the inversion base, and exists with or without the presence of stratus clouds in the marine layer below the inversion.

Often a second layer of ozone is found, usually near the 3500 foot (1 km) level. This layer appears to exist in stable air mass conditions but is not confined to a position just above an inversion base. It can also occur below an inversion aloft.

The highest concentration of ozone is usually found at the lower layer, that which is just above the inversion base. Concentrations varied during the course of the study, tending to be lower on days with high inversions and higher on low inversion days.

Maximum ozone aloft was detected during the 1500 PDT flight on July 10, 1975, reaching 0.43 ppm at 900 feet (0.3 km) over Oxnard, and 0.31 ppm at a similar height over Santa Monica. (Fig. 2) (Readings of ozone to 0.81 ppm were recorded on this flight, but pending further work, the data points where large changes in ozone occurred were not considered as valid.)

Trajectory determinations for air parcels over Oxnard in the maximum ozone layer were made for each day

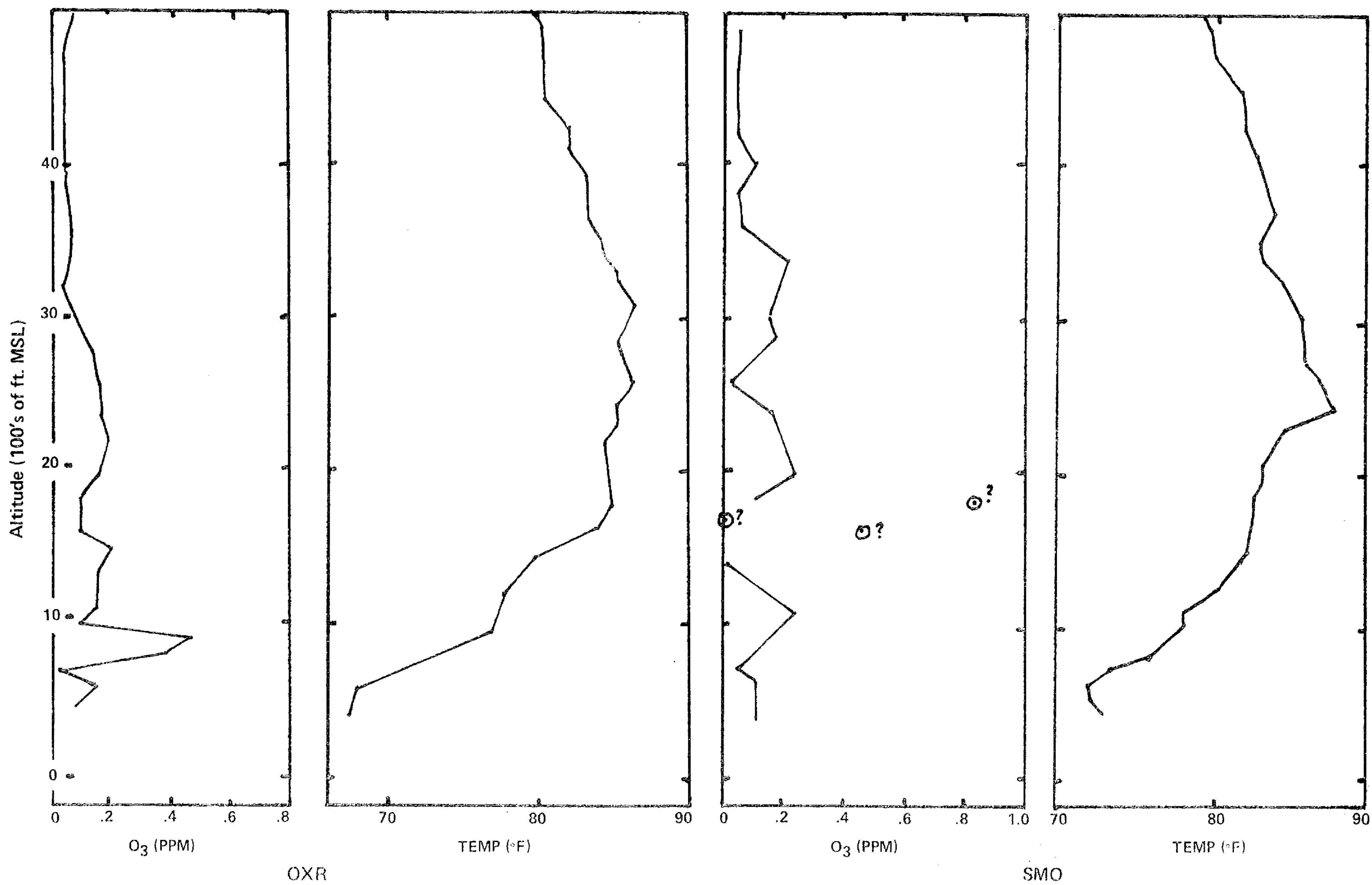

FIG. 2 Temperature and Ozone Sounding 7/10/75 1500 PDT

in the study. Trajectories calculated for the conditions existing at noon on these days are shown in Appendix E, together with the individual streamline maps used in the trajectory analysis.

A special trajectory was constructed to the parcel containing the highest concentration of ozone. The track of this air parcel is shown in Figure 3. From the wind data at 1000 feet (0.3 km) it is possible to track the high ozone parcel back to the Los Angeles Basin having passed over the coastline heading seaward between midnight and 0300 PDT on July 10, 1975.

The individual streamline maps from which this trajectory was constructed are included in Appendix E.

