FINAL REPORT

# APPLICATION OF CLIMATOLOGICAL ANALYSIS TO MINIMIZE AIR POLLUTION IMPACTS IN CALIFORNIA

Agreement A2-119-32

Prepared for

California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Executive Summary

by

T. B. Smith
W. D. Saunders
D. M. Takeuchi

August 1984

Meteorology Research, Inc.
25977 Sand Canyon Road
Canyon Country, CA 91351

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## SUMMARY

A summary of meteorological factors affecting air pollution potential in California has been prepared. The study utilized a data base from 1979-80 and included surface wind, temperature and humidity observations as well as available temperature soundings. Data were available from 47 surface stations and 17 sounding locations.

Distributions of temperature, wind speed and direction, humidity and mixing height were determined. The frequency of occurrence data are given in tables in the Appendix. Map representations of some of the data are included in the text.

The meteorological parameters or combinations of parameters have been used to obtain several alternative representations of air pollution potential. These include 850 mb temperature, maximum surface temperature, Holzworth potential, ventilation factors and a combination of low morning wind speeds and low afternoon mixing heights. The values of some of these parameters on a daily basis were correlated with maximum ozone concentration for the day. Highest and most consistent correlations were obtained using the two representations of temperature. Differences between the times of maximum ozone and maximum temperature were used to characterize source and receptor areas. An analysis of low wind speed occurrences during morning hours throughout the state indicated that the areas of Ukiah/Santa Rosa, parts of the Mojave Desert, the San Bernardino/March Field area and some inland areas of the San Diego Air Basin experienced lowest morning wind speeds. These areas are particularly susceptible to the morning accumulation of pollutants.

A number of detailed meteorological factors which influence air pollution potential in the state are described. These include eddy structures, slope flows, layers aloft, convergence zones and marine air intrusions. The effect of these factors is to redistribute the pollutants both horizontally and vertically over wider areas than utilized in simple transport models. In the case of upslope flow and convergence zones, these also constitute effective mechanisms for removing pollutants from the surface mixed layer and delivering the material to higher altitudes where it may be transported away from the area. In addition, upslope flow delivers high concentrations of pollutants to mountain areas. The western slopes of the Sierra Nevada and San Bernardino Mts. and the southern slopes of the San Gabriel Mts. experience high ozone concentrations in summer.

Interbasin transport of pollutants is a major factor in the state. Such transport has been documented from most of the primary source areas into adjacent air basins. Transport into low population, mountainous regions downwind of major source areas has also been shown.

The primary uncertainty in defining air pollution in the state from a meteorological standpoint relates to variations in mixing height characteristics, particularly in the coastal areas. Gradients in maximum surface temperatures in the coastal regions and the frequent afternoon intrusion of a marine layer complicate the characteristics of the mixing layer depth. Depths in these areas are not easily estimated from existing temperature soundings and may show considerable variation in space and time. Areas where additional mixing height data are needed include the Santa Rosa area, the south portion of the San Francisco Basin, the Salinas Valley, the San Bernardino/ Riverside area and the inland regions of the San Diego Air Basin.

## 1.0 INTRODUCTION

Air quality concentrations are determined not only by emission patterns but are strongly dependent on meteorological factors. In many regions of the United States, emissions tend to be distributed in a very non-uniform spatial manner. High emission sources are usually isolated and distributed sources tend to be maximized in urban areas. In California, the meteorological factors are also very diversely distributed. Local terrain varies from below sea level to over 14,000 ft. within the state. The cooling and stabilizing effects of the ocean in summer contrast with the intense heating of the desert areas. The combination of terrain and ocean influences results in an unusually wide variety of meteorological factors affecting air quality concentrations in the state.

The objective of the present study has been to describe these meteorological factors from a climatological viewpoint. The end product of the study has been an attempt to map out the statewide distribution of those meteorological factors related to air pollution potential. The study has not been concerned with emission patterns or with specific meteorological/air quality interrelationships. Instead, the study attempts to describe the air pollution potential in the state primarily from a meteorological viewpoint.

The study begins with a statewide description of the individual meteorological parameters most closely associated with air pollution potential. This material is followed by several different combinations of parameters which have been used to quantify air pollution potential. Finally, a section of the report describes a number of meteorological events which result from ocean/terrain effects and which markedly influence the air pollution potential in California.

## 2.0 BACKGROUND

The two principal studies which were aimed at an evaluation of meteorological air pollution potential in California have been:

a. Bell (1958) - State-wide summaries were prepared of surface wind directions and speeds, regional circulation patterns, temperature variations and upper air stability and inversion height parameters.

b. Staff Report, CARB (1974) - The CARB staff utilized the Holzworth (1972) dispersion model to calculate air pollution potential at selected locations in California. Data were obtained from radiosonde and aircraft soundings. Morning mixing heights and wind speeds were used in the urban model calculations.

Meteorological descriptions of air pollution potential have almost entirely focused on the primary parameters of wind speed and mixing height. As Aron (1983) points out, however, mixing height is a somewhat uncertain variable since it is estimated by making two critical assumptions concerning temperature lapse rate (Holzworth, 1972). These are 1) the morning mixing height is arbitrarily determined by adding $5^{o}$ C to the minimum surface temperature. This leads to considerable uncertainty under some temperature lapse rate conditions and 2) the afternoon mixing height is determined by considering an adiabatic lapse rate from the maximum surface temperature to the existing sounding. In many areas, there is often a super-adiatic lapse rate in the lower levels during the afternoon. Use of the maximum surface temperature under these conditions can lead to an overestimate of the mixing height. Generally, distribution of the two parameters (wind speed and mixing height) have been treated separately. Holzworth combined the parameters in an analysis of episodes.

