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OZONE OVER SAN FRANCISCO
Means and Patterns During Pollution Episodes

by

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ABSTRACT

Measurements of meteorological parameters were taken at six levels and ozone at four levels between 260m and 473m ASL on the Mt. Sutro T.V. Tower in San Francisco during the summers of 1974 through 1976. Hourly average ozone concentrations within the elevated inversion layer at this location exceeded the 8 pphm (160μg m^{-3}) National Ambient Air Quality Standard about 15% of the time.

High inversion layer ozone concentrations at this site were associated with high surface concentrations occurring during area-wide air pollution episodes. These episodes occurred when a lobe of the Pacific high pressure system penetrated inland and interrupted the normal onshore California monsoon flow, often in late summer and early fall when the monsoon is normally weakening.

During these episodes, superposition of synoptic scale and northeasterly flow and locally produced mesoscale flow caused easterly or light westerly flows during the late forenoon within the inversion layer and westerly flow in the late afternoon. Inland, where the inversion was destroyed from below, inversion layer and surface generated pollutants were convectively mixed. This mixing and the wind oscillation recycled pollutants. The episodes ended when the synoptic situation reverted to one more normal for the season and pollutants were advected from the area.

At the start of two September, 1974 case studies, ozone rich stratospheric air appears to have intruded into the subsidence inversion and may have acted as a photochemical trigger or have mixed additively to locally generated pollutants. There are some suggestions of transport from Los Angeles at the start of a third episode studied.

This report was submitted in fulfillment of Grant R802235 by San Jose State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from April 1973-August 1977, and work was completed as of August 1977.

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ACKNOWLEDGEMENTS

The cooperation of Sutro Tower, Inc. and especially chief engineer Harry Jacobs is gratefully acknowledged. Miles Imada and Edward Jeung and their associates of the Air and Industrial Hygiene Laboratory of the California Department of Health, the Air Resources Board, and Hanford Chew of the Bay Area Air Pollution Control District calibrated the air pollutant monitors. Auxiliary data were supplied by a number of agencies; the Bay Area Air Pollution Control District and Battelle Northwest Laboratories were especially helpful. The companion tower projects under Drs. Albert Miller and Jindra Goodman and supported by the National Science Foundation provided help and encouragement. Many undergraduate and graduate students have contributed to the project. The assistance of all is gratefully acknowledged.

SECTION 1

INTRODUCTION

The San Francisco Bay Area is a meteorologically and topographically complex area with rapidly expanding population. Air pollution generated by the expanding population and economy has become an increasingly noticeable social problem. Local governments and associations of local governments are asking the local Bay Area Air Pollution Control District for data, including output statistics from air pollution simulation models, for use in decisions on land use and other matters that may effect future air quality patterns.

Realistic simulation of meteorological and air pollution patterns by air quality simulation models then is necessary for governmental agencies to make well informed decisions. Most air quality computer models, such as the LIRAQ Model (McCracken and Suiter, 1975), consider the elevated inversion layer, which persists over the West Coast for nearly half the year, as an impenetrable lid to pollutants.

Previous measurements over the Bay Area (see Lowell and Miller, 1968; Miller and Ahrens, 1970; Gloria et al, 1974) and in the Los Angeles area (Lea, 1968; Edinger et al, 1972; Edinger, 1974) found significant concentrations of oxidants within the elevated inversion layer. These measurements, however, were made from such moving platforms as light aircraft or balloons. Construction of the Mt. Sutro TV Tower in San Francisco provided the opportunity to make measurements from a stationary platform which sticks into the inversion for most of the summer and fall months.

The results discussed in this report confirm the existence of high concentrations of inversion layer ozone over San Francisco. The following sections discuss the mean behavior of meteorological and air pollution parameters with emphasis on measurements made from the Mt. Sutro Tower, and then discuss the evolution of four periods of high oxidant concentration.

The results of this project, which was funded by EPA under the title, "Air Pollutant Background Profiles for Air Quality Simulation Models", should help in the improvement of such models for the Bay Area and perhaps other West Coast cities.

SECTION 2

CONCLUSIONS

Hourly average ozone concentrations measured with reference to the pre-1975 California Air Resources Board (ARB) neutral-buffered KI method of instrument calibration exceed the 8 parts per hundred million (pphm) National Air Ambient Air Quality Standards (NAAQS) about 15% of the time within the elevated inversion layer at the Mt. Sutro TV Tower over San Francisco during the late summer months. Ozone concentrations within the marine layer at this near coastal location exceed the NAAQS during about 3% of the hours. (These measurements are approximately equivalent to the EPA approved method.) O_3 concentrations in the inversion layer measured with reference to the 1975 and later ARB uv-absorption calibration technique exceed the NAAQS during about 9% of the hours. (8pphm=160μg m^{-3})

High inversion layer ozone concentrations are associated with high surface ozone concentrations measured at Bay Area Air Pollution Control District (BAAPCD) monitoring stations in inland portions of the area during air pollution episodes. A lobe of the Pacific high pressure system penetrating inland interrupts the normal onshore California monsoon. This interruption often occurs in the late summer and early fall when the monsoon is normally weakening.

During a high oxidant episode in the Bay Area, the daily average height of the base of the elevated inversion lowers until the peak day of the episode when the inversion base will be at or below the 250 m ASL peak of Mt. Sutro. The normal monsoon flow is re-established and the inversion base rises on subsequent days. Diurnal oscillations of the inversion base, similar to the average monthly behavior and produced locally, are superimposed on this behavior. The base of the inversion is highest in the early morning (04-07 PST) and lowest in mid afternoon (about 15 PST).

During these episodes, the mesoscale circulation produced by local heating and cooling is superimposed in northeasterly flow. The winds within the marine layer at Mt. Sutro are westerly or southwesterly throughout the day. As the inversion lowers in the late forenoon, winds above about 350 m ASL become northeasterly or weak westerly as synoptic scale flow dominates the weak onshore breezes. In the late afternoon, winds back to westerly as inland heating produces onshore flow. The duration and vertical extent of easterly component winds at the Sutro Tower increases until the peak oxidant day of the episodes.

The onshore flow that commences in the afternoon occurs both within the marine layer below the inversion base and within the very warm, dry air above.

Therefore, the structure of the leading edge of the incoming air is not like the typical sea breeze cold front. The inversion layer air is horizontally homogeneous and a frontal surface is therefore missing. The leading edge of the incoming marine layer is initially a typical sea breeze front. Ahead of the leading edge of the marine air, the inversion is destroyed by surface heating and convection. This allows inversion layer ozone and perhaps other pollutants to intermix with surface generated pollutants.

Other measurements (see e.g., Miller, 1966; Miller and Ahrens, 1970) have shown nearly stagnant air and high oxidant concentrations ahead of the leading edge of the marine air. The exact pattern of the leading edge of the marine air in the peak day of an episode should then determine which stations will get the highest oxidant concentrations. At night, cooling at inland locations sllows dynamic processes to reform the elevated inversion thereby trapping pollutants aloft. Downslope, down valley and land breezes combine to transport this polluted layer seaward. During the early morning and forenoon hours this layer remains near the coast where the inversion is intact and is brought back inland on the late afternoon breeze. Pollutants for each day of an episode then build upon successively higher backgrounds.

The monsoon circulation is re-established to end the episode and advect pollutants eastward from the area where they may contribute to high oxidant concentrations in the Central Valley or the Sierra Nevada.

At the beginning of one episode studied, there may have been pollutant transport from the Los Angeles basin. While this conjecture has not been proven, inspection of National Weather Service 850 m b analysis and available upper air wind data indicates the possibility of an isentropic trajectory from the Los Angeles basin to San Francisco. In two other cases studied, stratospheric ozone intrusion may have contributed significantly either additively or as a triggering mechanism.

SECTION 3

RECOMMENDATIONS

The evolution of air pollution episodes in the Bay Area should be studied in more detail. Measurements during a number of 1974 observation periods are presently being processed (Bay Area Air Pollution Control District, personal communication). These observations will be used for verification of the LIRAQ air pollution model (McCracken and Sauter, 1975). The need for further field measurements for model verification purposes should be evaluated once available data are processed and computer model runs completed. If further documentation of the evolution of Bay Area air pollution episodes is desired, either for control or for model verification purposes, then measurement periods should last for approximately a week to encompass build up, alert, and break down periods. Aircraft flights should measure the off-shore extent of the elevated polluted layer.

The existence and amount of pollutant transport from southern California to the Bay Area, especially at the start of a Bay Area air pollution episode, should be investigated, probably with the use of instrumented aircraft.

The possible role of stratospheric intrusion of ozone rich air, again especially at the beginning of a Bay Area air pollution episode, should be investigated. Computation of potential vorticity patterns coupled with measurements of radionuclides of stratospheric or upper tropospheric origin could estimate the significance of this possible source.

An important unsolved transport problem appears to be the fate of Bay Area generated oxidants and their precursors and their influence on the air quality of the Central Valley and Sierra Nevada of California. Oxidant monitoring for a complete season in a number of locations suspected of being receptors of Bay Area smog, coupled with field studies of transport parameters would provide impetus for the development of large scale transport simulation models.

SECTION 4

INSTRUMENTATION AND DATA ANALYSIS

THE MT. SUTRO T. V. TOWER

The Mt. Sutro T.V. Tower (Figure 1) is located atop a 254 m hill in the center of San Francisco (Figures 2, 3). The site is dominated by the tower and the transmission facilities building. A stand of Eucalyptus trees, whose tops extend to about 14 m above the tower base, borders the site from the north through west to south sides. The trees are about 30 m from the tower at their closest point.

The tower consists of three equally spaced legs connected by cross beams at three levels. It has an "hour glass" shape where the distance between legs is 46 m at the base, 19 m at the 162 m high waist, and 30 m at the 225 m top platform. Each leg is an equilateral triangle in cross section, 2.1 m on a side. Our instruments are installed on the west leg in which there is an elevator.

INSTRUMENT SUPPORTS AND METEOROLOGICAL INSTRUMENTS

The meteorological instruments and data signal conditioning electronics are attached to the ends of booms mounted at six tower levels (Figure 1). Boom heights and lengths are listed in Table 1. All boom lengths are between one and four tower-leg-widths long. The four uppermost ends are on a nearly vertical line (± 0.61 m or ± 2 ft.).

TABLE 1. INSTRUMENT BOOM CHARACTERISTICS

Level	Boom Height (m) Above Ground	Boom Height (m) Above Sea Level	Boom Length (m)
1	6.1	260.4	1.83
2	45.4	299.7	2.74
3	87.8	342.1	2.74
4	136.2	390.6	8.23
5	178.8	433.1	8.84
6	218.7	473.0	5.18

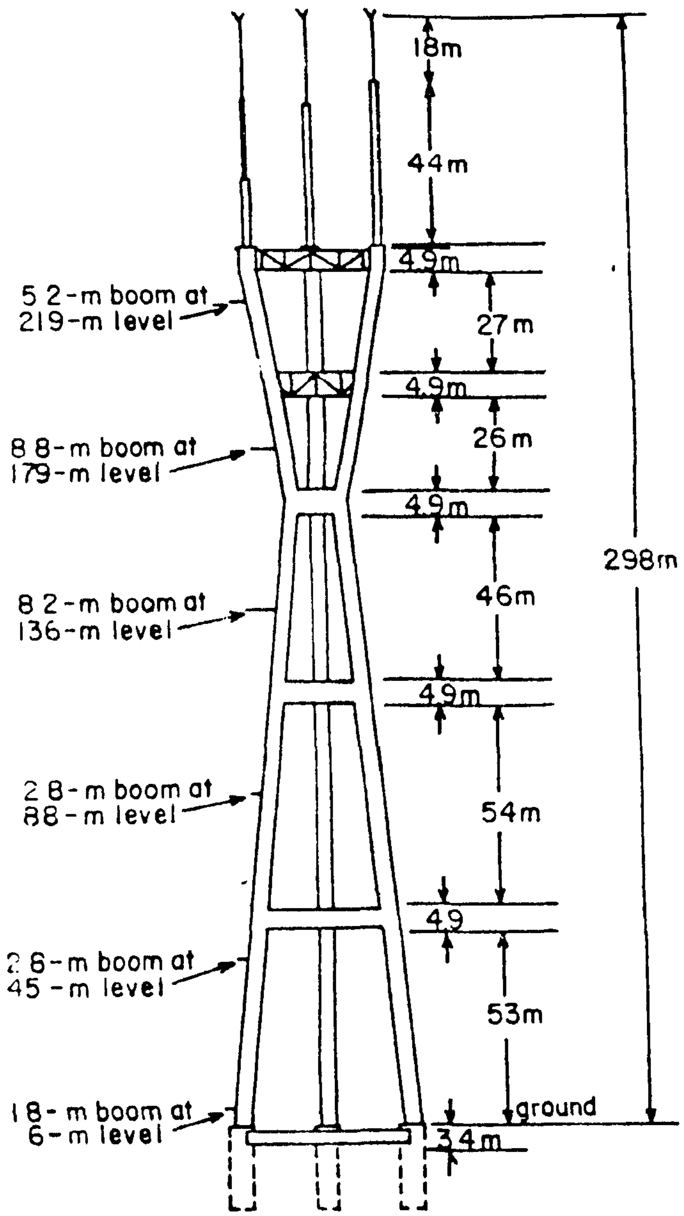
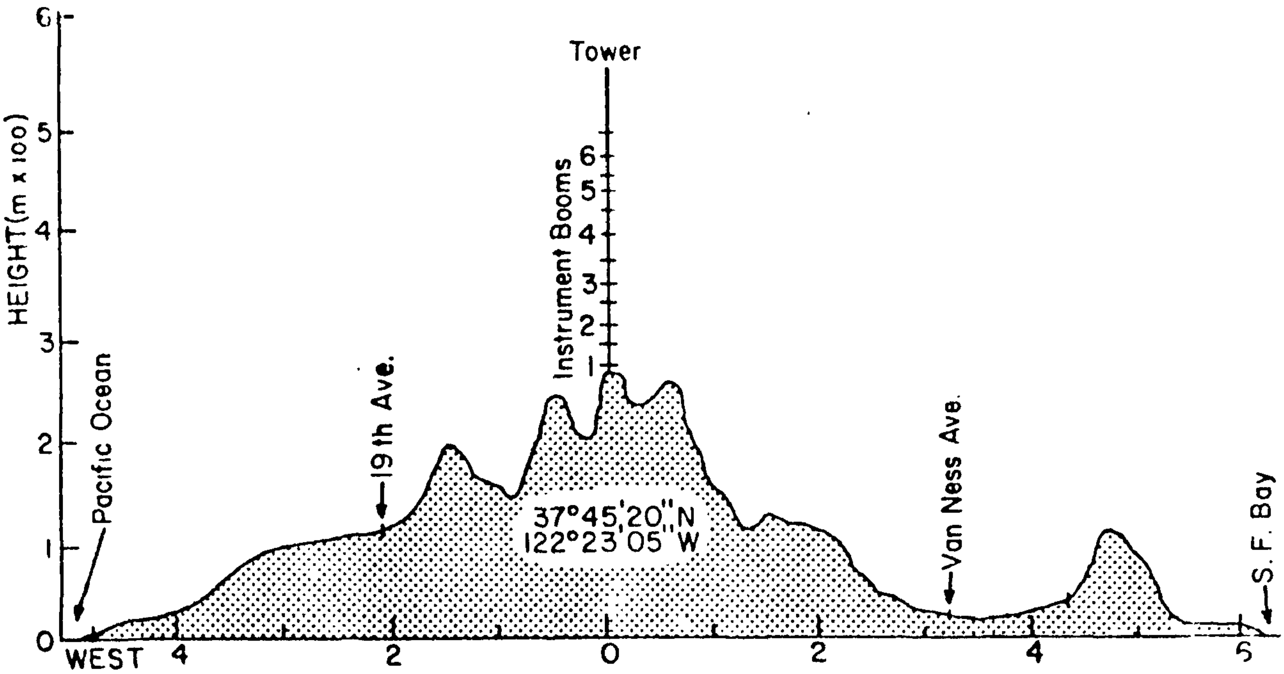


Figure 1. Mt. Sutro T.V. Tower

The lowest boom is fixed, while the other five are movable for access purposes. In order to service the instruments, the movable booms are lowered to service platforms. Cables are attached to both top and bottom of each boom near its free end and pass through pulleys to small winches located at the platform levels.

Prior to summer, 1975, stops prevented the booms from being raised beyond their horizontal position. Subsequently, potentiometric pendulums were installed in each boom so that deviations from the vertical along two orthogonal axes are continuously recorded.

The meteorological instruments are mounted as a unit (Figure 4) which then may be attached or removed from the boom end. Each package contains instruments for measuring the following parameters: air temperature, wet-bulb temperature, u-, v- and w- wind components and pressure. Table 2 lists the instruments for measuring each parameter.



DISTANCE FROM TOWER SITE (KM)

Figure 2. West-East profile of topography through tower site.

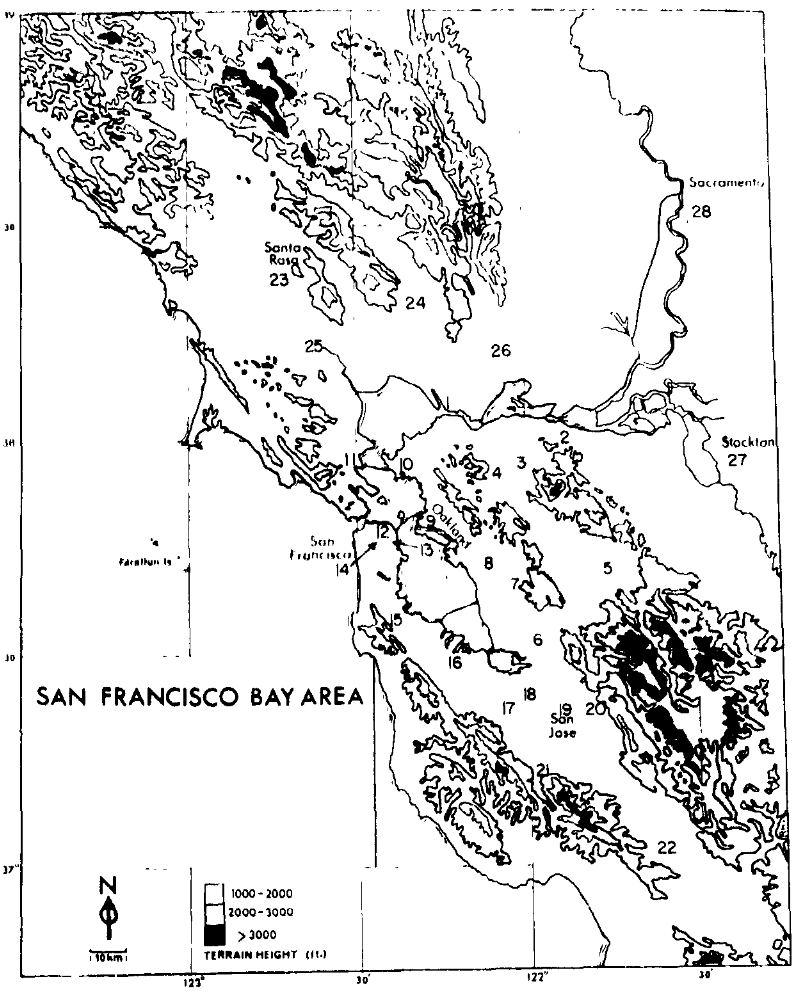


Figure 3. Map of area. Location 14 is Mt. Sutro, other locations are Bay Area Air Pollution Control District Monitoring Stations listed in Appendix.

TABLE 2. METEOROLOGICAL INSTRUMENTS

Parameter	Instrument	Remarks
Air Temperature	Yellow Springs Instrument Co. (YSI) Model 705 Thermistor	Attached to YSI Thermivolt Signal Conditioner
Wet-Bulb Temperature	Same, with wick	Same
Wind Components	Gill Model 27003 Propellor Anemometer	
Pressure	Rosemount Model 1201 A2G 8BD Pressure Transducer	Temperature of housing controlled to ± 3 C

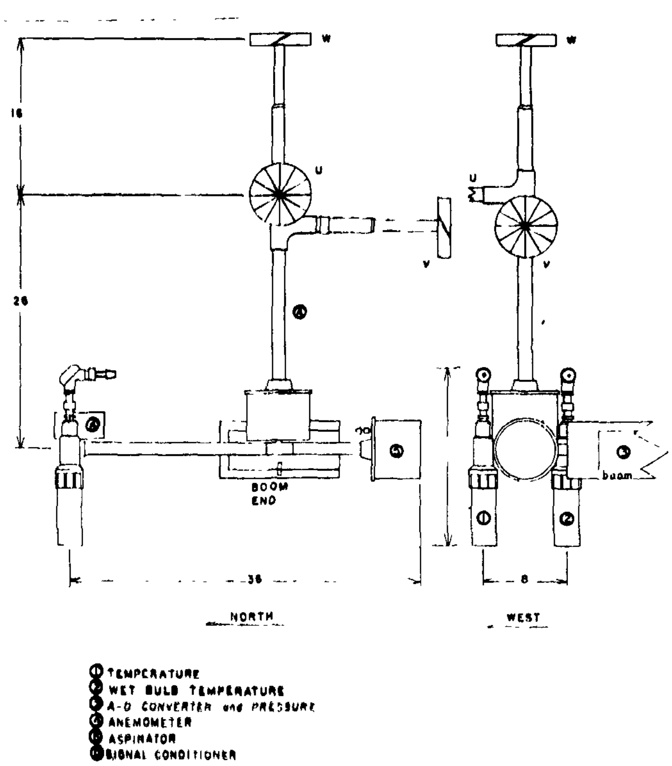


Figure 4. Instrument Package, dimensions in inches. Wind component sensors indicated by letters u, v and w.

DATA ACQUISITION SYSTEM

The data acquisition system (Figure 5) consists of a completely self-contained remote subsystem at each boom, the central data coupler, and recording devices.

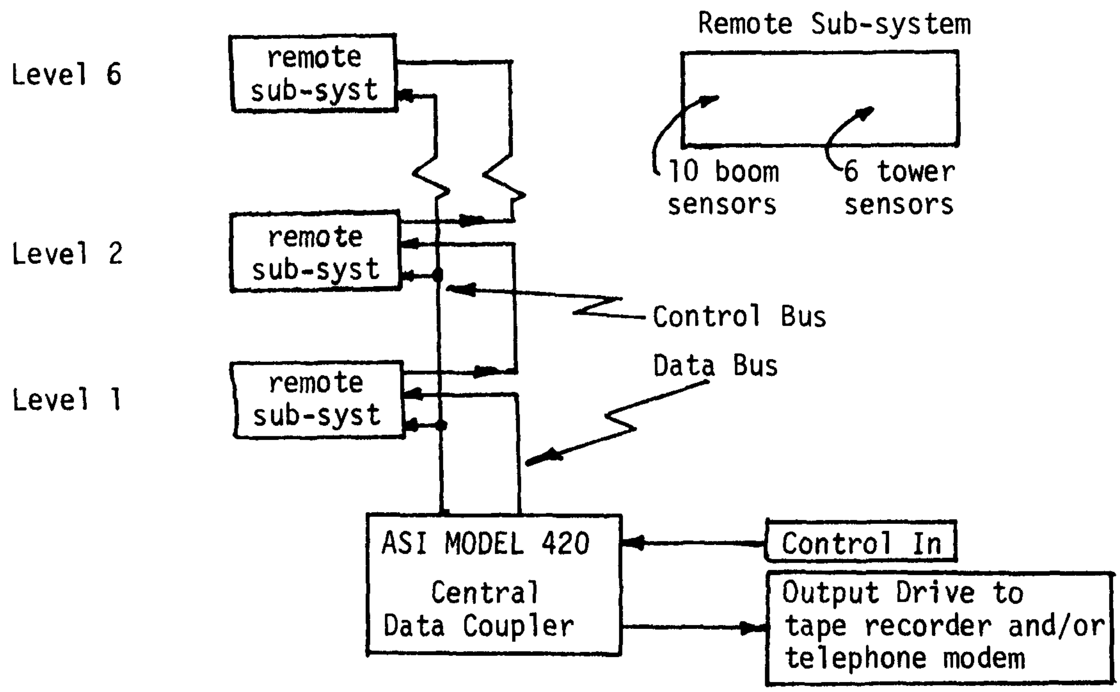


Figure 5. Data acquisition system block diagram.

The remote sub-systems receive analog signals from up to 16 instruments; ten signals from instruments located at the ends of the boom and six from instruments located inside the tower leg. The signal from an instrument passes first through a signal conditioning circuit which sets the zero offset and range. The conditioned signal then passes through an analog to digital converter and then through a differential line driver circuit for transmission down the tower. The digital information is bussed in a "daisy-chain" fashion in series via an individually shielded 32-pair conductor cable to the central data coupler.

The central data coupler is an Ambient Systems, Inc., Model 420 capable of interfacing with a minicomputer, magnetic tape recorder, teleprinter or telephone modem (remote telegraph or similar printer connected to the data coupler via telephone line). The coupler also controls querying each remote sub-system either automatically or manually. As signals are received from a remote sub-system they pass through a BCD interface card where the word format is assembled and converted into computer code. The coupler also inserts end of word, end of record or other gaps as required. An additional interface card provides for other inputs such as real time from a digital clock.

During 1974, data were recorded on a Kennedy Model 1400-1R magnetic tape recorder at IBM low density of 200 bits per inch. During 1975 and 1976 data were recorded on a Kennedy Model 9230 which writes at a higher speed and higher density of 800 per inch. Telephone modems at the Bay Area Air Pollution Control District and San José State University allowed each group to query the tower on an operational basis.

AIR POLLUTION INSTRUMENTATION

Ozone was measured by Dasibi Model 1003 AH Ozone Monitors which operate on the principal of ultraviolet radiation absorbtion. The monitors were housed in thermostatically controlled boxes inside of the west tower leg with 0.25 in ID tubing extending outside the tower.

Prior to installation each summer the instruments were calibrated by the Air and Industrial Hygiene Laboratory (AIHL) of the State of California Department of Public Health (1974 and 1975) or by the California Air Resources Board (1976). The AIHL calibrations used the ARB method using 2% neutrally buffered KI solution or by comparison with calibrated Dasibis.

During 1975 a study by the Ad Hoc Measurement Committee of the California ARB (1975) found that the ARB calibration procedures produced ozone readings that were high by about 25 to 30%. The EPA method, being similar to the ARB method, also read high. We decided that for a better data comparison, and since at the time of the 1975 calibration there was still some uncertainty, the 1975 calibration was done by the ARB "old" method. The 1976 calibrations were done using ultraviolet photometry as the absolute standard. No corrections for the different calibration procedures have been applied, however, if year to year comparisons are desired, a constant adjustment factor of 0.78 should be applied to the 1974 and 1975 data to make them conform to 1976 data.

The initial calibrations performed by the AIHL showed that 30 feet of 0.25 in ID tubing does not affect instrument readings.

Carbon monoxide was measured by ECO-lyser Model 3100 carbon monoxide analysers. The analyser pumps air through a filter system, humidifier and electrochemical sensor. The electrochemical sensor produces an electrical current directly proportional to the CO concentration from an overall reaction of

$$2\ CO + O_2 \rightarrow CO_2$$

Initial lab checks showed that the instruments had a maximum span drift of - 1 ppm CO day^{-1} and a maximum zero drift of - 1 ppm day^{-1}. Rise and fall times averaged about 45 sec for a reading of 90% of a step change in CO.

DATA RECOVERY

While data recovery for the meteorological data package was at an acceptable average of about 80% (Table 3), significant problems hampered air pollutant data recovery. An hourly average value was considered reliable if at least six five-minute instantaneous values were recorded. Tables 4 and 5 list the numbers of hours of each month for each tower level for which valid ozone and CO data were recorded.

TABLE 3. METEOROLOGICAL DATA RECOVERY-TOWER (percent)

Year Month	June	July	Aug	Sept	Oct
1974	100(24th-30th)	68	71	100(1st-24th)	-
1975		86	85	95	49
1976	52	75	88	90	94

TABLE 4. OZONE DATA RECOVERY (hours)

	1974				1975					1976			
Month Level	1	3	5	6		3	4	5	6	1	3	4	5
June	2	98	136	0	67	178	-	85	59	144	111	131	166
July	71	411	305	76	401	402	79	201	132	610	287	356	244
Aug	412	327	201	201	581	224	124	32	-	490	539	434	380
Sept	535	343	439	338	115	135	91	147	-	0	357	0	230
Oct	-	-	-	-	0	33	38	72	Note: Dash = no instrument installed				

TABLE 5. CO DATA RECOVERY (hours)

	1975				1976			
Month Level	1	3	4	5	1	3	4	5
June	139	120	0	210	69	277	241	222
July	452	182	92	528	575	408	660	659
Aug	620	297	154	274	443	564	612	681
Sept	575	474	216	312	597	0	690	690
Oct	259	342	324	321				

Data Recovery, 1974

During the presence of stratus at the tower, water was often drawn into the air sampling lines, plugging them and causing a zero reading on the ozone monitor. In order to test whether meteorological conditions were independent of whether or not the ozone monitors worked, wind direction frequency distributions were calculated for those hours when the ozone monitors recorded valid observations and for hours of missing data. If the ozone monitors malfunctioned in a random manner, then ratios of the frequencies of the two distributions should be constant over wind direction. The results showed that the ozone monitors worked relatively more often with easterly winds than with westerly winds. Since stratus conditions in San Francisco are associated with westerly winds we can conclude that the data for 1974 are biased towards clear conditions. Change of the tube configuration seemed to solve this problem.

Data Recovery, 1975

Data recovery for ozone fell to unacceptable levels in 1975 (Table 4) due to intermittent failure of O_3 readings to be recorded on the magnetic tape. Telephone modem readings obtained from the central processing unit by San José State and the Bay Area Air Pollution Control District indicate that the ozone monitors were working properly during times when no readings were recorded on magnetic tape. The cause of this intermittent failure is still baffling. Since all signals are conditioned at the remote sub-station electronics located at the instrument booms before being transmitted to the central processing unit, it would seem that either all signals should be recorded or none. The only significant change in the data processing system between 1974 and 1975 was replacement of the magnetic tape recorder, and so the problem most likely was in the interface between ozone monitor and data processing-tape recorder system. In addition, there is some indication that data recovery was lower at points where measured stray radiation from transmitting antennas was highest (levels 4 and 5). Whatever the problem, slowing down the scan rate ultimately seemed to solve this problem.

Data Recovery, 1976

Air pollution data recovery for 1976, while better than that for 1975, rose to the just barely acceptable level (Tables 4 and 5). While the O_3 recording problems of the previous year seemed to have been solved, ozone monitors failed at a fairly regular rate. This failure rate was probably due to the fact that the monitors were in their third season in a rather hostile environment.

Discussions with technicians of the BAAPCD indicate that one of the causes of failure may have been the number of times each instrument was turned off and on. According to their experience an instrument should be kept running as nearly continuously as possible. Each time an instrument is turned on causes a power surge. Their technicians, for example, try to remove the optical path tubes for cleaning while the instrument is kept running. The location of our instruments, however, required turning the instrument off, removing it from its housing, cleaning the optics at the base of the tower, turning on the instrument to check readings and then replacing it on the tower housing. Therefore, the instrument was turned on at least once and usually twice for each routine maintenance. Troubleshooting usually required more off-on cycles.

The effects of strong radio and TV radiation and relatively high temperatures in aging electronic components can only be guessed.

Miller (1976) also remarks on the difficulty in getting periods when all instruments worked properly.

SECTION 5

MEAN SUMMER BEHAVIOR

The mean summer distribution of meteorological and air pollution parameters is governed during the summer and early fall by the buildup and decay in the strengths of the Pacific High and Central Valley low pressure systems and the resulting progression of the summer portion of the California monsoon. Local heating and cooling patterns produce diurnal land-sea and slope winds which interact with this monsoon flow and with modifications of this flow produced by synoptic scale pattern changes. This section will review some relevant aspects of previous studies and summarize measurements of the mean behavior of meteorological parameters at the Sutro Tower.

SURFACE PATTERNS

Schroeder, et al. (1967) and Root (1960) reviewed the summertime climate patterns of the central California area. The Pacific Coast monsoon slowly transports mass onshore in both the marine and inversion layers from late spring until fall. The Pacific High and the Central Valley heat low produce a maximum onshore pressure gradient of about 1.9 mb per 100 km during July. Figure 6, from Root (1960) shows the greatest difference in mean maximum temperatures between Sacramento and San Francisco as well as the strongest afternoon winds occur in July. These measures of the strength of the monsoon are nearly as strong in August and decrease significantly in September.

Superimposed on the onshore monsoon flow is a diurnal circulation over the Bay Area, largely caused by diurnal variations in the Central Valley-Bay Area temperature differences. This circulation is, however, complicated by local heating and cooling effects caused by the Bay itself and by the complicated topography of the area. Root (1960) shows that summertime surface wind speeds are generally lightest at about sunrise and strongest in the late afternoon. Root also shows that the diurnal range in wind speeds along a line from the Farallon Islands to Sacramento is greatest at the coastline and decreases rapidly in either direction.

Figure 7 (Root, 1960) shows typical summer afternoon flow patterns and maximum temperatures for the Bay Area. Marine air reaches the Bay Area primarily through the Golden Gate, but also through smaller or higher gaps in the Coastal Mountain Range. Upon reaching the inland side of the coastal range the main portion of the flow diverges; the northern branch traversing San Pablo Bay ultimately reaching the central valley via the Carquinez Straits. The southern fork flows mainly to the Santa Clara Valley with a portion branching into the Livermore Valley.

Fosberg and Schroeder (1966) discuss the interaction of the sea breeze

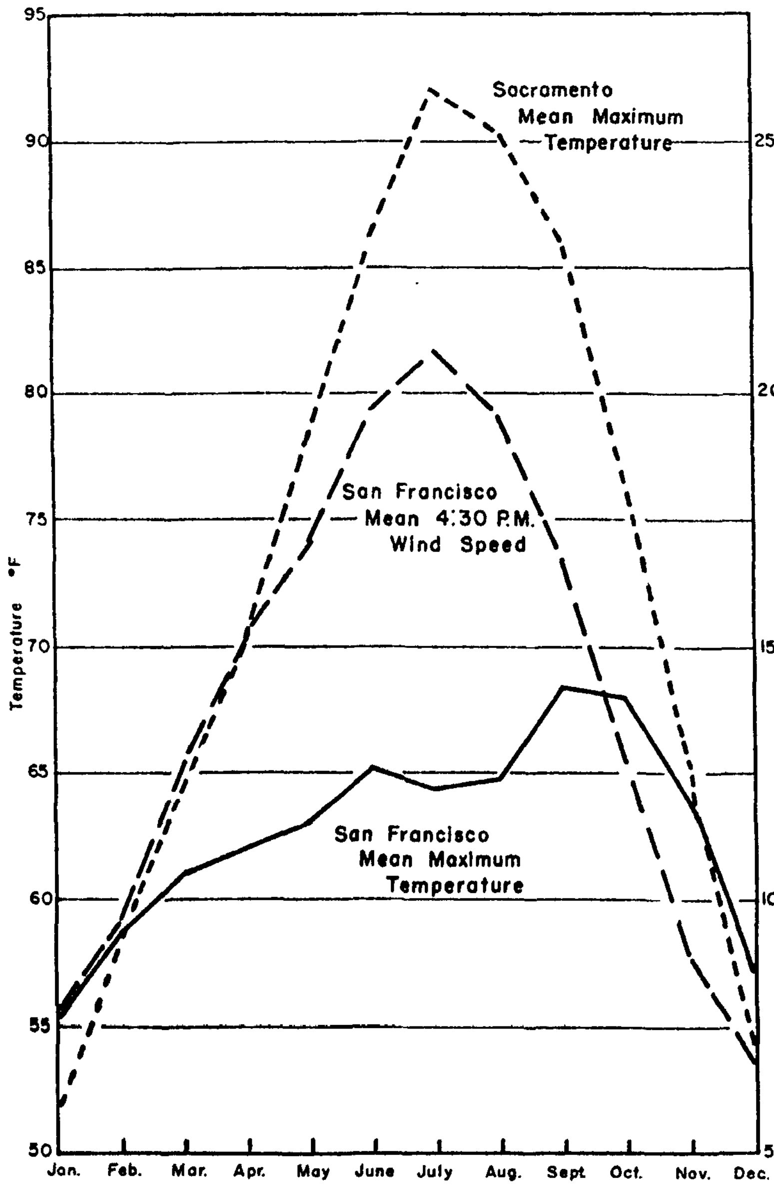
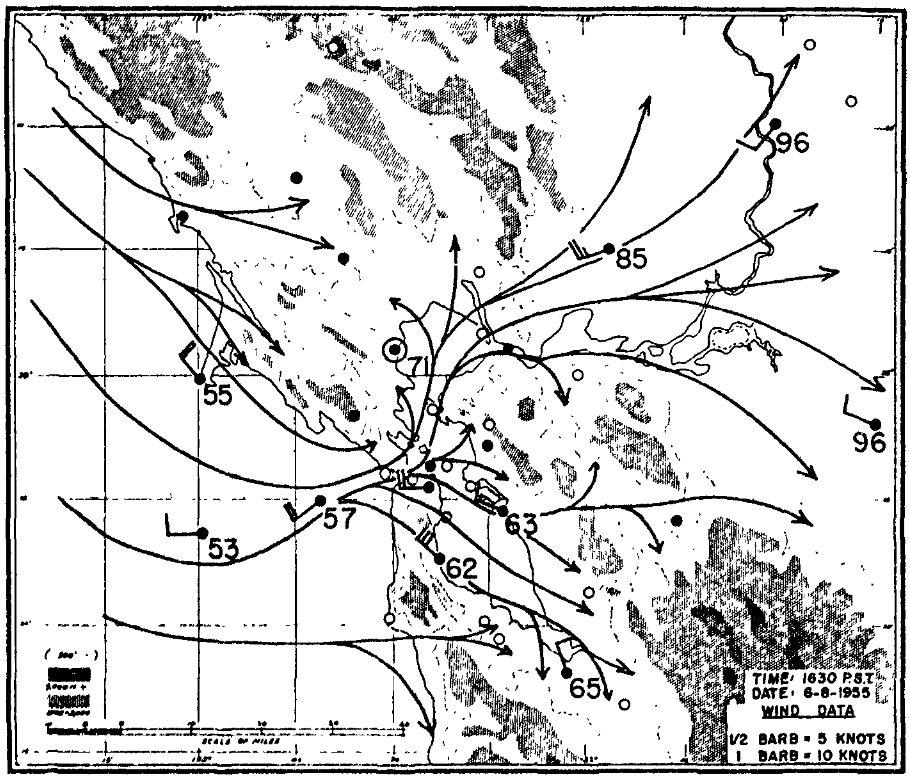


Figure 6. Mean maximum temperature for Sacramento and San Francisco and mean afternoon wind speed for San Francisco (Root, 1960).

with the synoptic situation and illustrate with one case study. When upper air features showed a ridge or fairly flat contour gradient and a lobe of the subtropical high at the surface extending inland over the Pacific Northwest, a "warm sea breeze" occurred. As they describe the situation, a sea breeze front, characterized by a wind shear line with cool air seaward and warm air inland, begins to move inland from the coast after sunrise. By about 11 PST, however, surface heating modifies the leading edge of the marine air producing a quasi-stationary temperature gradient zone and a wind shear line which continues to penetrate inland. No attempt was made to establish a mechanism for the inland penetration of the shear line after the density discontinuity has

Figure 7. Generalized afternoon flow pattern of marine air in the San Francisco Bay Area under typical summer conditions. The observed temperatures at 1630 PST are entered to illustrate the cooling effect of the sea breeze. (Root, 1960)



been removed.

Figure 8 (Fosberg and Schroeder, 1966) shows cross sections, running from Napa (Station 24, Figure 3) to the coast, of the west wind component and temperature for a time when the wind shift line and temperature gradient were coincident. Winds were light with slight easterly components above the inversion base. Ahead of the sea breeze front within the marine layer westerly wind speeds decreased rapidly.

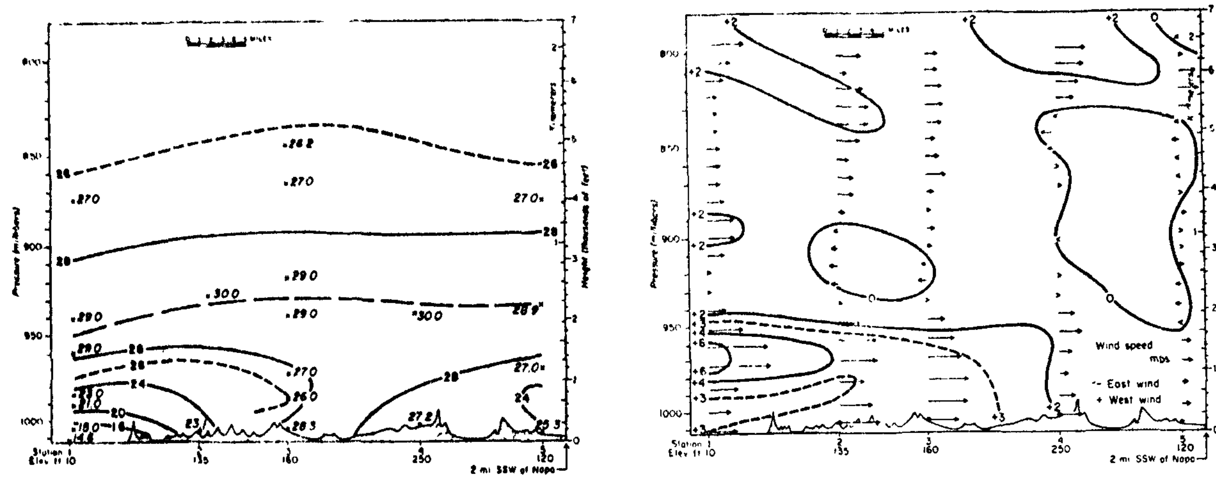


Figure 8. East-West cross sections of temperature (left) and west wind component (right) 10 PST, 15 August 1962. (Fosberg and Schroeder, 1966).

UPPER AIR PATTERNS

The July 1972 mean morning and afternoon Oakland and San Jose soundings (Figure 9) shows typical summertime inversion conditions over the Bay Area. The base of the inversion over Oakland is highest at 04 PST and lowest at 16 PST. At 04 PST the inversion base over San Jose is lower than over Oakland, while at 16 PST surface heating has essentially destroyed the inversion layer over San Jose.

Wind directions in the marine layer over San Jose indicate the typical surface layer diurnal wind reversal. If the top of the morning marine layer is defined as the point at which the mixing ratio begins to decrease rapidly, then the morning marine layer winds are down valley (about 140 deg.). While the afternoon marine layer is less distinct, there is a nearly constant mixing ratio below about 550 m with a decrease above. Winds in the first about 600 m are upvalley (about 310 deg.). This oscillation is produced by a combination bay-land breeze and slope breeze circulation.

TEMPERATURE

Miller (1976) has reported on some aspects of the mean behavior of the inversion layer over San Francisco as determined by measurements made from the Mt. Sutro T.V. tower. The average inversion base height is about 300 m ASL with a mean temperature increase above measurement Level 2 of 2.2 C/100 m. Temperature gradients as large as 12C/20 m have been observed just above the inversion base.

Figures 10 a, b, c show typical July, August and September temperature time sections at the Sutro Tower. Isotherms are highest between about 02-06 PST and lowest at 16-18 PST. The inversion base on individual days follows the same pattern. The mean diurnal temperature waves (Fig. 11) show that the diurnal temperature range is greatest at Levels 5 and 6 (4-6C) and least near Level 2 (1.5-2C).

WINDS

Figures 12, a, b, c show the average diurnal wind speed fluctuations for July-September 1974. The maximum wind speeds occur at 18-19 PST and the minima at about 09 PST at each level. Level 5 at about 100 m above the inversion base has the greatest average wind speed as well as the largest diurnal range. Both the average speed and diurnal range decrease from July to September. 1975 (Miller, 1976) and 1976 wind patterns (not shown) show similar patterns.

1974 summer wind roses (Fig. 13) show that winds are from the west 30 to 50 percent of the hours at all measurement levels. Winds at Levels 1-3, typically in the marine layer are usually slightly south of west, while those at Levels 4-6, typically in the inversion layer are typically more north of west.

Wind speeds from the westerly sectors average between 4.5 to 6.5 m sec^{-1} except near the surface. Average speeds from the easterly sections are about 1 to 3 m sec^{-1}.