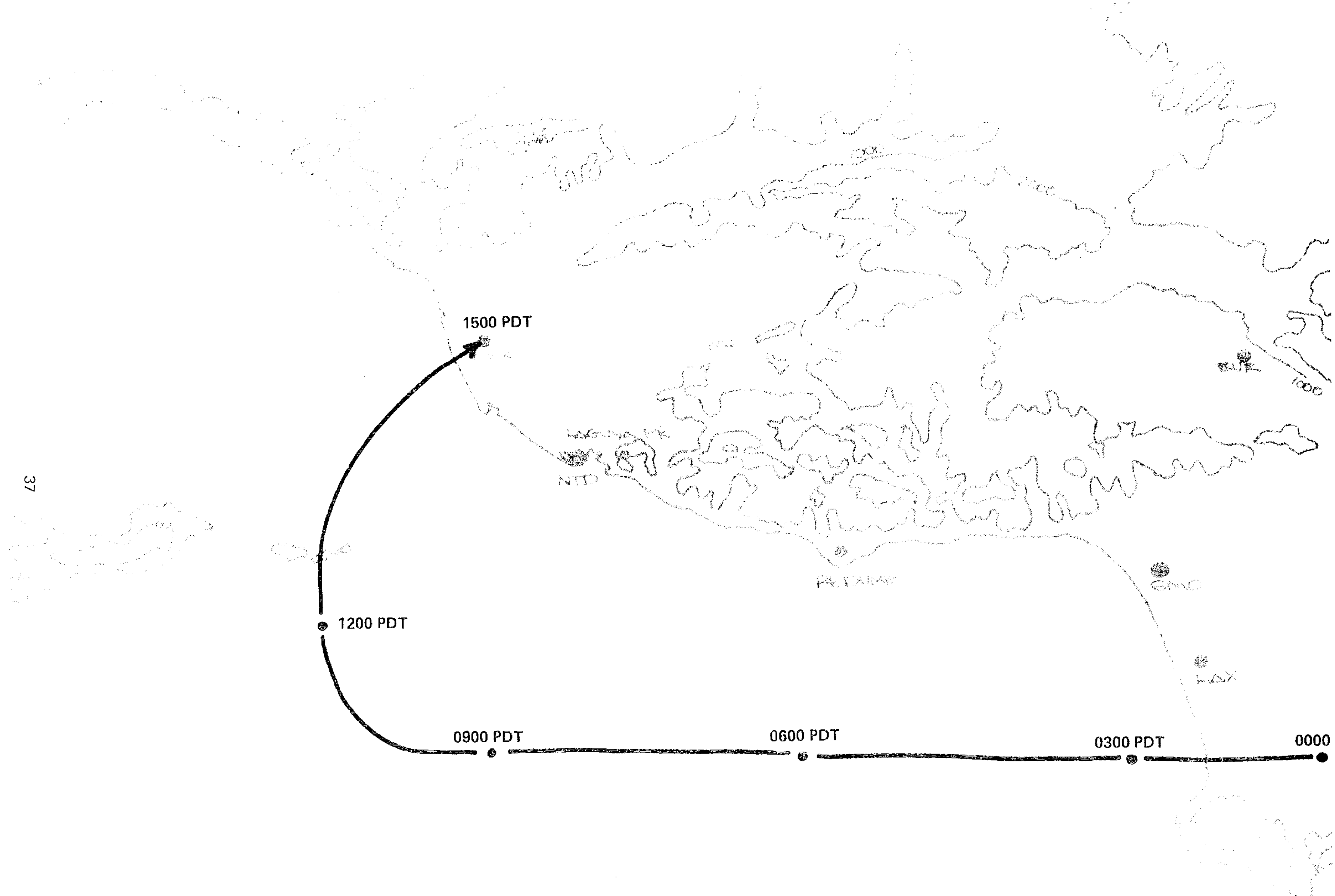

FIG. 3 Trajectory of Air Arriving at OXR with high
O_3 ues 7/10/75, 1500 PDT, 1000′ Altitude

VIII DISCUSSION

A. Ozone Distribution

1. Ozone Layers Aloft

The study data indicates the presence of ozone layers aloft in the coastal southern California area. While the field observational period covered only about ten days, the fact that ozone was detected aloft in characteristic locations with respect to marine layers, no matter whether that layer was deep or shallow, suggests that we are seeing what normally occurs.

Occurring with almost as great a frequency as the low level ozone just above the inversion base is a layer found near 3500 feet (1 km). This second layer appears to be within the stable air above the inversion base, but is not particularly associated with a specific atmospheric structure.

These ozone layers aloft are likely the result of a previous history of the air mass moving over elevated terrain where surface heating effects act to bring polluted air to the average crest height. Since the general height of the lowest ozone layer is above 2000 feet (0.6 km), it is a possibility that the coastal mountains could serve as the elevating mechanism. The upper ozone layer could, similarly, result from air movement up the inland foothills and mountains, such as those fronting the San Gabriel range of the Los Angeles Basin.

The height of the ozone layers aloft appear to rise or lower with time, responding to the general rising or subsiding of the coastal air mass.

2. Ozone Variability

a. Hourly Variations

The maximum ozone occurring aloft (above the base of the lowest inversion) was tabulated for both Santa Monica and Oxnard by time of day. Results of this summarization are given in Figure 4, showing the average maximum value for both locations peaking at 1500 PDT.

This diurnal pattern is at variance with that exhibited by coastal ground level stations; peaks at such locations occur at mid-morning rather than mid-afternoon.

The fact that ozone values aloft increase during the course of a day is indicative that some photo-chemical reactions are continuing to occur in what appears to be aged ozone clouds.

Ozone concentrations are greater on the average over the Santa Monica coast than the Ventura coast, as would be expected if the ozone aloft is an aged cloud that moves westward from the interior sections of the Los Angeles Basin out over Santa Monica Bay and thence to the Ventura area.

b. Small-scale Variability

During the course of the field work, occurrences of rapidly fluctuating ozone values were noted. Since the Dasibi ozone monitor