The primary attempt at construction of a quantitative pollution potential parameter was also provided by Holzworth who adapted a Gaussian dispersion model to an area source configuration of two different sizes. This model emphasizes the diffusion aspects of the air pollution potential. Evaluations of air pollution potential are consequently a function of urban size rather than having a unique value dependent on meteorology alone. From this standpoint the product of wind speed and mixing height (used by Holzworth to define episodes) is a better measure of meteolological air pollution potential.

## 2.1 Terrain

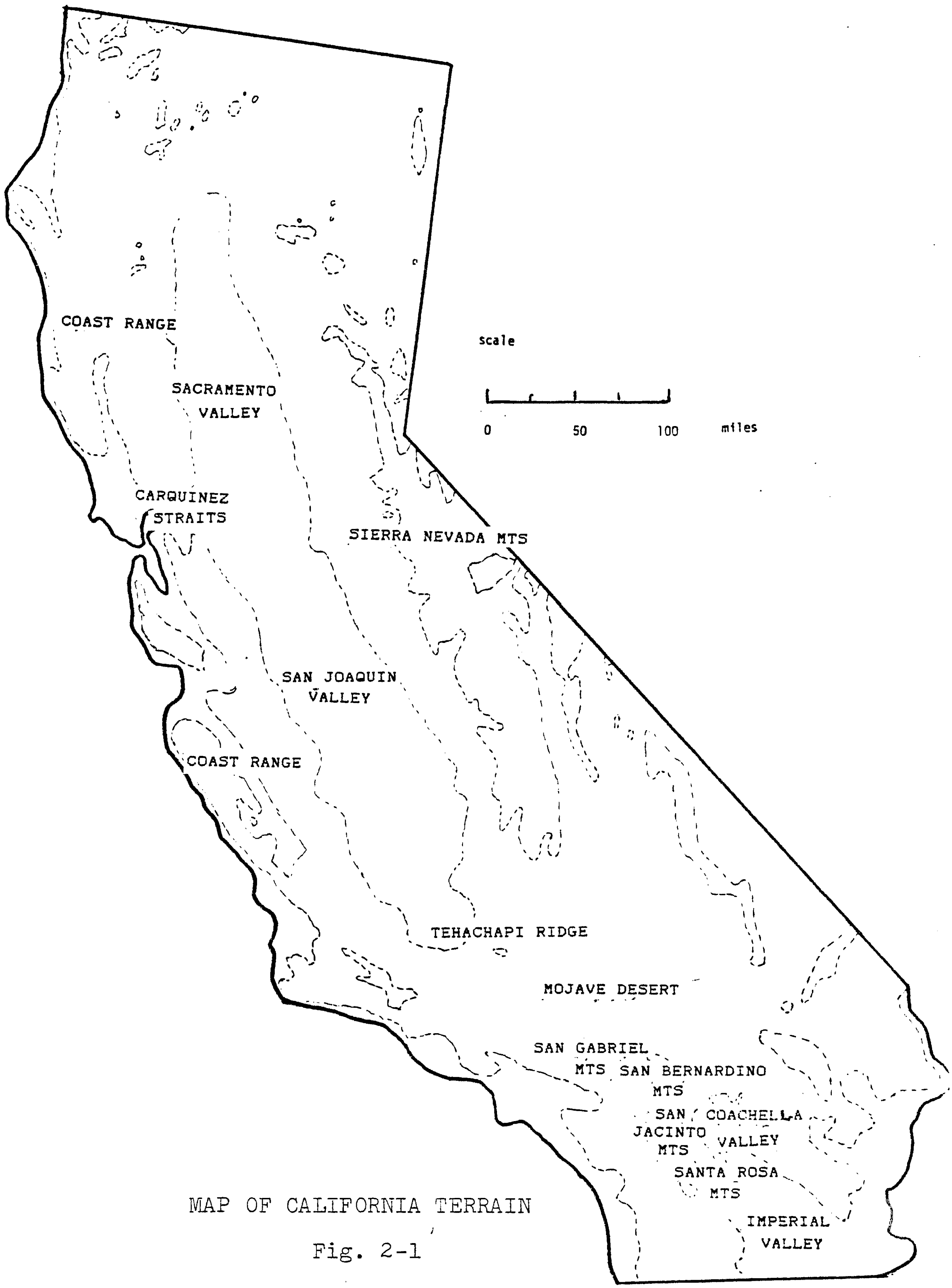
The terrain of California plays a very significant role in determining air pollution potential in the state. In particular, the combination of low inversion heights, high terrain and a strong diurnal heating cycle channel the summer flow patterns into a highly repeatable daily cycle. Since the source areas are largely fixed in location the receptor areas also tend to be similar each day but with minor fluctuations in wind speed and mixing height.

Fig. 2-1 shows a map of California including the principal terrain features which are of interest from an air pollution standpoint.

The Central Valley of California extends about 375 miles from north to south and includes the Sacramento Valley in the north and the San Joaquin Valley to the south. The valley averages 50-70 miles in width, depending on location. The valley is bordered on the east by the Sierra Nevada Mts. and on the west by the much lower coastal ranges. Principal entrance for air flow into the valley is the Carquinez Straits where the air flow is from the west 24 hours per day in summer. Principal exit zones are the western slopes of the Sierra Nevada Mts. and the Tehachapi Ridge to the southeast of Bakersfield.

In the south, the coastal plain which includes Los Angeles and San Diego is ringed to the east and north by the Santa Rosa Mts., San Jacinto Mts., San Bernardino Mts. and the San Gabriel Mts. To the east and north of these mountain ridges lies the Mojave Desert. The Coachella and Imperial Valleys are of particular interest since they represent the major populated areas in the desert.