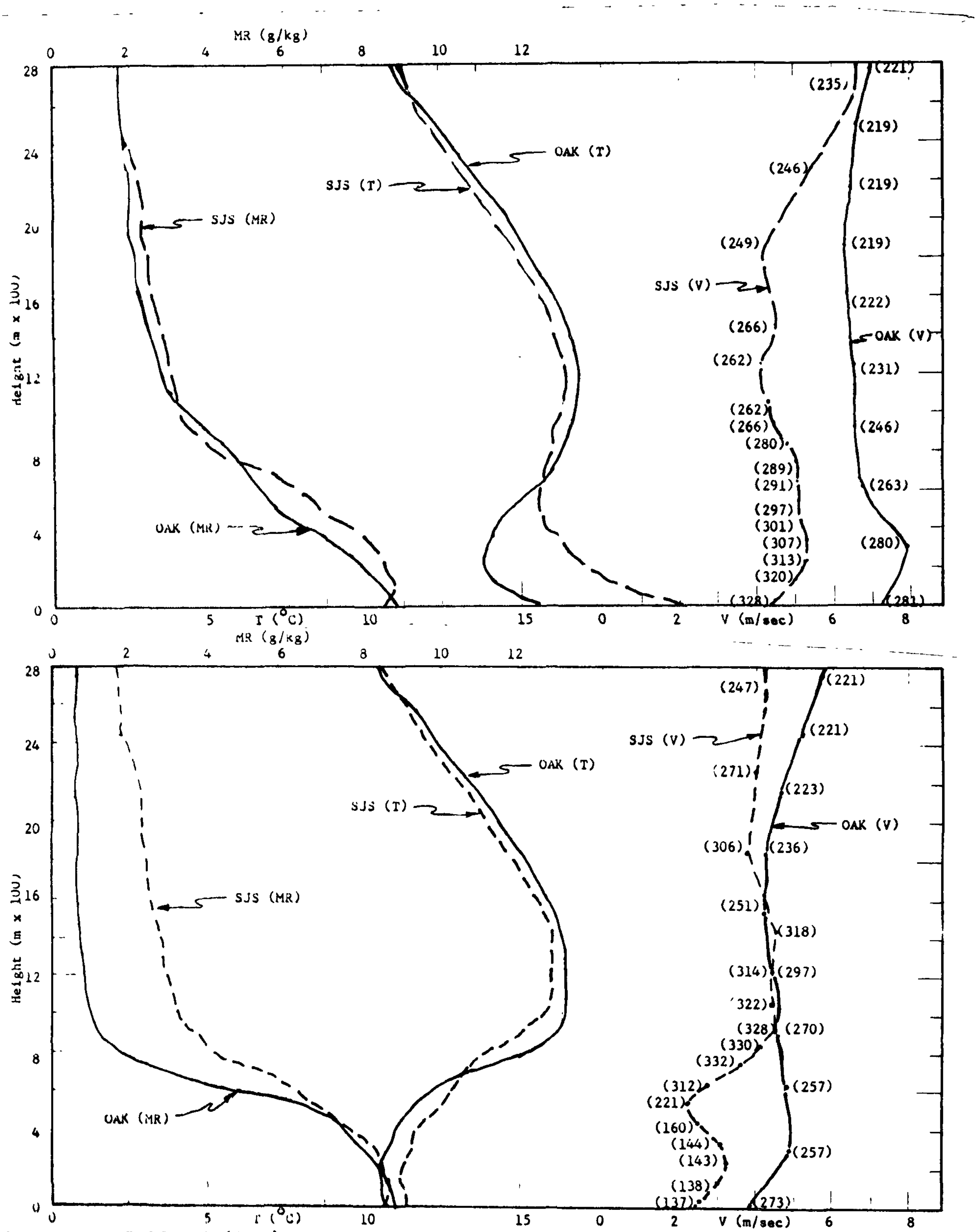


Figure 9. Oakland (OAK) and San Jose State (SJS) mean soundings for July 1972. Temperature (T), mixing ratio (MR), wind speed (V) and wind direction (in parentheses) profiles for morning (upper; 04 PST, OAK; 0630 PST, SJS) and afternoon (lower; 16 PST, OAK; 12 PST, SJS).

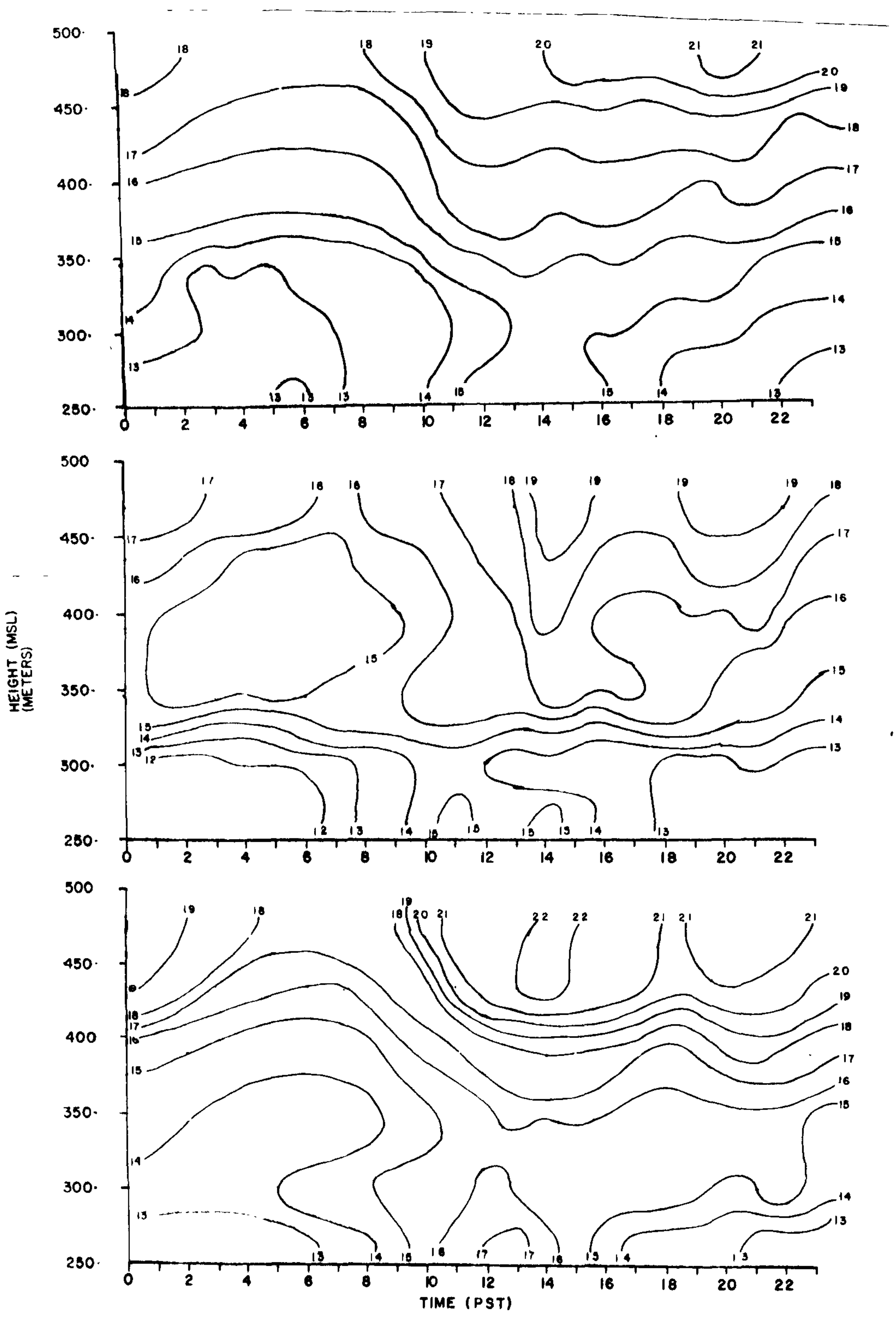


Figure 10. Time-height sections of hourly average temperature, Mt. Sutro Tower, July (upper), August (middle) and September (lower), 1974.

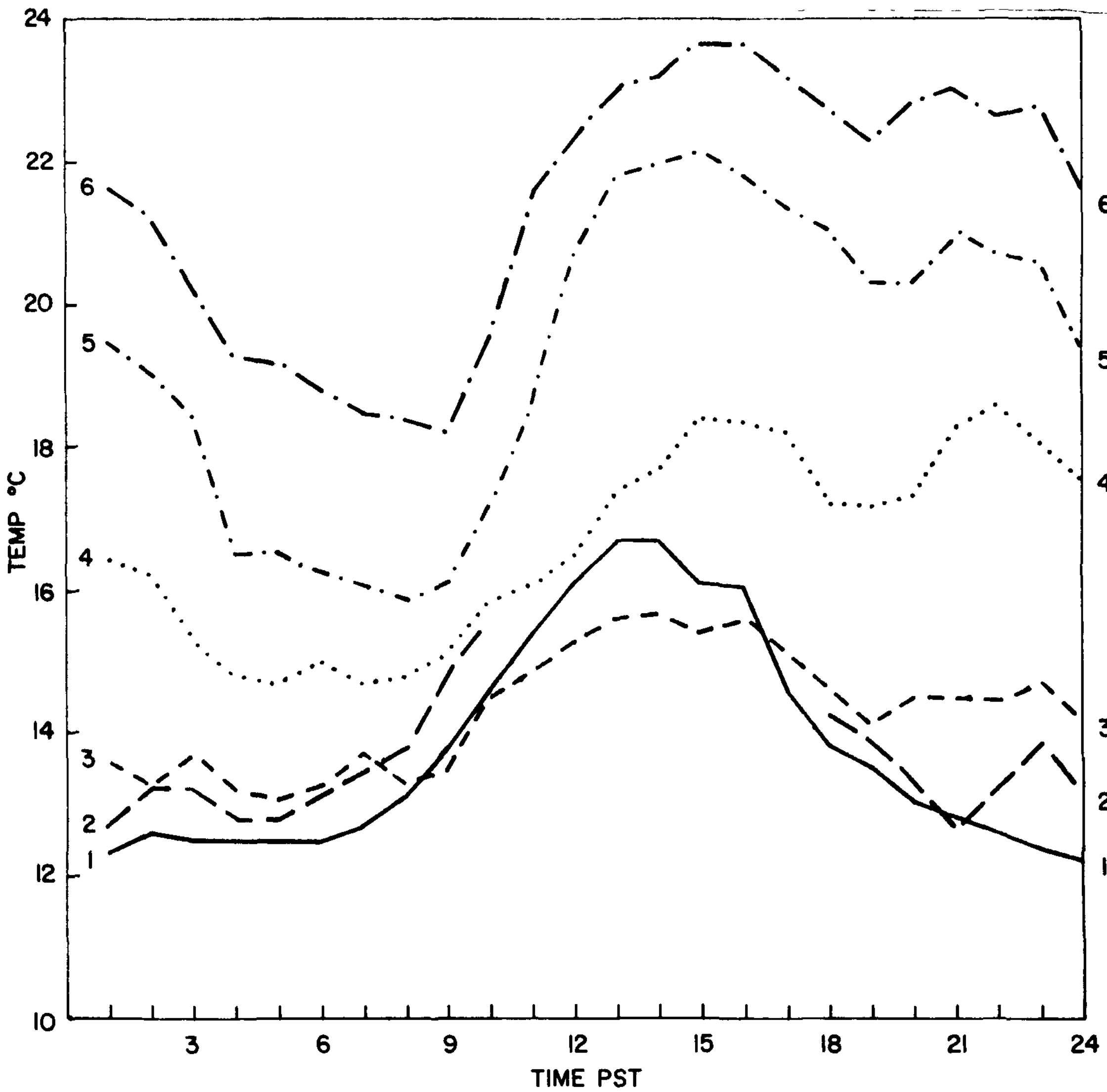


Figure 11. Hourly average temperatures, Mt. Sutro T.V. Tower, September 1974. Numbers at right indicate measurement level.

VERTICAL VELOCITIES

Figure 14 shows the average vertical velocity profiles for July and August 1974 (Miller, 1976). Large downward vertical velocities of 40 to 100 cm sec^{-1} and upward velocities of 30-60 cm sec^{-1} indicate the strong vertical convergence within the inversion layer. Miller (1976) attributes the vertical velocity pattern to a quasi-stationary standing wave with its trough normally lying a short distance east of the tower. He speculates that the wave has its greatest amplitude about 18 PST, when the inversion base is lowest, and smallest amplitude about 06 PST, when the inversion base is highest.

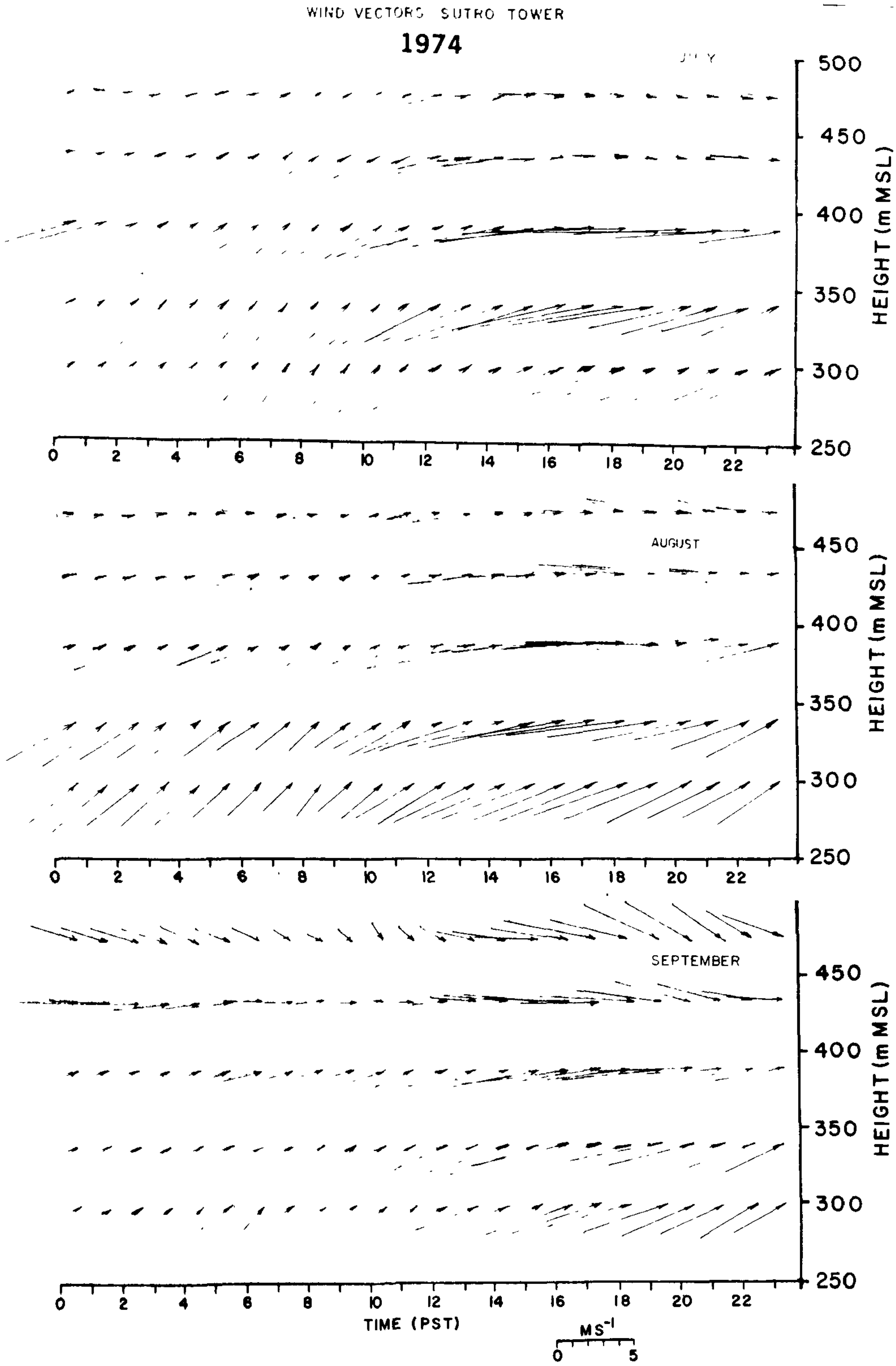


Figure 12. Monthly average vectors of horizontal wind Mt. Sutro Tower, July (top), August (middle), and September (bottom), 1974.

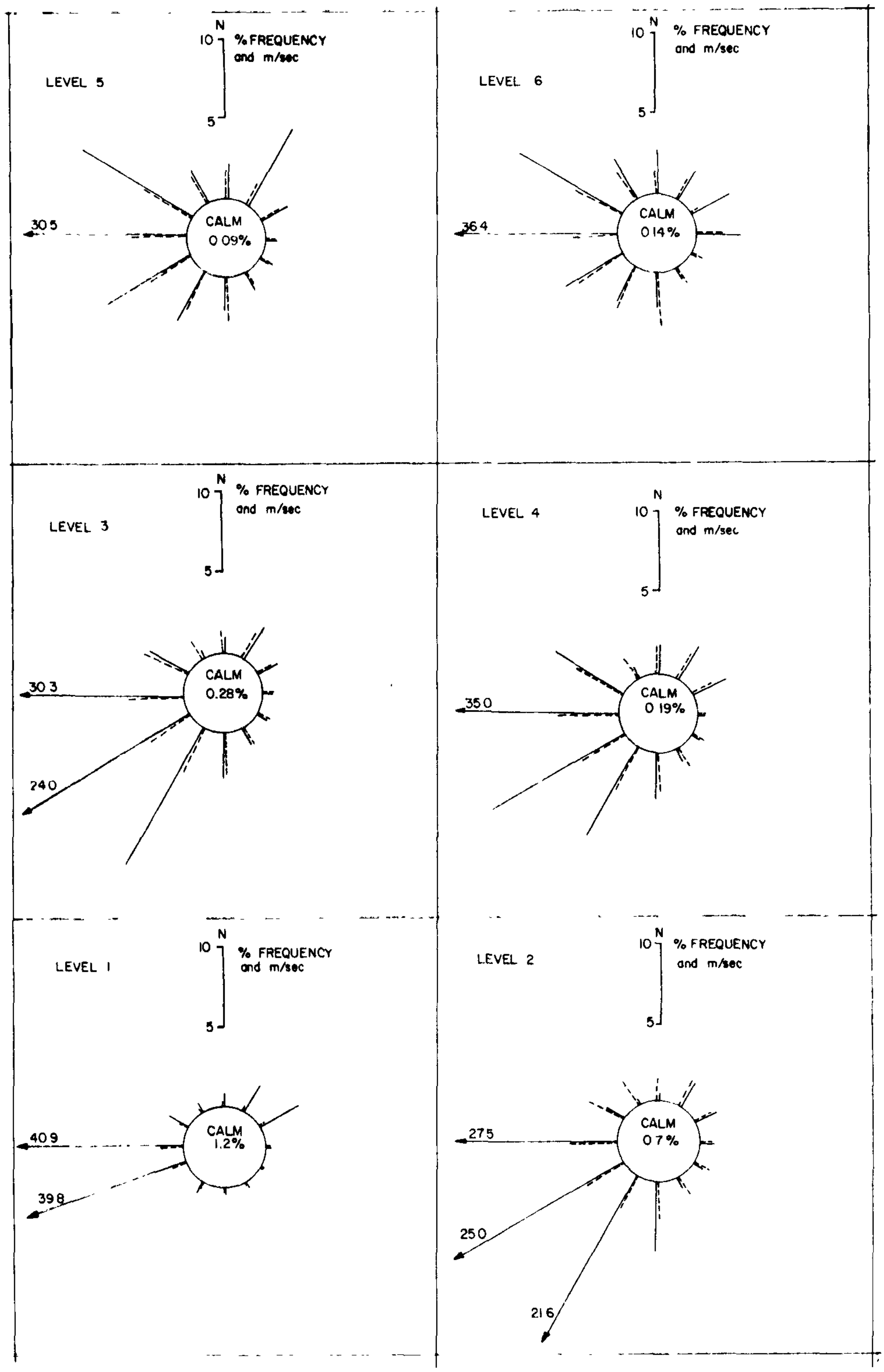


Figure 13. Wind roses at Sutro Tower, summer 1974. Solid lines represent % frequency, dashed lines represent wind speed.

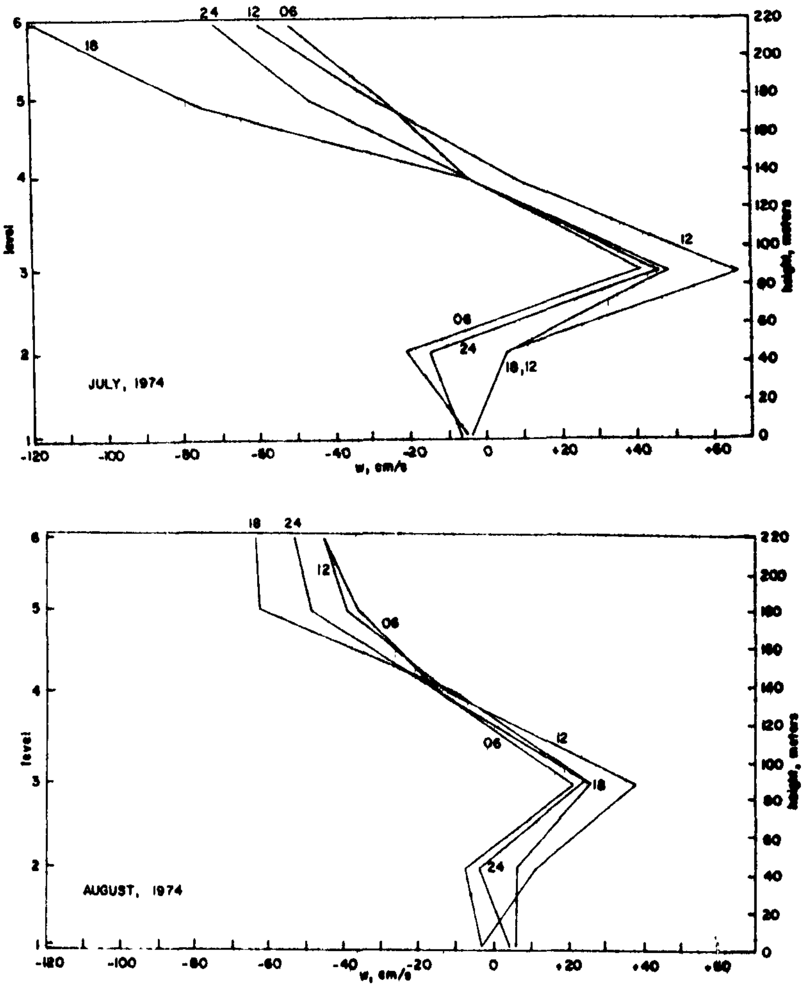


Figure 14. Mean vertical velocity distributions at Mt. Sutro Tower for July (upper) and August (lower) 1974. Times of observation (PST) indicated on profiles.

MEAN OZONE BEHAVIOR

Surface Distribution of Oxidants

Figure 15 (BAAPCD, 1976) shows the mean number of days with oxidants exceeding 8 pphm. The greatest number of NAAQS excesses occur in the inland Livermore Valley with the eastern side of the Santa Clara Valley experiencing nearly as many excesses.

Ozone Frequency Distributions

Figure 16 shows the co-cumulative frequency distributions of the hourly average values of ozone concentrations for the summers of 1974 through 1976. Note that the 1974 and 1975 data were obtained using the "old" ARB standard of calibration, while 1976 data were obtained under the "new" calibration method. Some ramifications of this difference will be discussed below. Table 6 gives values of the cumulative frequency distribution for 1974.

TABLE 6. FREQUENCY DISTRIBUTION OF HOURLY AVERAGE OZONE CONCENETRATIONS, SUTRO TOWER, 26 JUNE to 24 SEPTEMBER, 1974.

CONCENTRATIONS (PPB)	PERCENT OF SAMPLES > STATED CONCENTRATIONS				CASE COUNT
	LEVEL 1	3	5	6	
0	100.00 %	100.00 %	100.00 %	100.00 %	N/A
5	96.96 %	93.70 %	98.34 %	77.22 %	N/A
10	87.55 %	77.11 %	96.21 %	74.80 %	N/A
15	73.73 %	66.55 %	94.45 %	73.34 %	N/A
20	56.08 %	55.74 %	92.70 %	71.41 %	N/A
25	44.02 %	46.47 %	86.97 %	70.76 %	N/A
30	36.57 %	41.62 %	83.83 %	68.98 %	N/A
35	29.80 %	36.77 %	80.04 %	64.46 %	N/A
40	20.10 %	26.30 %	67.74 %	57.03 %	N/A
45	11.96 %	19.57 %	48.98 %	47.50 %	N/A
50	8.14 %	16.60 %	39.28 %	40.55 %	N/A
55	4.80 %	13.36 %	30.50 %	33.60 %	N/A
60	3.24 %	11.66 %	25.32 %	28.59 %	N/A
65	2.45 %	9.70 %	21.72 %	22.78 %	N/A
70	1.86 %	8.85 %	18.76 %	20.68 %	N/A
75	1.47 %	8.00 %	16.54 %	18.90 %	N/A
80	.88 %	7.32 %	14.97 %	16.32 %	N/A
85	.69 %	5.87 %	13.77 %	13.89 %	N/A
90	.29 %	5.36 %	12.29 %	12.92 %	N/A
95	.20 %	4.34 %	10.35 %	11.31 %	N/A
100	.20 %	3.32 %	8.50 %	9.21 %	N/A
105	.20 %	2.38 %	6.75 %	7.59 %	N/A
110	.20 %	2.30 %	5.64 %	6.30 %	N/A
115	.20 %	2.04 %	4.71 %	5.33 %	N/A
120	.20 %	1.96 %	4.16 %	4.68 %	N/A
125	.10 %	1.79 %	3.60 %	4.20 %	N/A
130	.10 %	1.45 %	2.87 %	3.39 %	N/A
135	.10 %	1.11 %	2.13 %	2.42 %	N/A
140	.10 %	.94 %	1.76 %	1.94 %	N/A
145	.10 %	.85 %	1.39 %	1.62 %	N/A
150	.10 %	.85 %	1.11 %	1.13 %	N/A
155	.10 %	.68 %	.92 %	1.13 %	N/A
160	.10 %	.60 %	.83 %	1.13 %	N/A
165	.10 %	.51 %	.65 %	.97 %	N/A
170	.10 %	.51 %	.46 %	.65 %	N/A
175	.10 %	.51 %	.46 %	.65 %	N/A
180	.10 %	.34 %	.46 %	.65 %	N/A
185	.10 %	.34 %	.37 %	.65 %	N/A
190	.10 %	.26 %	.37 %	.48 %	N/A
195	.10 %	.26 %	.37 %	.32 %	N/A
200	.10 %	.26 %	.37 %	.32 %	N/A
205	.10 %	.26 %	.28 %	.16 %	N/A
210	.10 %	.26 %	.28 %	.16 %	N/A
215	.10 %	.17 %	.28 %	.16 %	N/A
220	.10 %	.17 %	.28 %	0 %	N/A
225	.10 %	.17 %	.18 %	0 %	N/A
230	.10 %	.09 %	.09 %	0 %	N/A
235	.10 %	.09 %	.09 %	0 %	N/A
240	.10 %	.09 %	.09 %	0 %	N/A
245	.10 %	.09 %	.09 %	0 %	N/A
250	.10 %	0 %	.09 %	0 %	N/A
255	.10 %	0 %	.09 %	0 %	N/A
260	.10 %	0 %	.09 %	0 %	N/A
265	.10 %	0 %	0 %	0 %	N/A
270	.10 %	0 %	0 %	0 %	N/A
275	.10 %	0 %	0 %	0 %	N/A
280	.10 %	0 %	0 %	0 %	N/A
285	.10 %	0 %	0 %	0 %	N/A
290	.10 %	0 %	0 %	0 %	N/A
295	.10 %	0 %	0 %	0 %	N/A
300	.10 %	0 %	0 %	0 %	N/A
305	0 %	0 %	0 %	0 %	N/A
310	0 %	0 %	0 %	0 %	N/A
315	0 %	0 %	0 %	0 %	N/A
320	0 %	0 %	0 %	0 %	N/A
325	0 %	0 %	0 %	0 %	N/A
330	0 %	0 %	0 %	0 %	N/A
335	0 %	0 %	0 %	0 %	N/A
340	0 %	0 %	0 %	0 %	N/A
345	0 %	0 %	0 %	0 %	N/A
350	0 %	0 %	0 %	0 %	N/A
CASE COUNT	1020	1175	1082	619	

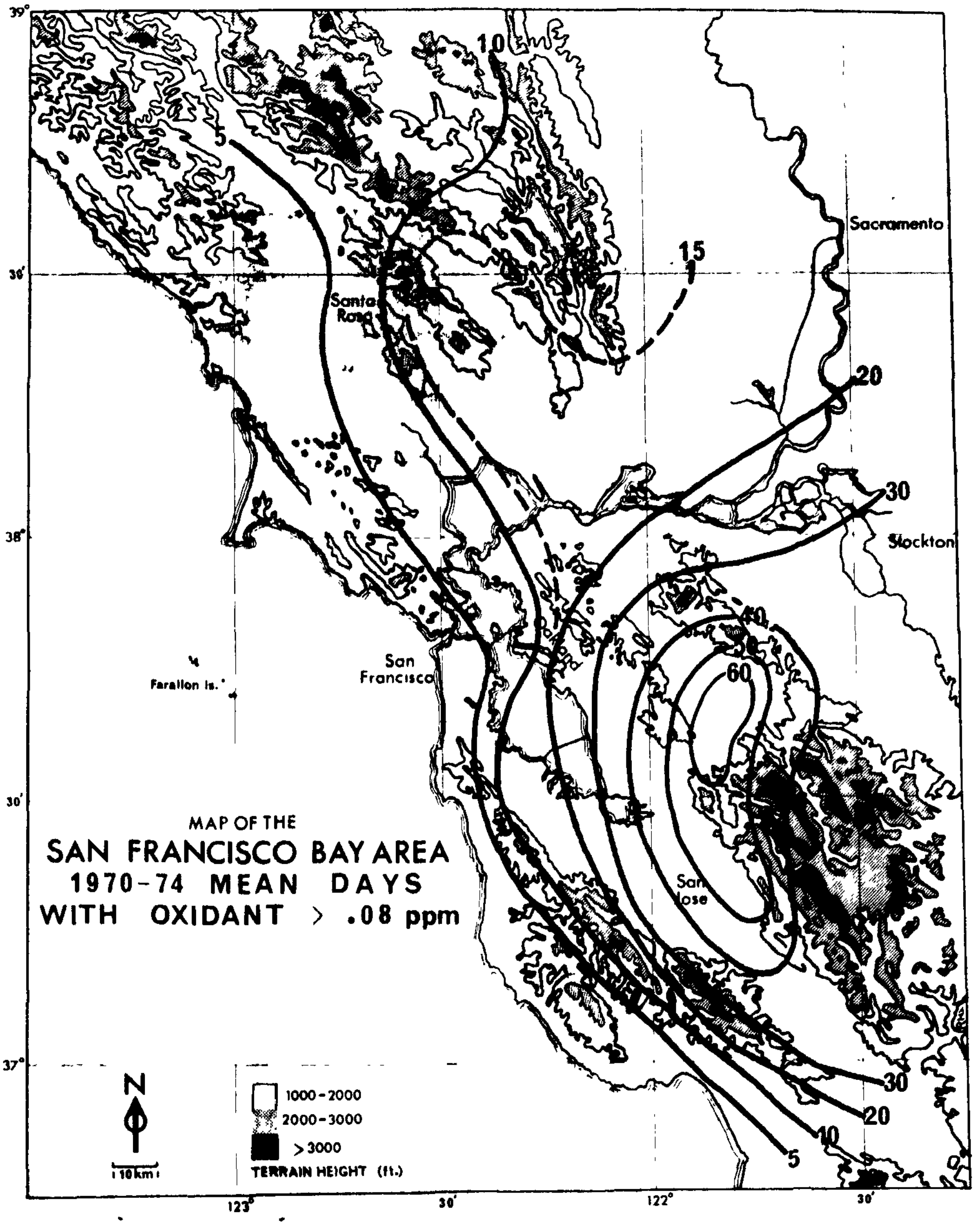
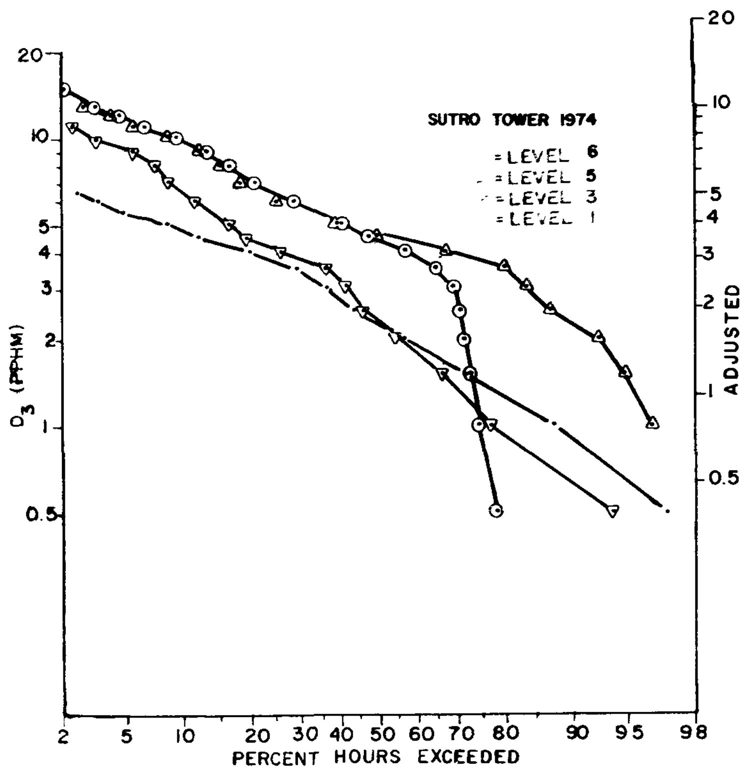
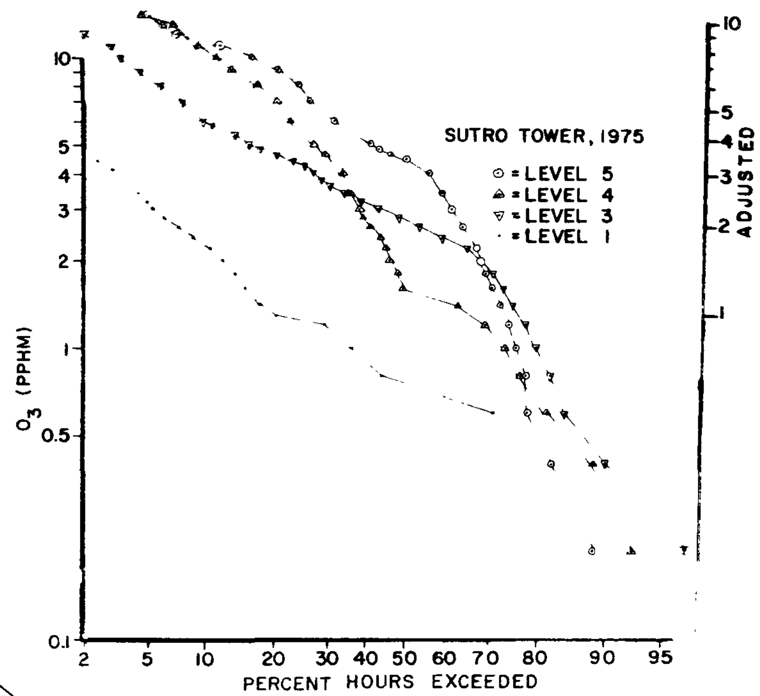


Figure 15. Mean number of days during 1970-1974 with oxidants exceeding 8 pphm (BAAPCD, 1976).

For each year the distributions show that concentrations in the inversion layer (Levels 3-6) are higher than those within the marine layer. The O_3 concentrations within the inversion layer exceeded the 8 pphm NAAQS between 6 and 25% of the hours recorded during 1974 and 1975. The distribution for 1975 overestimates the frequency of hours exceeding the 8 pphm level due to the recording difficulties mentioned in Section 4. Inspection of the monthly summaries for that year indicate that during periods of high O_3 concentrations data were more consistently recorded, possibly indicating that instrument voltages above some threshold value made it through our electronic





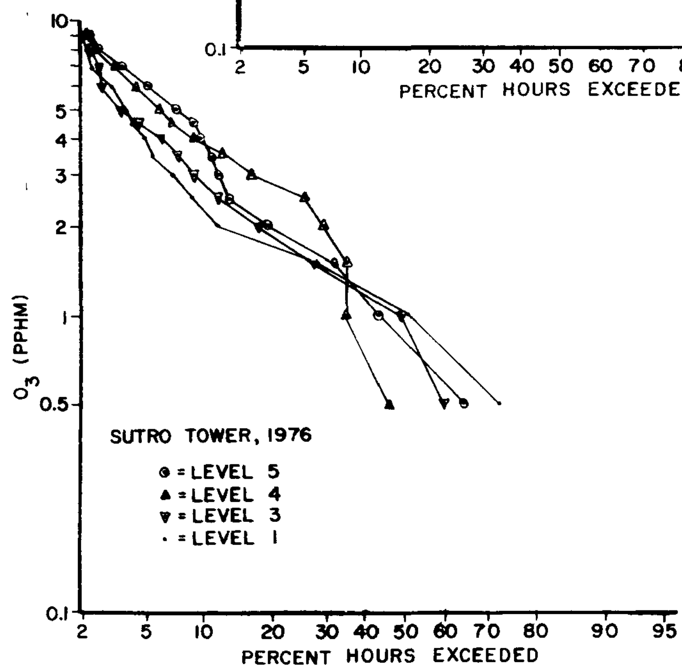


Figure 16. Co-cumulative frequency distributions of ozone at Sutro Tower, 1974, 1975, 1976.

maze. Thus the 138 measured hours of ozone concentrations exceeding 8 pphm at Level 5 during 1975 compares favorably with the 163 hours at that level during 1974, but represents a higher percentage of hours of recorded data. Inspection of Table 7 below indicates that at least for 1974 the percentage of the hours exceeding the 8 pphm NAAQS at selected BAAPCD surface stations is not too different than in the inversion layer at Mt. Sutro TV Tower.

TABLE 7. PERCENT OF HOURS EXCEEDING 8 PPHM
OXIDANTS AT SELECTED BAY AREA STATIONS, JULY-SEPTEMBER 1974

Station	Livermore	San Jose (4th St.)	Los Gatos	Walnut Crk.
% hrs >8 pphm	21	19	16	6.0

Some indication of the consequences of the adoption of new ozone monitor calibration standards by the California ARB between the summers of 1974 and 1975 can be seen from Table 8 which shows the number of hours exceeding 8 pphm at the same selected BAAPCD surface stations.

TABLE 8. NUMBER OF HOURS EXCEEDING 8 PPHM
AT SELECTED BAY AREA STATIONS, JULY-SEPTEMBER 1974 and 1975

Station	Livermore	San Jose (4th St.)	Los Gatos	Walnut Crk.
Hrs >8 pphm (1974)	269	233	196	84
Hrs >8 pphm (1975)	49	73	71	49

The ordinates on the right in Figure 15 for 1974 and 1975 reflect the calibration adjustment factor of 0.78. This adjustment indicates that the 8 pphm NAAQS was exceeded within the inversion during 3 to 9% of the measured hours during 1974 and 1976. As mentioned above, percent of measured hours exceeding 8 pphm during 1975 (11% at Level 4 and 16% at Level 5) are overestimations, while the 38 hrs. at Level 4 and 82 hrs. at Level 5 compare relatively well with surface data shown in Table 8.

While there are differences in detail, there is some indication that high concentrations at Level 5 (about 100 m above the mean inversion base) occur more often than at other levels.

The distributions shown in Figure 16 seems to fit the log-normal distribution at concentrations above about 2-3 pphm. A definite break occurs in some distributions; Level 6 during 1974, for example, could well be described by two straight lines on the log-normal distribution. Such a plot suggests sampling from two different populations. Such a distribution may occur due to the fact that O_3 concentrations are controlled both by wind speed and temperature. Since wind speeds are ordinarily log-normally distributed and temperatures normally distributed, the O_3 distributions could be composed of these two distributions.

Mean Diurnal Variation of O_3

Figure 17 shows the mean diurnal variation of O_3 for September, 1974, a month of consistently valid ozone data. Other months show similar patterns.

During the first six hours of the day O_3 concentrations at Levels 1, 3 and 6 fluctuate near 3.5 pphm, while concentrations decrease at Level 5 from 6 pphm to about 5. Near sunrise concentrations at Level 6 increase, those at Level 5 remain constant and those within the marine layer decrease somewhat, perhaps due to morning emissions of O_3-destroying NO_x. By about 09 PST concentrations at all levels increase until a maximum of 8 pphm is reached near 15 PST.

A secondary minimum occurs in the early evening, the time of minimum occurring later with height, at about 17 PST at Levels 1 and 3 and about 19 PST at Level 6. A secondary maximum occurs near 21 PST, with Level 5 recording the highest values. Similar nocturnal maxima have been reported by Teichart (1955, see Geiger, 1965, p. 134) and by Perl (1965, see Reiter, 1971, p. 149).

O_3 Variation with Wind Direction

Wind direction frequency distributions calculated for various O_3 concentration intervals would be biased by the prevailing westerly wind direction. Figure 18 shows the ratio of percent occurrence of wind direction with O_3 concentrations greater than or equal to 8 pphm to the percent occurrence of wind direction with O_3 concentrations less than 8 pphm for the summer of 1974.

At Levels 5 and 6, high ozone occurs most frequently with northerly through easterly winds. The pollution rose for Level 3 is not as statistically significant, but is included for completeness. High O_3 concentrations at Level 3 occur primarily with northwesterly directions with a secondary occurrence with easterly winds.

A break-down of the approximately 15% of the measured hours above 8 pphm at the upper measurement levels is not statistically warranted. However, wind direction frequency distributions for hours with O_3 above 8 pphm were calculated for each four-hour period during the day. Figure 19 shows that high O_3 concentrations occur with easterly directions primarily before noon and with westerly directions primarily between sunset and midnight.

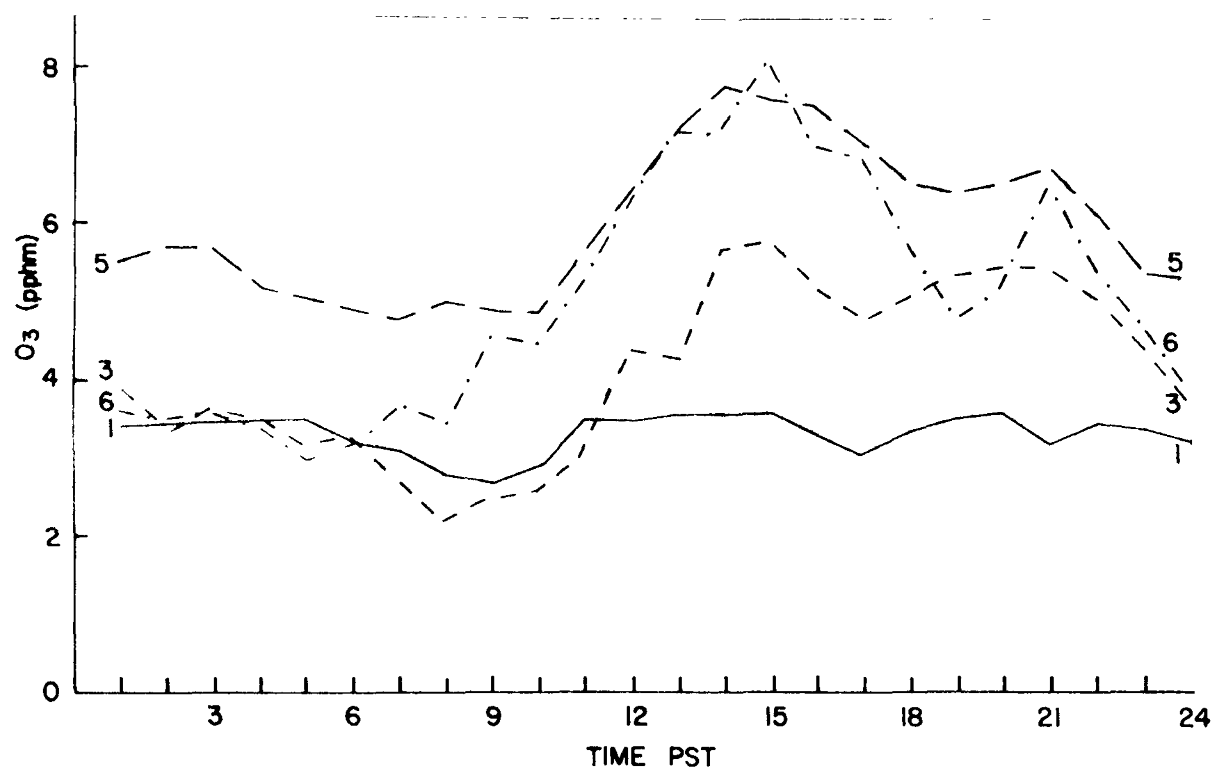


Figure 17. Mean diurnal variation of ozone, Sutro Tower, September, 1974.