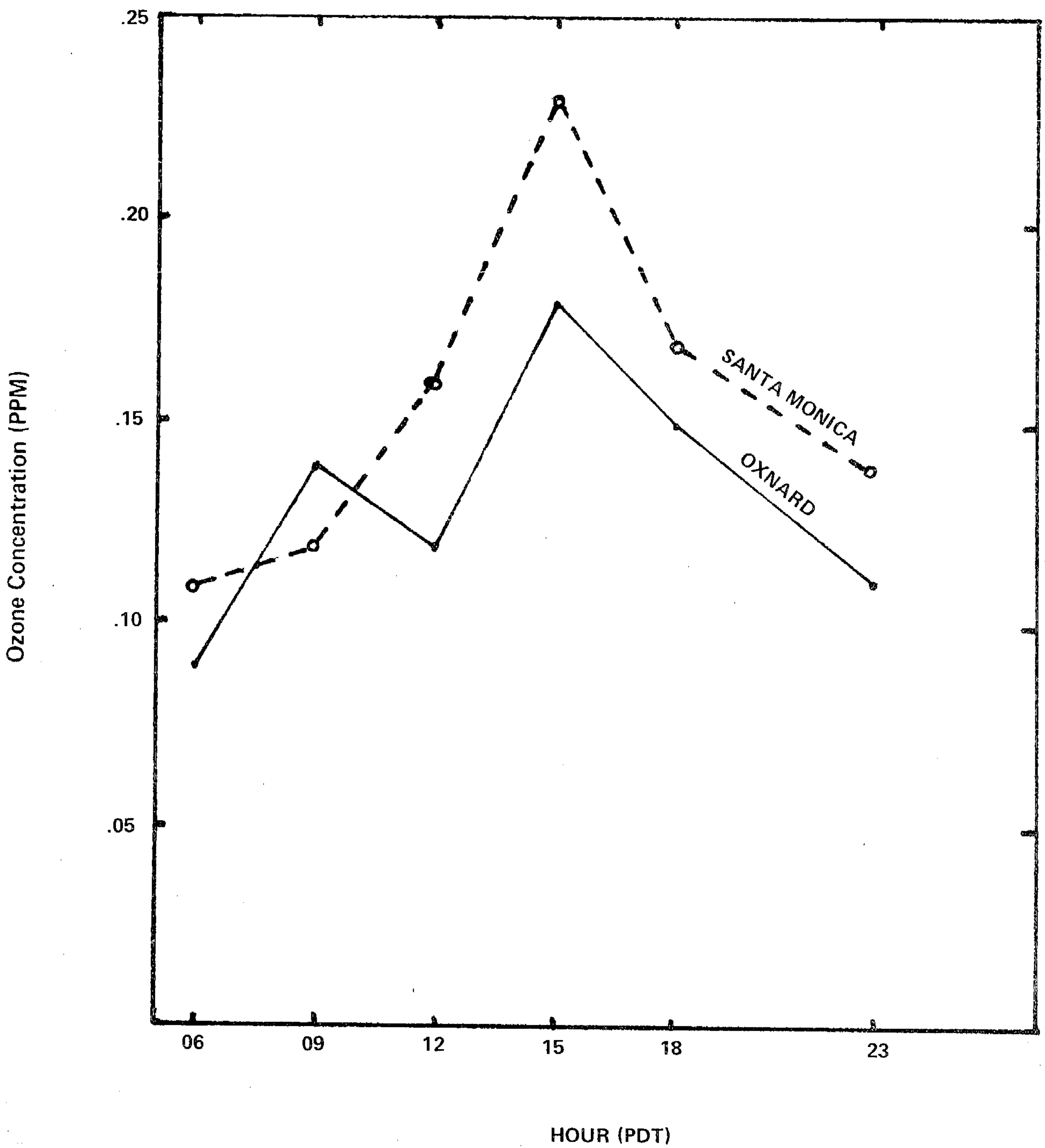

FIG. 4 Average Maximum Ozone Above Inversion Base, July 9-18, 1975

used on the project gave updated sample every 13 seconds, the indications were that there were bubbles of high ozone and relatively clean air with cross-sectional dimension of about 1600 feet (0.5 km).

This phenomenon was first noted when the sounding aircraft made a climb out of Burbank prior to beginning its traverse from Santa Monica to Oxnard. The instrumental response was normal until the aircraft was over the foothill spurs just south of Mount Wilson. Rapid changes in ozone values were recorded until the aircraft passed back over the center of the San Fernando Valley.

This occurrence made it appear possible that the ozone is carried upward in discrete parcels, along the heated slopes, as described by Edinger, et al (1972)

However, such occurrences were noted over the entire course of the field work, even during the seaward portions of the flight path.

Rapid changes in ozone aloft have also been reported by Baboolal, et al(1975) during the course of aircraft measurements over the the Santa Ynez valley of Santa Barbara county.

The instances of rapidly changing ozone values during the Santa Monica to Oxnard traverses were classified in various ways to determine if they had any consistant pattern, or were random in nature.

The first classification was by location. Of 26 instances of rapid changes in ozone noted, 13 were found during the climb phase, out over the water; 7 of these were out of Santa Monica, 6 were out of Oxnard.

When they occurred, they tended to be found at nearly the same altitude at both Santa Monica and Oxnard.

When stratified by 1000 foot (0.3 km) increments, the interval between 3000 and 4000 feet had slightly more occurrences than the other 1000 foot thicknesses.

Considering the stability of the air mass, there were 13 cases within inversion conditions compared to 10 with adiabatic lapse rates at the levels where the rapid changes occurred.