There are three principal passes from the South Coast Air Basin into the Southeast Desert. These are Soledad Canyon, Cajon Pass and San Gorgonio Pass. The latter appears to be the most significant pollutant transport route into the desert. Air flow in the South Coast Basin during pollutant periods is strongly controlled on a diurnal basis by temperature differentials between the ocean and the inland areas. As a result, pollutants generated in the South Coast Basin are frequently transported from their source regions into the eastern part of the basin and on into the desert.




MAP OF CALIFORNIA TERRAIN

Fig. 2-1

## 2.2 Data Resources

Data used in the study were obtained from both surface and upper air sources.

Surface data were obtained from the National Climatic Center in the form of hourly observations from 47 airport locations in the state. Data from January, April, July and October for 1979 and 1980 were summarized. Attention was focused on observations at 08, 12 and 16 PST for each monthly summary. 08 PST represents the light wind period in the morning when peak urban traffic occurs. 12 and 16 PST indicate the transport patterns for the pollutants accumulated during the morning hours. Surface wind flow regimes at night are of less interest, particularly for ozone transport.

Sounding data were obtained on tape from CARB for the 1979-80 period. These data included NOAA and Defense Department radiosondes together with the aircraft soundings made frequently by CARB under contract in various areas. All available data on the tape were processed for the study, regardless of time of day. The data were subsequently summarized into AM and PM groups.

3.0 METEOROLOGICAL PARAMETER DISTRIBUTIONS

Distributions of temperature, relative humidity and wind speed at 08, 12 and 16 PST for the 47 surface stations were summarized into 10, 50 or 90 percentile values for January, April, July and October. A few selected data are shown in map form in this section.

Comments on the distributions are:

a. Temperature - Data utilized represent 12 PST (90 percentile) data, i.e. the temperature exceeds the value shown 10% of the time at 12 PST in the given month.

The principal interest in temperature from an air pollution standpoint deals with its influence on chemical reaction rates, particularly ozone. 12 PST is generally slightly before the maximum temperature peak but adequately represents the environmental conditions during the period of ozone formation. Ninetieth percentile data are given to include conditions during peak ozone periods.

b. Relative Humidity - Relative humidity data have also been presented in terms of 12 PST (90 percentile) values for January, April, July and October. The reason for this presentation is similar to the previous temperature data. High humidity affects chemical reaction rates and contributes to the growth of hygroscopic aerosols at about 70% RH or higher. 12 PST is again an important period during the day for chemical reactions and for aerosol effects on visibility. In some cases, e.g. Red Bluff in October, there may be a considerable difference between 90 percentile and 50 percentile values.

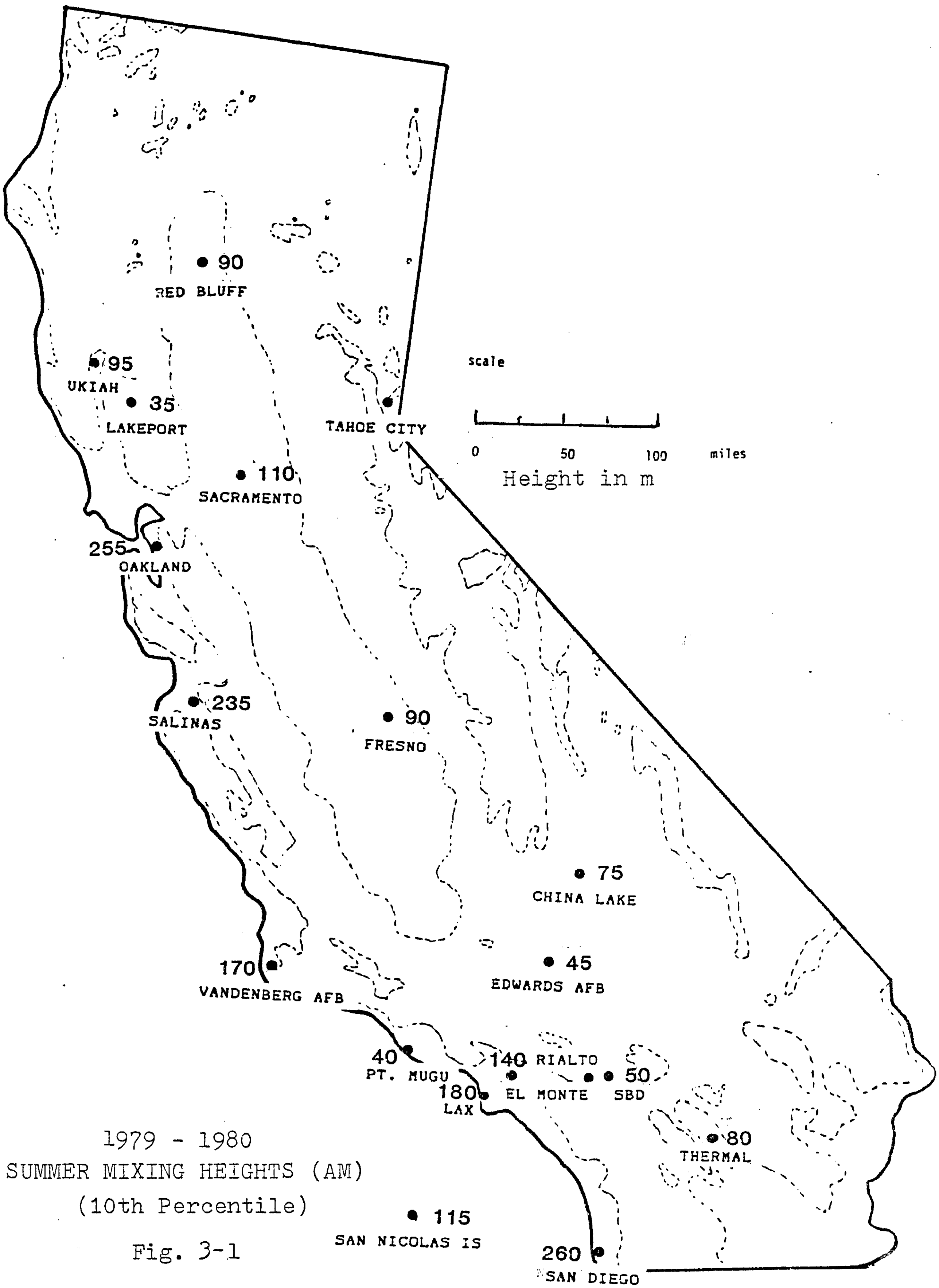
c. Wind Speed - Wind speed has an important effect on area ventilation and dilution of concentrations from individual source areas. Light winds occurring in conjunction with important emission sources lead to an accumulation of pollutants which may move downwind later in the day. This phenomenon is particularly noticeable in the forenoon in the Los Angeles area and in the morning commuter hours in the San Jose/Sunnyvale area.