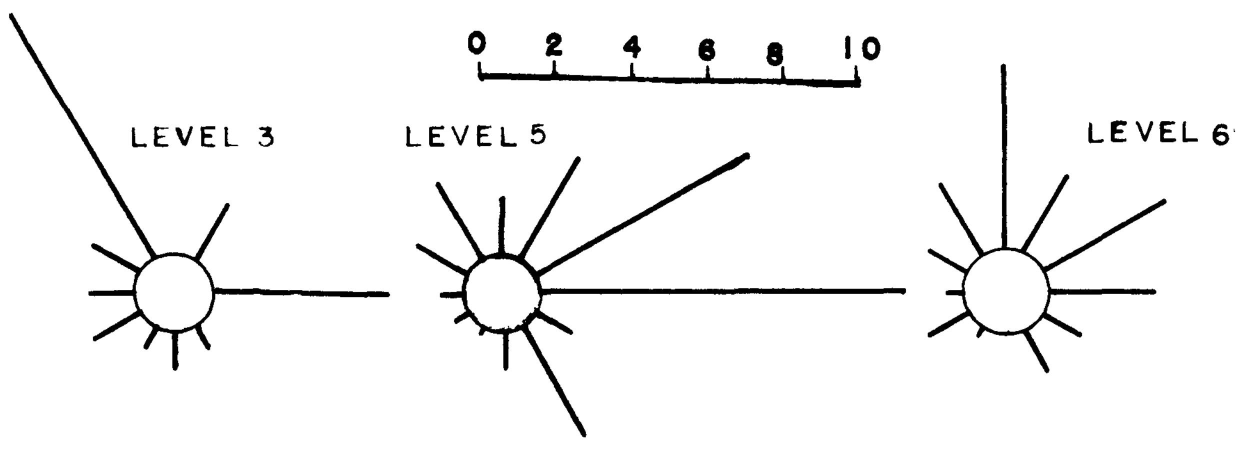


Figure 18. Distribution of the ratio of wind direction for hours with $O_3 \geq 8$ pphm to those with $O_3 < 8$ pphm. Sutro Tower, Summer, 1974. Calms not included.

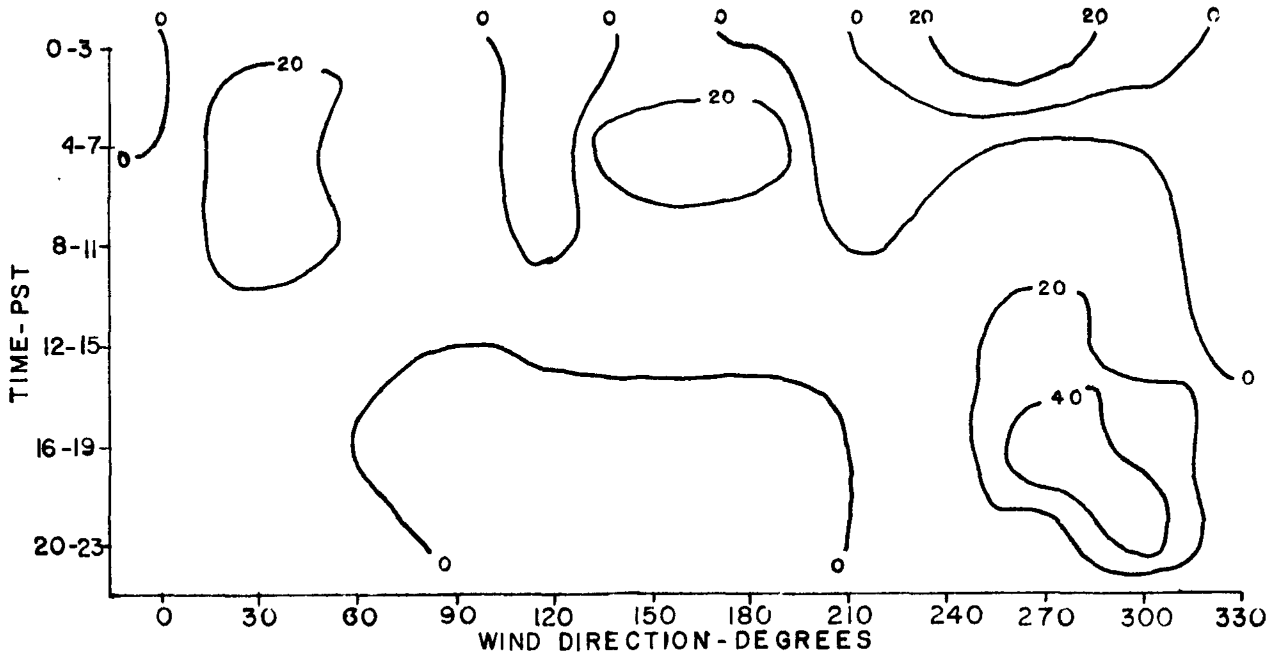


Figure 19. Diurnal distribution of wind direction percent frequency for hours with O_3 concentrations $\geq$ 8 pphm. Level 5, Sutro Tower, summer 1974.

Auxiliary Data - Quillayute, Washington

Ludwick, et al. (1976) reported on simultaneous surface measurements of O_3 and radionuclides of upper tropospheric and/or stratospheric origin at rural Quillayute, Wa. They found that high hour O_3 concentrations of 5 to 6 pphm occurred on days of high radionuclide measurements, indicating stratospheric origin of O_3 at this location.

Co-cumulative frequency distributions of the hourly O_3 concentrations at Quillayute calculated from data supplied by Ludwick show that the 90-th percentile concentration (Table 9) for September 1974 was the highest of the months June-October, 1974.

TABLE 9. MEDIAN AND 90TH PERCENTILE HOURLY AVERAGE O_3 CONCENTRATIONS (PPHM) QUILLAYUTE, WA. 1974

Month	June	July	August	September	October	June-October
Median	3.1	2.6	2.1	2.9	2.4	2.6
90%-ile	4.0	3.5	3.5	4.6	4.0	4.0

Figure 20 shows that the frequency distributions for measurement Level 1 at the Sutro Tower for the summer 1974 and for Quillayute for the period June-October, 1974 are similar at low concentrations. At high concentrations, the effects of pollution are shown by the slightly higher concentrations measured in San Francisco at the high end of the distribution.

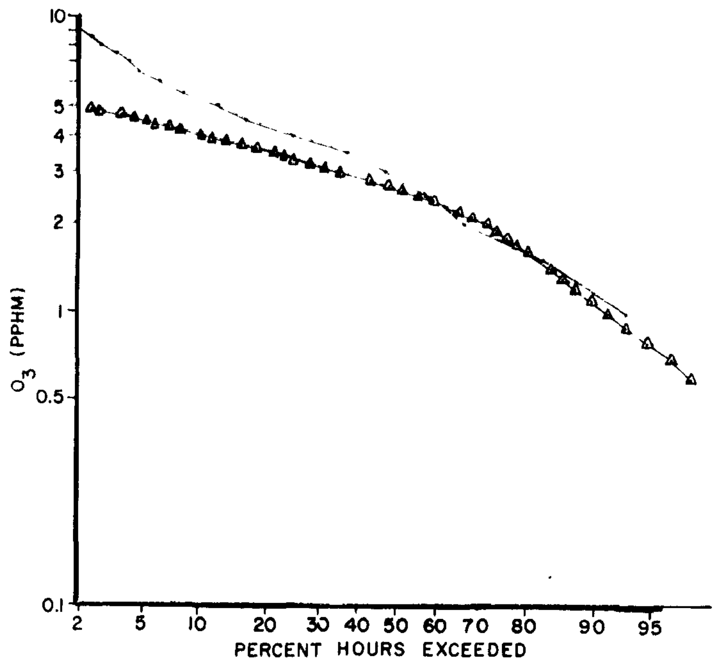


Figure 20. Co-cumulative frequency distributions of ozone at Quillayute, Wa. (triangles) and Level 1, Sutro Tower (dots), Summer 1974.

High radionuclide and O_3 concentrations at Quillayute occurred just prior to the two September Bay Area case studies to be discussed in Section 8 below. This coincidence led to preliminary studies of possible contribution of stratospheric O_3 to Bay Area air pollution episodes discussed below.

Mean Carbon Monoxide Behavior

CO concentrations in the Bay Area are typically lower during summer months than other times of the year.

Carbon monoxide concentrations measured at the Sutro Tower are approximately log-normally distributed (Figure 21). The difference in distribution details between levels is probably within the measurement error of the instruments over most of the range. However, it appears that at the higher concentration end of the distributions there is some tendency for concentrations to be higher at the lower measurement levels, as opposed to the pattern for O_3. The distribution for Level 1 for 1975 appears to be anomalously low.

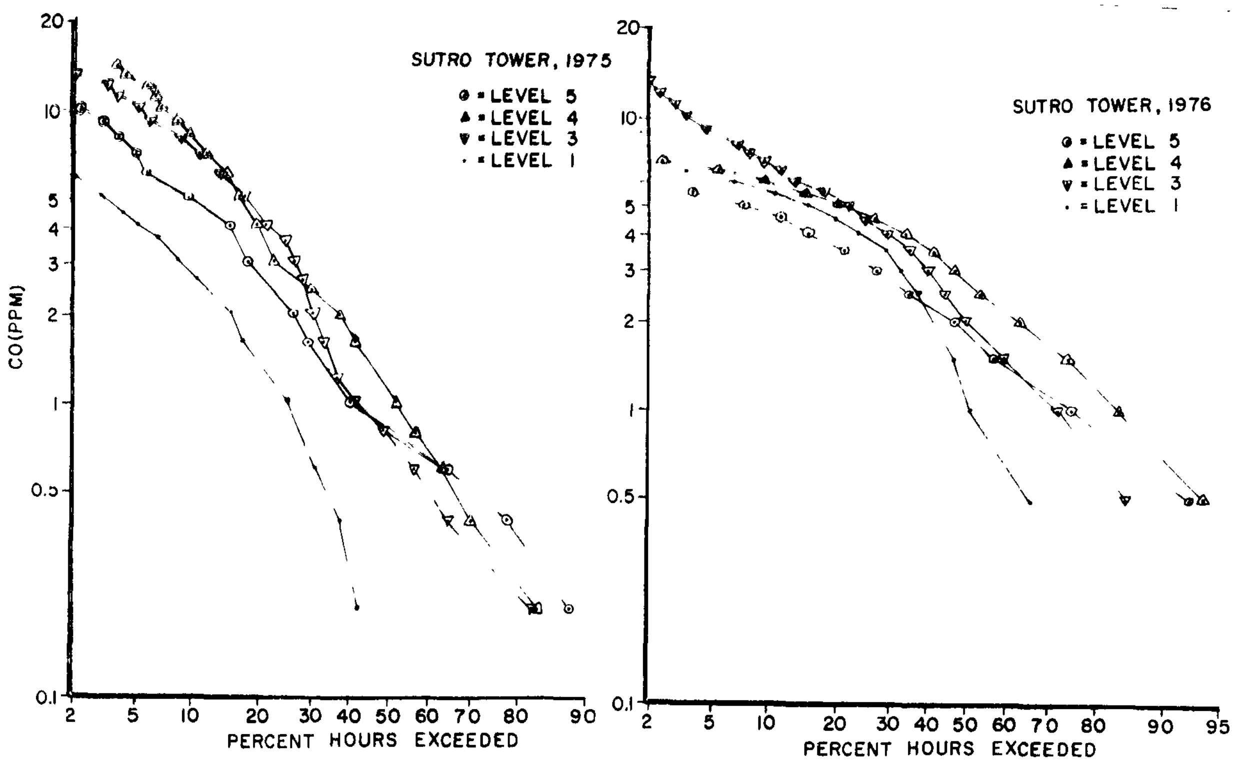


Figure 21. Co-cumulative freqyency distributions of CO, Sutro Tower, 1975 and 1976. (1 ppm = 1150 mg m^{-3})

Mean Dirunal CO Behavior

Figure 22 shows the mean diurnal CO behavior for September 1976, a month which appeared to have consistently reliable CO data. At Level 1, the morning and afternoon rush hour peaks appear to some degree. The location of the tower, however, is far enough away from traffic so that these peaks are not pronounced. At levels 4 and 5, CO concentrations decrease during the daytime hours, probably in response to the lowering of the inversion base during the day.

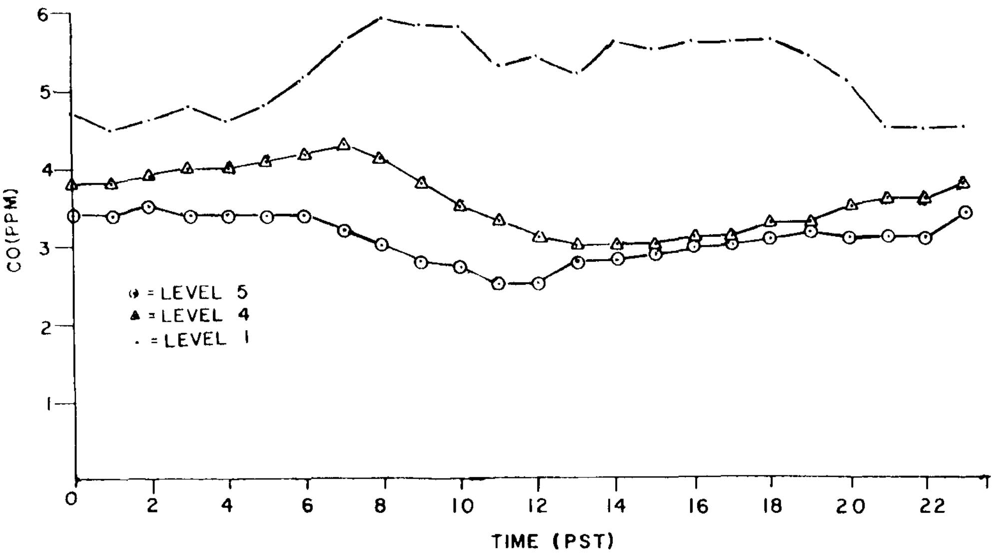


Figure 22. Hourly average CO concentrations, Sutro Tower, September 1976.

SECTION 6

CASE STUDY OF JULY 22-26, 1974*

by

Stephen H. Holets

During the Summer of 1974, four air pollution episodes occurred in the Bay Area in which Smog Advisories (a forecast of $\geq$ 20 pphm O_3) were issued. The episode of July 22-26, 1974, analyzed here, has been divided into the O_3 "buildup" (July 22, 23), "peak" (July 24), and "breakup" (July 25, 26) periods on the basis of changing meteorological and ozone patterns. This chapter compares mean and episode states of meteorological and ozone parameters.

SYNOPTIC PATTERN

The main 700 mb features for July (Figure 23; Wagner, 1974) are the trough located near the Pacific Northwest Coast, the ridge over the Central United States, and the small pressure gradient between the Great Basin and the East-Central Pacific. The trough along the Pacific Northwest Coast developed at the end of June with the decline of the mean mid-latitude westerlies (Wagner, 1974). Retrogression and weakening of the Eastern Pacific trough, coupled with retrogression of the ridge over Central United States and weakening of the Subtropical High, produced weak pressure gradients over California and a wide area of zonal flow by the end of July (Figure 24).

SURFACE PATTERNS

Temperatures

Large maximum temperature gradients between the maritime coastal areas and the sheltered inland valleys of the Bay Area dominate the mean July pattern (Figure 25). Isotherm troughs in the San Pablo Bay and San Francisco Bay-Eastern Santa Clara Valley show the strong marine air penetration through the Golden Gate and San Bruno gaps. The coastal range protects the western part of the Santa Clara Valley from marine air.

Maximum temperatures were above the mean during the July 22-26, 1974 air pollution episode (Figures 26a-c). The inland valleys heated by 8 F to the O_3 "peak" period with equivalent decreases during the "breakup" stage.

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* This section has been abstracted from "A Case Study of High Ozone in the San Francisco Bay Area" submitted in partial fulfillment of the degree of Master of Science at San Jose State University.

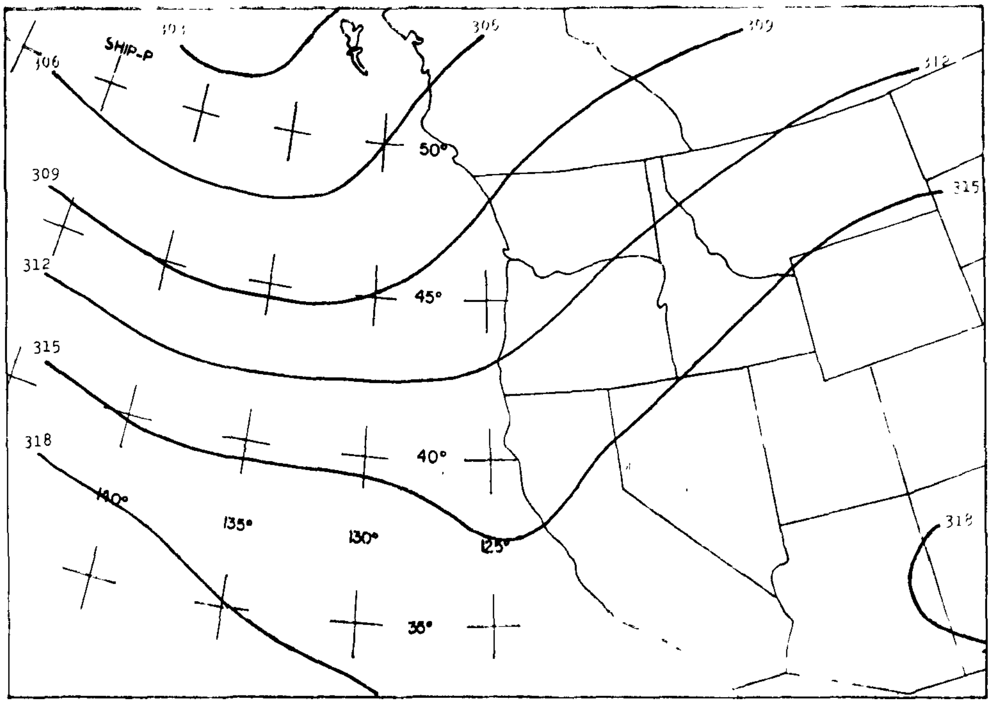

Figure 23. Mean 700-mb height contours (dekameters) for July 1974. After Wagner (1974).

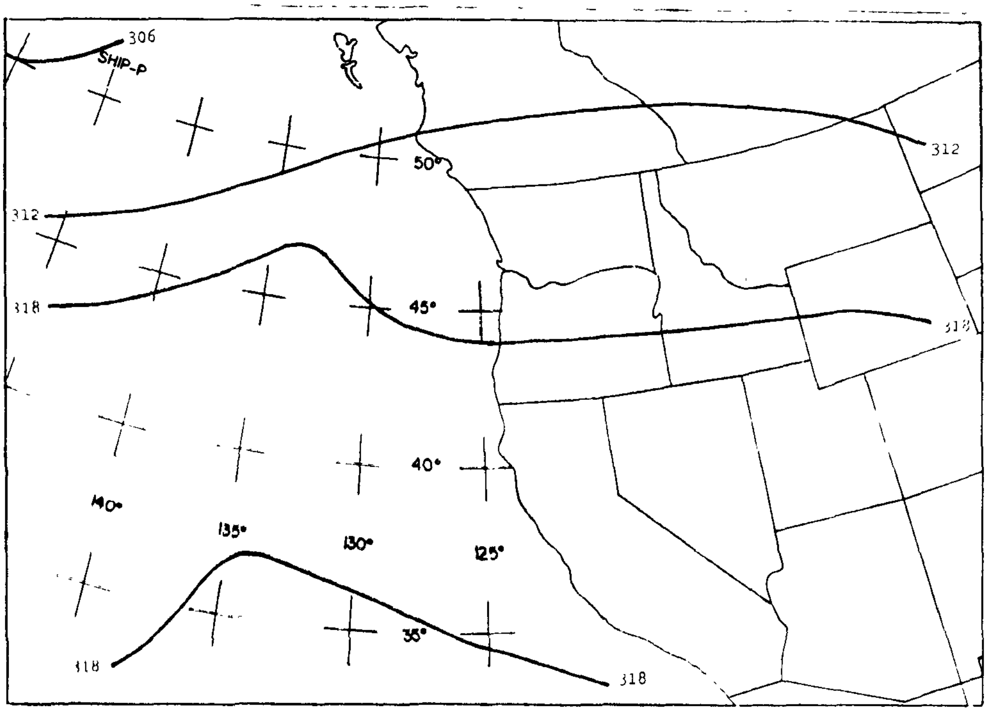

Figure 24. 700-mb height contours (dekameters) for 23-27 July 1974. After Wagner (1974).

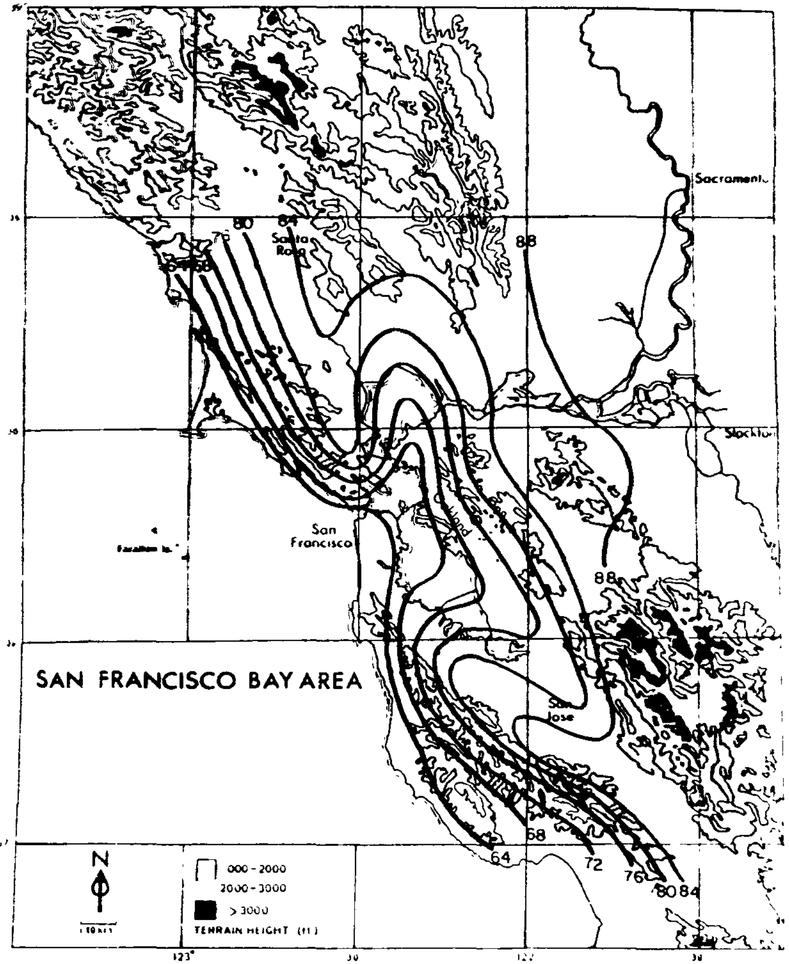

Figure 25. Mean July maximum hourly temperature (°F) distribution. After BAAPCD (1971).

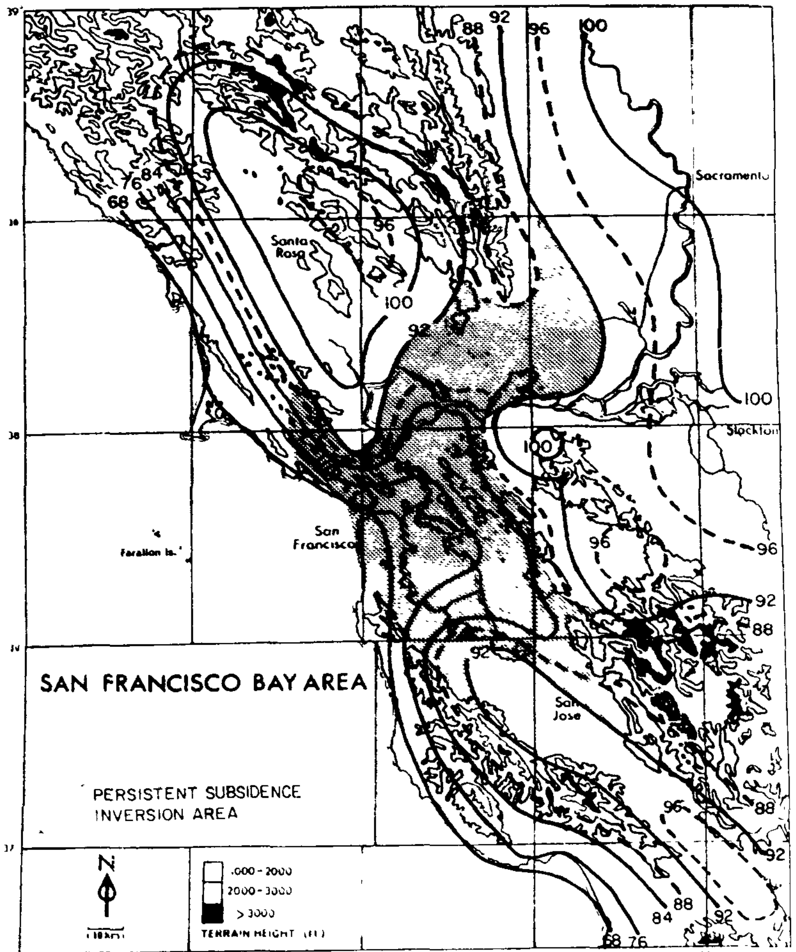

Figure 26a. Maximum hourly temperature (°F) distribution on 22 July 1974.

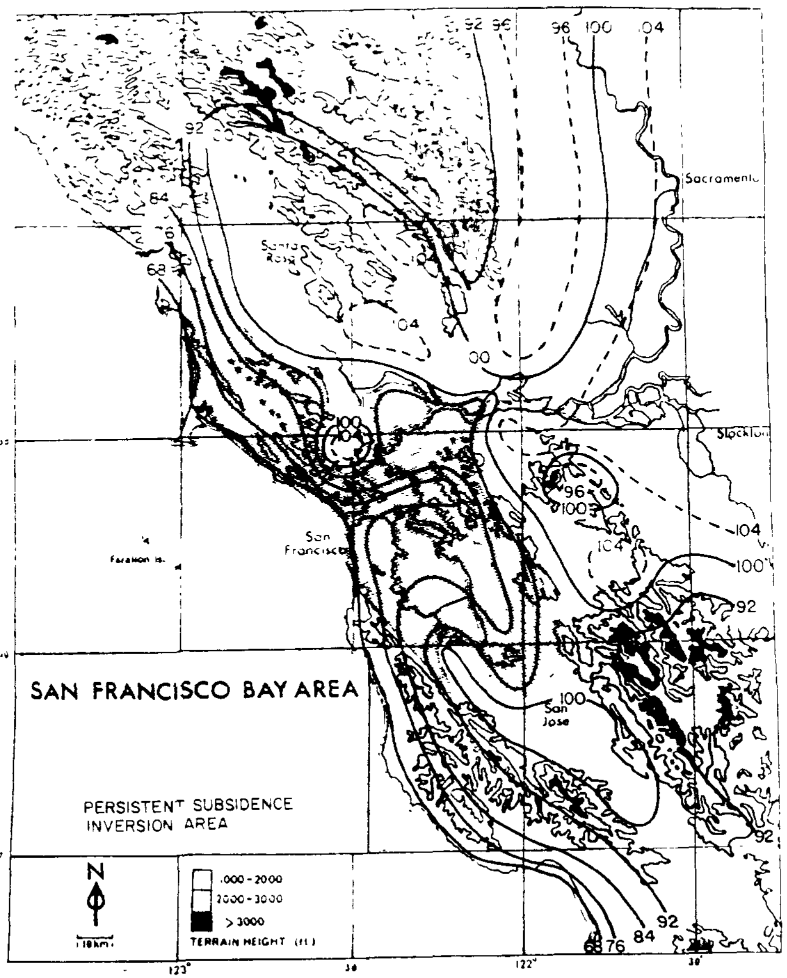

Figure 26b. Maximum hourly temperature (°F) distribution on 24 July 1974.

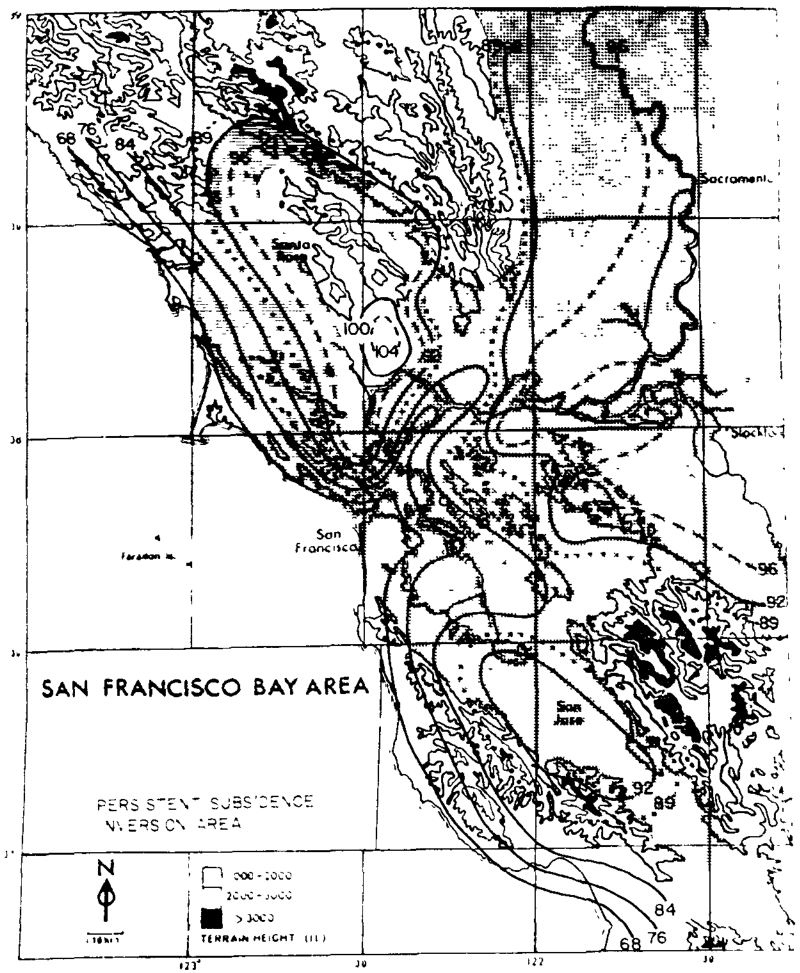

Figure 26c. Maximum hourly temperature (°F) distribution on 26 July 1974.

Winds

Typical early morning and afternoon flow patterns for the three periods of the July 22-26 episode are presented in Figures 27-29. Relatively strong flow occurred through the Carquinez straits during the early morning, with drainage flow in the Livermore, Diablo, and Santa Clara Valleys. By the afternoon, marine air persisted throughout the Bay Area. The O_3 "peak" stage displayed the highest degree of air stagnation.

Oxidant

Mean 1968-74 high-hour oxidant concentrations surpass the federal standard in the Central, Livermore, and Santa Clara Valleys (Figure 30).

Maximum high-hour oxidant concentrations during the day prior to this case study were 9 pphm at San Jose and Livermore. At the beginning of the "buildup" period, surface oxidant concentration surpassed the federal standard throughout much of the Bay Area (Figure 31a). On July 24 a Smog Advisory was issued by the BAAPCD for the Livermore and Santa Clara Valleys where oxidant increased to about 24 pphm (Figure 31b). A band of middle and high clouds formed across Central California on July 25, attenuating solar energy and reducing photochemical smog production. Westerly flow dominated the "breakup" stage as surface oxidant concentrations decreased substantially. Only the Smog Advisory region of July 24 surpassed the federal standard during this stage (Figure 31c).

UPPER AIR PATTERNS

Subsidence Inversion

The Oakland 0400 PST temperature profiles for the July 22-26 episode indicate a lowering of the inversion by July 24 with lifting thereafter, and a substantially warmer air mass than the mean (Figure 32a). Similar features occurred over San Jose (Figure 32b).

The mean diurnal temperature distribution for July (1974) on the Mount Sutro Tower (Figure 33a) shows that the inversion undulates with a 24 hour period; lowering from midday to 2000 PST, then rising to its highest point at 0600 PST. Hourly average temperature time-height sections at the Mount Sutro Tower on July 22, 24, and 26 show high temperatures and a stronger inversion intensity than the mean, waving in the inversion, and a general lowering of the inversion through July 24 and then lifting thereafter (Figures 33b-d).

Winds

Westerly flow persists during the early morning hours over Oakland in July while San Jose typically has easterly drainage flow to 600 m with westerlies above throughout the summer and early fall months (Figures 31a-b). During the afternoon, west winds dominate both locations.

Onshore flow prevails through the San Francisco gap as shown by the

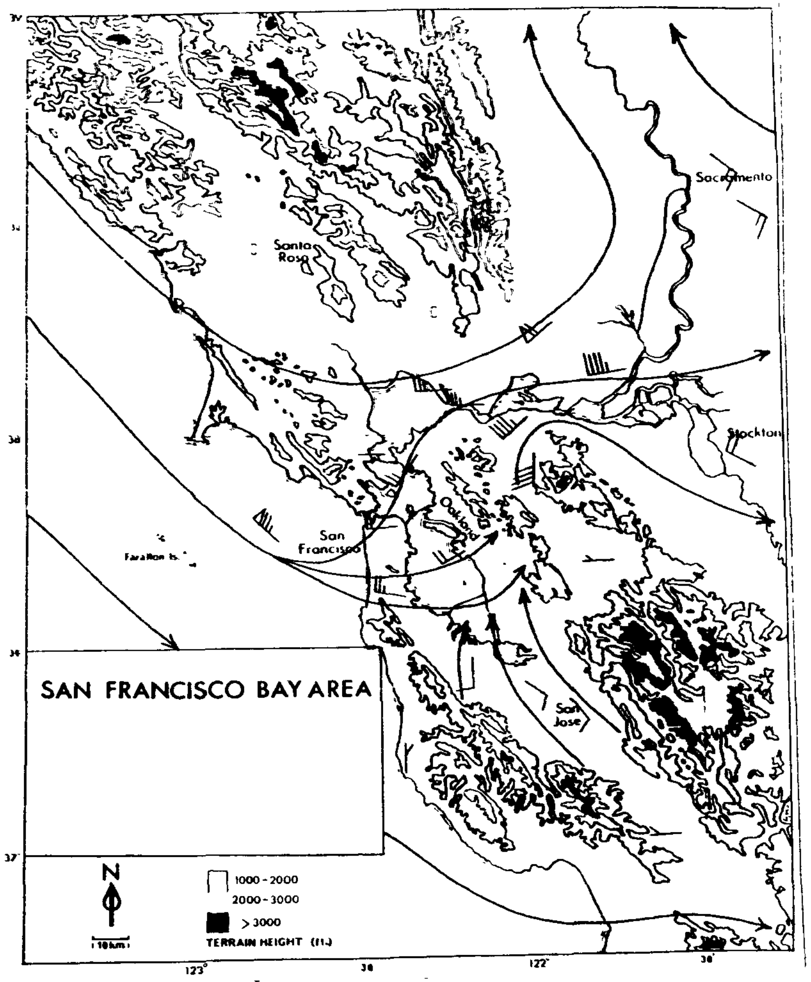

Figure 27a. Flow pattern on 22 July 1974, 0400 PST. Full barb = 1 m/sec; triangle = 5 m/sec; C = calm.

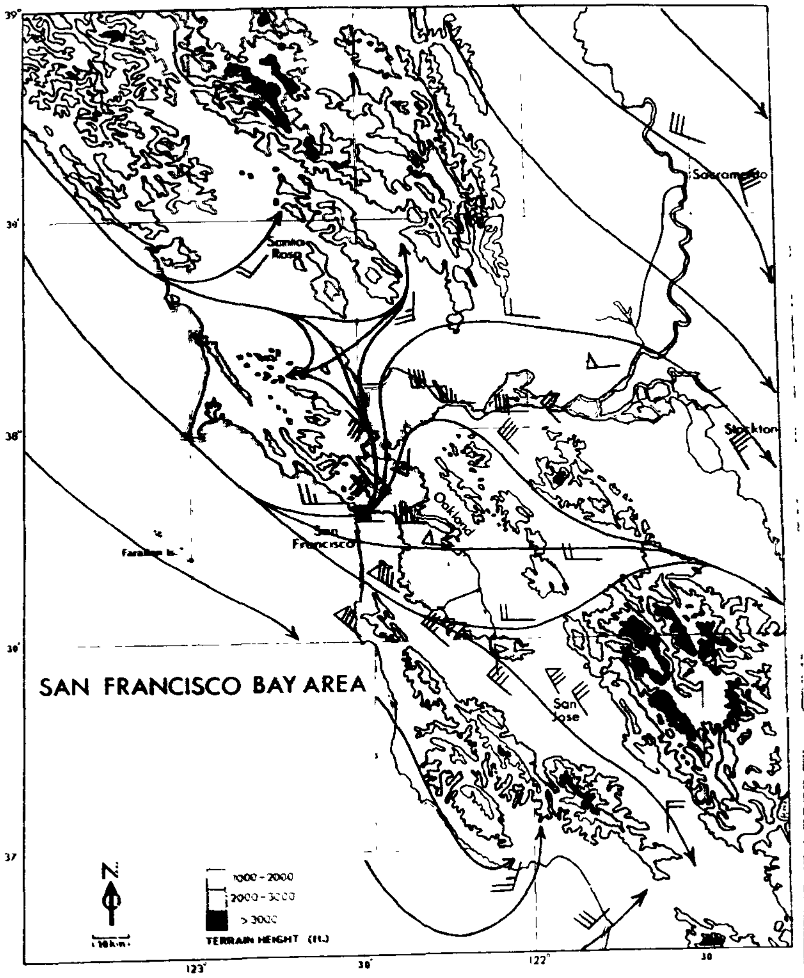

Figure 27b. Flow pattern on 22 July 1974, 1300 PST. Full barb = 1 m/sec; triangle = 5 m/sec.

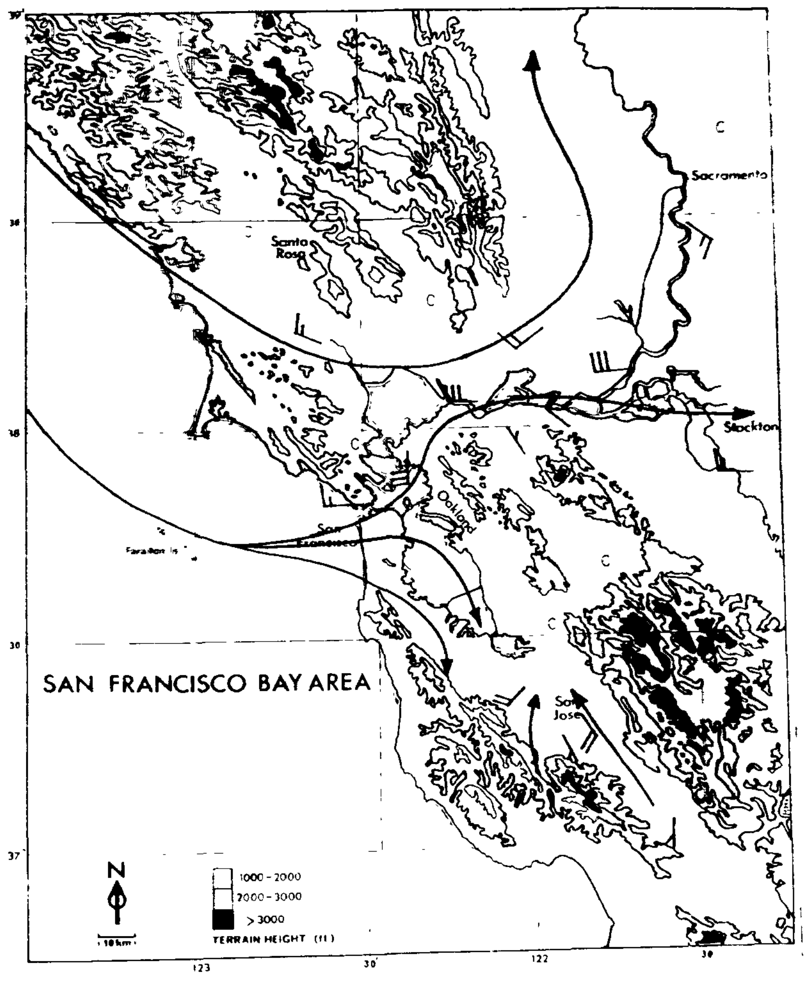

Figure 28a. Flow pattern on 24 July 1974, 0400 PST. Full barb = 1 m/sec; C = calm.

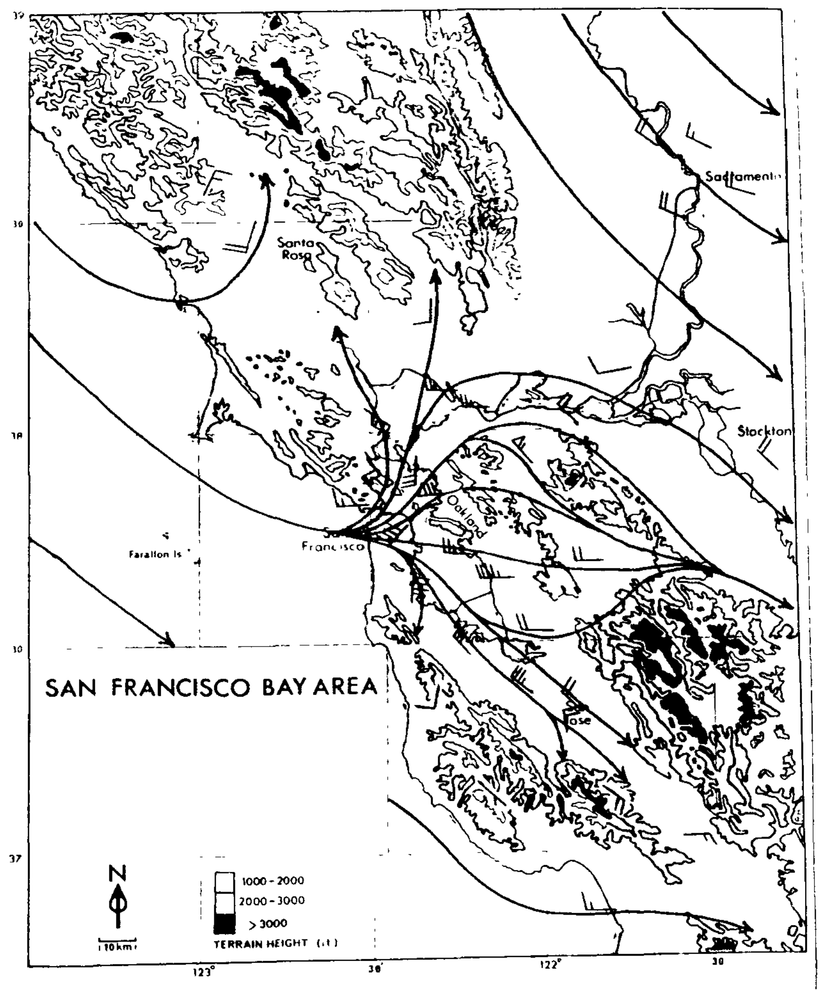

Figure 28b. Flow pattern on 24 July 1974, 1300 PST. Full barb = 1 m/sec; triangle = 5 m/sec.

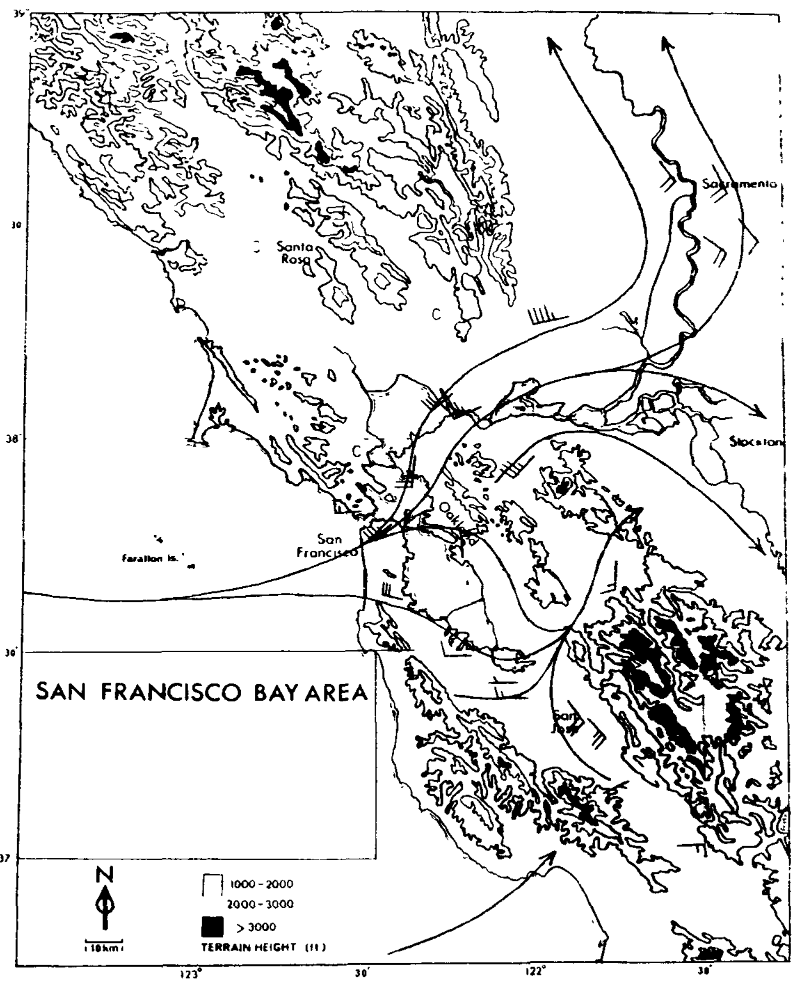

Figure 29a. Flow pattern on 26 July 1974, 0400 PST. Full barb = 1 m/sec; C = calm.