One significant relationship found in the study was that between occurrence and time of observation. Of the 26 occurrences, 16 were noted at the 1500 PDT traverse period, 7 were recorded at the 0900 PDT: only two occurred at 0600 PDT, one at 1800 PDT, and none at all at 1200 PDT and 1300 PDT.

The explanation of this non-random occurrence with time is not immediately apparent. While the afternoon maximum could be associated with surface heating effects, their occurrence during over-water portions of the traverses, where such effects would be minimal, makes it necessary to look for another explanation.

Equally puzzling is the absence of any such occurrences during the noon time period, even though the phenomenon was noted at 0900 PDT with a frequency of occurrence second only to that at 1500 PDT.

B Winds Aloft

An important aspect of this study was the air movement at levels above the surface, since pollutants postulated as existing aloft would be carried along by the upper level winds.

The program of pilot balloon observations from LAX to Oxnard provided data from which a limited wind climatology could be derived. While there were many instances when the winds aloft could not be measured due to the presence of low clouds, all data were summarized and where sufficient data were available, a most frequent wind was determined, together with the average wind speed (mph) associated with the particular wind direction.

The distribution of such winds with time for the various wind measuring stations is shown in Figure 5 Oxnard (OXR) and Point Mugu (NTD) are plotted together, representing as they do, the Ventura coastal area. The NTD wind is taken by electronic means, so readings are available even when low clouds were present.

The basic two-directional flow pattern is seen at all stations, with easterly winds existing during morning and night time hours, and westerlies during the afternoon.

The occurrence of easterly winds aloft with lower level westerlies is shown at the 1200 PDT period. Both LAX and OXR report westerlies at the 1000 foot level, 0.3 km, with easterlies above.