Wind speed data have been presented in map form in terms of the lightest (tenth percentile) winds occurring at the location at the given hour and season. In view of the importance of wind speeds throughout the day, data for three hours (08, 12 and 16 PST) were presented for all four months.

d. Mixing Heights - Mixing height data were estimated by the method suggested by Holzworth (1972). During the afternoon the maximum surface temperature was used with the measured sounding to construct a dry adiabatic lapse rate which intersected the sounding at the maximum mixing height for the day. The morning mixing height was estimated by increasing the minimum temperature by 5° C and determining the intersection of an adiabatic lapse rate with the measured sounding. Both techniques probably lead to slight overestimates of the mixing height.

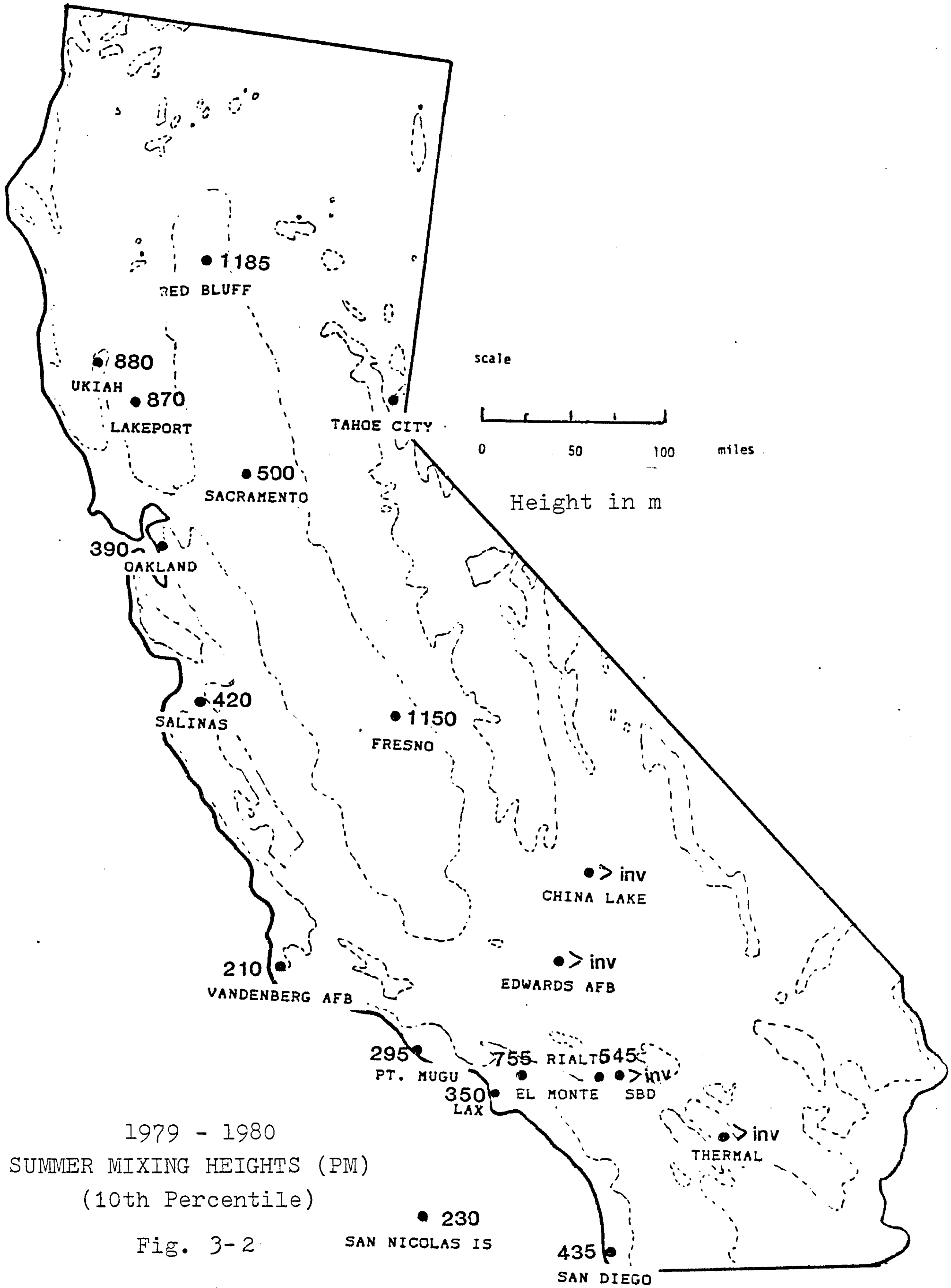
In addition to the difficulties with the estimating techniques there were notable gaps in the available data set. CARB aircraft flights do not occur each day and in some months there were relatively few data at some locations. As a consequence the results of the summarizations are more variable than might be expected in reality.