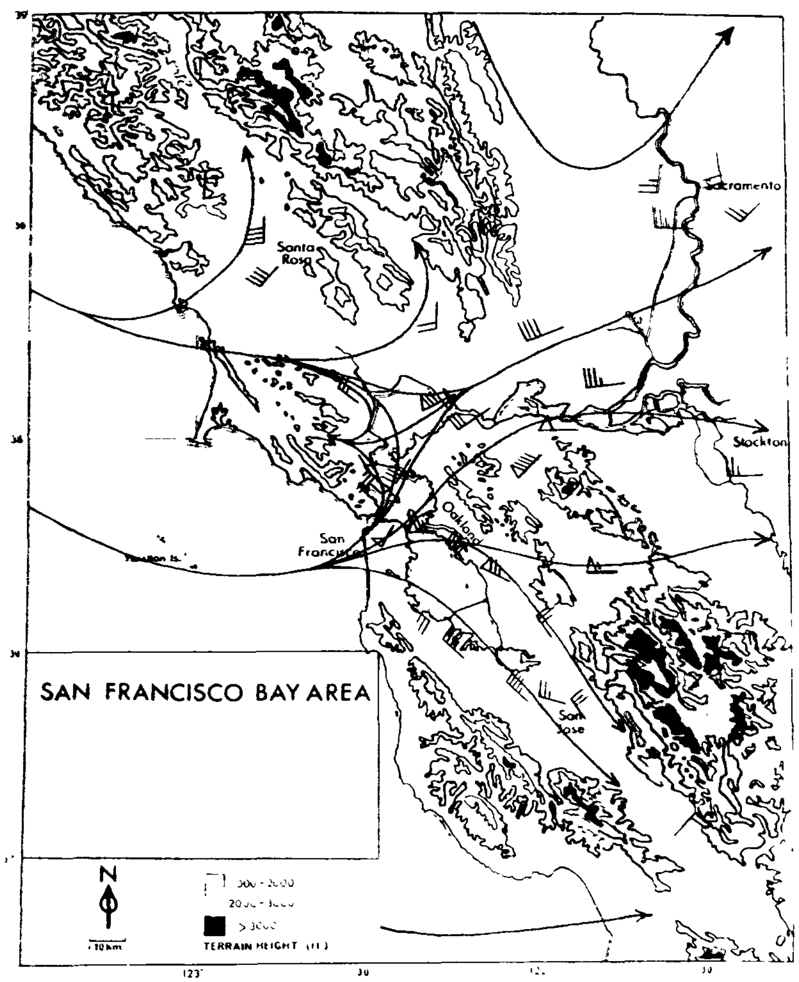

Figure 29b. Flow pattern on 26 July 1974, 1300 PST. Full barb = 1 m/sec; triangle = 5 m/sec.

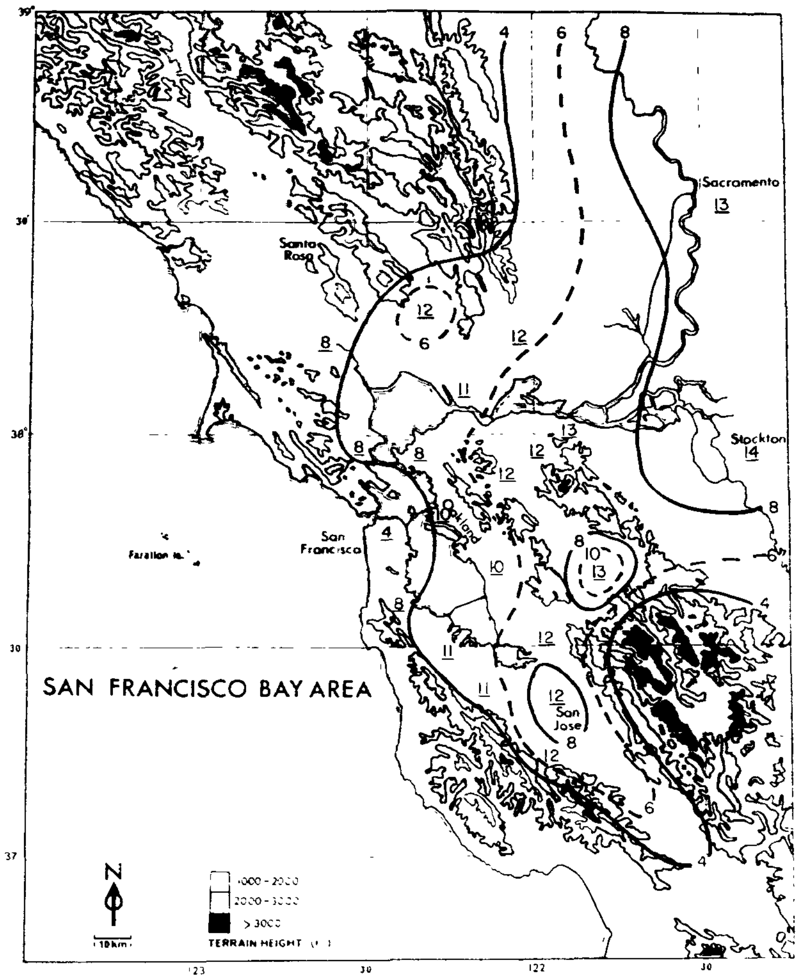

Figure 30. Mean high-hour oxidant (pphm) distribution for July (1968-74). Underlined numbers represent the mean time of the first high-hour oxidant concentration.

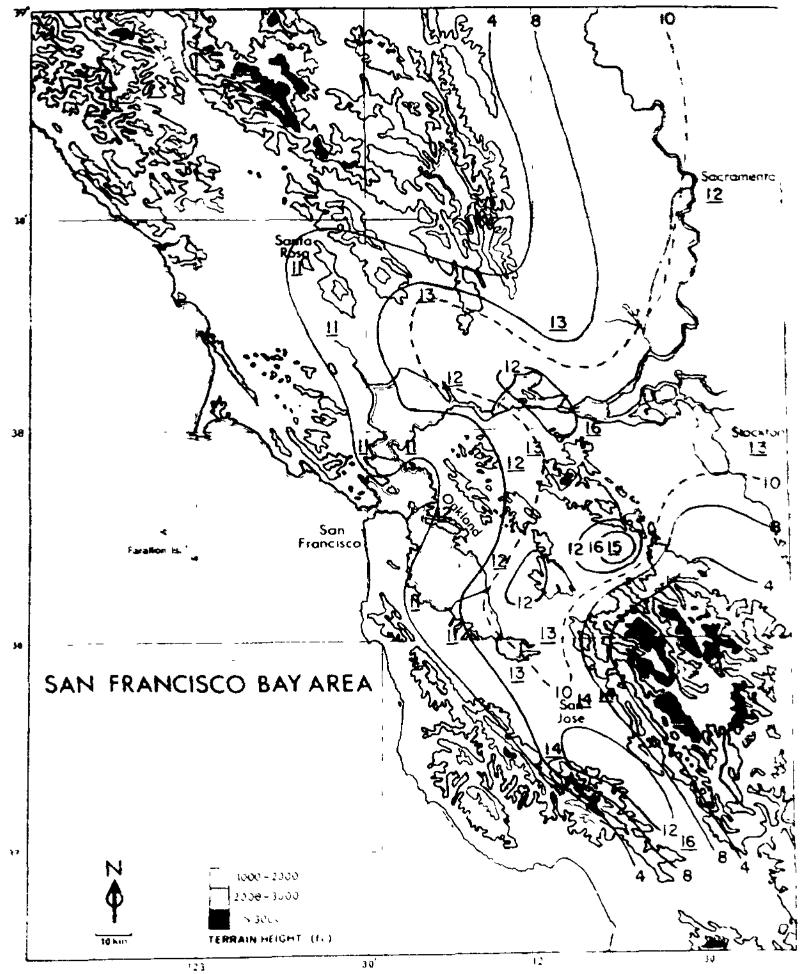

Figure 31a. High-hour oxidant (pphm) distribution on 22 July 1974. Underlined numbers represent the time of the first high-hour oxidant concentration.

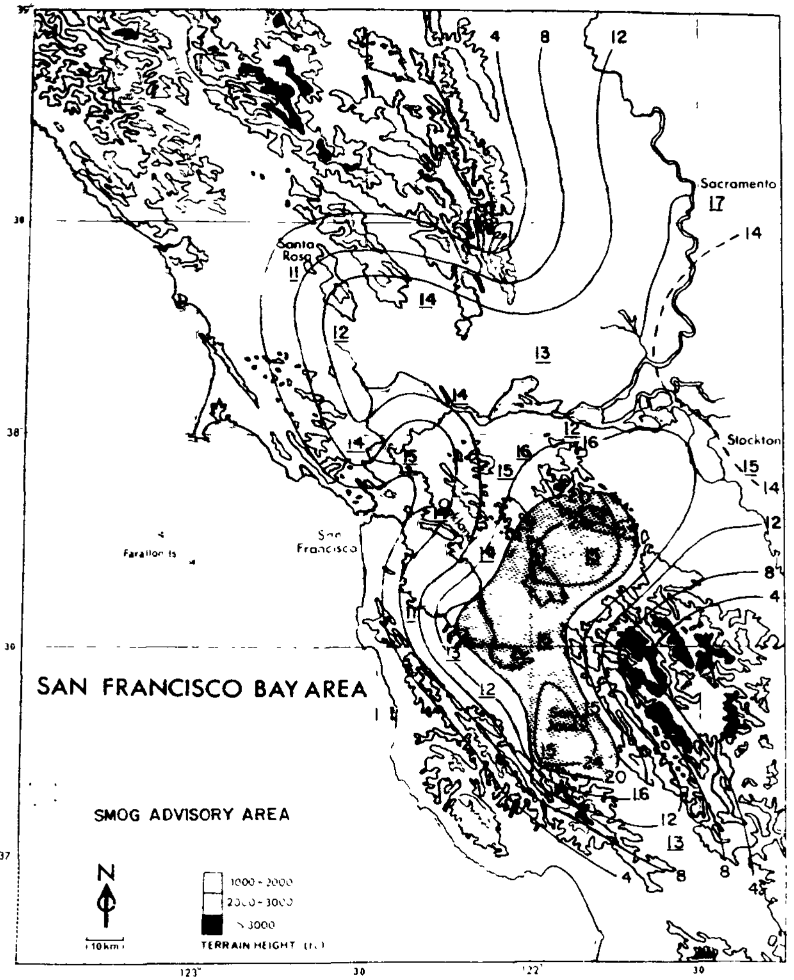

Figure 31b. Same as 31a, except for 24 July, 1974.

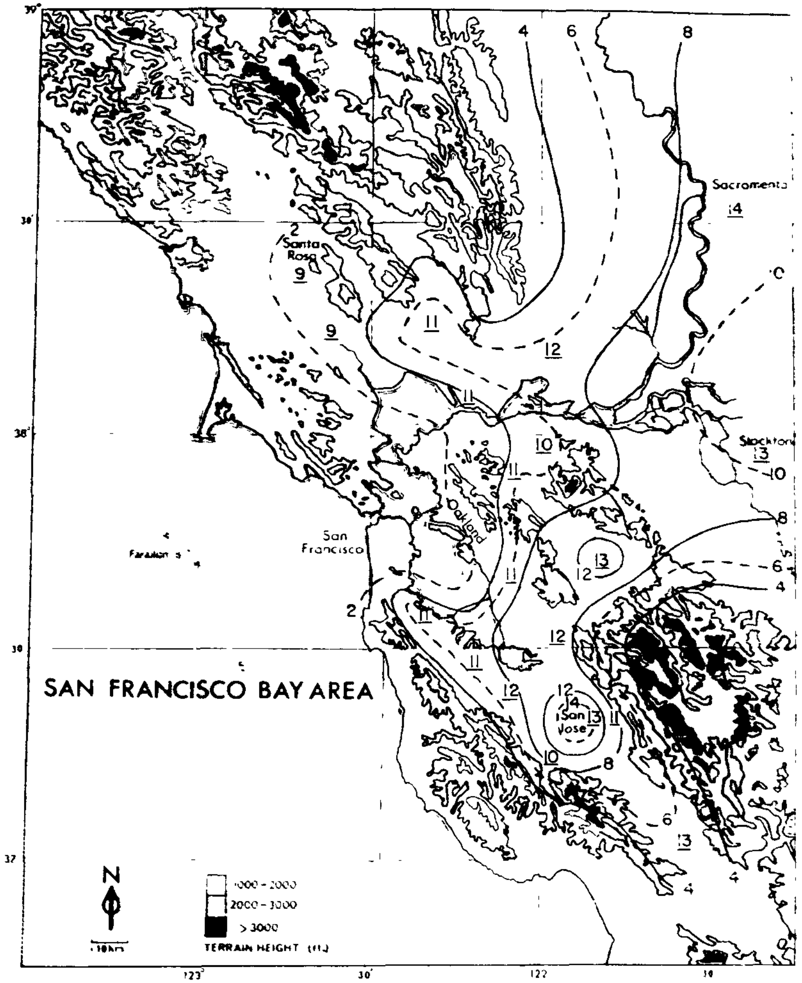

Figure 31c. Same as 31a, except for 26 July, 1974

mean July (1974) westerly component at the Sutro Tower (Figure 34a). During the July 22-26 episode, however, the easterly component increased steadily from July 21-24 and decreased rapidly during the "breakup" period (Figures 34b-d). Although westerly flow occurred on the upper tower levels on July 23 and 24, the speeds were low.

Ozone

In general, hourly average ozone concentrations increased with height at the Mount Sutro Tower during the Summer of 1974 (Figure 35a). At Level 5 (L5) the NAAQS was exceeded 149 hours during June 26-September 24, 1974, forty percent of these hours during July 23-25. Figures 35b-d show that ozone concentrations increased from O_3 "buildup" to the "peak" periods, reaching a maximum hourly concentration of 28 pphm on L5 at 1300 PST on July 24. By the end of the "breakup" stage, ozone had decreased to mean values.

On July 24 the ozone layer aloft lowered to within 88 m of the earth's surface over San Francisco (Figure 36) and appeared to extend throughout the subsidence inversion, as exemplified by the ozone profile over Hayward (Figure 37). The lower part of the subsidence inversion (200-400 m AGL) contained an ozone peak of 28 pphm. Since surface monitoring stations within the Hayward area recorded less than half the ozone of the polluted layer above, strong downward diffusion did not occur.

In summary, the trough off the West Coast of the United States and ridge over Central Canada retrograded, thus establishing weak pressure gradients between the Eastern Pacific and Great Basin regions. Surface temperatures and oxidant concentrations increased sharply from mean values during the "buildup" stage. By the time of the O_3 "peak" period, inland valley surface temperatures were 8-16 F above normal with maximum mixing depths of 1800 m, the inversion base lowered to the earth's surface, surface winds were relatively light with early morning southeast drainage flow in the lower Santa Clara Valley and anomalous offshore flow through the Golden Gate Gap, and maximum surface and inversion oxidant concentrations peaked near 17 pphm above normal. As westerly flow became persistent during the "breakup" stage, temperature and oxidant values returned to the mean state.

An ozone layer of 24 pphm in the inversion lowered to within 88 m of the Sutro Tower base where only 6 pphm were recorded. Continued lowering of the inversion or its partial destruction with downward mixing would quickly project ozone concentrations above the federal standard.

EVOLUTION OF THE JULY 22-26 EPISODE

The evolution of the July 22-26, 1974 air pollution episode is modeled schematically in Figures 38a-g. Although much interpretation was required, the model conforms to the available data.

On July 21, the maximum oxidant recorded in the Bay Area was 9 pphm. The National Weather Service 850 mb analysis (not shown) and available upper air winds along coastal California indicate the possibility of an isentropic trajectory from the Los Angeles Basin to San Francisco. This information,

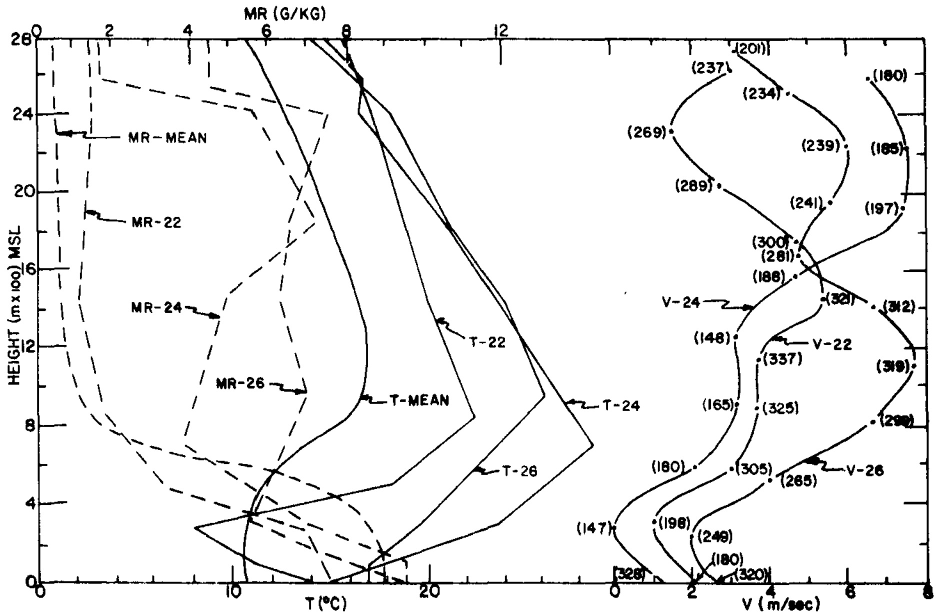

Figure 32a. Oakland temperature (T), mixing ratio (MR), and wind speed (V) soundings for 22, 24, and 26 July 1974, 0400 PST. Wind directions are in parenthesis. Mean soundings are for July 1972.

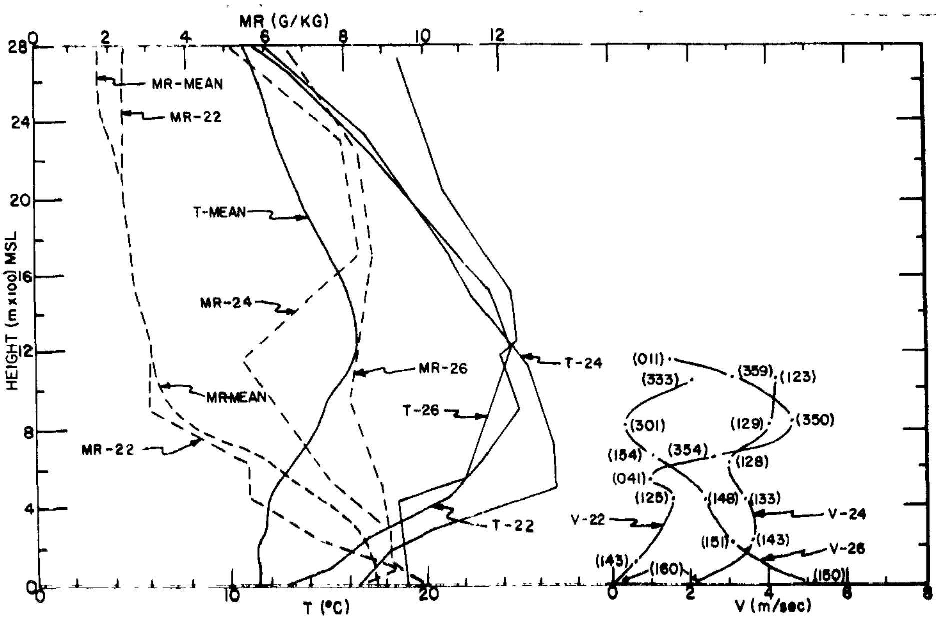

Figure 32b. San Jose State University temperature (T), mixing ratio (MR), and wind speed (V) soundings for 22, 24, and 26 July 1974, 0600 PST. Wind directions are in parenthesis. Mean soundings are for July 1972.

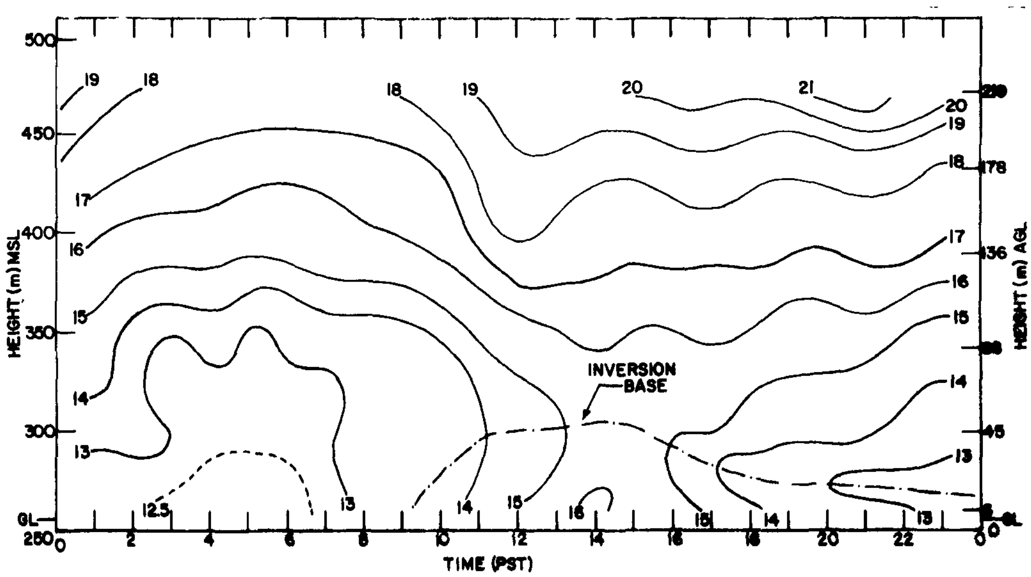

Figure 33a. Mean July (1974) hourly average time-height temperature (°C) section at the Mount Sutro Tower, San Francisco.

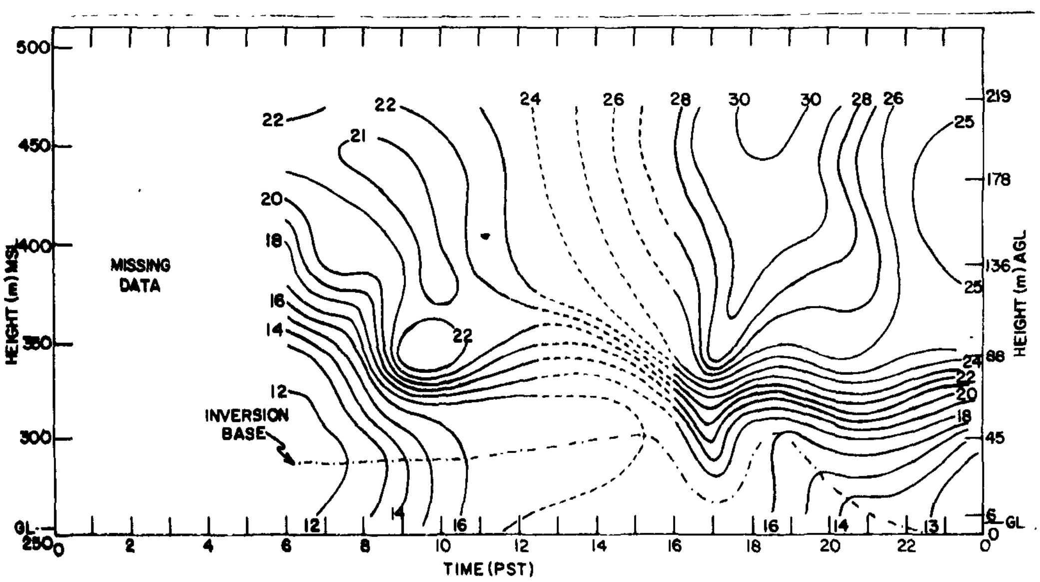

Figure 33b. Time-height section of hourly average temperatures (°C) at the Mount Sutro Tower, San Francisco on 22 July 1974. Dashed lines represent interpreted data.

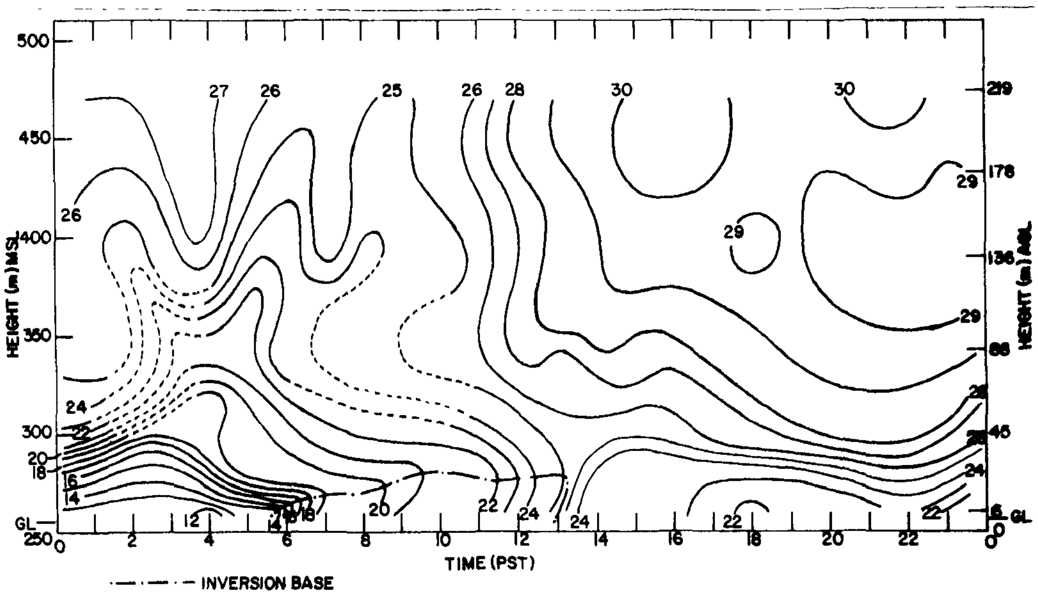

Figure 33c. Time-height section of hourly average temperatures (°C) at the Mount Sutro Tower, San Francisco on 24 July 1974. Dashed lines represent interpreted data.

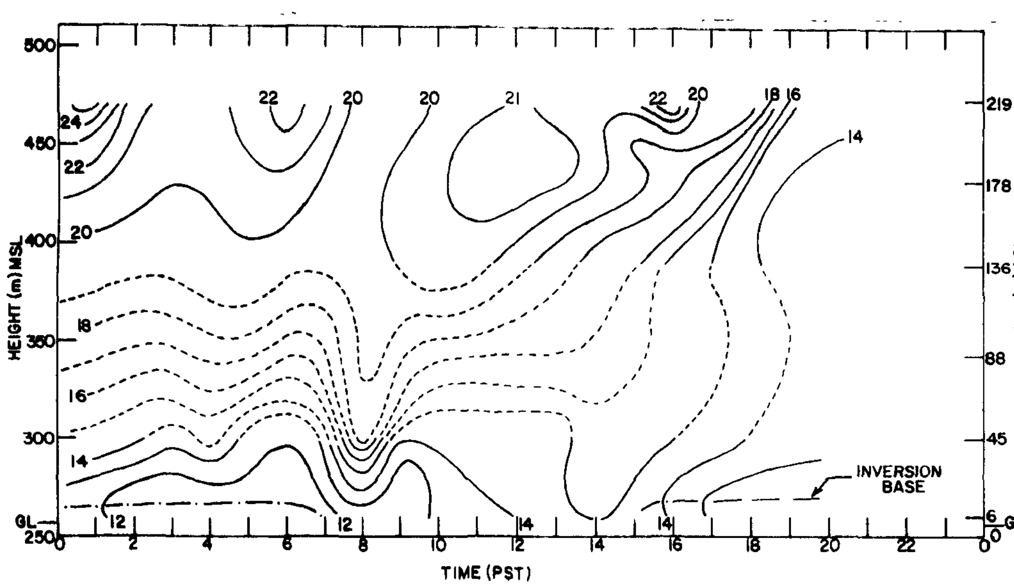

Figure 33d. Time-height section of hourly average temperatures (°C) at the Mount Sutro Tower, San Francisco on 26 July 1974. Dashed lines represent interpreted data.

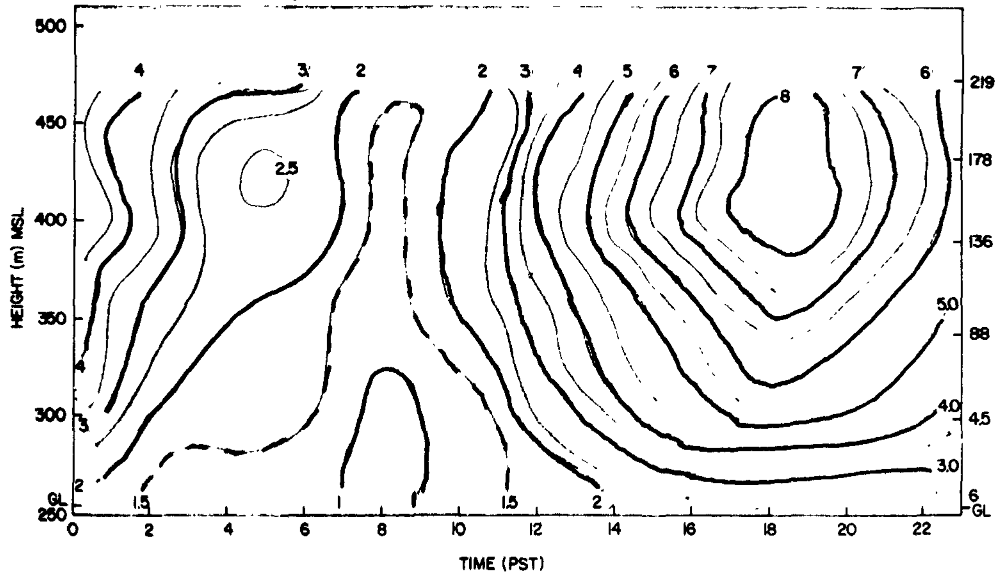

Figure 34a. Mean July (1974) hourly average west wind (m/sec) time-height section at the Mount Sutro Tower, San Francisco.

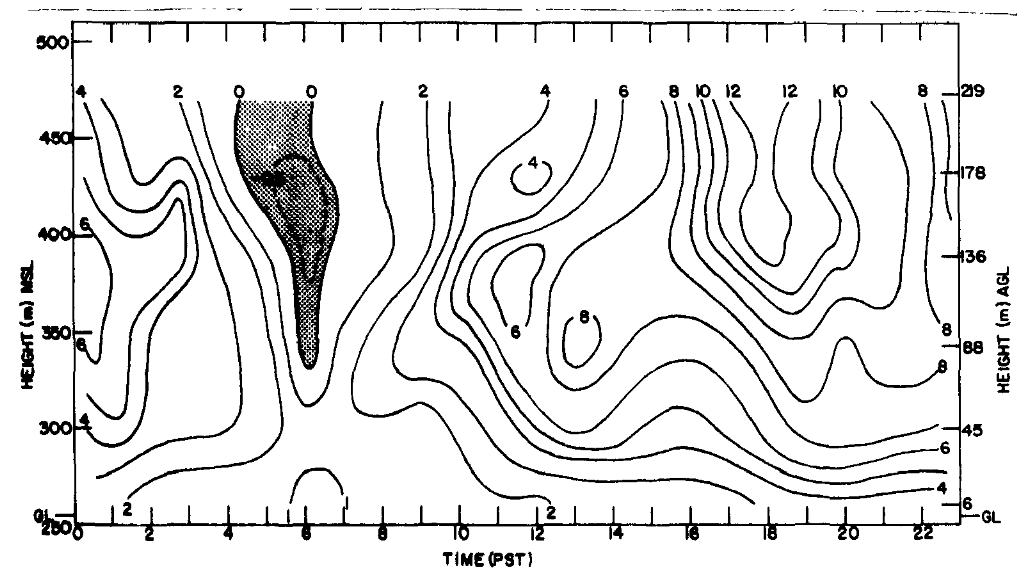

Figure 34b. Time-height section of hourly average west wind (m/sec) at the Mount Sutro Tower, San Francisco on 21 July 1974. Shaded region represents an easterly component.

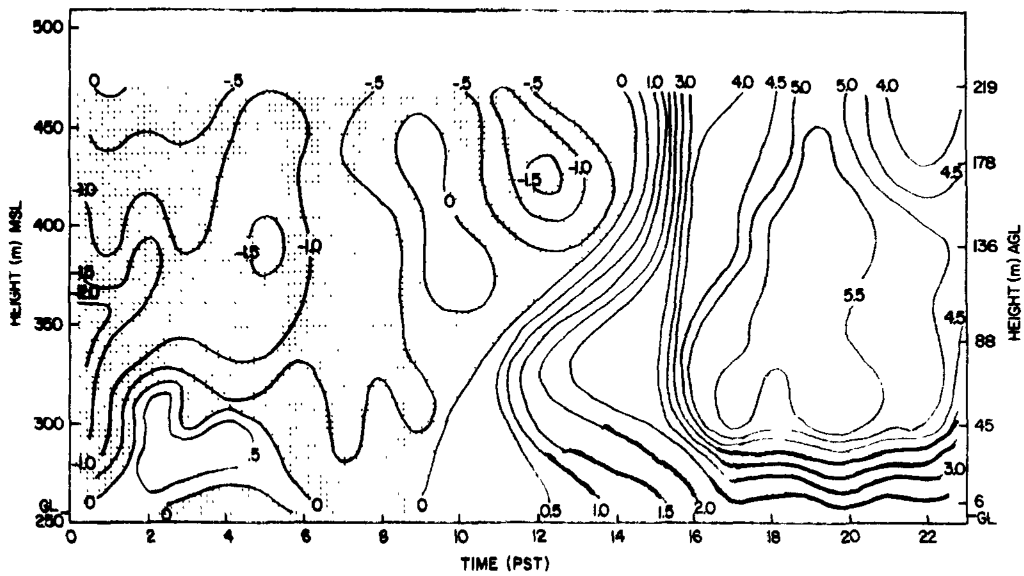

Figure 34c. Time-height section of hourly average west wind (m/sec) at the Mount Sutro Tower, San Francisco on 24 July 1974. Shaded region represents an easterly component.

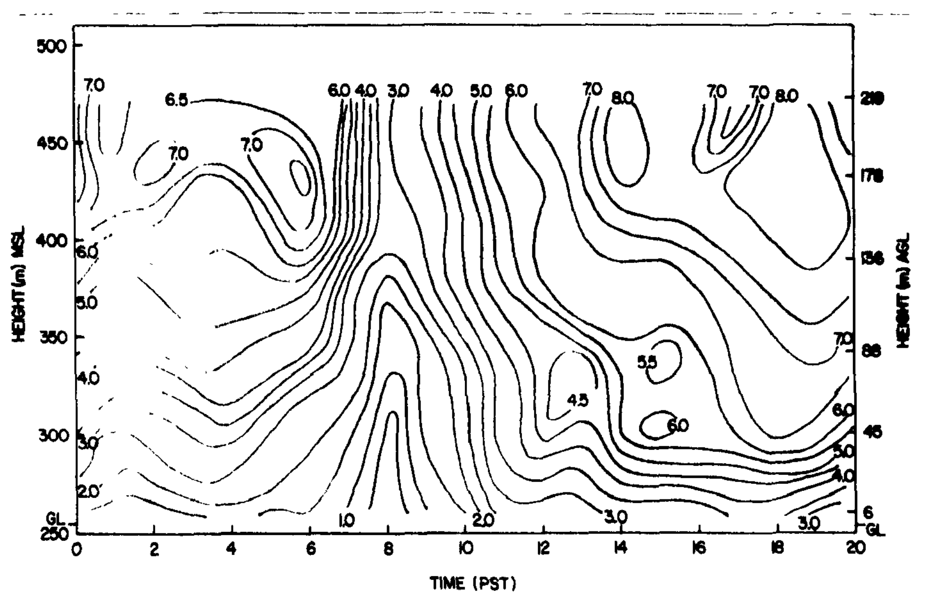

Figure 34d. Time-height section of hourly average west wind (m/sec) at the Mount Sutro Tower, San Francisco on 26 July 1974. Shaded region represents an easterly component.

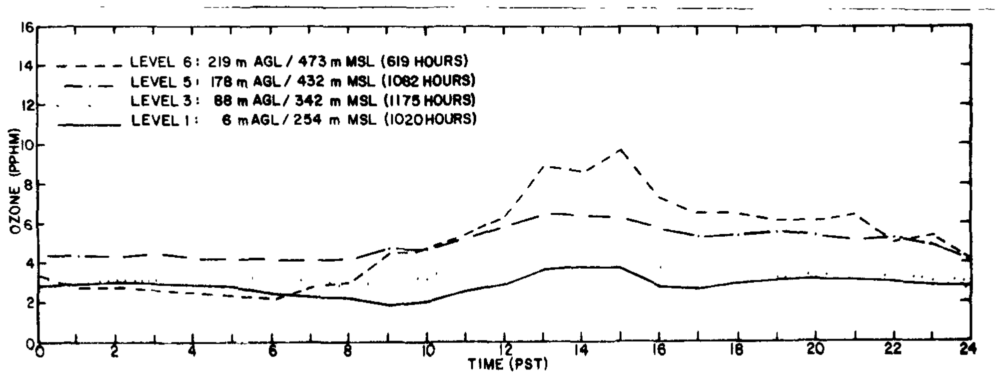

Figure 35a. Mean hourly average ozone time section at the Mount Sutro Tower, San Francisco (June 26-September 24, 1974).

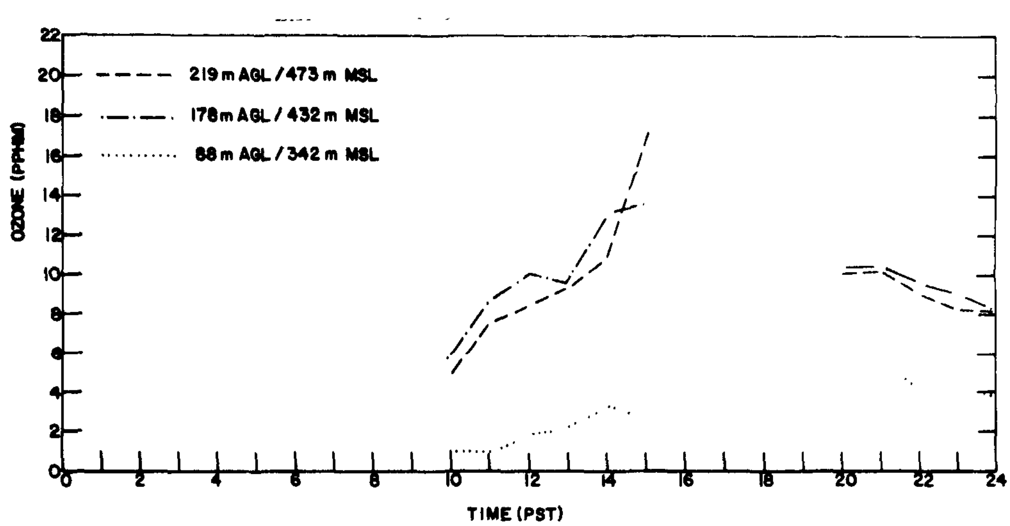

Figure 35b. Hourly average ozone time section at the Mount Sutro Tower, San Francisco on 23 July 1974.

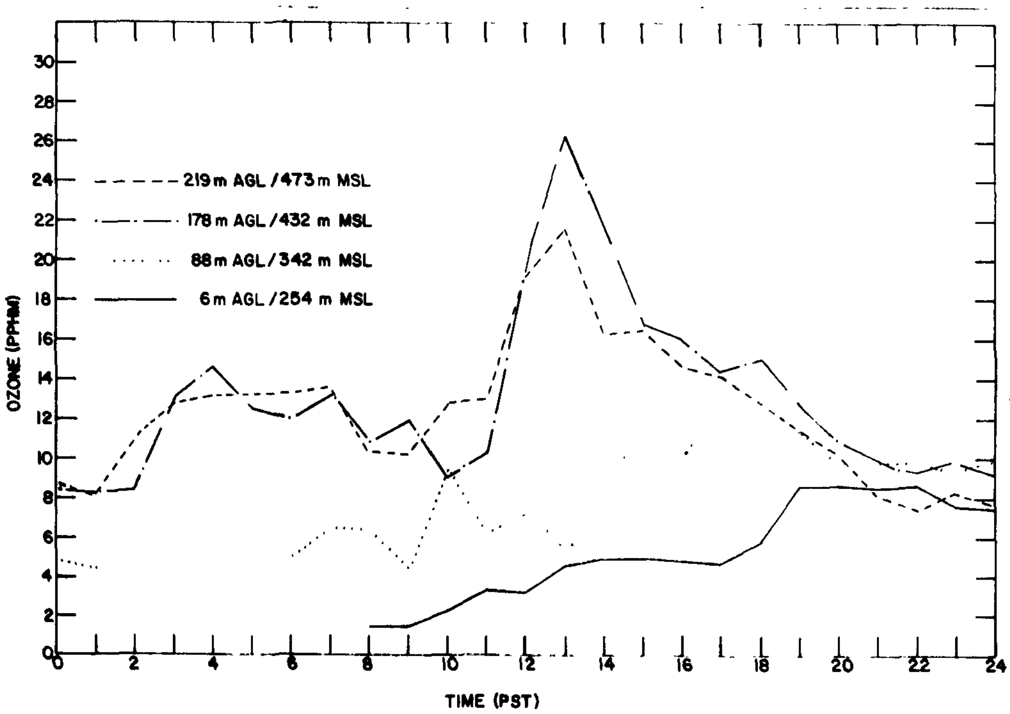

Figure 35c. Hourly average ozone-time section at the Mount Sutro Tower, San Francisco on 24 July 1974.

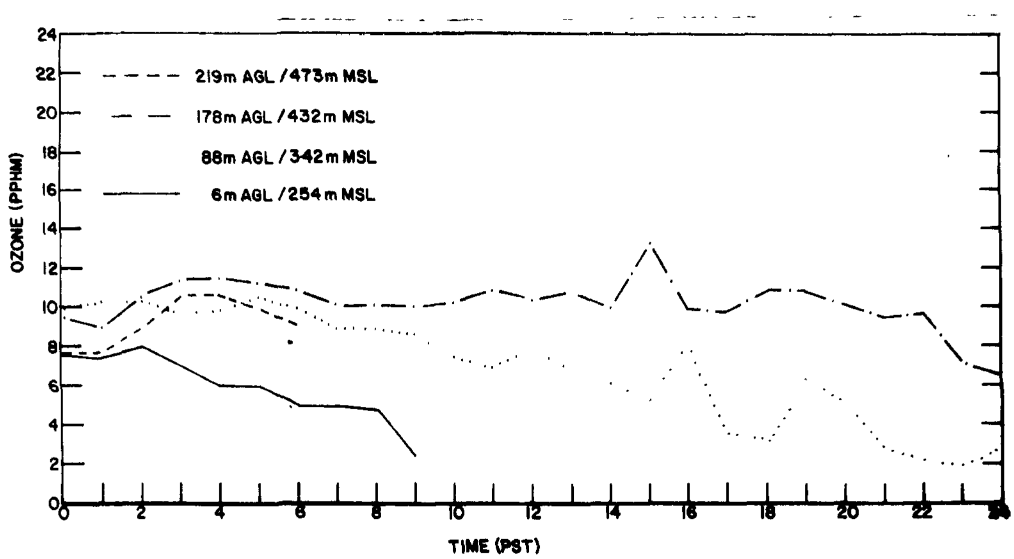

Figure 35d. Hourly average ozone-time section at the Mount Sutro Tower, San Francisco on 25 July 1974.