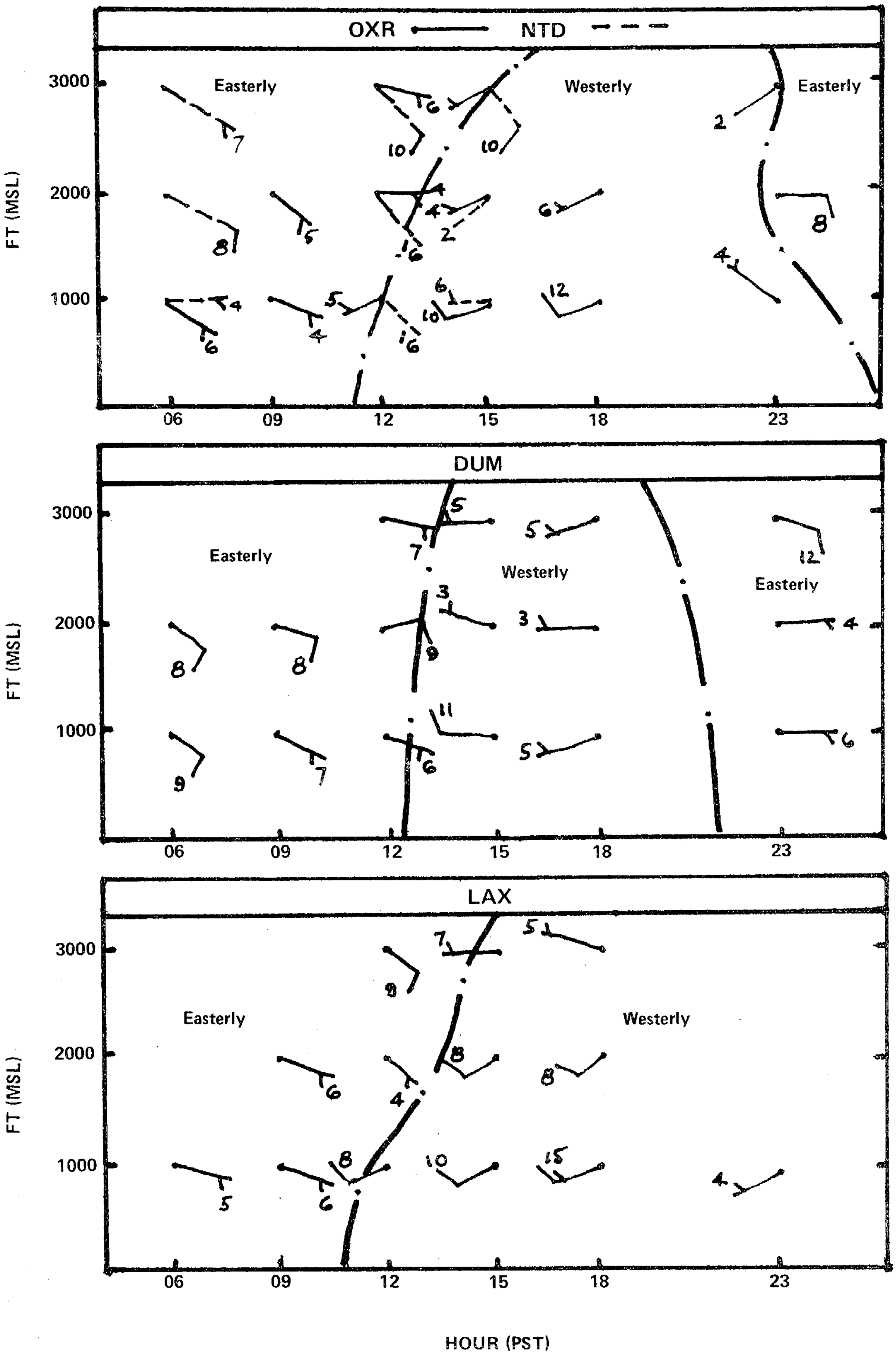

FIG. 5 Most Frequent Winds Aloft, June-July 1975

Considering the entire day, the winds aloft blow from the west for about 8 hours, while easterly winds dominate the other hours.

C. Trajectory Studies

The observed wind data were plotted on maps and streamline analysis performed for the various sampling periods. Trajectories of air parcels of interest were then constructed, using the streamline analysis and the wind data from Laguna Peak as guidance in determining the parcel movement.

Trajectories of air containing the maximum ozone aloft over Oxnard were constructed daily for the 1200 PDT period. This provided the historical-geographical background of the ozone aloft that was moving into Ventura county at noon each day.

Nine such trajectories were prepared. Five were found to have followed a track along the coast between Santa Monica Bay and the Ventura coastline. Three were located along a San Fernando valley-Thousand Oaks path.

Only one could not be traced into the Los Angeles Basin. In this case, the trajectory backward from Oxnard indicated the parcel as coming up the coast from Los Angeles, but that it never went on shore in the Los Angeles Basin. However, if the winds moving the air parcel were slightly stronger than the wind reporting stations indicated, the ozone parcel could easily be traced back to the Los Angeles source region.

The occurrence with the highest reported ozone concentration over Oxnard, that of July 10, 1975, 1500 PDT, was also analyzed in trajectory terms. Figure 3 presents the path taken by a parcel at 1000 feet (0.3 km).

It appears that the ozone-parcel was over the southern portion of the Los Angeles Basin at midnight.

While no further trajectory analysis was performed for times earlier than midnight, one can surmise that the parcel had been over the interior portion of the Basin during the early evening hours, and had returned toward the coast with the onset of an easterly land-breeze flow.