Low mixing heights are of primary interest in air pollution work. Data are plotted in map form in Figs. 3-1 to 3-2 in terms of the lowest 10th percentile for the summer morning and afternoon estimates. Since there were more morning soundings than afternoon, the afternoon estimates were based on the morning sounding and the afternoon maximum temperature.




1979 - 1980
SUMMER MIXING HEIGHTS (AM)
(10th Percentile)

Fig. 3-1




1979 - 1980
SUMMER MIXING HEIGHTS (PM)
(10th Percentile)

Fig. 3-2

## 4.0 TRANSPORT PATTERNS

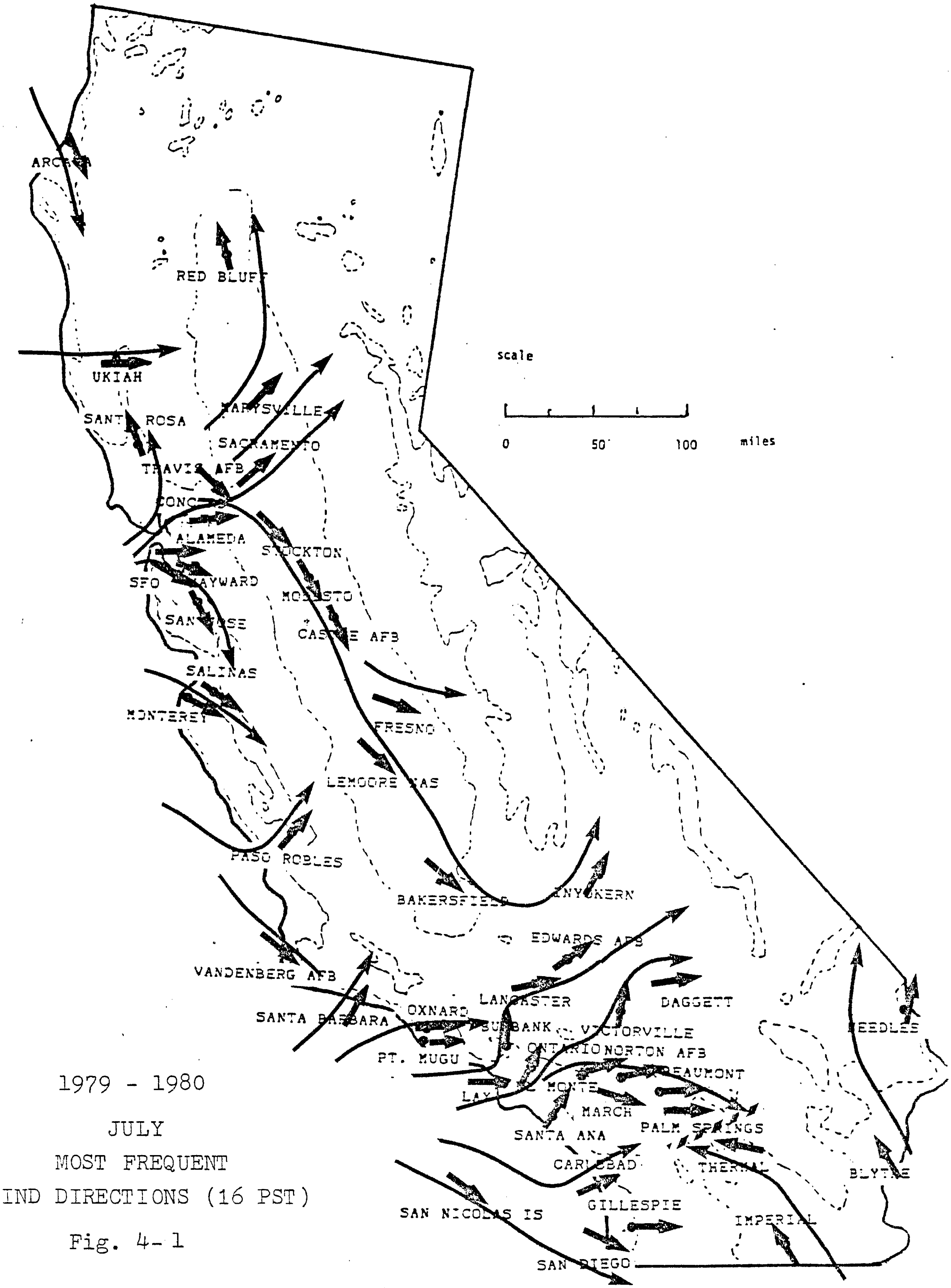
### 4.1 Most Frequent Streamlines

Most frequent wind directions have been obtained for the 47 surface stations in California at 08, 12 and 16 PST for the months of January, April, July and October. One of the resulting maps is shown in Fig. 4-1. In many instances the most frequent wind was a "calm" (less than 3 knots). A similar but more detailed presentation of predominant wind flow patterns has recently been published by Hayes et al(1984) in a CARB climatology study.

The strong influence of terrain on dominant wind flow patterns in California is emphasized in Fig. 4-1. There are only limited openings in the terrain along the coast through which surface air flow can reach the interior. A major opening is the Carquinez Straits to the east of San Francisco. During most of the year there are low level trajectories through the Straits into the Central Valley. A portion of the flow is deflected northward into the Sacramento Valley while part of the flow passes south into the San Joaquin Valley. Minor intrusions of coastal air into interior valleys are shown to the southeast of Arcata and Salinas. The flow from the Bay Area into the Central Valley occurs through the Carquinez Straits and through Altamont Pass (east of Livermore). These routes represent by far the major transport corridors into the Central Valley in northern California.