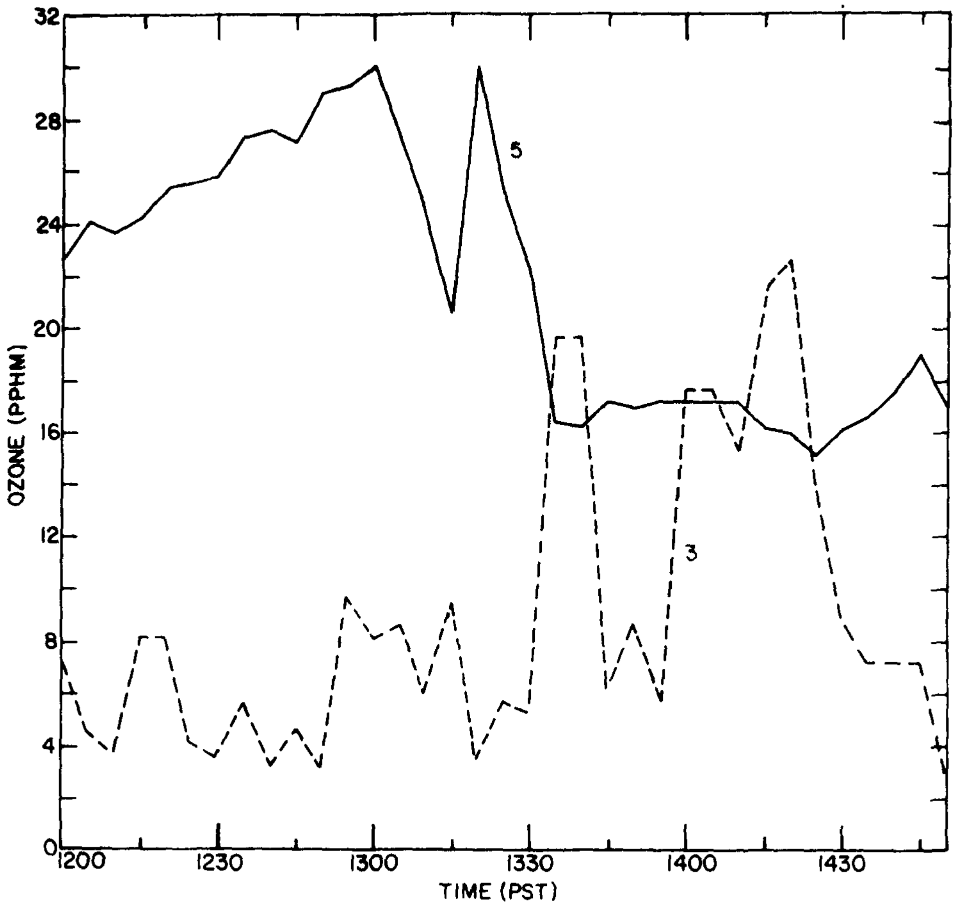

Figure 36a. Variation of five minute average values of ozone, Levels 3 and 5, Sutro Tower, 24 July 1974.

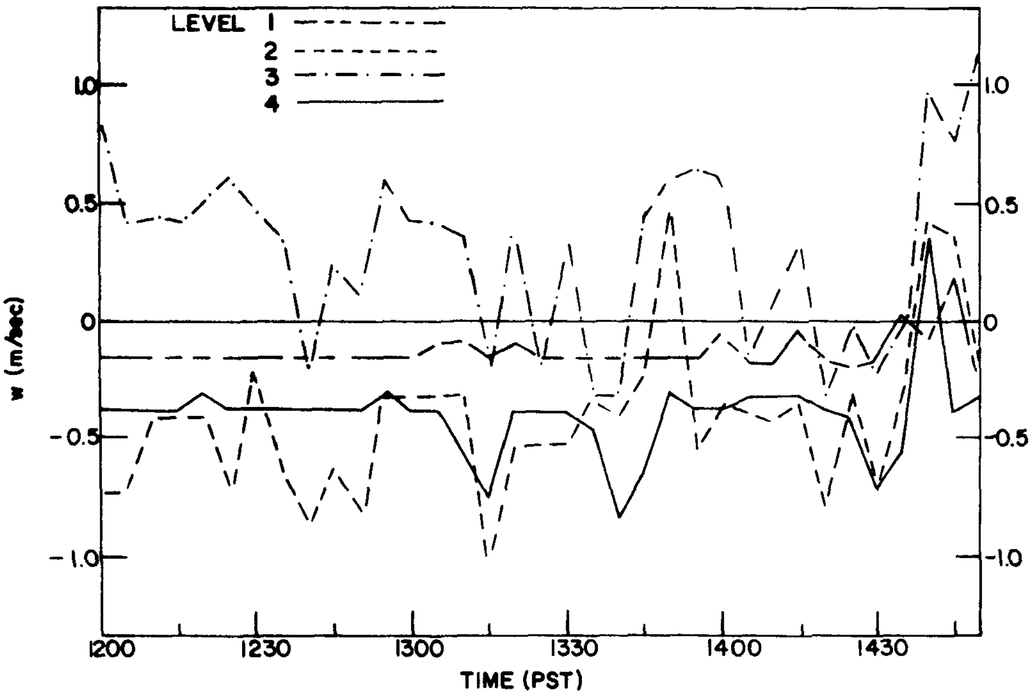

Figure 36b. Variation of five minute average vertical velocities, Mount Sutro Tower, San Francisco, 24 July 1974.

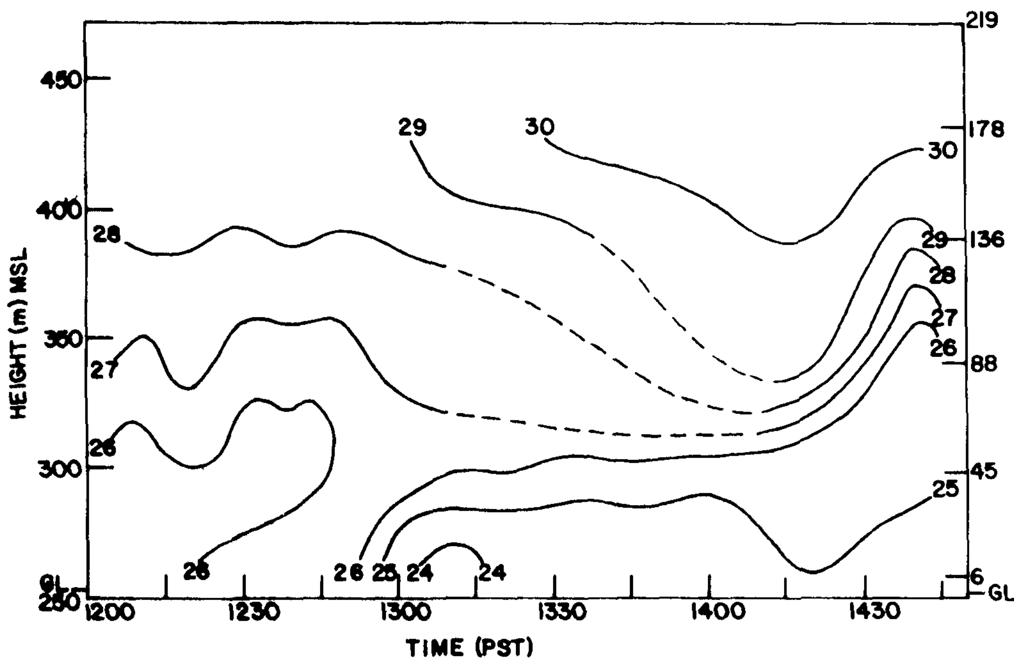

Figure 36c. Time-height temperature (°C) section at the Mount Sutro Tower, San Francisco on 24 July 1974. Dashed lines represent interpreted data.

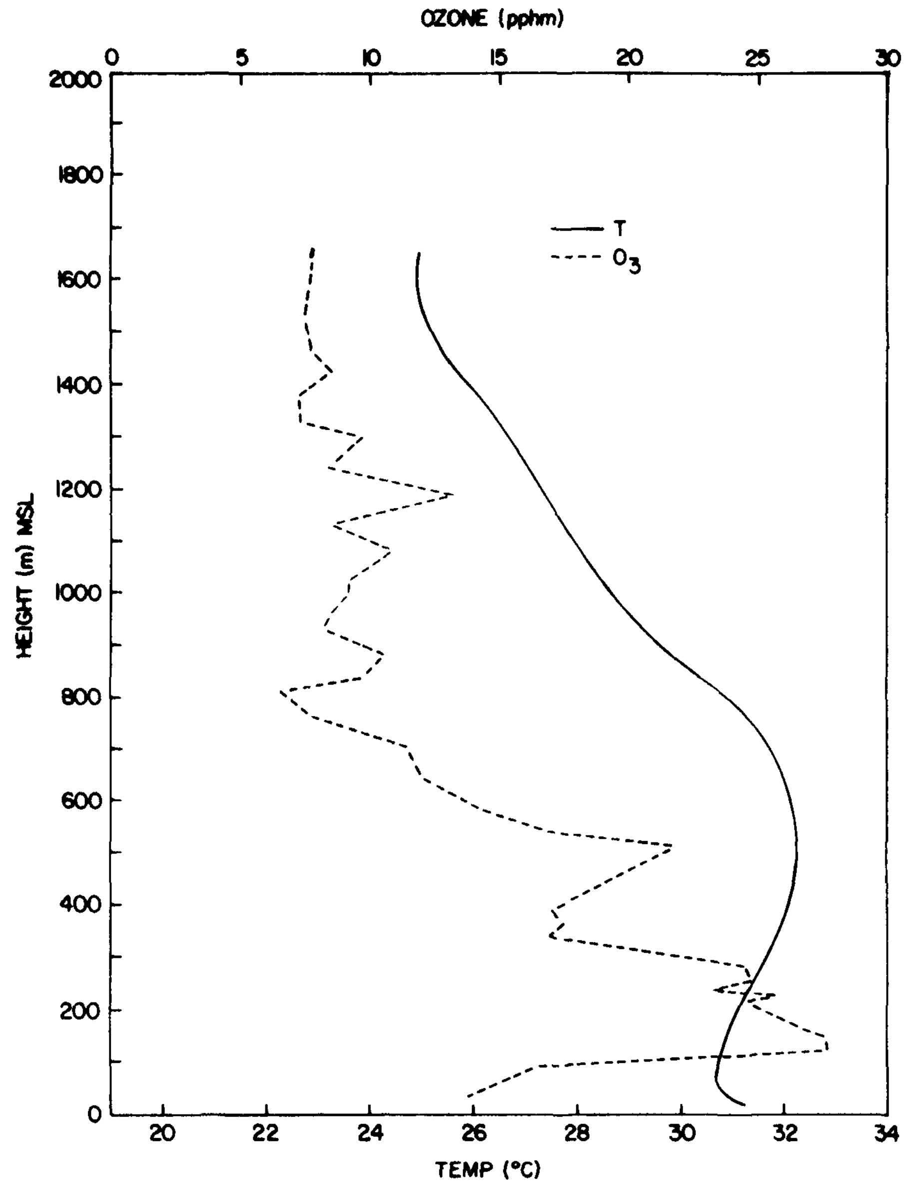

Figure 37. Temperature and ozone profile at Hayward, California on 24 July 1974, 1450-1525 PST.

coupled with the fact that oxidant concentrations at higher elevations in the South Coast Air Basin during the prior few days, suggests possible transport of oxidants from the Los Angeles area.

Baboolal, et al (1975) found indications of aged Los Angeles pollutants being transported some 200 km northwest to the Santa Yuez Valley. Kauper and Nemann (1975) have documented over water transport of oxidants within the inversion layer from the Los Angeles Basin to Ventura, about 100 km to the northwest. The possibilities of longer distance transport to the San Francisco Bay, while not proven, seems possible and should be studied.

The midafternoon condition during the first day of the "buildup" period is shown in Figure 38a. The subsidence inversion was present over San Francisco and extended to the southern edge of the San Francisco Bay where it was destroyed by surface heating. Northwest flow advected ozone (2-6 pphm) and its precursors into the Santa Clara Valley. Surface concentrations increased downstream due to enhanced emissions during advection and photochemical production. In the Santa Clara Valley, where the inversion was destroyed, O_3 buildups of 10-15 pphm occurred due to decreased O_3 destruction rates, the accumulation of precursors and high temperatures.

As the inversion reformed at night, ozone below the inversion was quickly destroyed by the earth's surface (Figure 38b). Within the inversion, however, O_3 concentrations of 5-15 pphm probably persisted as proposed by Gloria et al. (1974). Under light southeast flow, the pollutant layer was advected northward with the edge of the layer advancing to the San Rafael-Mount Tamalpais area by noon. In addition, ozone increases to 10 pphm at the Sutro Tower show the subsequent advection over San Francisco of Santa Clara Valley generated O_3.

About noon (Figure 38c), winds to 500 m AGL became northerly and the O_3 layer receded back over San Francisco. Ozone concentrations increased by 8 pphm by 1500 PST at the Sutro Tower as photochemistry of the aged pollutant layer progressed. Once again, ozone and its precursors were advected into the Santa Clara Valley. Pollutants accumulated in the upper Santa Clara Valley, however, as southeasterly flow of marine air into the lower Santa Clara Valley from the Monterey Bay Area established a convergence zone with a 13 pphm ozone gradient between the two air masses.

On July 24, this cycle was repeated (Figure 38d). The inversion reformed over San Jose during the night of July 23, becoming surface based due to radiation cooling and increased subsidence. Ozone was destroyed near the earth's surface but persisted above. Southeast flow advected the O_3 layer from the San Francisco Bay and upper Santa Clara Valley to the northern Bay Area, as suggested by Tower air trajectories. A high ozone pocket was advected over the Sutro Tower between 0200-0400 PST when concentrations increased from 8.5 pphm to 14.5 pphm (Figure 35c). By 1000 PST the winds veered to the northeast, producing strong offshore flow. Once again, O_3 generated in the Santa Clara Valley was advected over San Francisco. Concentrations at the Sutro Tower rapidly increased to a high-hour value of 26 pphm and a peak of 30 pphm at 1300 PST as photochemistry of the aged pollutant layer progressed.

By 1400 PST, northwest winds commenced, which advected the pollutant cloud southeastward down the Santa Clara Valley (Figure 38e). As a result, O_3 concentrations on the Tower decreased by 10 pphm in two hours. The advection of ozone and its precursors, plus photochemical production due to a large mixing depth, produced O_3 buildups of 15-30 pphm in the Santa Clara Valley. Opposing southeast flow from the Monterey Bay area was conspicuously absent during this period.

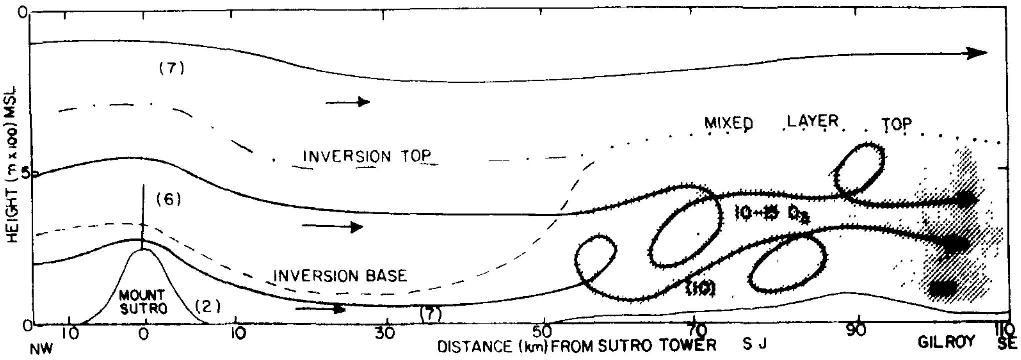

Figure 38a. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the afternoon (13-16 PST) of 22 July 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 10-15 pphm ozone is shaded.

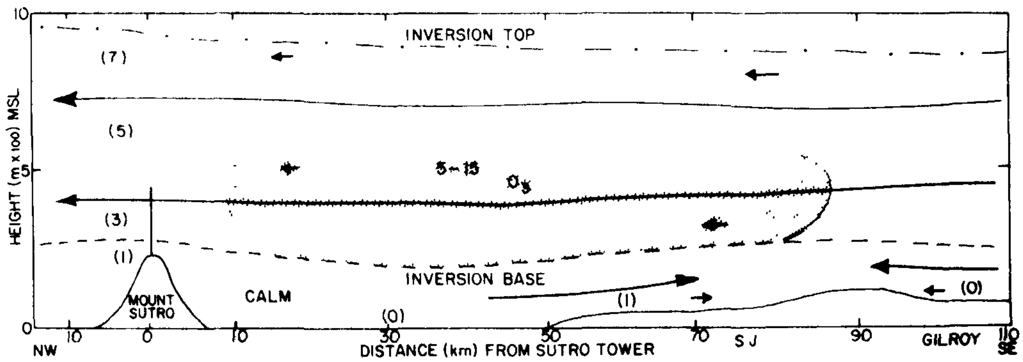

Figure 38b. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the morning (04-07 PST) of 23 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 5-15 pphm O_3 is shaded.

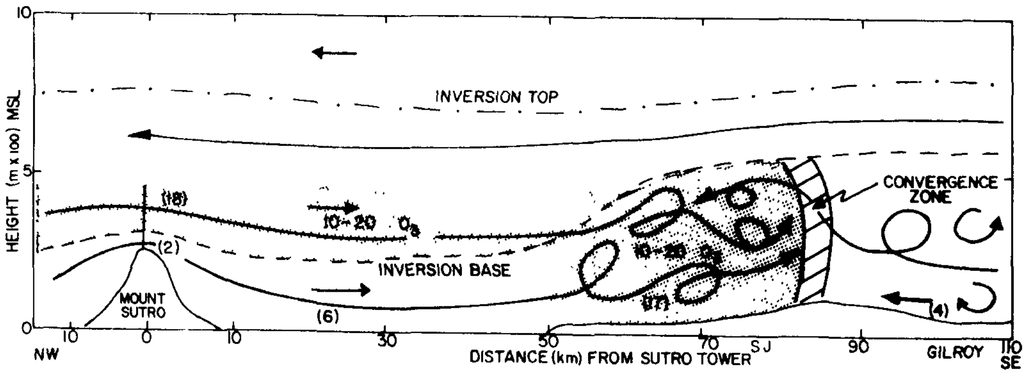

Figure 38c. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the afternoon (13-16 PST) of 23 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 10-20 pphm O_3 is shaded.

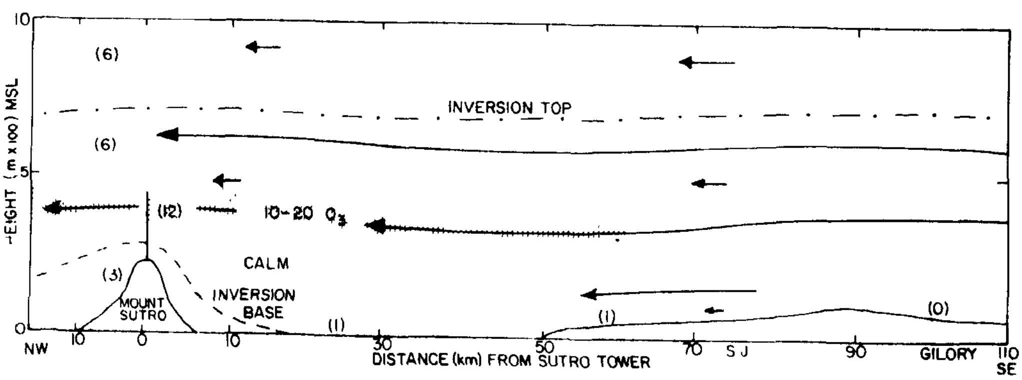

Figure 38d. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the morning (04-07 PST) of 24 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 10-20 pphm O_3 is shaded.

Except for a four hour period during the early morning of July 25, westerly flow prevailed over San Francisco. Coupled with reduced photochemistry due to the presence of middle and high clouds over the Bay Area, O_3 concentrations decreased to those values recorded on July 23.

During the morning of July 26, westerly flow prevailed over San Francisco and the San Francisco Bay (Figure 38f). Opposing southeast drainage flow over the Santa Clara Valley produced a convergence zone near the southern edge of the San Francisco Bay. Ozone concentrations at this time had decreased below 10 pphm.

By the afternoon of July 26, westerly flow prevailed through the Bay Area (Figure 38g). Ozone concentrations northwest of the Santa Clara Valley were only 5-10 pphm. However, the advection of ozone and its precursors, photochemical production, and low O_3 destruction due to large mixing depths produced O_3 buildups of 10-20 pphm in the Santa Clara Valley.

The dominant westerly flow through July 27 advected pollutants out of the Bay Area. As a result, high-hour oxidants of only 10 pphm occurred over San Jose, thus signalling the end of the episode. High oxidant concentrations at Chico and Redding in the Sacramento Valley on 25-27 July hint at possible transport there from the Bay Area (Table 10).

The primary injection process of O_3 into the subsidence inversion was the destruction of the inversion during the day by surface heating and its reformation at night by radiation cooling. Secondary pollutant injection processes may have been the downward flux of stratospheric ozone, aircraft emissions, and the destruction and reformation of the inversion by gravity waves, aircraft turbulence, and sea breeze induced convergence zones. At the beginning of the "buildup" period a 110 knot jet stream at 300 mb was located in the Gulf of Alaska. As the jet progressed eastward, however, air trajectroies reaching the lower troposphere over the Bay Area were from the southeast to southwest, thus suggesting a minimal stratospheric contribution.

Gravity waves, sea breeze convergence zones, and aircraft also appeared to provide only small contributions to the inversion ozone buildup. Although waving of the inversion occurred within the subsidence inversion during July 23 and 24, there was no evidence of the waves "breaking" with exchanges between the marine and inversion air masses. Although sea breeze convergence zones occasionally occurred over the San Pablo Bay during this episode, pollution was light, and therefore could not contribute substantially. Early morning convergence in the upper Santa Clara Valley was typical during this episode. Since winds were very light, updrafts penetrating the inversion appear unlikely.

In summary, under weak pressure gradients, a "sloshing" of air pollution beneath the subsidence inversion top, parallel to the NW-SE Santa Clara Valley axis, effectively trapped pollutants in the area. The Santa Clara Valley was the region of ozone generation, since ozone and its precursors were advected there from numerous upwind sources, and O_3 destruction rates were low during the day. Upon reformation of the inversion at night, pollutants became

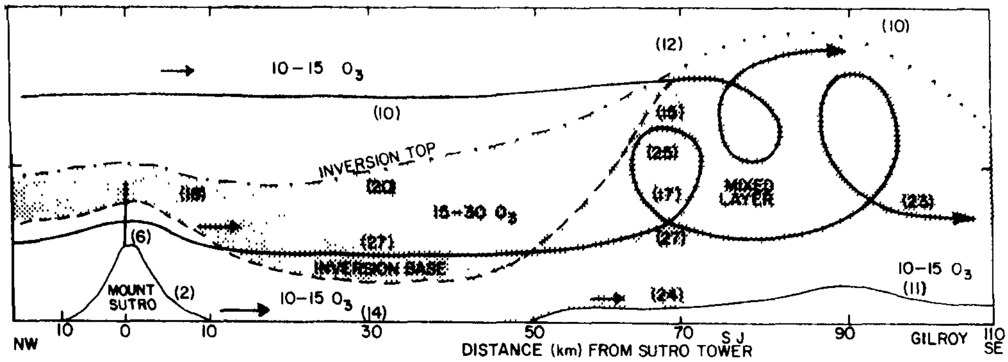

Figure 38e. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the afternoon (13-16 PST) of 24 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 15-30 pphm O_3 is shaded.

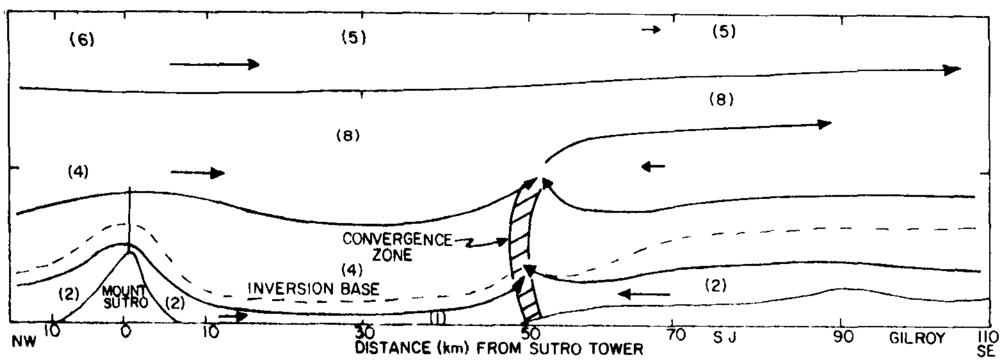

Figure 38f. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the morning (04-07 PST) of 26 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 10-15 pphm ozone is shaded.

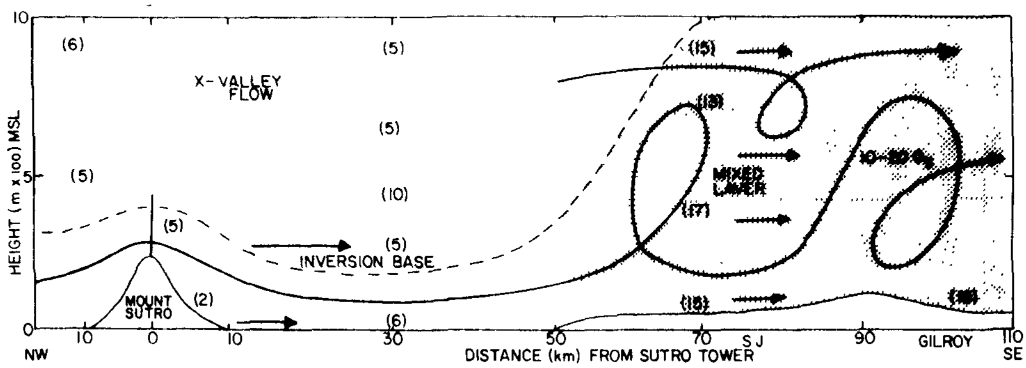

Figure 38g. NW-SE schematic cross section of air flow, inversion and mixed layer heights, and ozone concentrations (in parenthesis) during the afternoon (13-16 PST) of 26 July, 1974. Winds recorded over Oakland are presented vectorially with (→) = 4 m/sec. Region of 10-20 pphm O_3 is shaded.

trapped within the stable layer and persisted. The polluted layer was advected to the northwest during the night and returned during the afternoon. As westerly flow increased, pollutants were advected out of the valley and O_3 concentrations decreased below the federal standard at most locations.

The primary injection process of O_3 into the subsidence inversion was the destruction of the inversion during the day by surface heating and its reformation at night by radiational cooling. Secondary pollutant injection processes were the lowering of the inversion during the day, and may have included downward flux of stratospheric ozone, aircraft emissions, and the destruction and reformation of the inversion by gravity waves, aircraft turbulence, and sea breeze induced convergence zones.

TABLE 10. SURFACE OXIDANT CONCENTRATIONS (pphm) JULY 22-31, 1974

Chico (76 m MSL)

Date/PST Time	10	11	12	13	14	15	16	17	18	19	20	21	Max. High Hour BAAPCD Oxidant Concentration
22	8	9	9	8	8	7	6	5	4	2	1	2	18
23	8	8	8	8	7	7	6	6	5	3	1	2	17
24	7	8	7	9	8	8	8	8	6	3	2	3	25
25	9	10	10	9	9	9	8	8	7	4	4	7	15
26	7	8	8	9	10	10	12	12	12	12	11	8	15
27	7	8	8	9	9	8	8	8	9	6	6	5	10
28	7	8	8	8	8	8	8	7	8	7	5	5	10
29	7	7	8	8	M	7	6	6	4	3	1	1	9
30	8	9	10	10	9	9	9	9	9	9	7	7	10
31	6	8	9	10	10	10	9	10	9	6	6	8	9

Redding (220 m MSL)

Date/PST Time	10	11	12	13	14	15	16	17	18	19	20	21	Max. High Hour BAAPCD Oxidant Concentration
22	3	4	M	5	5	5	4	4	4	4	4	3	18
23	M	M	M	M	M	M	M	5	5	6	5	3	17
24	5	6	6	6	8	10	10	8	7	7	6	4	25
25	6	6	6	6	7	7	7	8	8	11	10	9	15
26	7	8	12	15	14	14	12	11	10	11	10	6	15
27	5	8	10	14	13	13	13	12	11	9	9	7	10
28	8	9	11	13	12	10	8	11	10	9	7	6	10
29	5	8	9	10	10	10	8	9	9	9	7	3	9
30	M	7	7	7	6	7	7	5	5	5	6	7	10
31	7	10	13	14	13	13	13	11	10	9	9	5	9

SECTION 7

CASE STUDY OF JULY 22-27, 1975
by
Betsy L. Babson*

This case study occurred almost a year to the day after the one discussed in the previous section. Following the terminology of Section 6, July 22-24 are referred to as the "intensification" or "build-up" period, July 25 the "peak" or "health advisory alert" day, and July 26, 27 as the "break-up" or "restoration" period. On July 25, five monitoring stations reported oxidant levels of 20 pphm or greater, causing the BAAPCD to issue a health advisory alert for the Santa Clara Valley. This section compares and contrasts the evolution of the two July episodes studied.

SYNOPTIC PATTERN

A dynamic low centered in the Gulf of Alaska persisted throughout this episode. High pressure dominated the western United States above 850 mb, and a trough was located over the Great Lakes region. During the intensification period a lobe of the Subtropical High penetrated into the Pacific Northwest to join with a Great Basin High over the northwestern United States.

On July 25, the Low in the Gulf of Alaska began to fill. At 850 mb the Great Basin High separated from the Subtropical High as a trough of low pressure developed in the southwestern United States. A weak front at the surface approaching from the northwest dissipated as it crossed over northern California at 12 GMT on July 25.

By July 27 the High over California had weakened. West-northwest winds prevailed over San Francisco as a heat trough became well established throughout the Central Valley.

SURFACE TEMPERATURE PATTERN

Mean daily maximum temperatures recorded during July, 1975, were similar to those of July, 1974, and exhibited a large temperature gradient between the coastal regions and the Santa Clara and Sacramento Valleys (Figure 39a).

On July 22, temperatures throughout the Bay Area were generally 8°F above the mean. Within the next three days temperatures increased as much as

*Abstracted from "A Case Study of the San Francisco Bay Area Air Pollution Episode, July 1975" submitted in partial fulfillment of Weather Analysis and Forecasting class, San Jose State University, Meteorology Department.

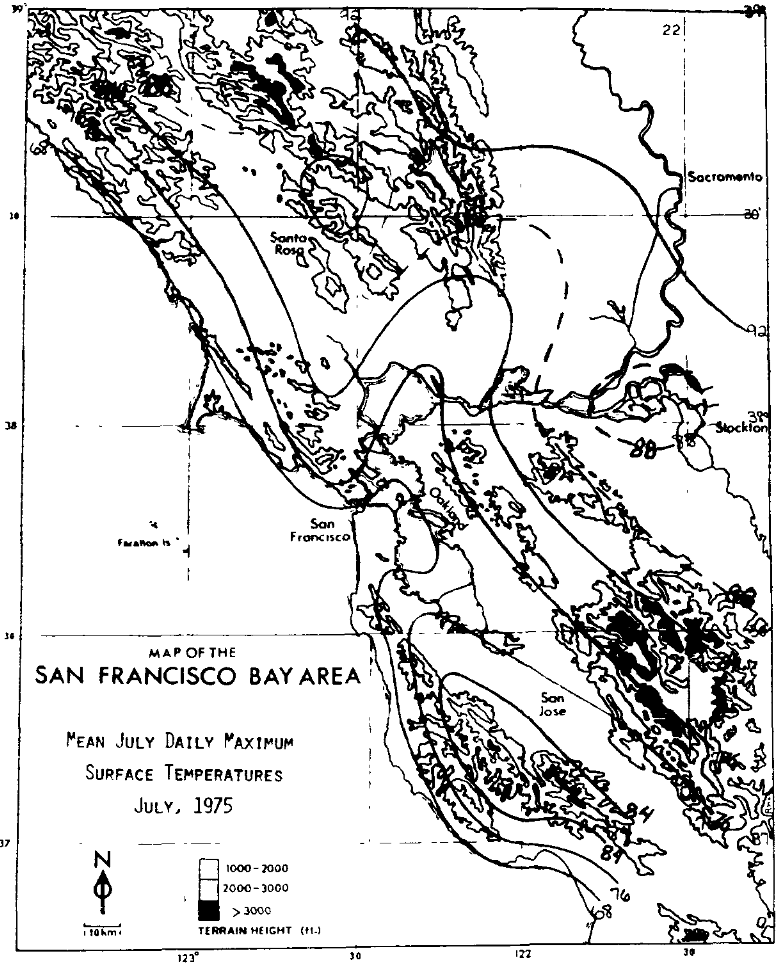

Figure 39a. Mean maximum hourly surface temperatures, San Francisco Bay Area, July, 1975.

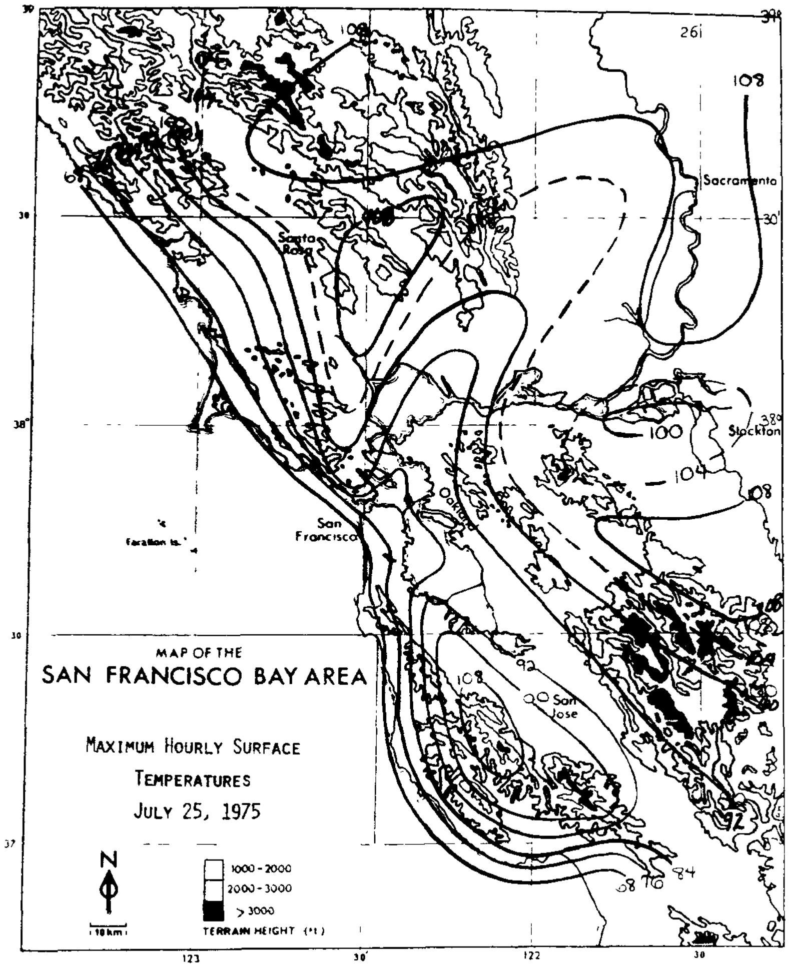

Figure 39b. Maximum hourly surface temperatures, San Francisco Bay Area, July 25, 1975.

12 degrees, reaching 100°F in the Santa Clara Valley on July 25 (Figure 39b). During the restoration period, temperature decreases were less rapid than rates of increase for the initial stages of the pollution episode.

SURFACE WINDS

Surface flow patterns for the July, 1975, air pollution episode were similar to those presented in Section 6 for July, 1974. BAAPCD stations reported calm conditions throughout the Bay Area at 04 PST except in the vicinities of the Golden Gate gap and Carquinez Straits where relatively strong flow prevailed during the intensification and restoration periods.

By 16 PST, wind speeds increased, and northwest winds dominated the Santa Clara Valley.

SURFACE OXIDANT CONCENTRATIONS

During the ozone build-up period of the July, 1975, air pollution episode, oxidant concentrations reached 12 pphm in the Santa Clara and Sacramento Valleys. On July 25, concentrations exceeded the Federal Standard throughout the entire Bay Area except at San Francisco and coastal areas. A Health Advisory Alert was issued in the Santa Clara Valley where oxidant levels of 20 pphm were reached at the Hayward, Fremont, Alum Rock, Sunnyvale, Mountain View, and San Jose BAAPCD monitoring stations. The highest average hourly concentration recorded was 23 pphm at the Hayward station at 14 PST (Figure 40). By July 27, oxidant concentrations were reduced below the Federal Standard at all stations except Los Gatos, San Jose, and Alum Rock.

The distribution of oxidants throughout the Bay Area was similar during both the July, 1974, and July, 1975, air pollution episodes, though concentrations in the Santa Clara Valley were slightly higher in 1974.

UPPER AIR WINDS

Time sections of horizontal wind vectors at the Mount Sutro Tower are shown for the three periods of the episode (Figure 41). Southwest winds prevailed below the inversion base during the Intensification Period, while flow was generally from the northwest aloft. Light northeast winds were recorded at all levels during the morning of the alert day when the temperature inversion base dropped below the Tower base. Wind speeds increased in the evening as flow shifted from westerly to north-northwesterly between 14 and 20 PST, and the inversion base rose above 250 meters. By July 27, the inversion base lifted above 400 meters, and winds at all levels of the Tower were strong out of the southwest.

West-northwest winds ranged from 3 to 9 m/sec over Oakland at 04 PST on the alert day (Figure 41). During the previous year, winds were northwest at the surface and south-southeast aloft, while speeds varied from calm to a maximum of 3 m sec^{-1}. West-southwest winds prevailed within the inversion during the restoration periods of both episodes, though winds speeds were approximately 4 m sec^{-1} greater during July, 1975.

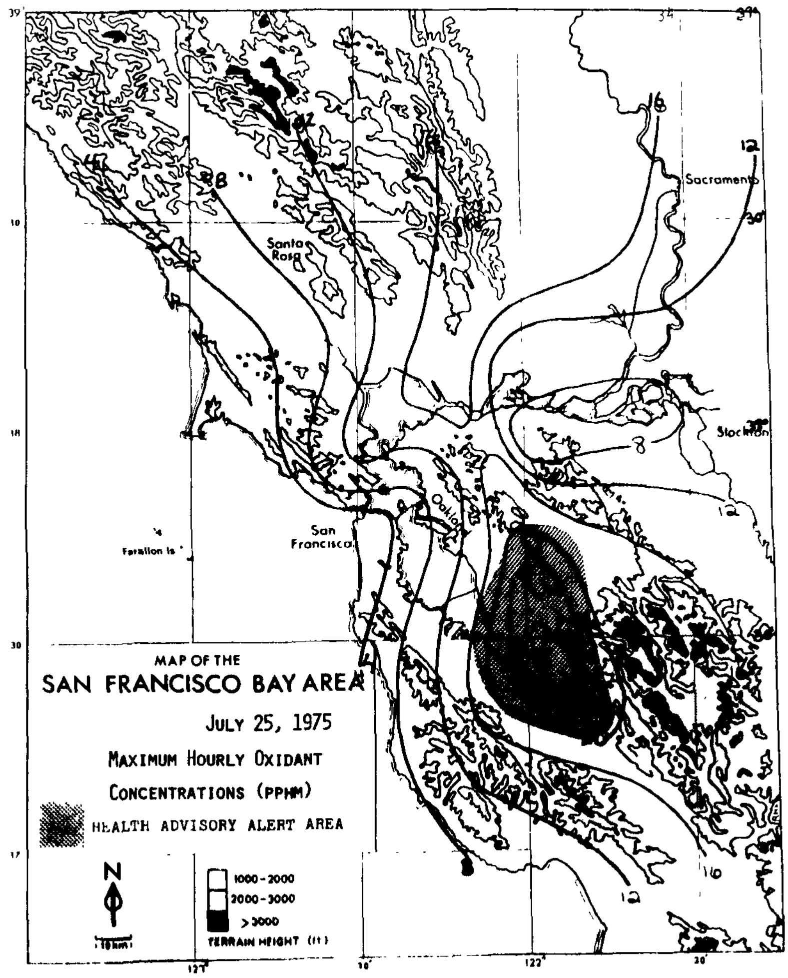

Figure 40. Maximum hourly oxidant concentrations at BAAPCD Measurement Stations, 25 July 1975.

A comparison of the horizontal wind vectors for the July 1974 and 1975 alert days (Figures 42 and 43) shows similarities and difference between the two episodes. Flow was north-northeast during the pre dawn hours of the 1975 alert day, whereas winds were south-southeast during the same period of the previous year. In both cases winds were light from the northeast between the early morning and the commencement of strong westerly winds in the mid afternoon.

Section 6 emphasized the advection of pollutants northward from the Santa Clara Valley. Figure 42 shows that no such advection occurred during this period, but that the period of light offshore flow during the forenoon and early afternoon periods were common during both episodes.

OZONE ALOFT

Time-height sections of O_3 concentrations at the Mt. Sutro Tower for the study period (Figure 44) show O_3 peaks within the inversion at heights of 400 to 450 m. During the intensification period of the July, 1975, pollution

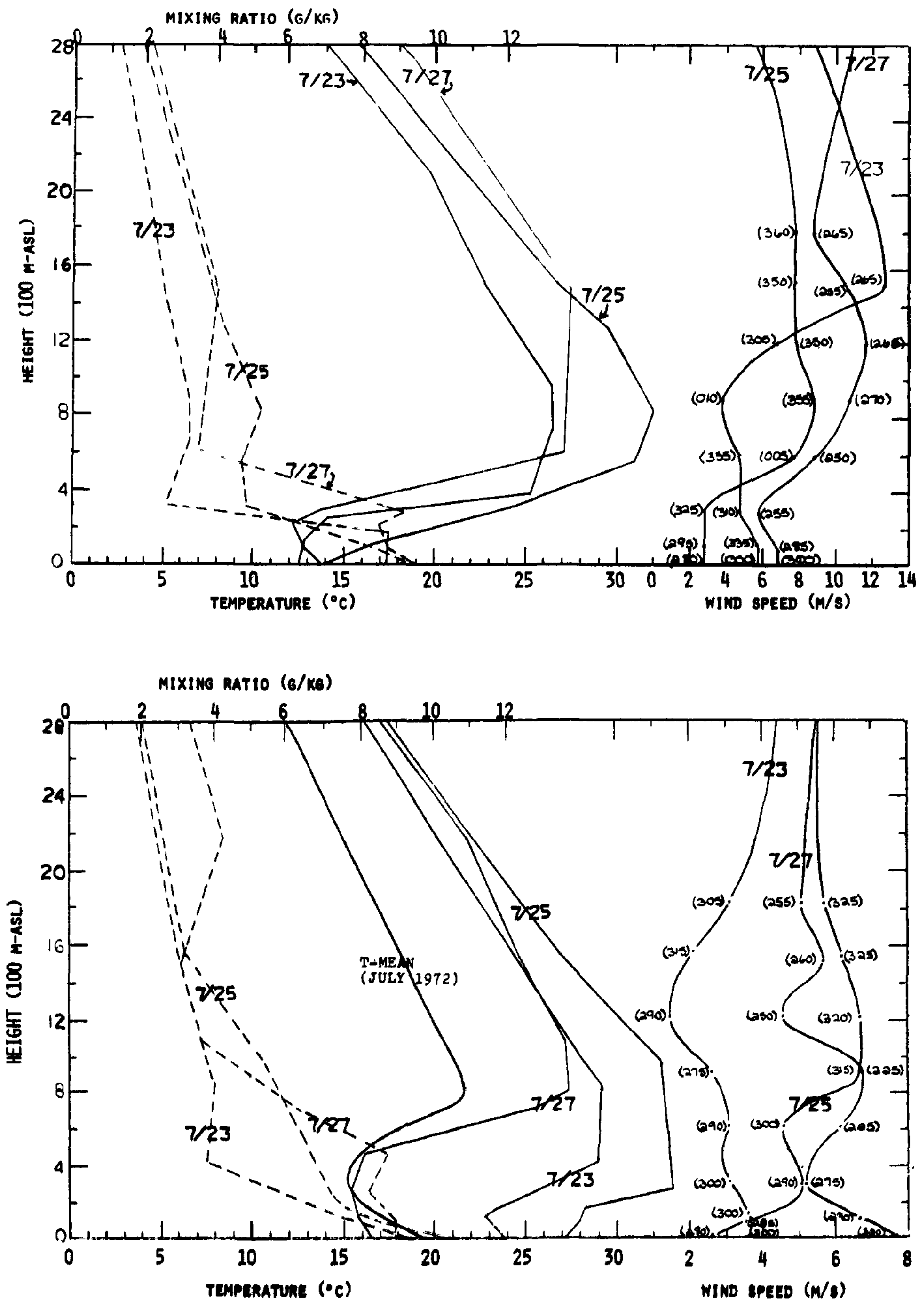

Figure 41. Rawinsonde profiles of temperature, mixing ratio and wind speed and direction; Oakland, CA, July 23, 25, 27, 1975 at 04 PST (top) and 16 PST (bottom).