Inspection of the trajectories indicates that the over-water trajectory is more likely when the marine layer is shallow. The trajectories which indicated movement into Ventura from the San Fernando valley were associated with the deeper marine layer conditions.

Since the project was specifically designed to track the polluted air aloft which was arriving at the Ventura coastline, no trajectories were constructed in a forward time sense. That is, the movement of an air parcel arriving over Oxnard is not followed during the course of each afternoon, when it may be assumed that the air is moving inland over the eastern portions of Ventura county.

IX CONCLUSIONS AND RECOMMENDATIONS

The occurrence of ozone-rich layers aloft moving into the Ventura county coastal area has been documented as coming from the Los Angeles Basin.

Analytical procedures used to arrive at this conclusion were streamline analysis and subsequent trajectory construction, based on winds aloft measured at three locations between the Los Angeles area and Oxnard.

The over-water trajectory between Los Angeles and Ventura is the normal situation, although with deep marine layers, a path between the San Fernando valley and Ventura county is also found.

To better document the frequency of occurrence of this ozone flow aloft, it is recommended that consideration be given to establishing two or three ozone-measuring sites along the Santa Monica mountain chain, from West Los Angeles to Ventura.

A series of winds and ozone aloft measuring periods should be conducted during the various seasons, to document the air flow aloft that occurs in conjunction with the ozone concentrations reported by the mountain-top ozone stations.

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