In the southern part of the state the major terrain feature is the extensive coastal plain which permits easy access of coastal air to an inland distance of 50-60 miles from Los Angeles to San Diego. There are several passes which permit coastal air to be transported into the desert from the coastal plain.

The diurnal influence on dominant wind flow patterns is quite strong. Inland heating during the daytime results in intensified pressure gradients during the afternoon from the coast - inland. These power a diurnal monsoon which influences most of the state.




1979 - 1980

JULY

MOST FREQUENT

WIND DIRECTIONS (16 PST)

Fig. 4-1

## 4.2 Interbasin Transport

During the past ten years CARB has carried out a number of research studies to investigate interbasin transport in the state. The following paragraphs summarize the results of these studies.

### San Francisco Bay Area Air Basin

Pollutant trajectories from the San Francisco Bay area into the Sacramento Valley/San Joaquin Valley were documented in two CARB studies (Smith et al, 1977 and Lehrman et al, 1981). Tracers were released from locations in the Carquinez Straits area (e.g. Vallejo and Pinole). Results from one tracer release from Vallejo indicated significant impact in the Sacramento area itself and transport into the Sacramento Valley, including Marysville and Williams. A more frequent transport route from the Bay area is through Lodi-Stockton into the San Joaquin Valley. An additional route through Livermore and the Altamont Pass into the San Joaquin Valley has been documented by a tracer release. These trajectories are more frequent and significant in the summer.

Another CARB study (Dabberdt et al, 1983) examined the transport from the San Francisco Bay Area Air Basin into the North Central Coast Air Basin. The trajectory follows an offshore route from San Francisco southward into Monterey Bay. A second route was observed through the Santa Clara and San Benito Valleys between San Jose and Hollister.

### Sacramento Valley Air Basin

Pollutant trajectories from the Sacramento Valley Air Basin were obtained from CARB tracer studies reported by Lehrman et al (1981).

During a summer afternoon the principal trajectory from the urban area of Sacramento is toward Auburn and the western slopes of the Sierras (Duckworth and Crowe, 1979). These areas are a part of the Mountain Counties Air Basin. Some transport into the Lake Tahoe Air Basin may take place under the same conditions (Unger, 1978) but on a much less significant scale.

In view of the close proximity of Sacramento to the northern boundary of the San Joaquin Valley Air Basin it is inevitable that pollutants can, on occasion, be transported into the

San Joaquin Valley Air Basin. This transport, however, has not been documented in formal studies.

San Joaquin Valley Air Basin

The main exit route for pollutants from the San Joaquin Valley Air Basin is out the southeast end of the valley over the Tehachapi Ridge. A CARB study (Smith et al, 1981) provided information to document this pollutant transport, (Reible et al, 1982) analyzed the transport of tracer and aerosols from the Oildale area and demonstrated their impact on the Southeast Desert Air Basin from Inyokern to Mojave.

The trajectories are most significant and frequent during the summer months but may occur at other times of the year with less impact.

South Central Coast Air Basin

Trajectories from the South Central Coast Air Basin into the South Coast Air Basin were obtained from tracer releases by Lamb et al (1978). Releases were made from the Oxnard Plain near Ventura. Tracer samples were obtained as far east as Burbank and at Lennox along the coastal strip. These trajectories represent an afternoon path eastward through the San Fernando Valley and a (generally) offshore track along the coast and inland with the sea breeze. The latter path may also occur during the daytime hours in the presence of offshore pressure gradients.

South Coast Air Basin

A major study was carried out by CARB in 1981 to investigate the transport of pollutants into the Southeast Desert Air Basin (Smith et al, 1983a). Principal transport routes were through Soledad Canyon, Cajon Pass and San Gorgonio Pass. Impacts on the northern end of the Coachella Valley are both frequent and significant. The transport is a dominant feature of the summer months but also occurs at other times of the year.

There has recently been considerable interest in the impact of South Coast Air Basin pollutants on the South Central Coast Air Basin. Two transport routes have been identified. One of these is offshore from the South Coast, northwestward and thence inland in the Ventura area with the sea breeze. This pattern has been discussed by Kauper and Niemann (1975), Shair et al

(1982) and by Smith et al (1983b). A tracer study by Shair et al produced direct evidence of this transport.

The second transport route is westward from the San Fernando Valley into eastern Ventura County. Smith et al (1983) show evidence of this transport aloft. Recent studies indicate that the impact in the eastern part of Ventura County can be significant.

Kauper and Niemann (1977) carried out a study to document transport of ozone from the South Coast Air Basin into the San Diego Air Basin. The transport route suggested was offshore from the South Coast Air Basin, southeastward and then inland on the sea breeze.

San Diego Air Basin

There are two principal air flow routes from the San Diego Air Basin into the Southeast Desert Air Basin. One of these is along the U.S - Mexican border through Mountain Springs Pass. The other empties into the Borrego/Anza through valleys which are oriented in a northwest-southeast direction.

Although tracer studies have not been carried out along these routes there is evidence of the flow through Mountain Springs Pass and at Borrego. In addition, westerly winds at Imperial occasionally appear in the afternoon, accompanied by characteristic changes in humidity as the marine air enters the desert.

## 5.0 CHARACTERISTICS OF AIR POLLUTION POTENTIAL

The preceding sections have dealt with the distributions of some of the individual parameters which influence air pollution potential in California. The present section discusses several techniques for utilizing some of these parameters to represent meteorological air pollution potential in the state.

### 5.1 850 mb Temperature

For a number of years the 850 mb (about 5000 ft. msl) temperature has been used as a simple guideline for expressing air pollution potential in California (e.g. Kinosian and Duckworth, 1973). Most of the supporting studies to justify this usage have expressed the relationship between the daily 850 mb temperature and the highest ozone value occurring in the basin of interest.