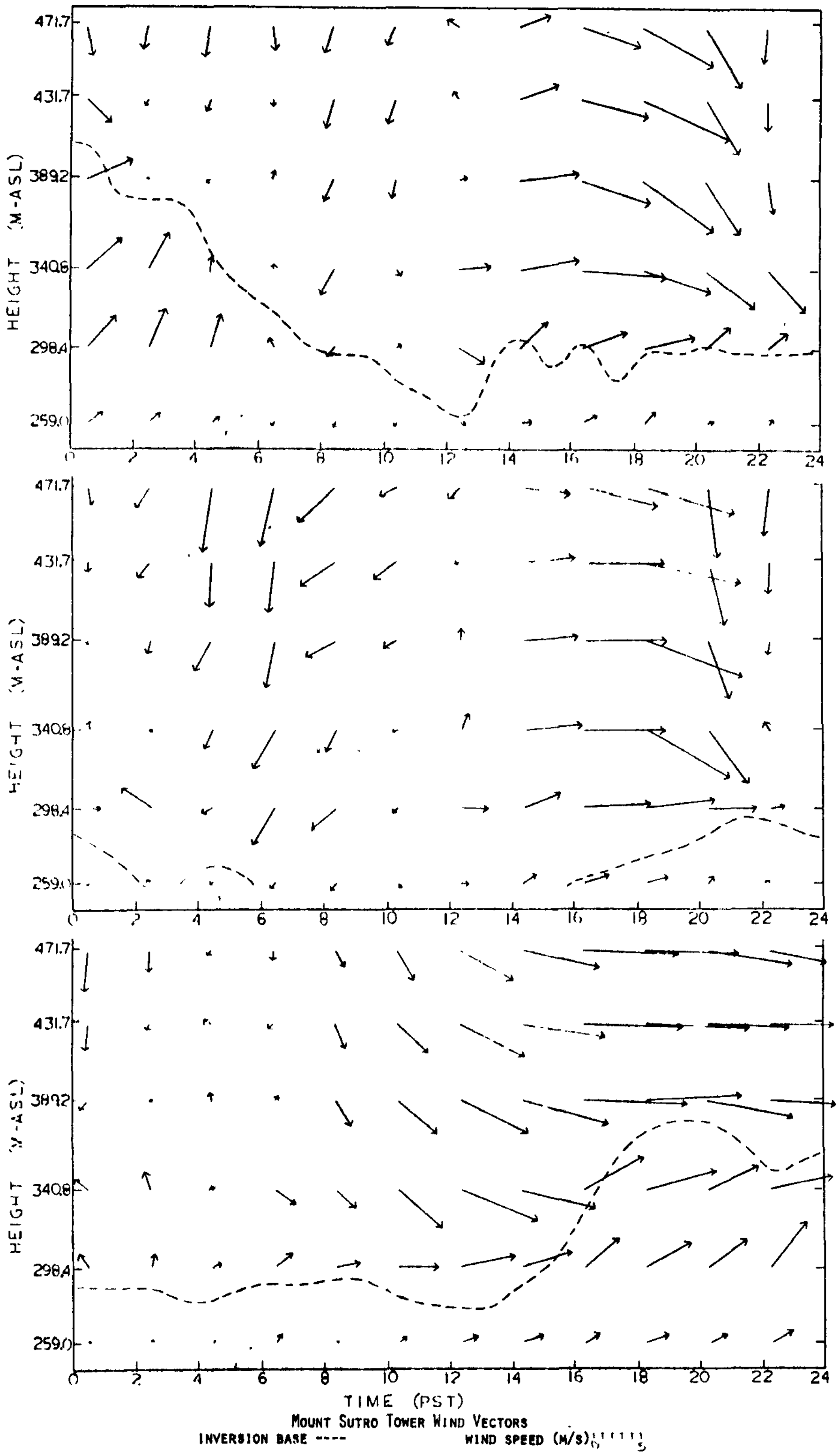

Figure 42. Hourly average horizontal wind vectors. Mt. Sutro Tower. July 24 (top), July 25 (middle) and July 26 (bottom), 1975.

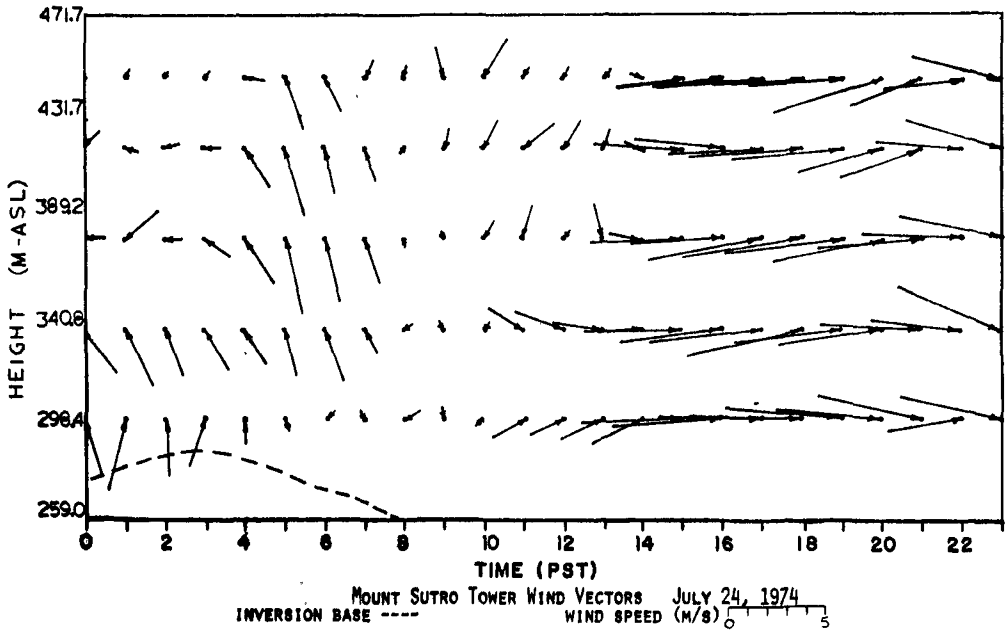

Figure 43. Hourly average horizontal wind vectors, Mt. Sutro Tower, July 24, 1974.

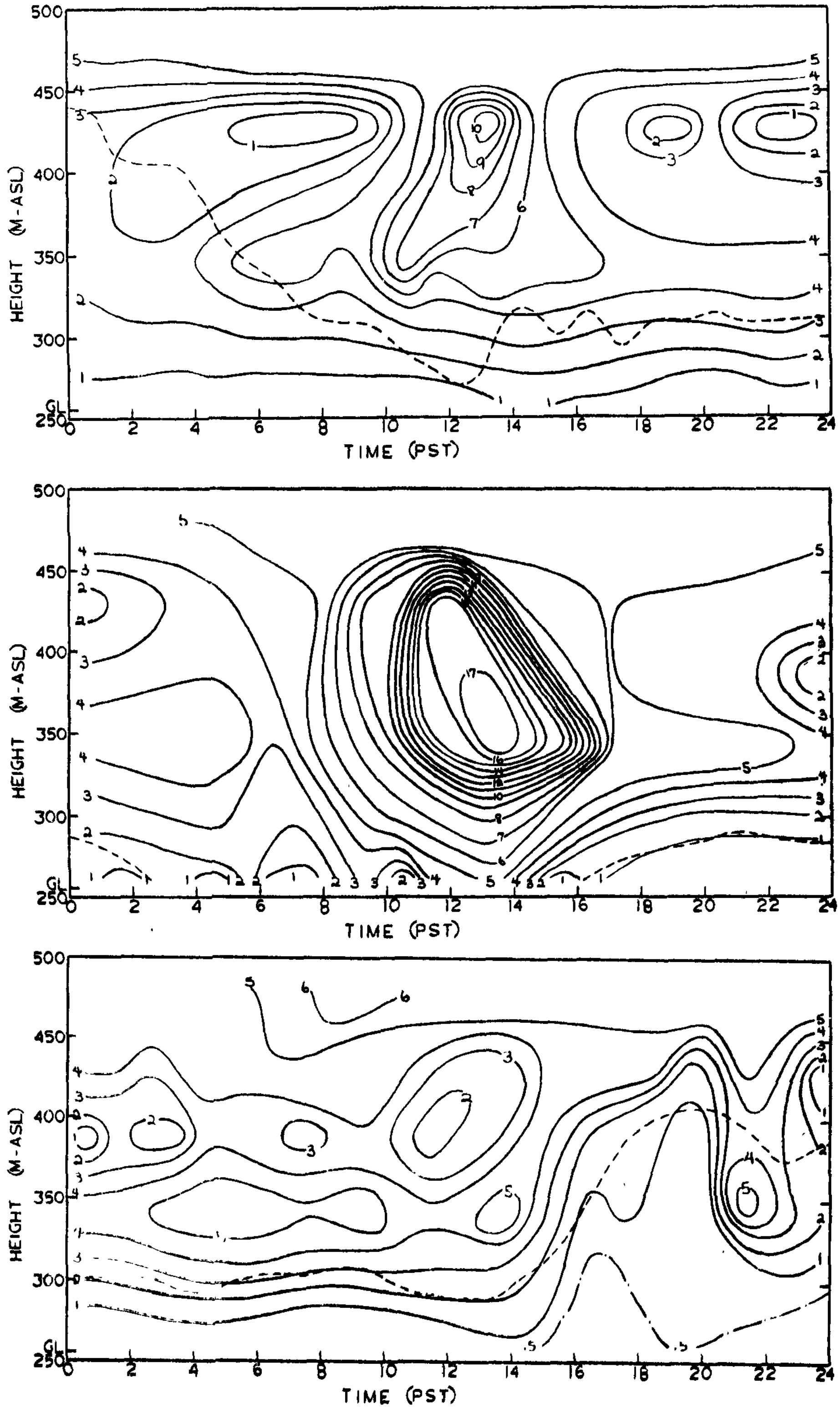

Figure 44. Time-height sections of hourly average ozone concentrations, Mt. Sutro Tower, July 24 (top), July 25 (middle, and July 26 (bottom), 1975. Units are pphm.

episode, a strong vertical gradient of ozone occurring above the inversion base dipped down to ground level as the inversion base lowered. On July 25, when the inversion base was below the Tower, a peak of 17 pphm occurred near 400 meters at 1300 PST. Maximum ozone values occurred at the same level and time during the alert day of the July, 1974 episode, though concentrations reached 26 pphm for this case.

The restoration period was characterized by a decrease in ozone concentrations aloft. The inversion base rose from 280 meters on July 26 to above 475 meters at 0700 PST on July 27, 1975. Ground concentrations dropped below 0.1 pphm at this time.

CONCLUSIONS

The synoptic pattern of the July, 1975, air pollution episode closely resembled that of the July, 1974 incident. Weak pressure gradients were established over the San Francisco Bay Area due to the presence of a Great Basin High in the Pacific northwestern United States and the Subtropical High off the California coast.

Surface wind flow was similar to the mean monthly pattern for July during both episodes. Wind speeds were light throughout the Bay Area in the morning and increased in the afternoon as northwest flow dominated the Santa Clara Valley. Within the inversion layer, north-northwest flow prevailed over Oakland and San Francisco at 0400 PST during the July, 1975, incident, whereas winds were from the south-southeast at this time during the previous year. According to the "sloshing" effect described in Section 6, a southerly wind component is necessary for the advection of pollutants northward during the early morning hours to confine pollutants within the Bay Area. Though this effect was not observed during the July, 1975 episode, there may have been appreciable "sloshing" of pollutants within the inversion layer due to a diurnal shift in the winds.

Surface temperatures during both pollution episodes exceeded the July monthly means, climbing to over 100°F on the respective alert days. During July, 1975, the vertical temperature gradient was greater and the inversion base lower at Oakland than for the previous year at both 0400 and 1600 PST.

Surface oxidant levels recorded at BAAPCD monitoring stations were similar for the July, 1974 and 1975 air pollution episodes except for relatively low concentrations recorded at Livermore during the latter episode. Though surface temperatures at Livermore were high during July 25, 1975, winds were extremely light. The low oxidant levels can be attributed to a minimum advection of ozone precursors from surrounding areas since the Livermore Valley is not a major source for ozone and its precursors.

Ozone within the elevated inversion layer over the Mount Sutro Tower exceeded 10 pphm between 1000 and 1600 PST on July 25, 1975. Concentrations at the surface throughout the Bay Area reached maximum values between the hours 1100 and 1500 PST. The largest oxidant value recorded during the alert day was 23 pphm at Hayward at 1400 PST. The BAAPCD monitoring station at Hayward is 260 meters ASL, in the elevated peak of ozone concentration within the inversion layer situated over the Bay Area.

If the temperature profile throughout the Bay Area resembled that of Oakland at 1600 PST on July 25, 1975, (Figure 41), high ozone concentrations could be explained by high production rates near the surface and horizontal diffusion of ozone from surrounding areas. Though mixing depths would be small due to the intense surface based inversion, ozone destruction rates would be less than production rates due to high temperatures and weak vertical mixing.

Since the height and intensity of the inversion varies considerably over the San Francisco Bay Area (Ahrens and Miller, 1969), the inversion over the Santa Clara Valley may have been destroyed due to surface heating instead of being surface based as at Oakland. This condition would be analogous to the July, 1974, air pollution episode in which Holets found large mixing depths and low ozone destruction.

Miller and Ahrens (1969) found high concentrations of ozone at the leading edge of the marine air where the mixing depth is large and temperatures are high. Ozone buildups along this inversion edge marked the limit of inland penetration of polluted marine air in which there is a high production of oxidants. Figures 39b and 40 show that areas along the coast, where the marine inversion persisted, had low ozone concentrations compared to the inland valleys. Due to stagnant conditions over the Bay Area, the seabreeze did not penetrate far inland. High ozone concentrations produced at the leading edge of the marine layer "spread out" into the Santa Clara Valley causing large oxidant levels to accumulate within the valley during the day. In the absence of appreciable winds, ozone was confined within the valley due to the mountains to the east and the marine inversion to the west. Assuming the inversion was reestablished during the evening, maxima of ozone that had been generated in the surface layer were cut off from the surface and persisted within the stable layer aloft. Concentrations near the surface decreased due to increased destruction rates and low production rates during the night. As the inversion lowered or was destroyed on the following day, downward diffusion of ozone contributed to concentrations generated near the surface. The pollution episode ended when temperatures dropped and wind speeds increased causing oxidants and their precursors to be advected out of the Bay Area.

SECTION 8

CASE STUDY SEPTEMBER 3-8, 1974

As this period opened only San Jose exceeded the NAAQS when it recorded 9 pphm on September 3. During the peak of the episode, Livermore recorded 24 and 28 pphm on September 5 and 6, while 20 BAAPCD stations exceeded the 8 pphm NAAQS. At the end of the period, no stations in the Bay Area exceeded 8 pphm.

SYNOPTIC PATTERN

During the first ten days of September a 500 mb long wave ridge persisted with its axis roughly along the west coast near 130 W. Just prior to the episode, the pattern north of 45 N resembled an omega block, leaving the Pacific Northwest and British Columbia under subsiding northerly flow (Figure 45). On 2 September Quillayute, Wa. recorded a high hour concentration for the day of 400 DPM/KSCM (disintegrations min^{-1} per 1000 standard m^3) indicating stratospheric intrusion on that day, and possibly on 3 September (Ludwick, et al. 1975, 1976).

As the period opened, a trough moved through the Pacific Northwest producing more zonal flow by 4 September (Appendix 2) and decreasing stability while increasing marine layer depths over the Bay Area. By 5 September the 500 mb contour gradients were weak over most of the Southwest with light 500 mb westerly winds over coastal California. As the episode ended, the high contour center moved eastward producing moderate 500 mb zonal flow over Central and Northern California.

At 700 mb, Figure 46 shows the effects of the short wave trough on 4 September producing fairly strong zonal flow over Central and Northern California. After the trough passed, weak 700 mb gradients over much of the Southwest produced light flow over coastal California. Increased subsidence produced by air and, as shown below, lowered the inversion base to the surface. By 8 September the deepening southward moving low produced zonal flow over the Pacific Northwest with moderate westerlies over Central California.

Surface analyses (not shown) show moderate onshore pressure gradients along coastal California on September 3 and 4. By 04 PST on 5 September, the axis of the California low was situated at or near the coastline producing offshore pressure gradients. At the end of the period, an approaching surface front re-established onshore flow along the coast.

SURFACE PATTERNS

Temperatures

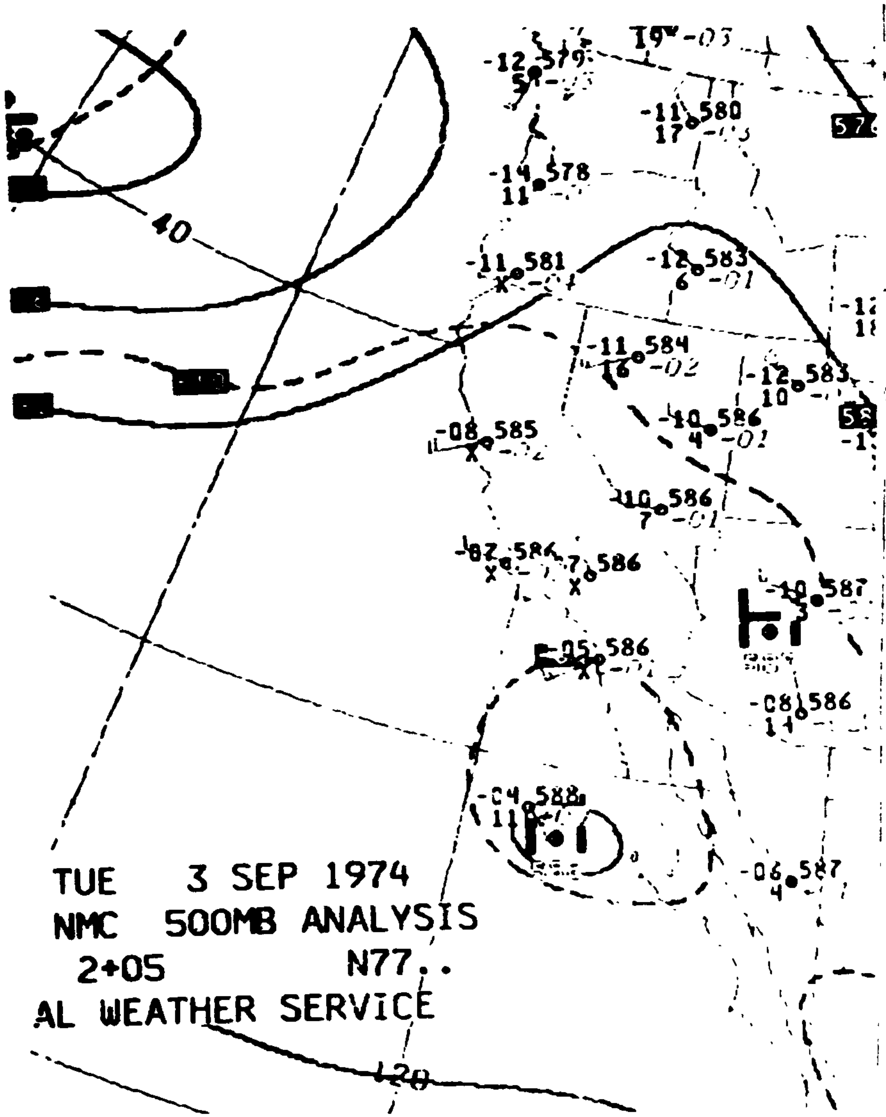

Figure 45. National Weather Service 500 mb analysis, 12 GMT, 3 September.

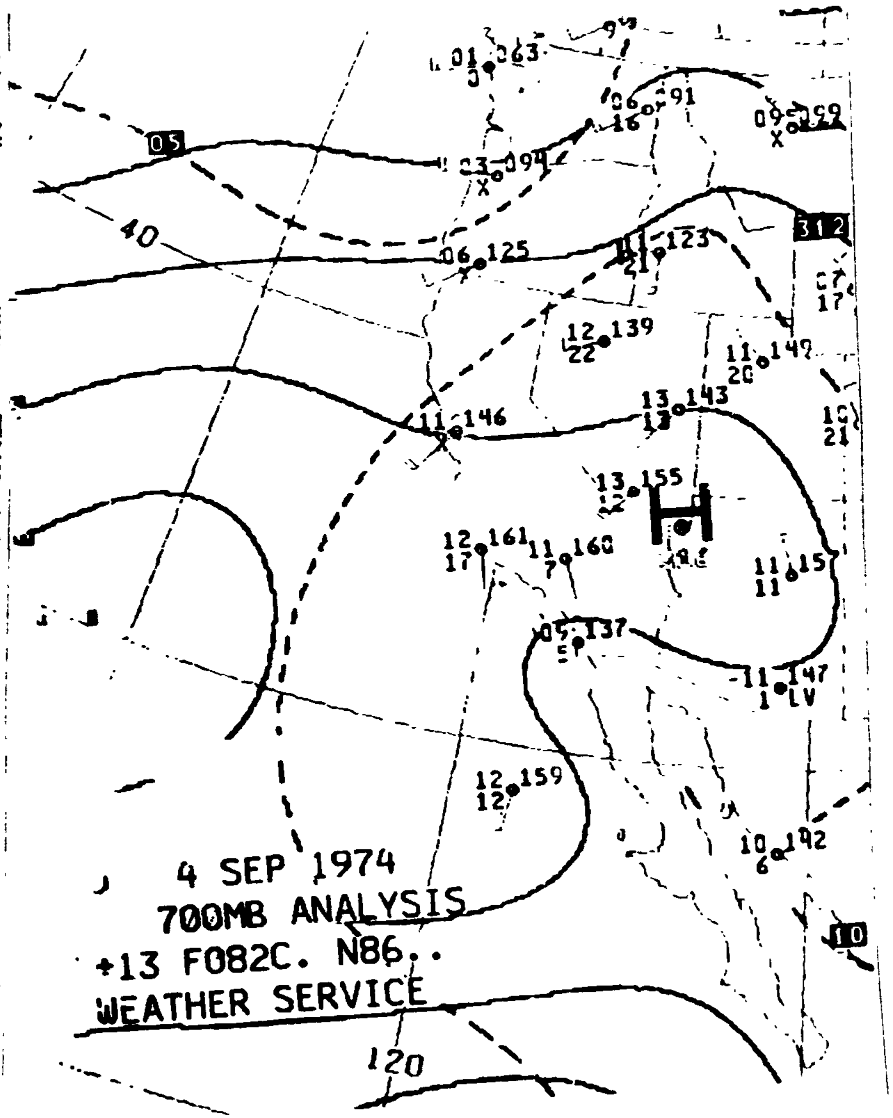

Figure 46. National Weather Service 700 mb analysis, 12 GMT, 4 September 1974.

Table 11 lists the maximum temperatures for selected stations in California for the period. On September 3, maximum temperatures were near the monthly average throughout the Bay Area and Central Valley. On September 5 and 6 maximum temperatures were 10F to 15F warmer than the monthly average throughout the Bay Area and about 5F warmer than the monthly average in the Central Valley. On September 7, Berkeley and Oakland returned to near average maximum temperatures. The rest of the Bay Area stations returned to near average maximum temperatures on September 8. In the Central Valley, central and southern stations remained somewhat above the monthly average while Red Bluff decreased to about 3F below the monthly average.

TABLE 11. MAXIMUM TEMPERATURES (°F)
SEPTEMBER 3-8, 1974

Station Date	3	4	5	6	7	8	Average September 1974
Marine Influenced							
Berkeley	70	70	83	78	70	74	69.3
Oakland	68	68	71	80	80	69	71.5
Intermediate							
San Jose	76	83	92	92	90	82	80.3
Inland							
Los Gatos	81	90	99	95	90	85	84.9
Livermore	88	95	102	100	98	92	90.6
Gilroy	90	89	96	102	102	98	88.5
Central Valley							
Bakersfield AP	96	96	100	104	102	97	96.5
Fresno AP	95	97	100	101	101	98	94.8
Sacramento AP	91	93	98	99	99	93	90.4
Red Bluff AP	97	98	101	101	101	93	96.3

Oxidants

On September 3 only San Jose exceeded the 8 pphm Federal Standard with a high hour oxidant concentration of 9 pphm (Table 12). By September 5 and 6, Livermore recorded high hour concentrations of 24 and 28 pphm respectively while 20 stations exceeded 8 pphm on September 5, and 18 stations exceeded that value on September 6. At the end of the period, no stations exceeded 8 pphm.

TABLE 12. HIGH HOUR OXIDANT PATTERNS
SEPTEMBER 3-8, 1974

Date	Station of Highest Maximum	Highest Maximum (pphm)	Number of BAAPCD Stations > 8 pphm
3	San Jose	9	1
4	Livermore	14	9
5	Livermore	24	20
6	Livermore	28	18
7	San Jose, Los Gatos	15	7
8	Los Gatos	8	0

In the early afternoon of the peak day of September 5, oxidant maxima were found near San Rafael in the north, Hayward in the central portion of the eastern bay shore and San Jose in the south (Figures 47a). Tongues of relatively clean air were caused by marine penetration through the Golden Gate and the Crystal Springs gap. At 14 PST (Figure 47b) the northern maximum shifted to the Vallejo area, Hayward increased to its maximum of 21 pphm and San Jose decreased slightly. During the next two hours, concentrations continue to increase.

During the post sunset hours of 5 September, five stations (East San Jose, Hayward, Pittsburg, Walnut Creek and Livermore) recorded O_3 concentrations greater than 8 pphm until 21 PST. Figure 48 shows the hourly oxidant concentrations for Livermore, Hayward and (downtown) San Jose for September 5 and 6. Note that while nighttime concentrations lower to 1 pphm, those at Livermore and Hayward remain high throughout much of the night of 5/6 September, and Hayward concentrations remain relatively high until midnight of 6 September.

The five stations mentioned above, as well as Los Gatos and Concord which showed nighttime concentrations almost as high, are all located relatively near mountain slopes. It appears therefore that oxidant rich air from aloft is carried to the surface by downslope gravity winds at these locations.

Daytime concentrations at Livermore and San Jose reach 28 and 21 pphm respectively while Hayward records a peak of 13 pphm on 6 September. Eighteen

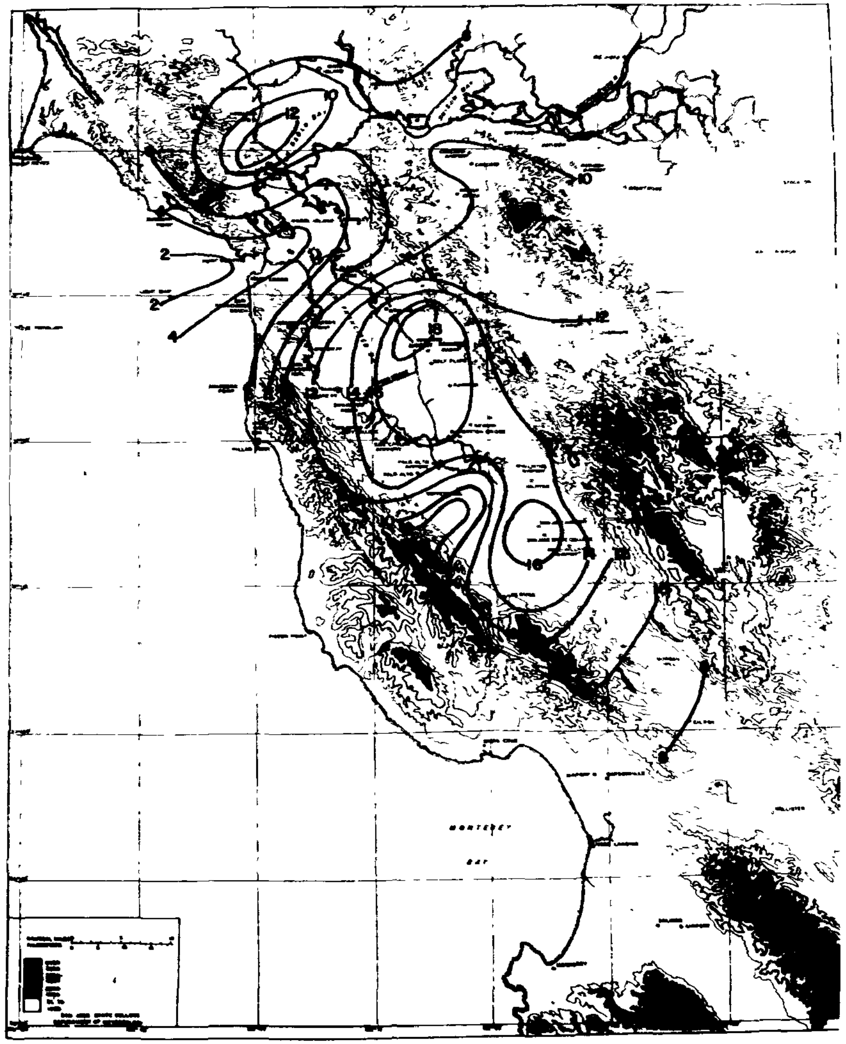

Figure 47a. Hourly average Oxidant Concentrations (pphm) for hour beginning 13 PST, 5 September, 1974.

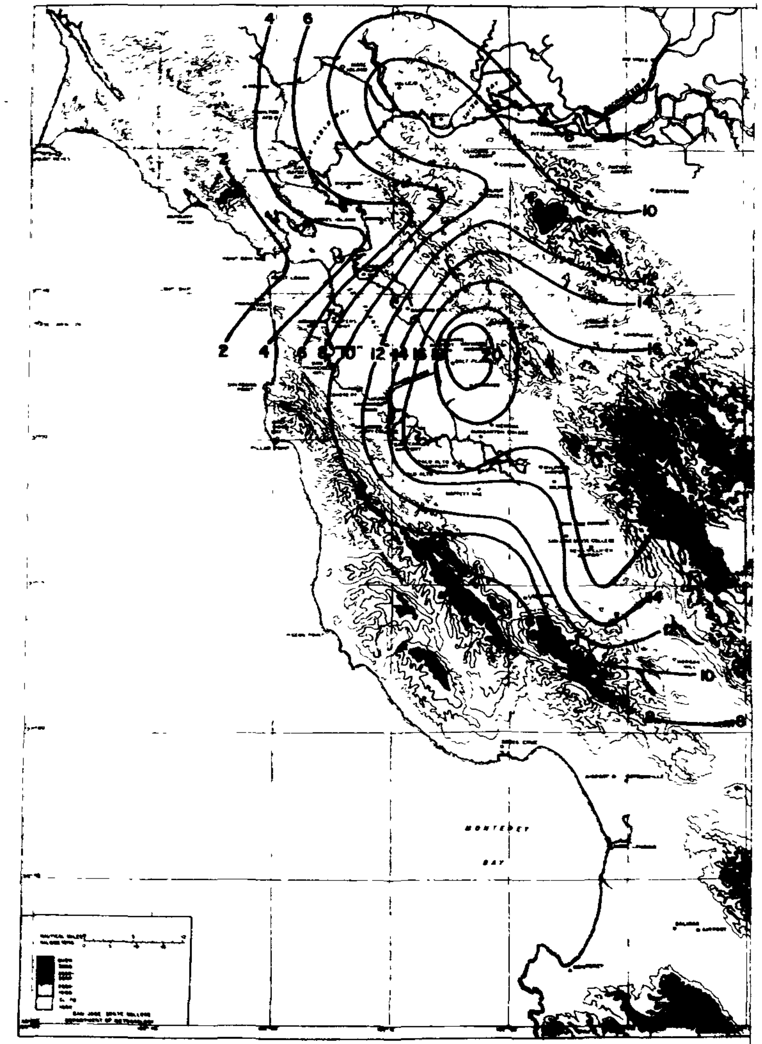

Figure 47b. Hourly average Oxidant Concentrations, 14 PST, 5 September, 1974.

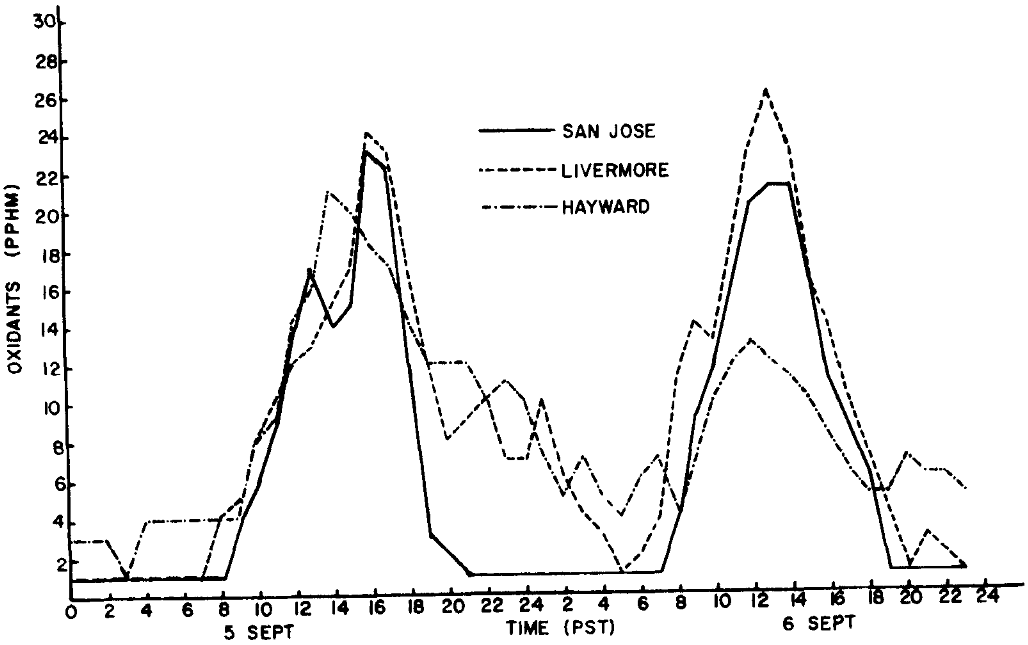

Figure 48. Hourly oxidant concentrations, San Jose, Livermore and Hayward BAAPCD monitoring stations, September 5-6, 1974.

BAAPCD monitoring stations recorded high hour oxidant readings exceeding 8 pphm. On 7 September the maximum high hour oxidant recordings were 15 pphm at San Jose and Los Gatos and seven BAAPCD monitoring stations recorded high hour values greater than 8 pphm. On 8 September, a Sunday, no BAAPCD readings exceeded 8 pphm.

UPPER AIR PATTERNS

Subsidence Inversion

The depth of the marine layer at Oakland showed the normal diurnal oscillation with maximum depth in the morning and minimum in the afternoon. Superimposed on this oscillation was a continued lowering of the inversion base until it reached the surface at 16 PST September 4. The inversion base remained at the surface until 04 PST, September 6 and then began to lift. A north-south cross section along the west coast (not shown) shows isentropes sloping steeply downward from Medford, Oregon to Oakland.

At the Sutro Tower, the inversion base remained above 350 m throughout September 3. A time-height section of temperature for September 4 (Figure 49) shows the inversion lowering to the surface in the early afternoon. The inversion remained on the surface until about 10 PST September 5 when rapid warming near the surface commenced. After an unstable period near noon, cooling of about 8C in two hours occurred at the surface, and the inversion re-established at about 15 PST. A similar pattern occurred on September 6; a strong inversion was based at or near the surface until about 9 PST; between

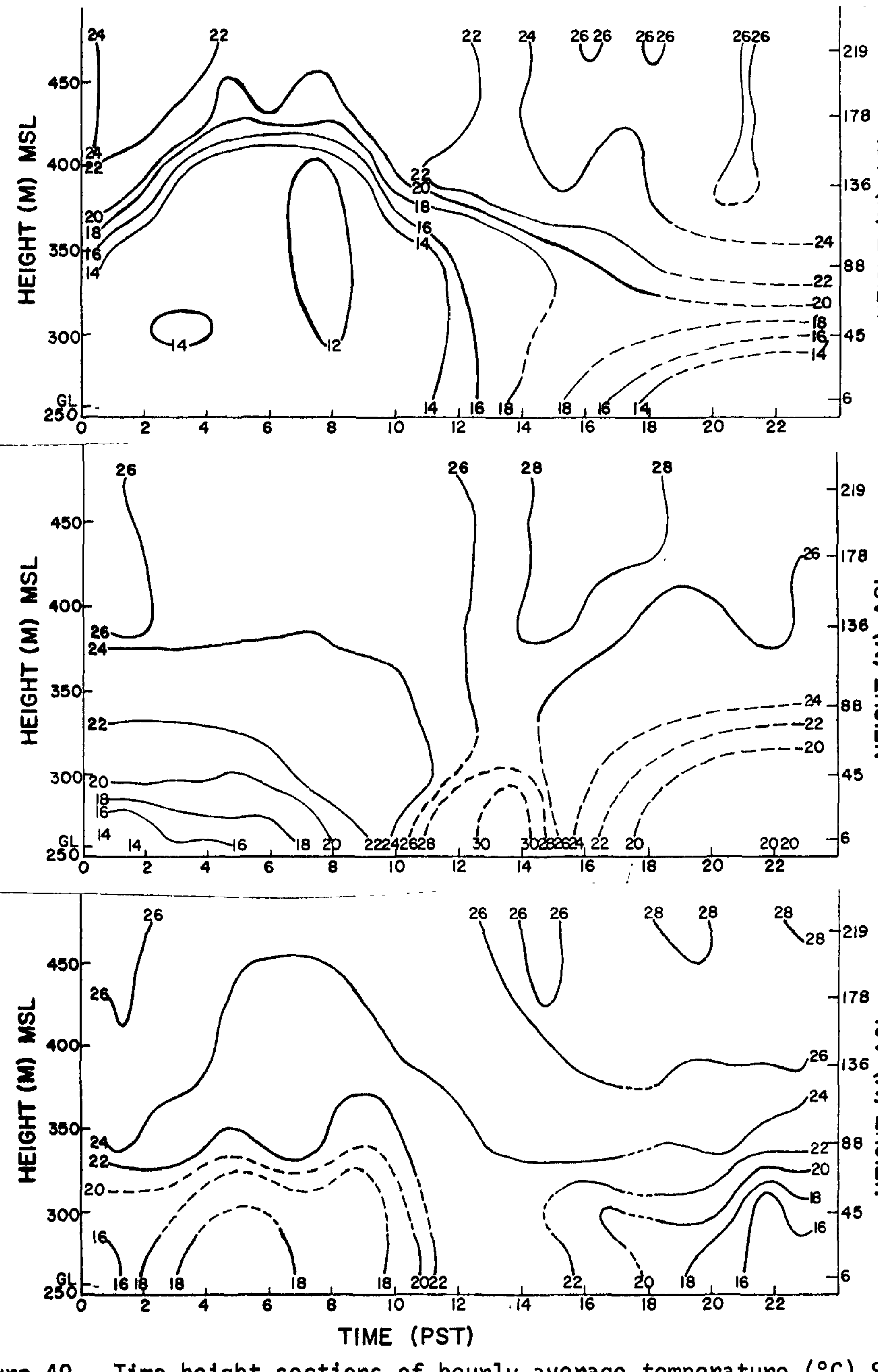

Figure 49. Time-height sections of hourly average temperature (°C) Sutro Tower, September 4 (top), 5 (middle) and 6 (bottom), 1974.

9 and 11 PST rapid warming occurred near the surface. A near surface neutral or slightly unstable layer existed until about 14 PST when near surface cooling commenced and the inversion re-established and remained surface based until about 07 PST September 7 (not shown). After some oscillations, the inversion lifted from about 40 m above ground at 17 PST to about 150 m at midnight. The inversion base remained at least 100 m above the peak of Mt. Sutro throughout September 8.

Winds

Mean surface to 5000 ft. winds over Oakland (Table 13) were from the northwest at speeds ranging from 8 to 11 knots until 16 PST on 4 September when the direction was from 260°. On September 5 winds were light easterly, shifting to southwest from the morning of September 6 to the afternoon of September 7 as speeds increased. By the morning of September 8 winds were from the northwest.

Wind vectors plotted for each hour at each measurement level show the possible recirculation of inversion layer pollutants (Figure 50). On 4 September hourly average winds at Levels 5 and 6 are 1 m sec^{-1} with often a slight offshore component from 08 PST until westerlies of about 5 m sec^{-1} start at 15 or 16 PST. From about 20 PST on 4 September through about 14 PST on 5 September winds have an offshore component; northeasterly at 3 to 4 m sec until near sunrise then light easterly continue until westerly winds commence near 16 PST. Westerly winds at Levels 5 and 6 on 6 September are interrupted by southerly winds in the forenoon.

TABLE 13. MEAN SURFACE TO 5000 FT. WINDS MEASURED AT OAKLAND

Date	Time (PST)	Direction (Deg)	Speed (Kts)
3	04	280	8
3	16	290	11
4	04	290	9
4	16	260	4
5	04	70	4
5	16	80	5
6	04	195	6
6	16	245	9
7	04	235	8
7	16	265	10
8	04	280	12

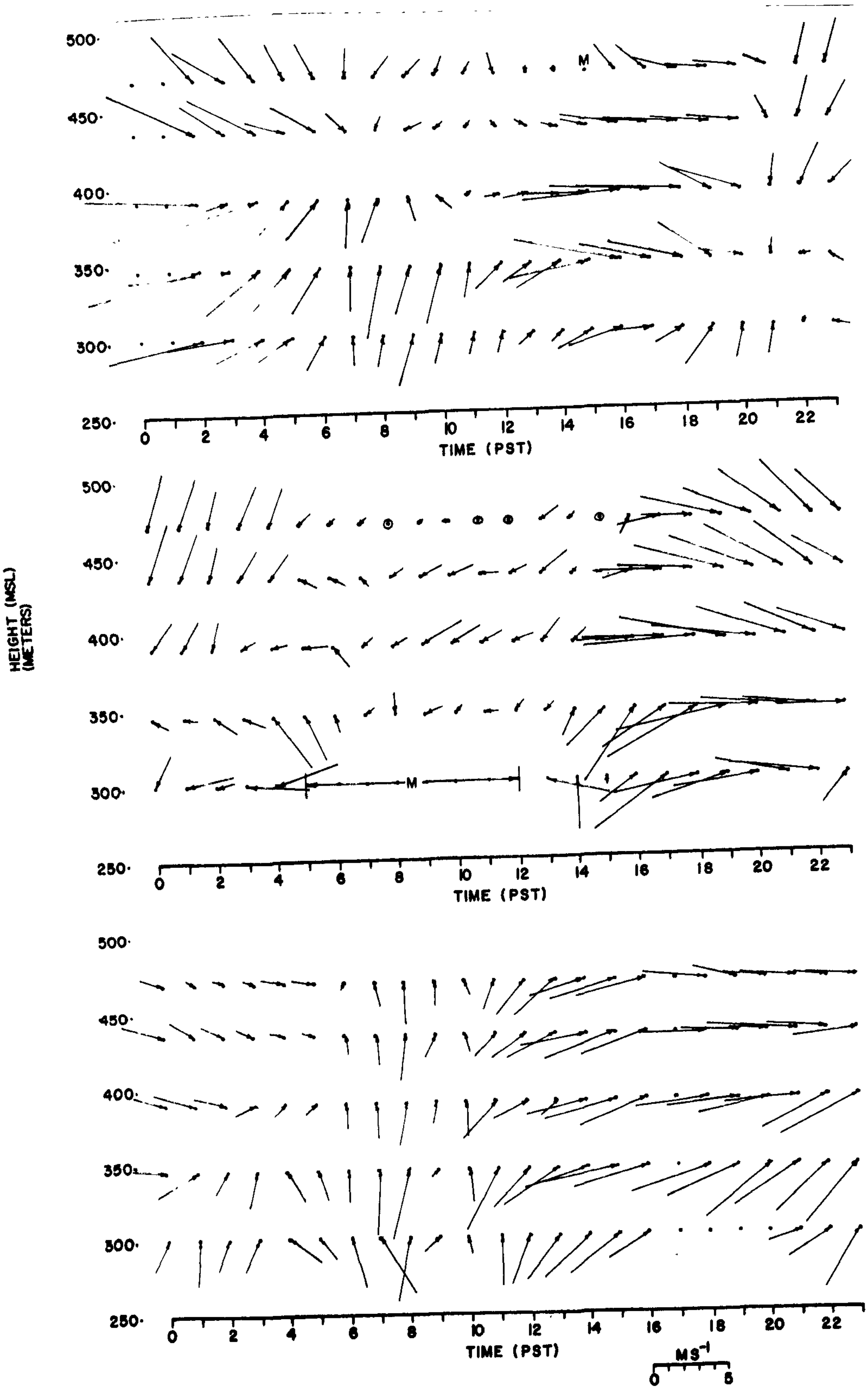

Figure 50. Hourly average wind vectors, Sutro Tower, September 4 (top), 5 (middle) and 6 (bottom), 1974.