The value of the 850 mb temperature as an indicator of air pollution potential is related to the information on stability which it provides. Low inversion heights and pronounced inversion strengths occur with warm temperatures aloft. Along the coast in the summer, the surface temperatures are strongly influenced by the ocean temperatures and remain fairly constant from one day to the next. The temperature aloft then provides a direct measure of the vertical stability, particularly near the coast.

Table 5-1 gives correlation coefficients between peak hourly ozone and daily 850 mb temperature (morning sounding) for several key locations in the state. For Sacramento the temperature at 5000 ft. from the aircraft sounding was used.

Table 5-1

Correlation of 850 mb Temperature and Peak Ozone
(July - August)

| 1979-80 Ozone Location | Year | Correlation | Temperature Location |
|---|---|---|---|
| Sacramento | 1979 | .55 | Sacramento * |
| | 1980 | .52 | |
| Fresno | 1979 | .76 | Los Angeles |
| (Olive St.) | 1980 | .66 | |
| Bakersfield | 1979 | .64 | Los Angeles |
| (Chester St.) | 1980 | .52 | |
| Fontana | 1979 | .71 | Los Angeles |
| | 1980 | .61 | |
| Piru | 1979 | .78 | Los Angeles |
| | 1980 | .74 | |

* 5000-ft. temperature

The correlations in Table 5-1 range from 0.52 to 0.78 for the indicated locations. Highest correlations were found at Piru which is only a short distance from the coast. Sacramento and Bakersfield appear to have the lowest correlations.

## 5.2 Ventilation Factors

Holzworth (1972) developed a technique for evaluating urban air pollution potential based on wind speed, mixing height, city size and a dispersion equation. The technique was used in a CARB study (Staff Report, 1974) to develop state-wide potential estimates. The technique was used in the present study but was frequently found to depend primarily on wind speed. Under these conditions, the technique did not seem to discriminate very well between dissimilar climatological regions of the state.

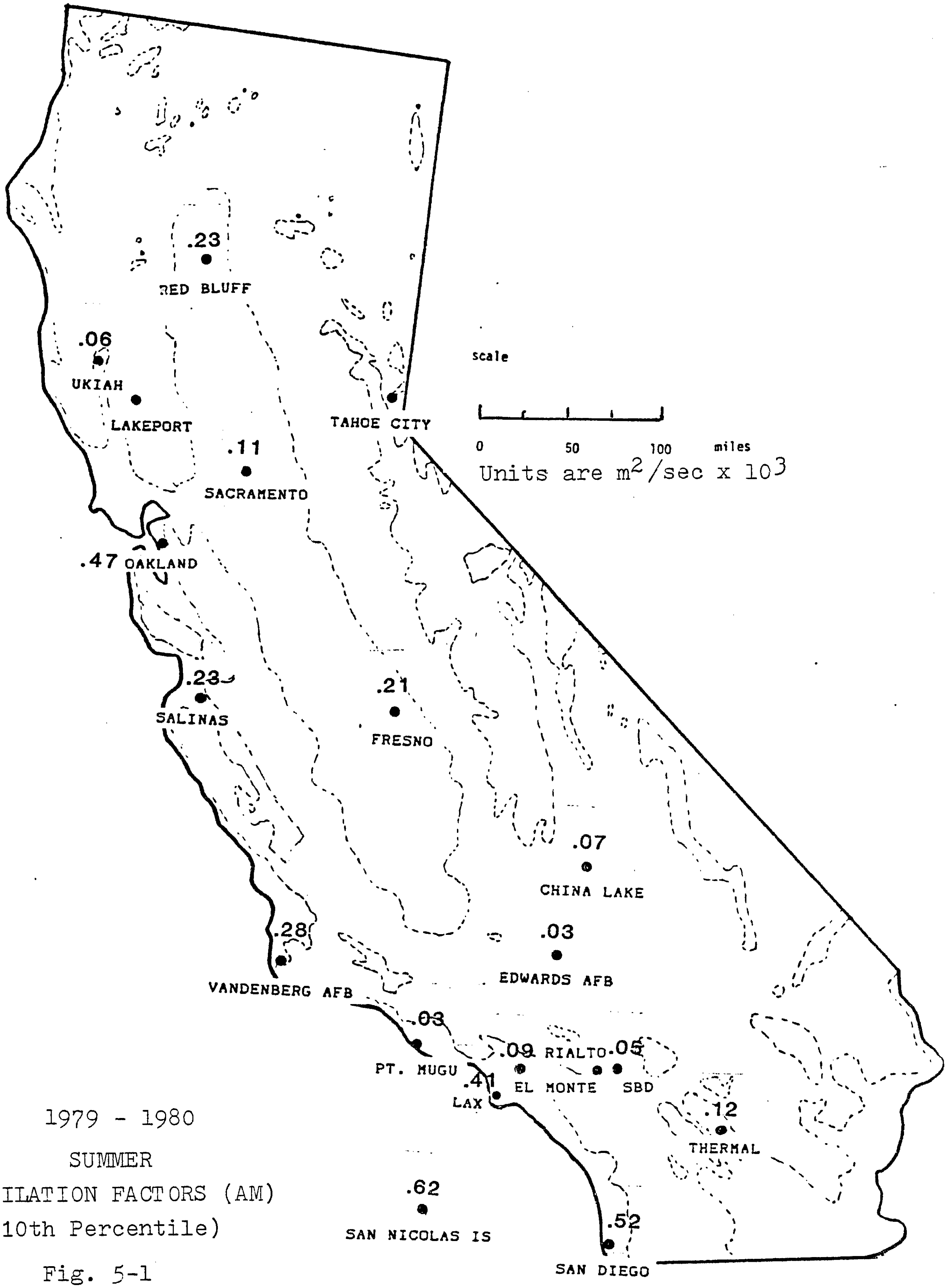
An alternative to the Holzworth technique is to calculate a "ventilation factor" defined as the product of the mixing height (H) and the average wind speed (u) in the mixed layer. This factor has the advantage of including both parameters in a physically meaningful manner for all stations. The factor represents the denominator of a standard box model in a dispersion computation. Low wind speeds and low mixing heights lead to small ventilation factors which translate into large pollution potential.