Ozone

Ozone concentrations at all measurement levels at the Sutro Tower remained below about 4.5 pphm on September 3 (not shown). Data are missing for the morning of September 4. In the afternoon of September 4 Level 6 measured 9.5 pphm for the hours beginning at 16 and 17 PST while Level 5 reached 8 pphm at 17 PST (not shown). Nighttime values decreased to about 4 pphm at all levels. Level 1 remained below 4 pphm throughout the day.

Figure 51 shows that O_3 concentrations remained below about 4.5 pphm until about 09 PST, 5 September when concentrations started to increase at all levels. O_3 concentrations increased to peaks of 20 pphm at Level 6 and 23.5 pphm at Level 5 at 14 PST and 25 pphm at Level 3 at 15 PST. The near surface measurement level recorded a daytime peak of just under 8 pphm at noon. A secondary peak of 18 pphm at Level 3 and the daily maximum of 12.5 pphm at Level 1 occurred at 20 PST, while increases to about 12.5 pphm occurred at Levels 5 and 6 at 21 PST.

On 6 September, O_3 concentrations were higher at Levels 1 and 3 than at Levels 5 and 6 until about sunrise. In the early forenoon, concentrations were about uniform at the top three measurement levels. The highest concentration is 12.5 pphm at 15 PST at Level 5. A secondary maximum occurred at 22 PST with Level 3 recording 10 pphm. Concentrations at Level 3 remain near 9 pphm until 04 PST, 7 September (not shown) and remain below 8 pphm at all measurement levels for the rest of the day.

SUMMARY

The high oxidant period of this case study began and ended rather abruptly. At the beginning of the period a short wave trough was followed by a short wave ridge to initiate the period. At the close of the period an approaching upper level trough with associated surface front and increased westerly winds ended the high oxidant concentrations.

Wind patterns measured at the Sutro Tower indicate that a recirculation of pollutants occurred within the Bay Area. On 4 September a period of few hours of offshore winds occurred at the upper measurement levels. A few hours of westerly winds that afternoon were then followed by offshore flow of decreasing strength until westerlies returned in the late afternoon of 5 September. While the apparent recirculation pattern is not as readily apparent on 6 September, it appears that there may have been transport along the NW-SE axis of San Francisco Bay.

High concentrations of ozone and ^{7}Be at Quillayute, Wa. about two days prior to the Bay Area episode combined with subsiding northerly flow suggest the possibilities of stratospheric contributions at the beginning of the episode.

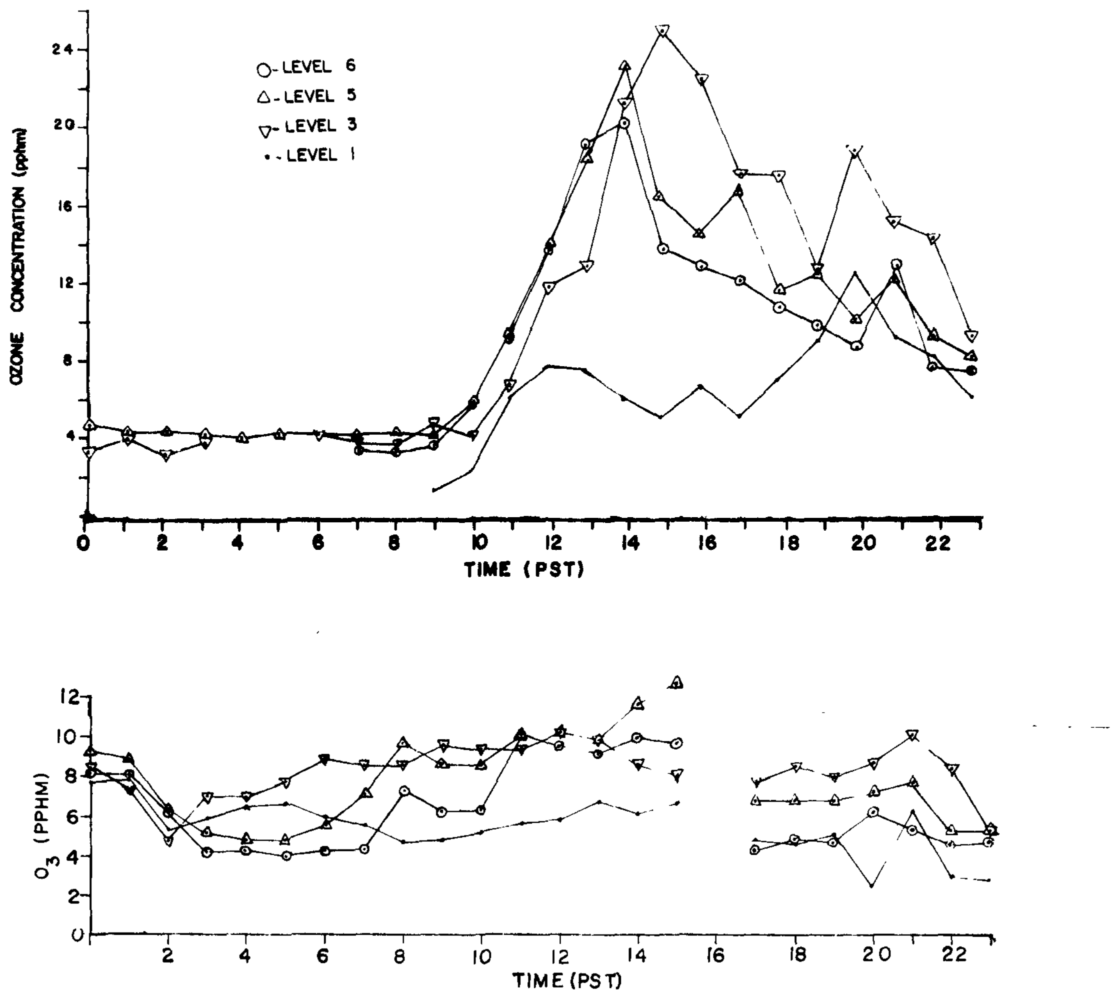

Figure 51. Hourly average ozone concentrations, Sutro Tower, September 5 (top) and 6 (bottom), 1974.

SECTION 9

CASE STUDY OF SEPTEMBER 14-18, 1974

Ozone concentrations in the Bay Area did not reach the 20 pphm BAAPCD alert level during this period. However, the case period does show some similarities in meteorological patterns to those discussed in previous sections. In addition, potential vorticity analysis on the 312 K isentropic surface indicates that air of presumed stratospheric origin penetrated at least to the 700 mb surface during the early portion of the period.

SYNOPTIC PATTERN

On the afternoon of Friday the thirteenth the synoptic situation was dominated by a developing omega block. A rather intense low over the Gulf of Alaska was followed by a high pressure system near the northern Washington border and a trough near eastern Nevada. Figure 52a shows the 312 K isentropic surface at 691 mb over Oakland with northerly winds and a mixing ratio of 0.8 gm/kg. Potential vorticity isopleths on this surface (not shown) show values below 50 (in units of 10^{-10} cm sec °K gm^{-1}).

By the morning of September 14 (Figure 53a) the trough over eastern Nevada had formed a cutoff low. The 312 K isentropic surface lifted to 684 mb over Oakland. A potential vorticity maximum occurred over eastern Nevada (Figure 53b), with values of 50 to 75 over central California.

Twelve hours later (Figure 54a) the high center had drifted south to central Oregon while the 312 K isentropic surface had lifted to 670 mb. A 300 potential vorticity maximum developed over central Nevada (Figure 54b), while values of 100 covered most of central California. A value of 97.7 was calculated for Oakland.

A cross section from Salem, Oregon to Winslow, Arizona (Figure 54c) shows the 312 K isentrope centered in a stable layer sloping down from about 500 mb over Ely, Nevada to about 680 mb over Salem, Oregon.

At 04 PST on September 15, the synoptic pattern was similar to previous days (Figure 55a). The 312 K isentropic surface lowered to 697 mb and a potential vorticity value of 112 was calculated for Oakland (Figure 55a). Twelve hours later, a stream function trough had developed over central California (Figure 56a) while potential vorticity values dropped to about 50 over the area (Figure 56b).

SURFACE PATTERNS

A deep marine layer at the beginning of the period caused many stations in areas either above the normal inversion base or in areas where the inversion is normally eroded during the day to experience maximum temperatures less than the average for the month. Maximum temperatures at stations usually influenced by marine air were near the average for the month (Table 14). Berkeley and Oakland, for example, were 1.3 F and 0.5 F respectively, below the average maximum temperature for the month, while Gilroy and Los Gatos were 10.5 F and 4.9 F cooler, respectively. Central Valley maximum temperatures were about 5 F cooler than the average for the month.

Maximum temperatures decreased over most of the Bay Area on the 15th and 16th. Inland stations, however, recorded maximum temperatures on the 16th the same as or slightly greater than those of the 15th. Central Valley warmed more in the north than the south on the 15th and then increased temperatures slightly on the 16th.

Bay Area maximum temperatures increases significantly on the 17th, while those of the Central Valley increased slightly. As the period ended, Bay Area maximum temperatures decreased somewhat at marine influenced and elevated stations but remained high in the inland valleys. Central Valley temperatures decreased somewhat in the north and remained about constant in the south.

TABLE 14. MAXIMUM TEMPERATURES (F), SEPTEMBER 14-18, 1974

Station	Date	14	15	16	17	18	Ave. Sept. 74	Normal
Marine Influenced								
Berkeley		68	64	65	70	66	69.3	
San Jose AP		80	77	74	81	80	80.3	
Oakland		71	65	65	70	68	71.5	
Inland								
Los Gatos		80	79	81	89	82	84.9	
Gilroy		78	85	85	88	95	88.5	
Livermore		84	84	86	98	96	90.6	
Central Valley								
Bakersfield AP		89	89	90	94	94	96.5	
Fresno AP		89	92	94	95	96	94.8	
Sacramento AP		86	90	92	94	93	90.4	
Red Bluff AP		90	98	98	101	99	96.3	

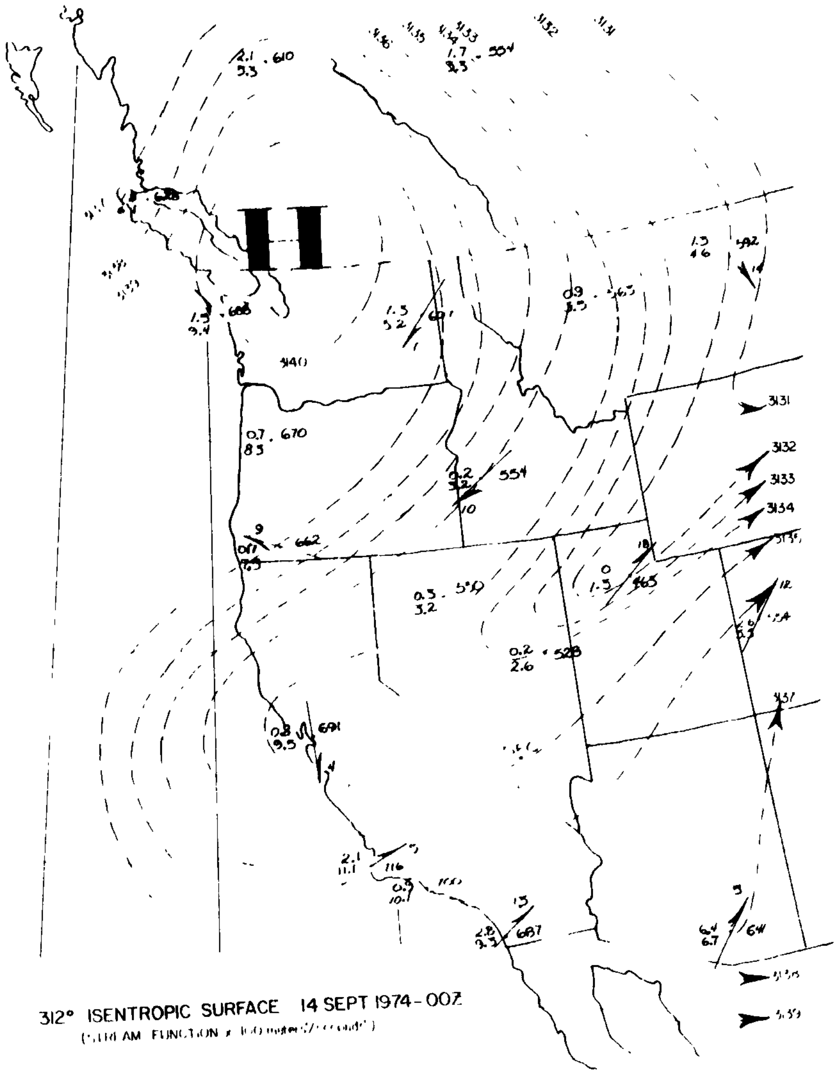

Figure 52 . Montgomery stream function on 312 K surface, 00 GMT, 14 September, 1974.

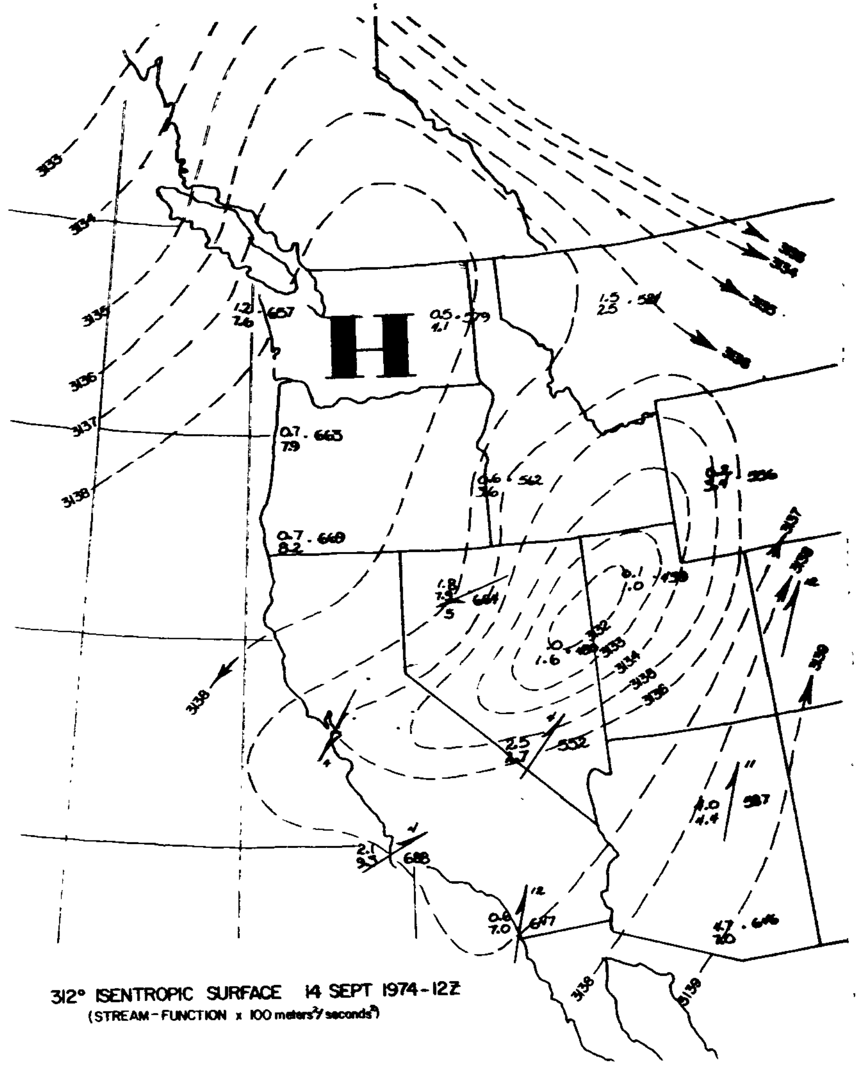

Figure 53a. Montgomery stream function on 312 k surface, 12 GMT, 14 September, 1974

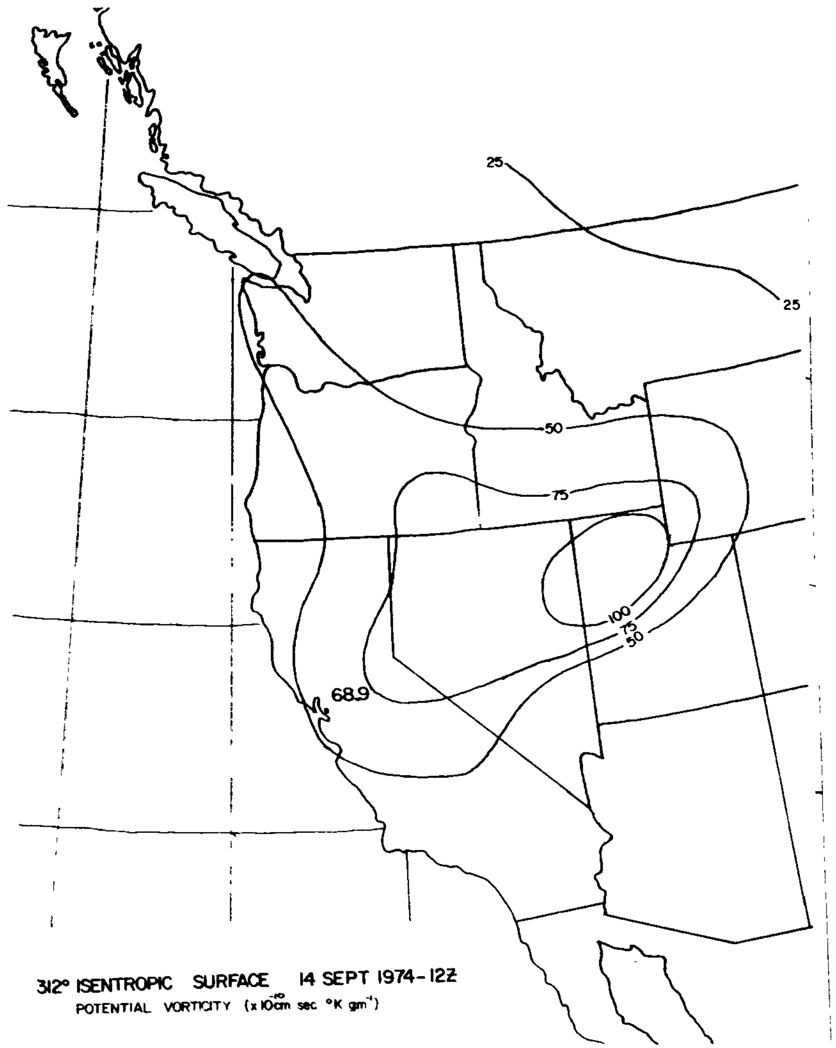

Figure 53b. Potential vorticity analysis, 312 K surface, 12 GMT, 14 September, 1974

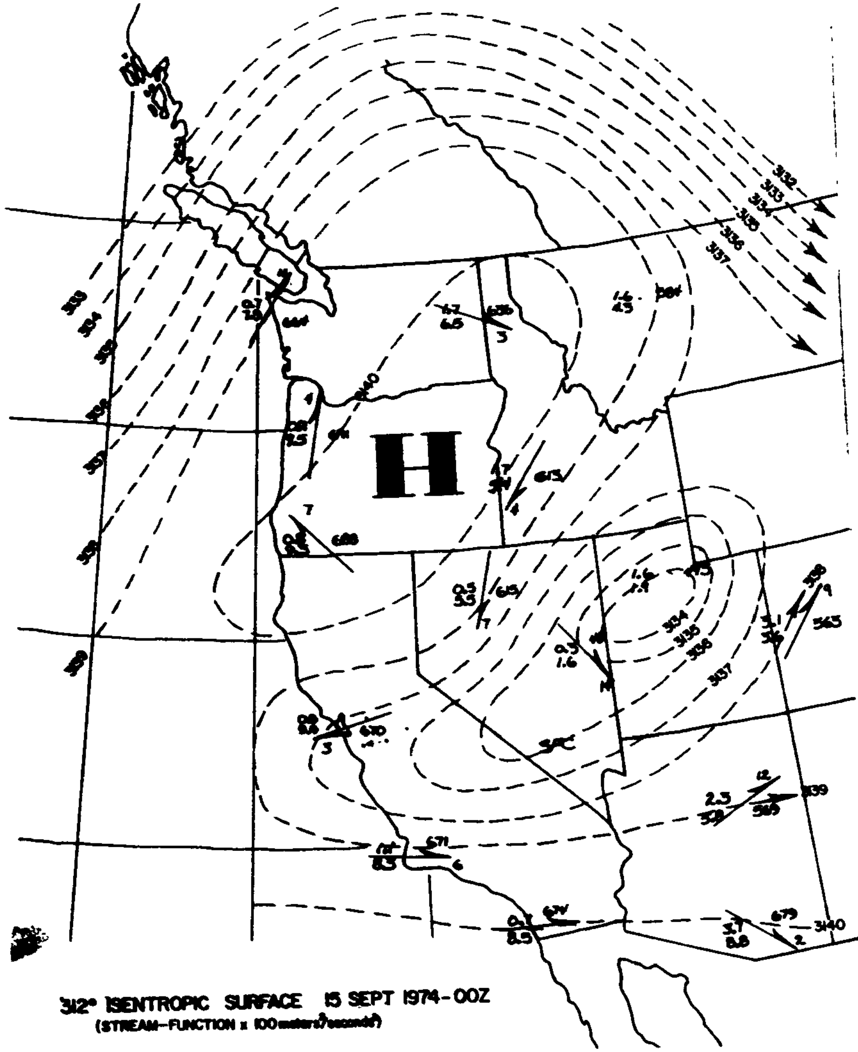

Figure 54a. Same as Figure 53a except for 00 GMT, 15 September, 1974.

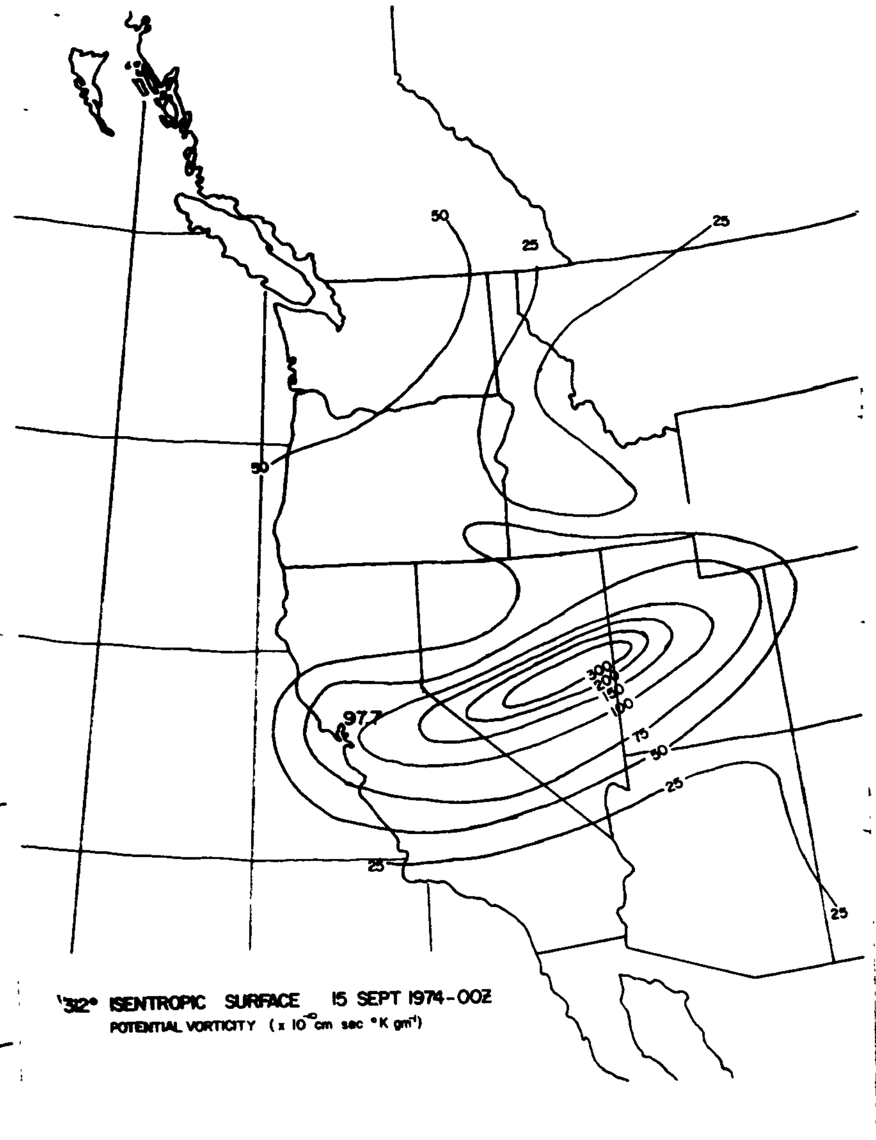

Figure 54b. Same as Figure 53b except for 00 GMT, 15 September, 1974.

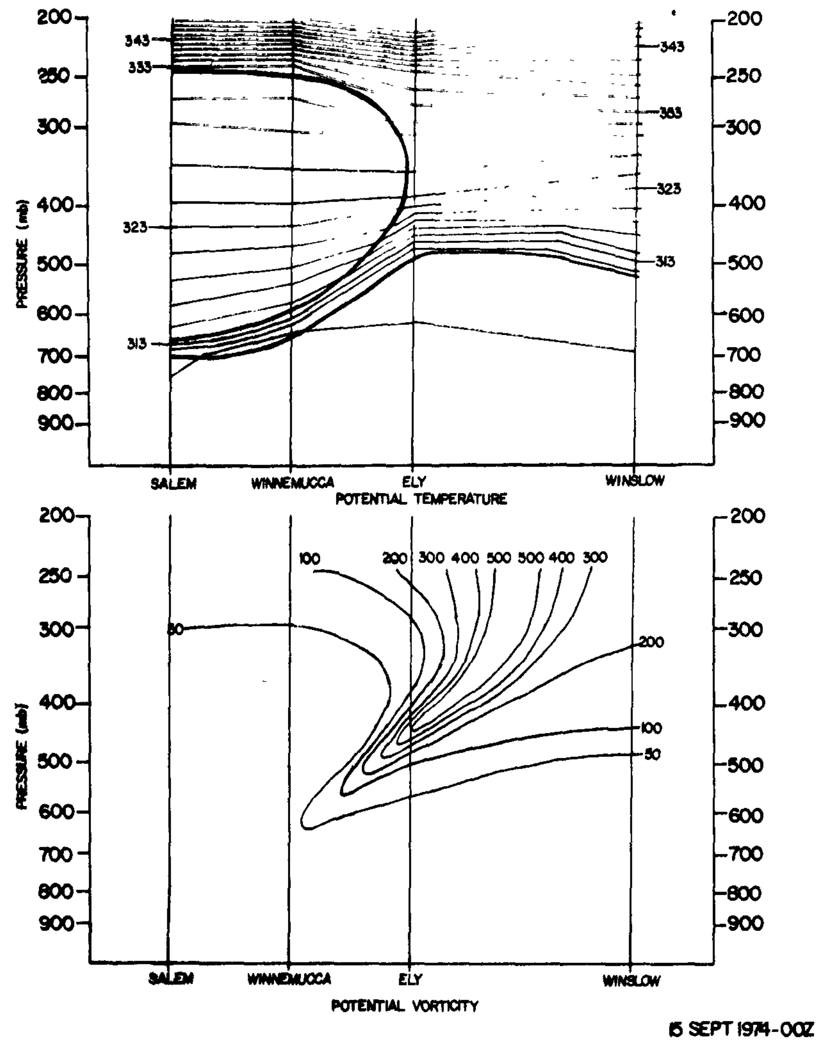

Figure 54c. Northwest-Southeast cross section of potential temperature (°K, top) and potential vorticity (10^{-10} cm sec °K gm^{-1}, bottom), 00 GMT, 15 September, 1974.

Winds

Surface winds along the coast were governed by a Pacific cyclonic circulation at the beginning of the period (Figure 57). Bay Area winds, channeled by topography, were similar to those shown in Section 6. Surface stream line analyses for the remainder of the period (not shown) approximated those discussed in Section 6.

Oxidants

Prior to the case study period, the 20 pphm BAAPCD health effects level was exceeded on September 10 at Livermore, Alum Rock and San Jose with a maximum of 26 pphm at San Jose. On this day 17 BAAPCD stations exceeded the 8 pphm NAAQS. High hour concentrations decreased until September 14 when the maximum recorded in the Bay Area was 11 pphm and five stations exceeded the 8 pphm Federal Standards.

Early morning surface observations for each day of the period were similar to those at 09 PST September 15 (Figure 58a). Concentrations were 4 to 5 pphm over the southern San Francisco Bay, probably due to reduced destruction rates over the water surface. Those throughout the rest of the area ranged from 2 to 3 pphm.

Afternoon oxidant readings increased until 17 September. Figure 58b shows centers of 16 pphm at Livermore and 14 pphm at Los Gatos on the afternoon of September 17. The areas of the Santa Clara Valley and Livermore-Diablo Valleys exceed the 8 pphm NAAQS. Afternoon patterns throughout the period are similar. Table 15 indicates the extent of violations of the NAAQS for the period.

TABLE 15. HIGH HOUR OXIDANT PATTERNS, SEPTEMBER 14-19, 1974

Date	Station of Highest Maximum	Highest Maximum (pphm)	Number Stations > 8 pphm
14	Livermore, San Jose	11	4
15	Livermore	10	3
16	Livermore	12	4
17	Livermore	17	14
18	Livermore, Los Gatos	14	6
19	Livermore	12	4

UPPER AIR PATTERNS

The Subsidence Inversion

Heights of the inversion base (Table 16) measured over Oakland at 16 PST lowered until September 16, remained low on September 17 and then began to lift on September 18. Afternoon mixing depths were estimated at San Jose and Livermore from the intersection of the dry adiabat through the maximum surface temperature with the Oakland afternoon soundings. Mixing depths over San Jose lowered through September 16 and raised on September 17 and 18. Intense heating in the Livermore valley on September 17 produced a mixed layer 1220 m deep.

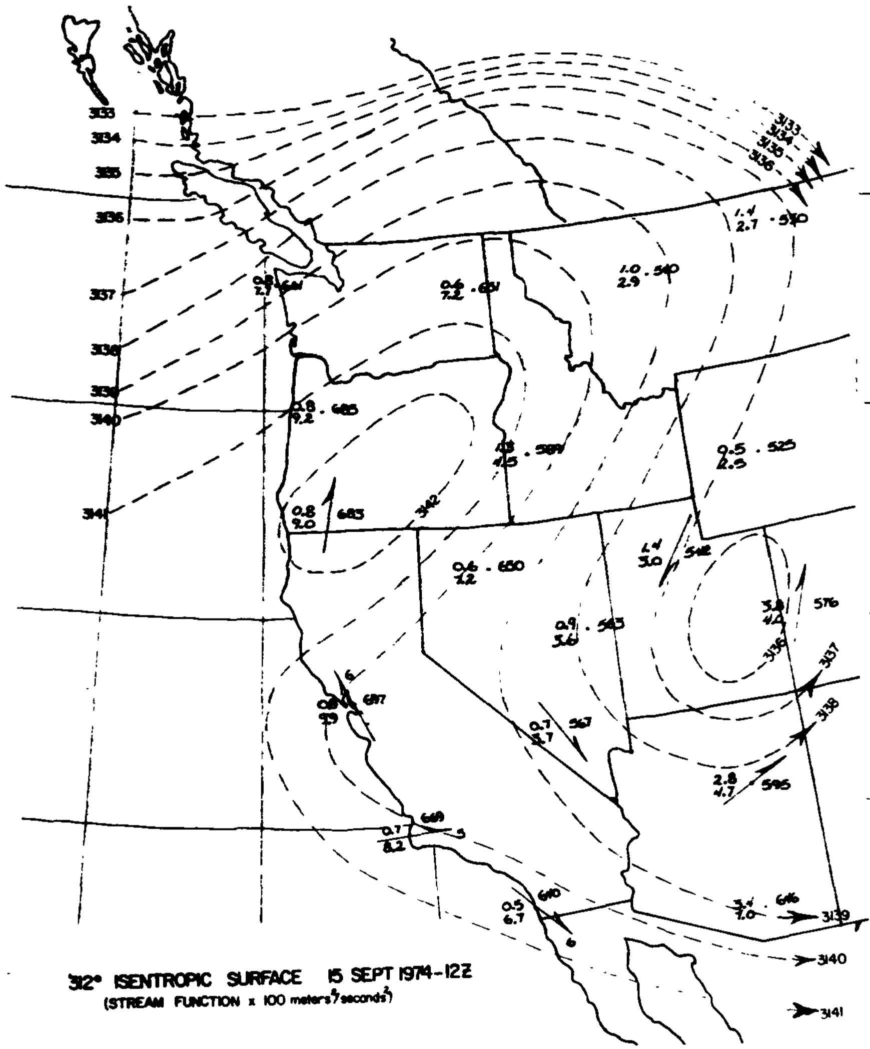

Figure 55a. Same as Figure 53a, except for 12 GMT, 15 September, 1974.

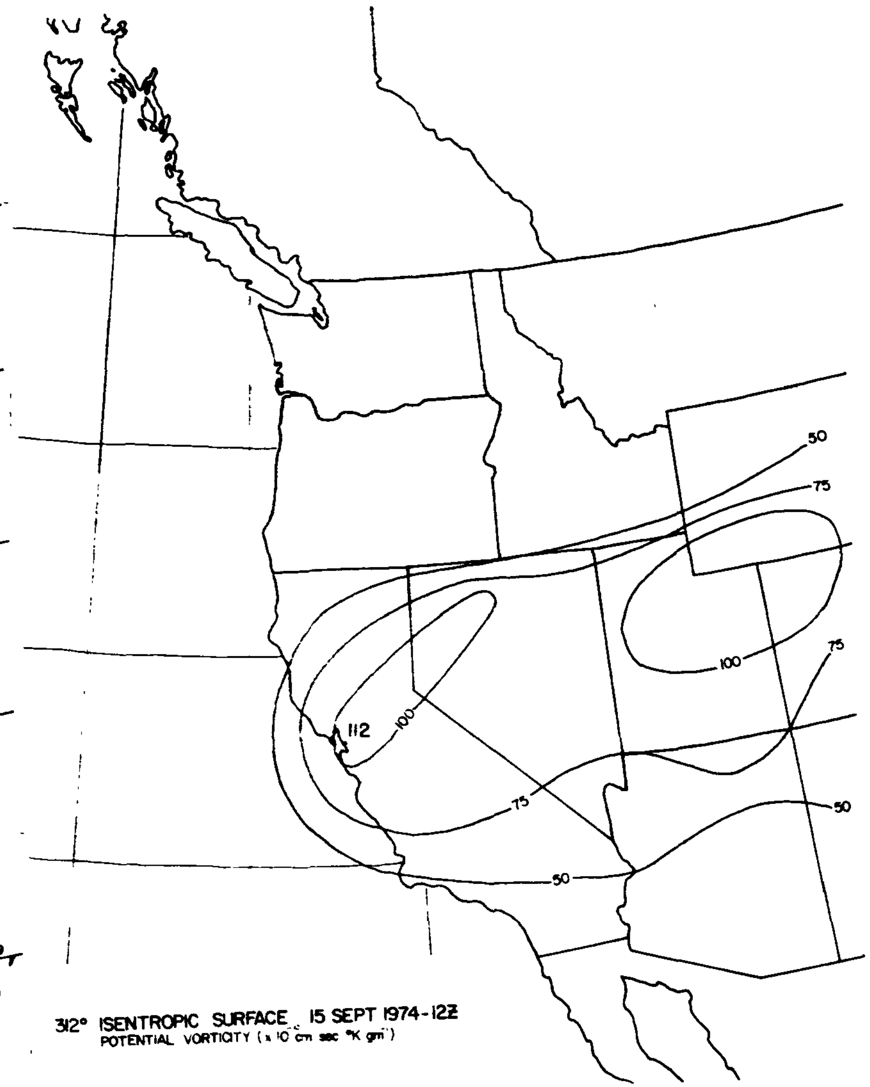

Figure 55b. Same as Figure 53b, except for 12 GMT, 15 September, 1974.

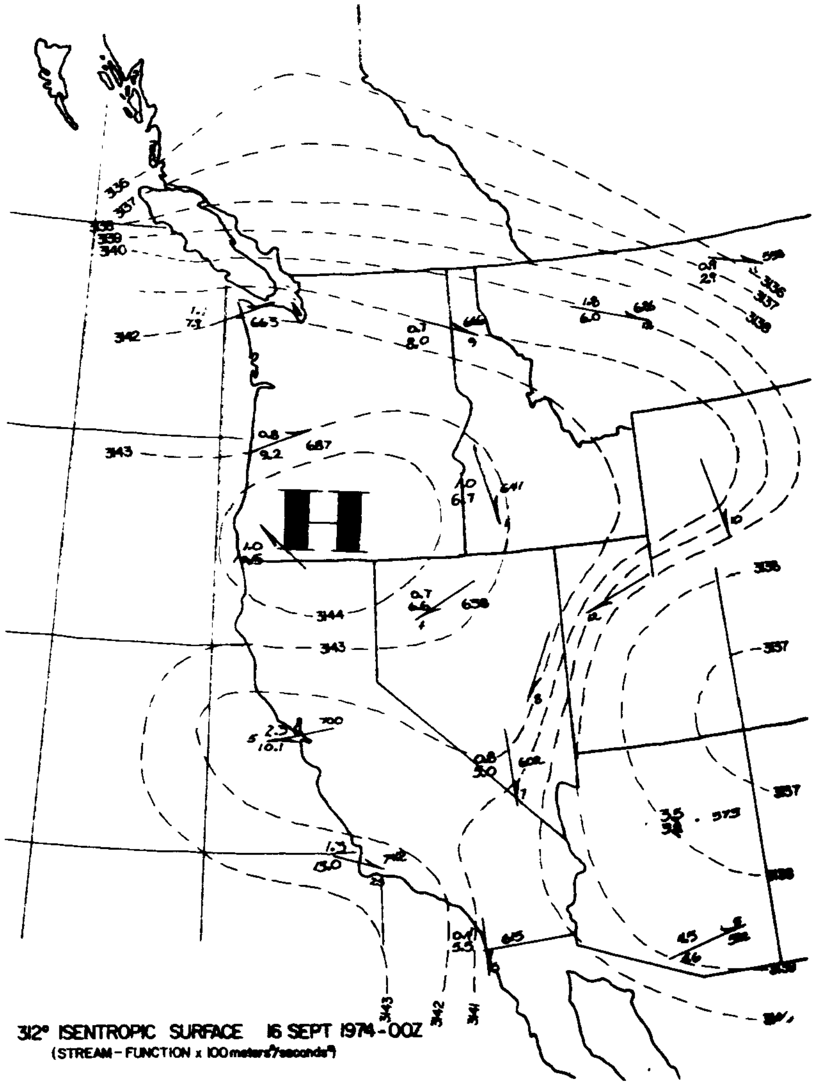

Figure 56a. Same as Figure 53a, except for 00 GMT, 16 September, 1974.

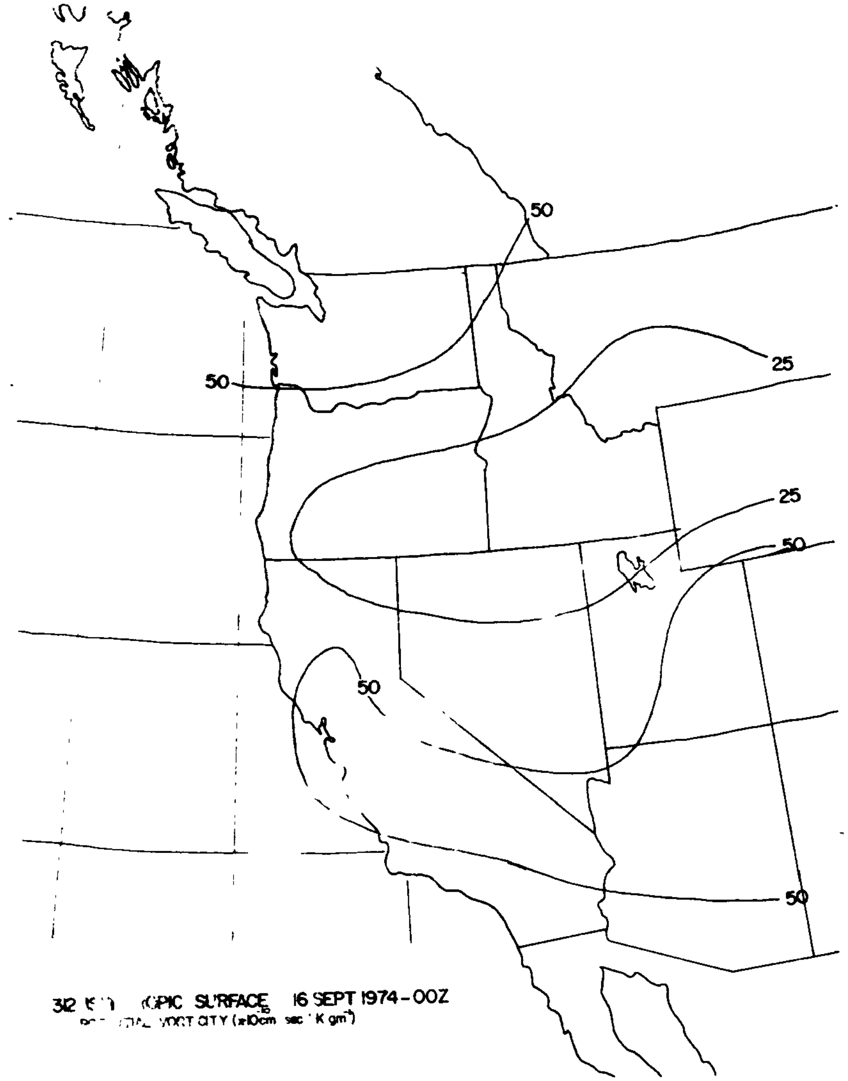

Figure 56b. Same as Figure 53b, except for 00 GMT, 16 September, 1974.

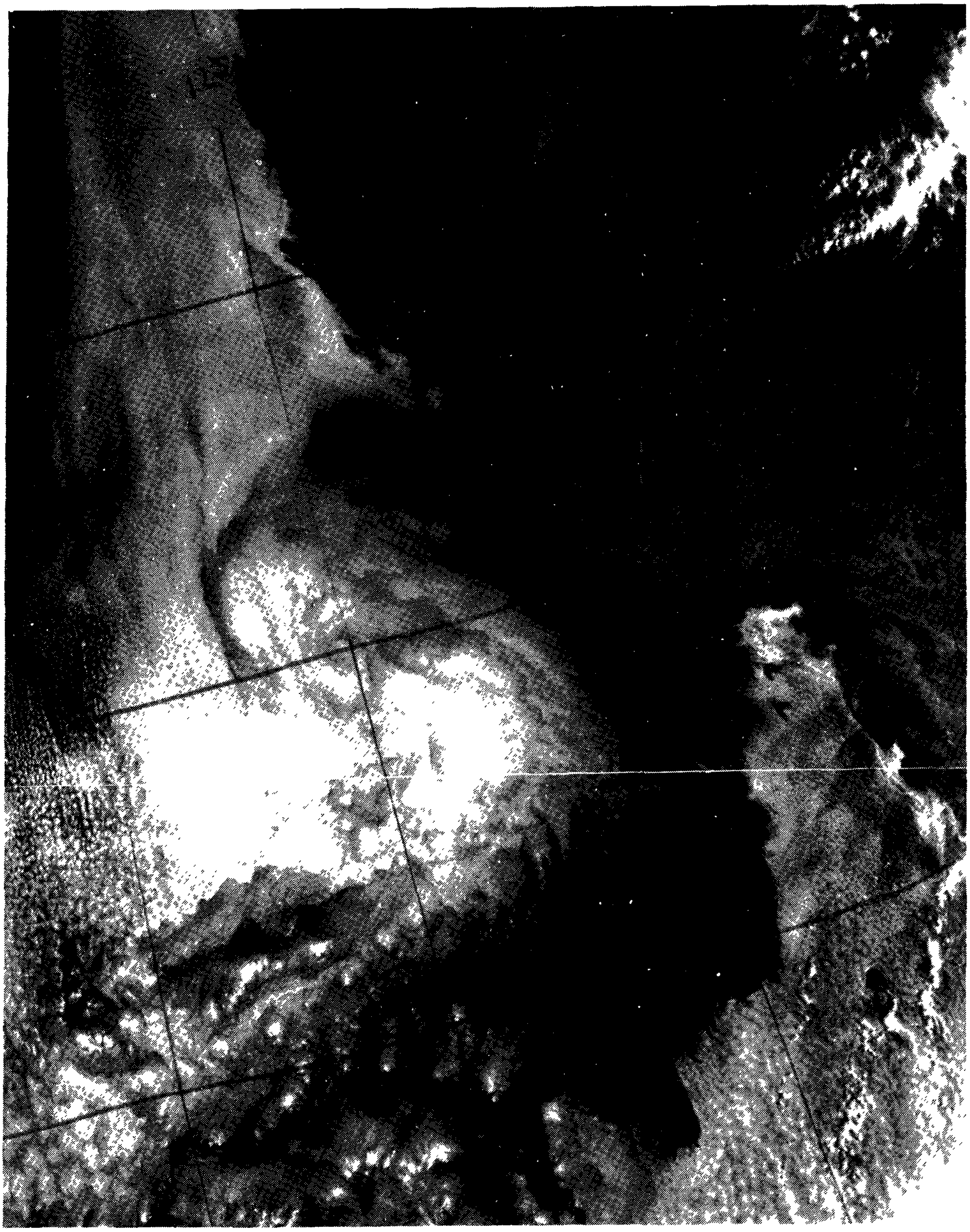

Figure 57. NOAA B visual satellite picture of California and eastern Pacific, 1721 GMT, 14 September, 1974.

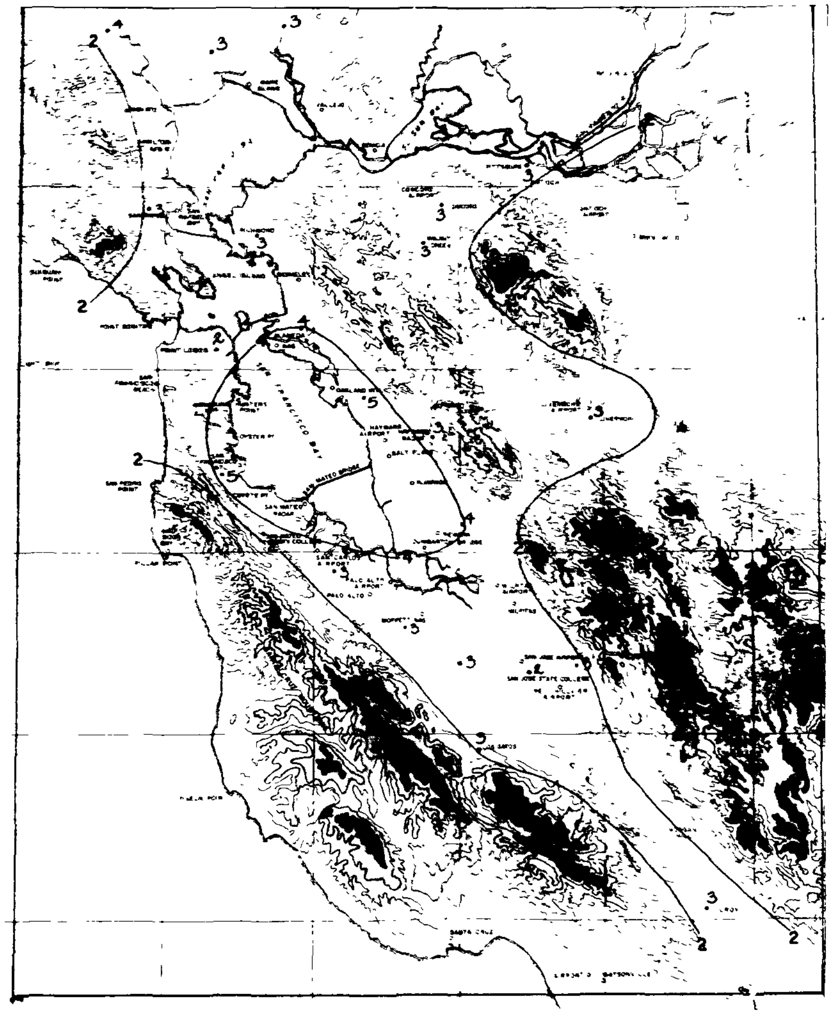

Figure 58a. Surface O_3 concentrations, San Francisco Bay Area, 09 PST, 15 September, 1974.

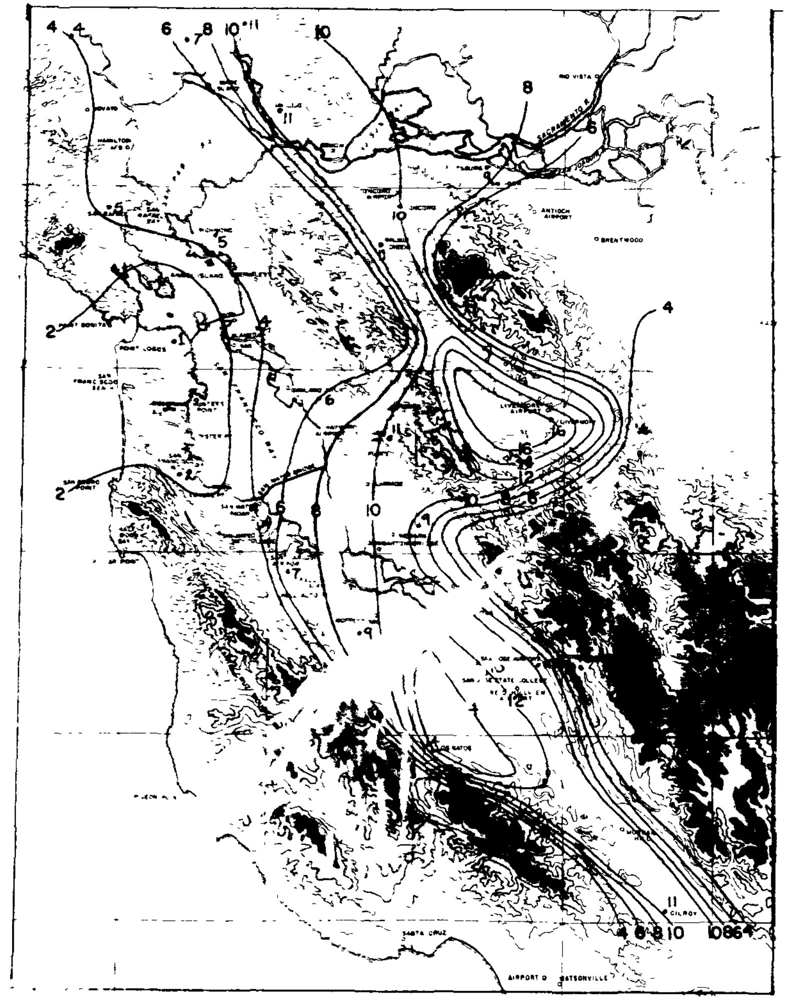

Figure 58b. Same as 58a, except for 15 PST, 17 September, 1974.

TABLE 16. ESTIMATED MIXING DEPTH PARAMETERS FROM 1600 PST OAKLAND SOUNDINGS

DATE	Inversion Base (mb)	Mixing Depth (meters) Livermore	San Jose
13	930	1018	811
14	975	975	853
15	970	613	508
16	1000	582	408
17	1000	1219	443
18	980	948	501

Winds

A time-height section of the westerly wind at Oakland through the tropopause for the period of study is shown in Figure 59. Easterly winds dominate through most of the troposphere above about 1000 m. Below about 1000 m rawinds at 12-hour intervals show winds with a persistent westerly component.

SUTRO TOWER PATTERNS

A temperature time-height section for 14 September (not shown) shows no inversion through the daylight hours. A weak inversion was established at about 20 PST. Winds had a westerly component throughout the day.

Figure 60 shows the variations of hourly average temperature and horizontal wind vectors for the period 15-18 September. The average inversion height lowers until 17 September and then lifts the next day. Superimposed on this drecrease in marine layer depth are diurnal oscillations similar to the average pattern for the month. The inversion base was highest in the early morning and lowest in late afternoon or early evening. It appears that the inversion begins to descend from its post-midnight maximum somewhat earlier each day until the peak day of 17 September.

Marine layer winds were southeasterly throughout the period. Within the inversion layer, winds were strong westerly or northwesterly from near sunset until about the time of the lowering of the inversion. As the inversion lowers, winds veer to the north or northeast. As the episode develops, the strength and duration of easterly wind components increases until 17 September when wind at the top two measurement levels are northeasterly at about 5 m sec^{-1} for nearly six hours. Near sunset, winds become more westerly as the inversion base rises.

Ozone concentrations remained below 4 pphm throughout 14 September at all

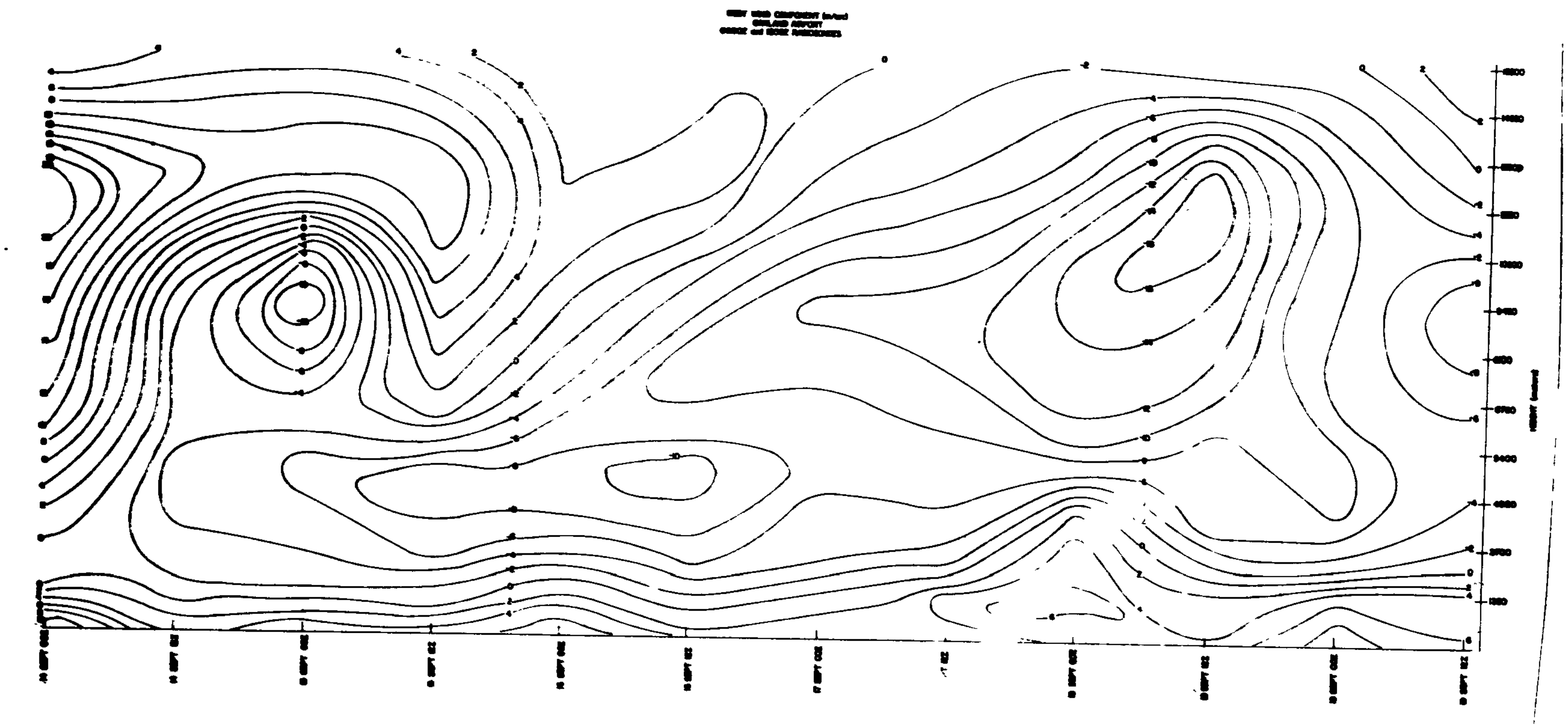

Figure 59. Time-height section of westerly winds (m sec^{-1}), Oakland, CA, September 14-19, 1974.

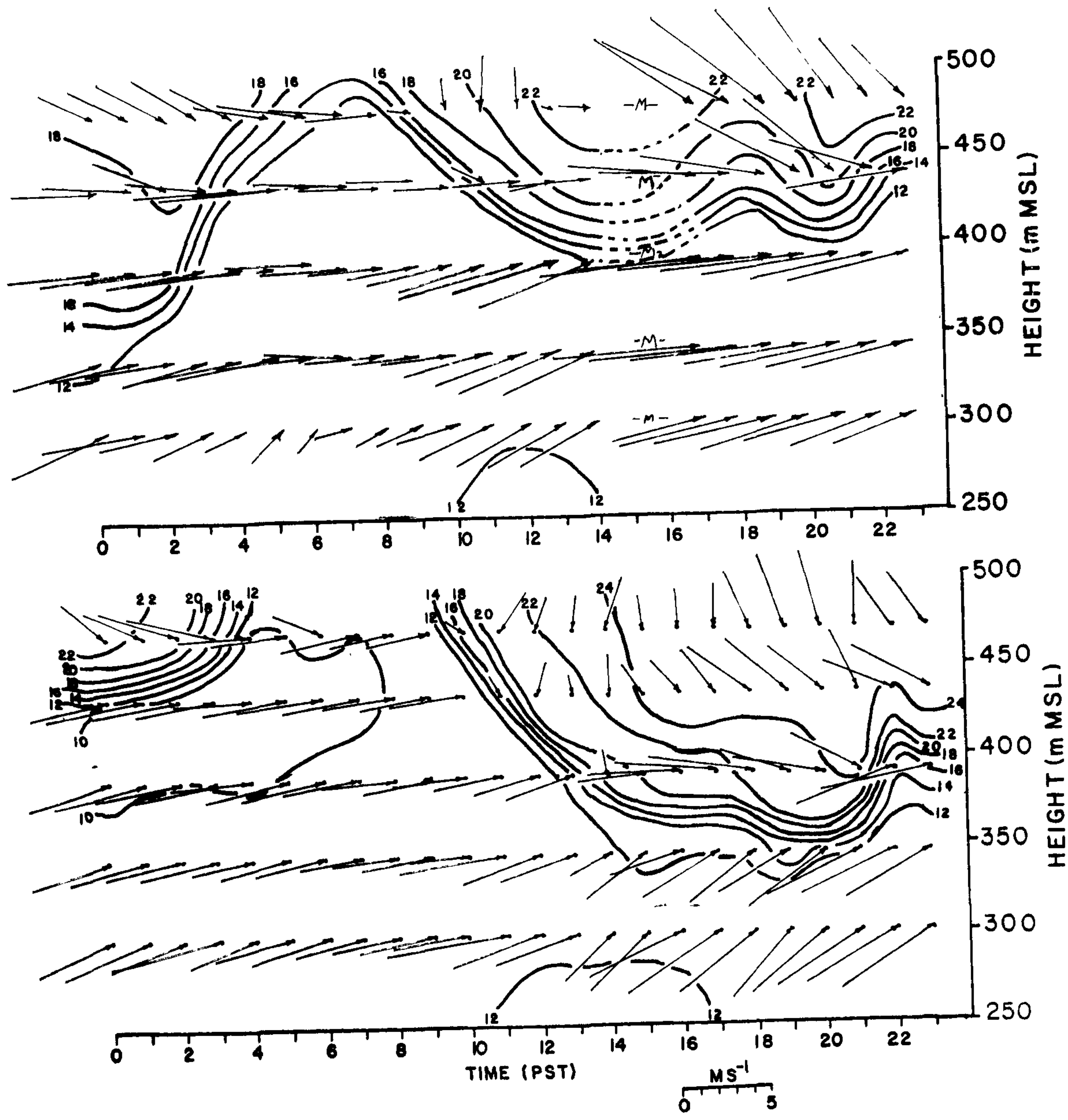

Figure 60. Hourly average horizontal wind vectors and temperatures (°C), Sutro Tower, September 15 (top) and 16 (bottom), 1974.

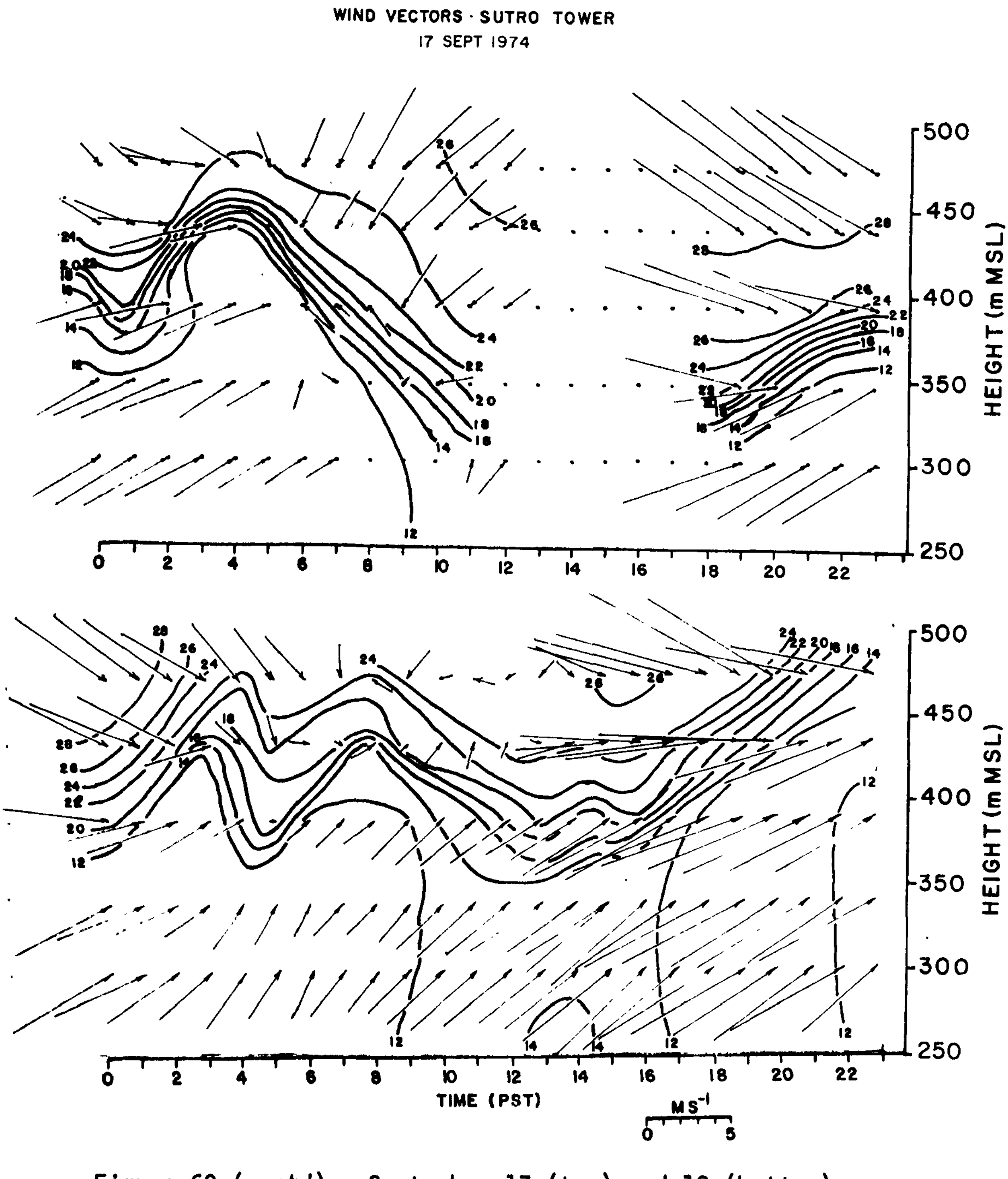

Figure 60 (contd). September 17 (top) and 18 (bottom).

measurement levels.

Comparison of the variations of wind and temperature (Figure 60) with those of ozone (Figure 61) show evidence of high ozone concentrations located near the upper edge of the strong isotherm gradient. On 15 September, the ozone maximum of 7.5 pphm at 03 PST coincides with the dip in the 18C isotherm below the measurement level. As the inversion base lifts, concentrations at Level 5 decrease before those at Level 6. During the hours 06-08 PST, while the whole tower is within the marine air layer, there is no difference in O_3 concentration from the top to bottom measurement level. As the inversion lowers in midmorning, O_3 concentrations at Level 6 increase about an hour prior to those at Level 5 since the former encounters inversion layer air first. The nocturnal maximum at Levels 5 and 6 also coincide with a minimum in the inversion base height.

On 16 September, all measurement levels were within or below the strong isotherm gradient and experience about the same O_3 concentrations for the first half of the day. Near noon, the inversion base begins to descend and concentrations at the top two measurement levels begin to increase. The nocturnal maxima at these levels occur near the time of minimum inversion height.

Analysis on 17 September is hampered by the loss of six critical hours of data, however the pattern appears similar to those of the previous two days. Nocturnal O_3 minima at the top two levels coincide with maximum inversion base height. Increases in concentration at these two levels beginning about 08 PST occur at about the time when the strongest thermal gradients are below these levels. These increases appear to be too rapid and too early in the day to be due to in situ photochemical production.

The pattern on 18 September is again similar, with the secondary minimum near 14-15 PST coinciding with an upward undulation of the inversion base. As the inversion lifts above the tower near midnight, there is only a slight vertical gradient in ozone. September 19 concentrations remained below 4 pphm at all measurement levels.

SUMMARY OF THE SEPTEMBER 14-18 CASE STUDY

The study period begins with a deep marine layer extending to 930 mb on the afternoon of Friday the 13th. The relatively large marine layer depth is probably influenced by an offshore cyclonic circulation, which appears from satellite photo to be the remnants of a tropical depression. The other main synoptic feature which will continue to dominate the period is an "omega" block: an intense low in the Gulf of Alaska, a high centered over eastern Washington and another low centered over Nevada.

As the offshore depression weakens, the base of the elevated inversion lowers. Upper level air flows around the high and is from the north east over the Bay Area. On the afternoon of September 15, potential vorticity analysis shows what appears to be air of stratospheric origin at the 312 K isentropic surface, which over Oakland is at about 700 mb.

High hour O_3 concentrations at Quillayute, Wa. were 5 pphm on 13 Septem-

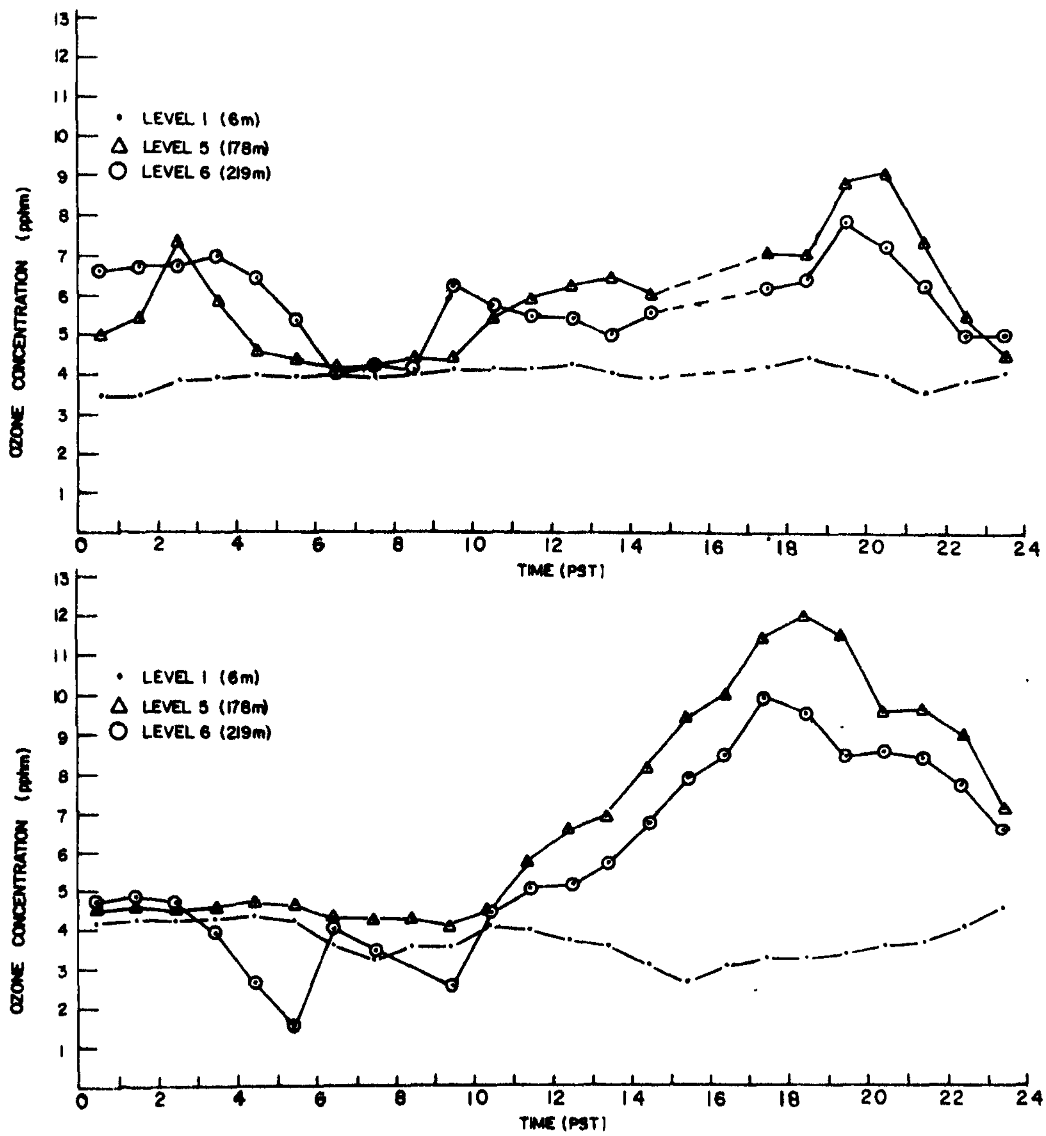

Figure 61. Hourly average ozone concentrations, Sutro Tower, September 15 (top) and 16 (bottom), 1974.

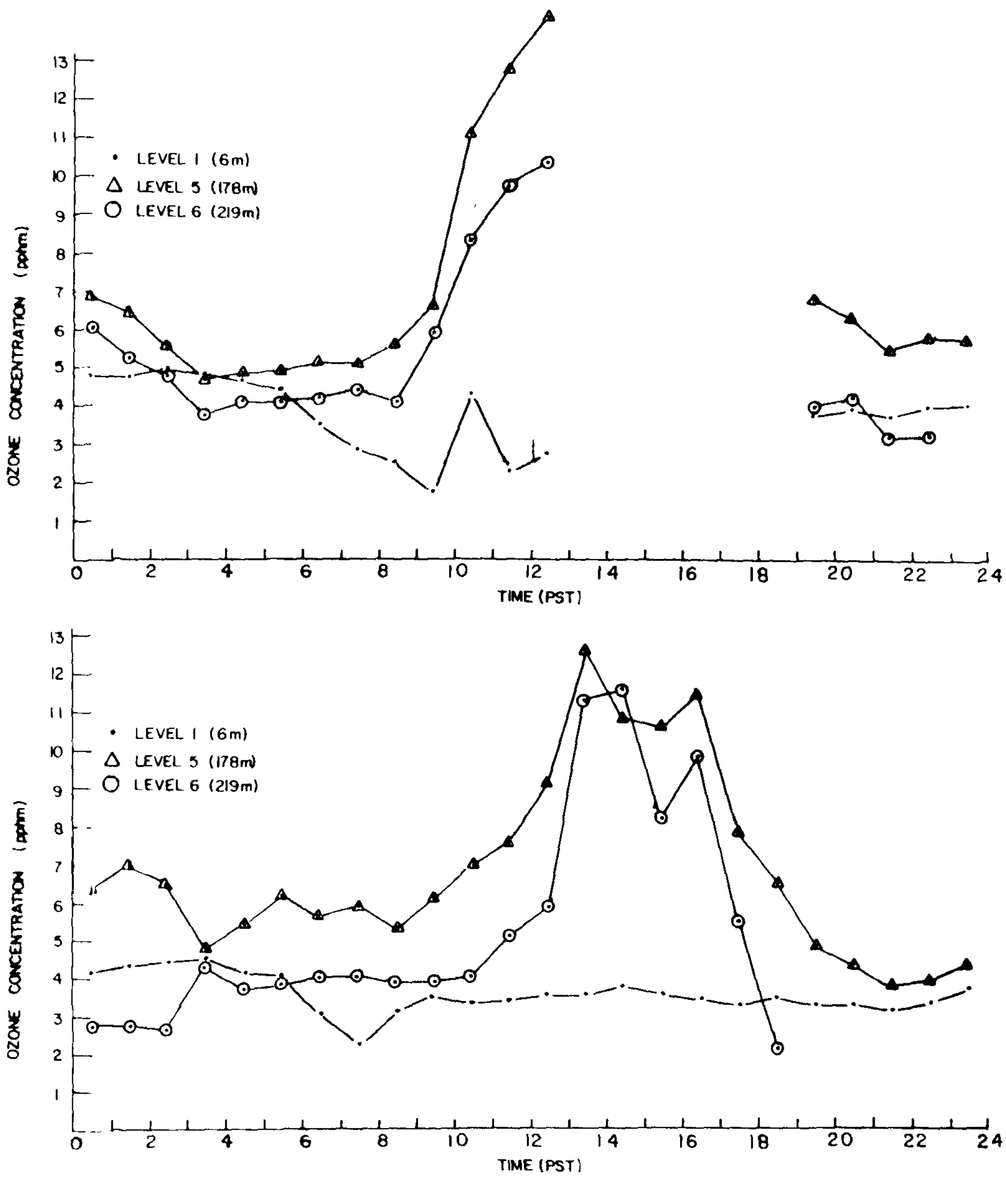

Figure 61 (contd). September 17 (top) and 18 (bottom), 1974.

ber and 6 pphm on 14 and 15 September (Ludwick et al., 1975, 1976). These concentrations, correlated with high radionuclide measurements, suggest air of stratospheric origin at the surface in rural Washington.

Lack of data hampers analysis of the mesoscale circulation patterns. It appears, however, that a weakened form of the Pacific monsoon-sea breeze circulation dominates the case study period. Compare the Sutro Tower time height cross sections of temperature and wind vectors for the individual days of September 15th through 18th with the means for September 1974 (Figures 60 and 12). Each figure shows that the maximum inversion h ight occurs a few hours before sunrise with lowering until midafternoon and a relatively constant base height until a couple of hours after midnight. Westerly wind components are weakest in midmorning, reach a peak at about 300 m near sunset and then decrease until the next morning minimum.

During the period of this case study, however, the synoptic scale offshore flow masks the usual monsoon circulation upon which the sea-breeze is superimposed. This results in winds with an easterly component over the Sutro Tower commencing in the late forenoon or early afternoon. Near noon of the September 16 and 18 period the zone of easterly wind component appears briefly and reaches only down to about 450 m. On September 17, the easterly component zone engulfs the tower from about 09 PST until sometime in the afternoon. (Data are missing between 12 and 20 PST on this important day.) These wind shifts are not reported by the Oakland radiosonde because the time of easterly winds is less than the 12 hours between observations and/or the intervals between reported winds are too gross to pick up this flow. The only corroborating evidence is the surface observations at San Francisco International which report winds with easterly components from 0655 to 1155 PST on September 17.

If there is an afternoon circulation reversal, wind vector patterns indicate a recycling of ozone and/or its precursors above the inversion base. In the Livermore valley, and perhaps other sheltered inland valleys the inversion is eroded from below and convection through relatively large mixing depths (4000 ft. on September 17) carry surface pollutants up and mix those from aloft to the surface. As the cycle repeats, each succeeding day's pollution builds upon a higher base and maximum concentrations increase.

Stratospheric air which appears to have reached down at least to 700 mb during the beginning of the period may play a role either additively or as a trigger in the photochemistry, although its significance is difficult to assess.

SECTION 10

SUMMARY AND DISCUSSION

Ozone concentrations within the elevated inversion layer over San Francisco exceeded 8 pphm during about 15 percent of the measured hours during the summer of 1974. (Adjustment to reflect the change of calibration procedures during 1975 reduce this percentage to about 9 percent.) This percentage compares favorably with the percent of the summer hours exceeding the 8 pphm NAAQS for oxidants at those Bay Area Air Pollution Control District monitoring stations with most frequent violations. In addition, the majority of hours of violation occurred during the three 1974 case study episodes discussed previously; for example, 109 of 164 violation hours at measurement Level 5 and 64 of 101 hours at measurement Level 6 occurred during these three 1974 periods. We assume that the remainder of violation hours at the upper tower levels occurred during periods of high surface O_3.

The average summer wind flow over the Bay Area is onshore, caused by a combination of the summer Pacific monsoon and a more local sea breeze circulation. At the Sutro Tower, the inversion base is highest near 04 PST and the winds at that time are westerly or southwesterly at all levels. Near 10 PST, the inversion base begins to descend and winds veer from southwesterly to westerly at the lower tower levels or from westerly to northwesterly at the upper levels. (See Figures 10 and 12). The inversion base is lowest in late afternoon when onshore flow is strongest.

During the study periods considered, a closed low off the British Columbia coast with high heights over the Bay Area was the typical 500 mb pattern. This pattern produced subsiding offshore flow which weakened or interrupted the monsoon sea breeze induced onshore flow. As the episodes progressed, the first one or two days of the intensification period experienced winds with slight easterly components during the period when the inversion layer subsided. The most severe day of the episode typically showed a deep layer of easterly winds, often extending to the ground, existing from late forenoon to late afternoon. This is similar to the measurements by Fosberg and Schroeder (1966, see Figure 8) showing easterly flow above the inversion layer and very light flow ahead of their wind shift line.

The superposition of synoptic pattern, Pacific monsoon and local circulations produces a recirculation of pollutants. During periods when the local circulation is weakest, flow from the large scale pattern carries polluted air offshore above the inversion layer. In the late afternoon the sea breeze flow returns these pollutants onshore. In many cases this oscillating flow is not measured by rawind soundings because the flow may be relatively shallow and because the offshore component occurs between observation times.

Daytime heating during episode periods destroys the inversion layer in the inland valleys. Ozone rich inversion layer air can be mixed downward to add to oxidants generated from the present day's accumulation of precursors.

The "warm sea breeze" model of Fosberg and Schroeder (1966) may describe the inland penetration of modified marine layer air. Measurements reported by Miller and Ahrens (1970) show maximum oxidant concentrations at the inland edge of the inversion base. It would seem, therefore, that the locations of high surface oxidant concentrations would be on the inland edge of the "warm sea breeze front" where the inversion has been destroyed and inversion layer ozone can be mixed downward.

At night surface cooling re-establishes the elevated inversion, causing O_3 below the inversion to be destroyed at the surface while cutting off inversion layer O_3 from surface destruction. The nocturnal inversion layer air is advected coastward by air produced by a combination of local cooling effects.

During the episode, the elevated polluted layer may reach to within a hundred meters or so of Mt. Sutro. Nighttime high oxidant concentrations at stations located near mountain slopes probably reflect nocturnal downslope flow bringing down inversion layer ozone. High concentrations at Hayward during the night of 5/6 September, 1974 (Figure 48) reflects the 258 m station elevation and its location near the mountain slope.

At the end of the episode return of westerly flow advects pollutants from the area. It is possible that these Bay Area oxidants contribute to high pollutant levels within the Central Valley on subsequent days.

Remote source contribution to Bay Area oxidant concentrations is possible, but hard to document with available data. Baboolal et al (1975) concluded that high ozone levels observed in the Santa Ynez Valley "could not be wholly attributable to local sources." This Valley is about 200 km northwest of Los Angeles. Kauper and Niemann (1975) show that, with a shallow marine layer, over water trajectories of elevated O_3 layers moving into the Ventura county coastal area from the Los Angeles Basin is the "normal Situation." Gloria et al (1975) found high O_3 concentrations within the inversion layer over the Pacific Ocean.

Just prior to the July 1974 case study, inspection of NWS 850 and 700 mb analyses suggest isentropic trajectories from Los Angeles to San Francisco. Available upper air wind data from coastal locations and the fact that surface oxidant concentrations at high elevations in the Los Angeles basin reached about 25 pphm do not contradict this suggestion. Total time of travel from Los Angeles, if such trajectories were real, would be on the order of 48 hours.

The air quality control implications of the possibility of such long range transport involve more than the local Bay Area Air Pollution Control District. A coordinated effort is needed to document adequately the reality of this transport. This effort would involve instrumented aircraft, a coastal network of pibal and/or rawinsonde measurements and perhaps tetroons. Measurements must cover a distance of some 600 km during specific synoptic situations.

The possibilities of a stratospheric contribution to the inversion layer ozone burden has been discussed here in a preliminary manner. Just prior to each of the September 1974 case studies imultaneous high surface concentrations of ozone and radionuclides of stratospheric or upper tropospheric origin were measured at Quillayute, Washington by Ludwick, et al (1975). The coincidence of these atmospheric components indicates intrusion of stratospheric air. In each case, the synoptic pattern was in the form of an "omega" block where flow around the upper level ridge could have brought stratospheric air into the Bay Area. Although hand analysis and computation of potential vorticity distributions contain a number of inherent inaccuracies, such analysis suggests that stratospheric air penetrated to 700 mb over Oakland at the beginning of the 14-18 September, 1974 period. If true, and since this was not a particularly intense episode, it is very likely that stratospheric ozone contributes either additively or as a chemical trigger in similar and more intense situations.

The possible contribution of stratospheric ozone involves broader policy questions. Synoptic situations producing air pollution episodes in the Bay Area are also those which produce strong upper tropospheric subsidence. If the natural stratospheric contribution is purely additive and of the order of 5-6 pphm, then what would just be a smoggy day might become a Health Alert Advisory (oxidant concentrations $\geq$ 20 pphm). The possibilities of stratospheric O_3 as a photochemical trigger would require measurements of precursors and detailed synoptic analysis combined with numerical modelling of photochemical kinetics.

The fate of oxidants and their precursors generated in the Bay Area is a further subject of needed study. As discussed above, a Bay Area pollution episode ends as the synoptic situation reverts to the normal summer pattern and pollutants are advected eastward from the area. Observations along the pollutant path from the area are needed to determine the effects of Bay Area pollution on the air quality of the Central Valley and the Sierra Nevada. Such observations might provide the impetus for extending air quality simulation models to include such long-range transport.

REFERENCES

1. Baboolal, L.B., I.H. Tombach, and M.I. Smith, 1975: Mesoscale flows and ozone levels in a rural California coastal valley, 1st. Conf. on Mesoscale Modeling, Analysis and Prediction, Amer. Meteor. Soc., Las Vegas, Nev.

2. Bay Area Air Pollution Control District, 1971: Aviation Effect on Air Quality in the Bay Region. San Francisco, Ca.

3. Bay Area Air Pollution Control District, 1976: Oxidant Experience in the San Francisco Bay Area, 1965-1975. Technical Services Division, Information Bulletin, March 12, 1976, 11 pp.

4. California Air Resources Board, 1975: Final Report of the ad hoc Oxidant Measurement Committee, No. 75-4-4, February 20, 1975.

5. Edinger, J.G., 1973: Vertical distribution of photochemical smog in Los Angeles Basin. Environ. Sci. Technol. 7:247.

6. Edinger, J.G., M.H. McCutchan, P.R. Miller, B.C. Ryan, M.J. Schroeder, and J.V. Behar, 1972: Penetration and duration of oxidant air pollution in the South Coast Air Basin of California. J. Air Poll. Control Assoc., 22:882.

7. Geiger, R., 1965: The Climate Near the Ground. Harvard University Press, Cambridge, 611 pp.

8. Gloria, H.R., G. Bradburn, R.F. Reinish, J.N. Pitts, Jr., J.V. Behar, and L. Zafonte, 1974: Airborne survey of major air basins in California. J. Air Poll. Control Assoc., 24, 645-652.

9. Kauper, E.K., and B.L. Niemann, 1975: Los Angeles to Ventura over water ozone transport study. Tech. Rept. under Contract ARB 4-1126. Metro Monitoring Services, Covina, Ca. 91723.

10. Lea, D.A., 1968: Vertical ozone distribution in the lower troposphere near an urban pollution complex. J. Appl. Meteor., 7:252.

11. Lovill, J.E., and A. Miller, 1968: The vertical distribution of ozone over the San Francisco Bay Area. J. Geophys. Res., 73:5073.

REFERENCES

12. Ludwig, J.D., T.D. Fox, and L.L. Wendell, 1976: Ozone and radionuclide correlations in air of marine trajectory at Quillayute, Wa. J. Air Poll. Contr. Assoc., 26, 565-569.

13. MacCracken, M.C. and G.D. Sauter, 1975: Development of an Air Pollution Model for the San Francisco Bay Area. Final Report to NSF-UCRE51920, Lawrence Livermore Laboratory, Ca., 215 pp.

14. Miller, A., 1966: Land-Sea Boundary Effects on Small Scale Circulations. San Jose State College M teorology Department, 97 pp.

15. Miller, A., 1975: Project STABLE. Bull. Amer. Meteor. Soc., 56, 52-55.

16. Miller, A., 1976: Wave Properties in the West Coast Inversion. San Jose State University, 1976, 95 pp.

17. Miller, A., and C.P. Ahrens, 1970: Ozone within and below the west coast temperature inversion. Tellus 22:328.

18. Perl, G., 1965: Das Bodennake Ozoniu Arosa Seine, regelmässigen und unregelmassigen Schwankungen, Arch. Meteorol. Geophys. Bioklimatol., Ser. A 14:449-458.

19. Reiter, E.R., 1971: Atmospheric Transport Processes, Part 2: Chemical Tracers. USAEC. Div. of Tech. Infor., TID 25314, 382 pp.

20. Root, M.E., 1960: San Francisco, the air conditioned city. Weatherwise, 13.

21. Schroeder, M.J., M.A. Fosberg, O.P. Cramer, and C.A. O'Dell, 1967: Marine air invasion of the Pacific Coast: A problem analysis. Bull. Amer. Meteor. Soc., 48, 11, 802-808.

22. Teichart, F., 1955: Vergleichende Messung des Ozong e haltes der Luft am Erboden und in 80 m Höhe, Z. Meteorol. 9:21-27.

23. Wagner, J.A., 1974: Weather and circulation of July 1974-heat wave and drought over the middle third of the Country. Mon. Wea. Rev., CII, 10, 736-742.

APPENDIX A

Surface Monitoring Station Locations and Histories

Location in Figure 3	Station*	Observations Began	+
1	Vallejo	1969	+
2	Pittsburg	1969	
3	Concord	1972	
4	Pleasant Hill-Walnut Creek	1968	
5	Livermore	1968	+
6	Fremont	1962	+
7	Hayward	1973	
8	San Leandro	1963	
9	Oakland	1962	+
10	Richmond	1962	+
11	San Rafael	1962	
12	San Francisco	1962	+
13	San Francisco (East)	1974	
14	Mt. Sutro Tower*	1974	
15	Burlingame	1962	+
16	Redwood City	1966	
17	Mountain View	1972	+
18	Sunnyvale	1973	
19	San Jose	1962	+
20	San Jose (Alum Rock)	1974	
21	Los Gatos	1972	
22	Gilroy	1974	
23	Santa Rosa	1970	+
24	Napa	1969	+
25	Petaluma	1971	+
26	Fairfield	1969	+
27	Stockton*		
28	Sacramento*		

*All stations under jurisdiction of BAAPCD except 14 (San Jose State University) and 27, 28 (California Air Resources Board).

+Indicates stations which have been relocated one or more times within the given city.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/4-77-046	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE OZONE OVER SAN FRANCISCO Means and Patterns During Pollution Episodes		5. REPORT DATE November 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Kenneth P. MacKay		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS San Jose State University San Jose, CA 95192		10. PROGRAM ELEMENT NO. 1AA603 AD-02 (FY-77)
		11. CONTRACT/GRANT NO. R802235
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED Final 4/73 - 5/77
		14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Measurements of meteorological parameters were taken at six levels and ozone at four levels between 260m and 473m ASL on the Mt. Sutro T.V. Tower in San Francisco during the summers of 1974 through 1976. Hourly average ozone concentrations within the elevated inversion layer at this location exceeded the 8 pphm (160 μg m^{-3}) National Ambient Air Quality Standards about 15% of the time. High inversion layer ozone concentrations at this site were associated with high surface concentrations occurring during area-wide air pollution episodes. These episodes occurred when a lobe of the Pacific high pressure system penetrated inland. During these episodes, superposition of synoptic scale northeasterly flow and locally produced mesoscale flow caused easterly or light westerly flows during the late forenoon within the inversion layer and westerly flow in the late afternoon. Inland, where the inversion was destroyed from below, inversion layer and surface generated pollutants were convectively mixed. This mixing and the wind oscillation recycled pollutants. The episodes ended when the synoptic situation reverted to one more normal for the season and pollutants were advected from the area.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Air pollution * Ozone * Meteorological data Towers	San Francisco, CA	13B 07B 04B 13M

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 123
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