The ventilation factors were computed for the 17 sounding locations. 50th percentile and 10 percentile values were computed by months and seasons. Tenth percentile values for the morning for the four seasons are plotted in Fig. 5-1.

The morning ventilation factors are found to be highest along the coast from Salinas to Oakland and in the South Coast Air Basin. Winter and fall ventilation along the coast is the lowest during the year while summer shows the highest values, particularly along the South Coast. Morning ventilation values in the Central Valley are higher than most other inland areas.

On a state-wide basis peak ventilation is greatest during summer afternoons as might be expected. Minimum afternoon values occur during the winter months on a tenth percentile basis. During the summer months the ventilation is generally greater in the inland areas than along the coast. During the balance of the year these peak ventilation factors are more comparable.

Morning ventilation in the Bay Area and the South Coast Air Basin decreases rapidly with distance from the coast. The desert areas are characterized by low values during the morning in all seasons.




1979 - 1980

SUMMER

VENTILATION FACTORS (AM)

(10th Percentile)

Fig. 5-1

Correlations of ventilation factors and peak ozone concentrations are shown in Table 5-2.

Table 5-2

Correlations of Peak Ozone Concentrations and Ventilation Factors (July - August)

| Location | Year | Time | Correlation |
|---|---|---|---|
| Sacramento | 1979 | AM | -.60 |
| | | PM | -.23 |
| | 1980 | AM | -.58 |
| | | PM | .04 |
| Fresno | 1979 | AM | -.58 |
| | | PM | -.44 |
| | 1980 | AM | -.47 |
| | | PM | -.03 |
| Pt. Mugu (Piru) | 1979 | AM | -.21 |
| | | PM | -.14 |
| | 1980 | AM | -.27 |
| | | PM | -.41 |
| San Bernardino (Fontana) | 1979 | AM | -.63 |
| | | PM | -.07 |
| | 1980 | AM | -.12 |
| | | PM | -.06 |
| Los Angeles (UCLA) (Fontana) | 1979 | AM | -.29 |
| | | PM | -.55 |
| El Monte (Fontana) | 1979 | AM | -.52 |
| | | PM | -.31 |

### 5.3 Temperature Relationships

It has been recognized from smog chamber tests that warm temperatures increase the rate of ozone formation. It is therefore reasonable to examine the relationship between maximum temperature and peak ozone at several key locations in the state. Table 5-3 gives the correlations obtained.

Table 5-3

Maximum Temperature vs. Peak Ozone
(July - August)

| | 1979 | 1980 |
|---|---|---|
| Red Bluff | .53 | .44 |
| Sacramento | .70 | .69 |
| Fresno | .81 | .84 |
| Bakersfield | .71 | .57 |
| Lancaster | .20 | .40 |
| San Bernardino | .73 | .73 |
| Palm Springs | .48 | .60 |

At all comparable locations the correlation coefficients shown in Table 5-3 are higher than given in Table 5-1 which used the 850 mb temperature.

In Table 5-3 the correlations at Red Bluff, Lancaster and Palm Springs are relatively low in comparison with the remainder of the locations. These areas are not recognized as significant source areas so that a lower correlation between ozone and maximum temperatures at those locations is not surprising.

The relationship between the time of peak ozone and the time of the maximum temperature also contains useful information. If the peak ozone concentrations and maximum temperatures are related as suggested above, it might be expected that maximum ozone and temperature might occur at nearly the same time.

Table 5-4 shows the relationships between these times for the stations shown in the previous table.

Table 5-4

Comparison of Times of Peak Ozone and Temperature
(July - August)
(1979-80)

| Location | Median Time between Peaks |
|---|---|
| Red Bluff | -4 hours |
| Sacramento | -2 |
| Fresno | -4 |
| Bakersfield | -4 |
| Lancaster | 1 |
| San Bernardino | 0 |
| Palm Springs | 4 |

(negative sign means that ozone peak occurs first)

There is a wide range of time differences shown in the table. For those locations from Red Bluff to Bakersfield the ozone peak occurs some two to four hours before the temperature peak. This will occur if the precursor concentrations are diluted significantly by the time of the maximum temperatures. Prior to this time, ozone and precursor concentrations are higher. Such dilution can take place by rapid vertical mixing or by horizontal transport away from the area. In either event these locations should be considered as source areas which transport their pollutants to other areas.

In a case such as Palm Springs where the peak ozone tends to occur about four hours after the maximum temperature, this condition must occur through transport into the area from upwind. Palm Springs would thus be considered as a receptor area.

Lancaster shows a median time difference of one hour. This suggests that Lancaster is a receptor area but that significant ozone development may occur within a short distance upwind.

San Bernardino has a median time difference of zero hours. This could be interpreted as ozone formation in the vicinity of San Bernardino, corresponding to the daily temperature cycle, or transport from upwind which happens to arrive at the time of the maximum temperature.

Unger (1983) approached the problem of source/receptor areas on the basis of the ratio of maximum ozone concentrations vs. morning precursor concentrations ($NMHC+NO_x$). High values of the ratio suggested receptor areas while low values indicated source areas. Lancaster and San Bernardino were found to be high in the rank order of ratios (receptor areas).

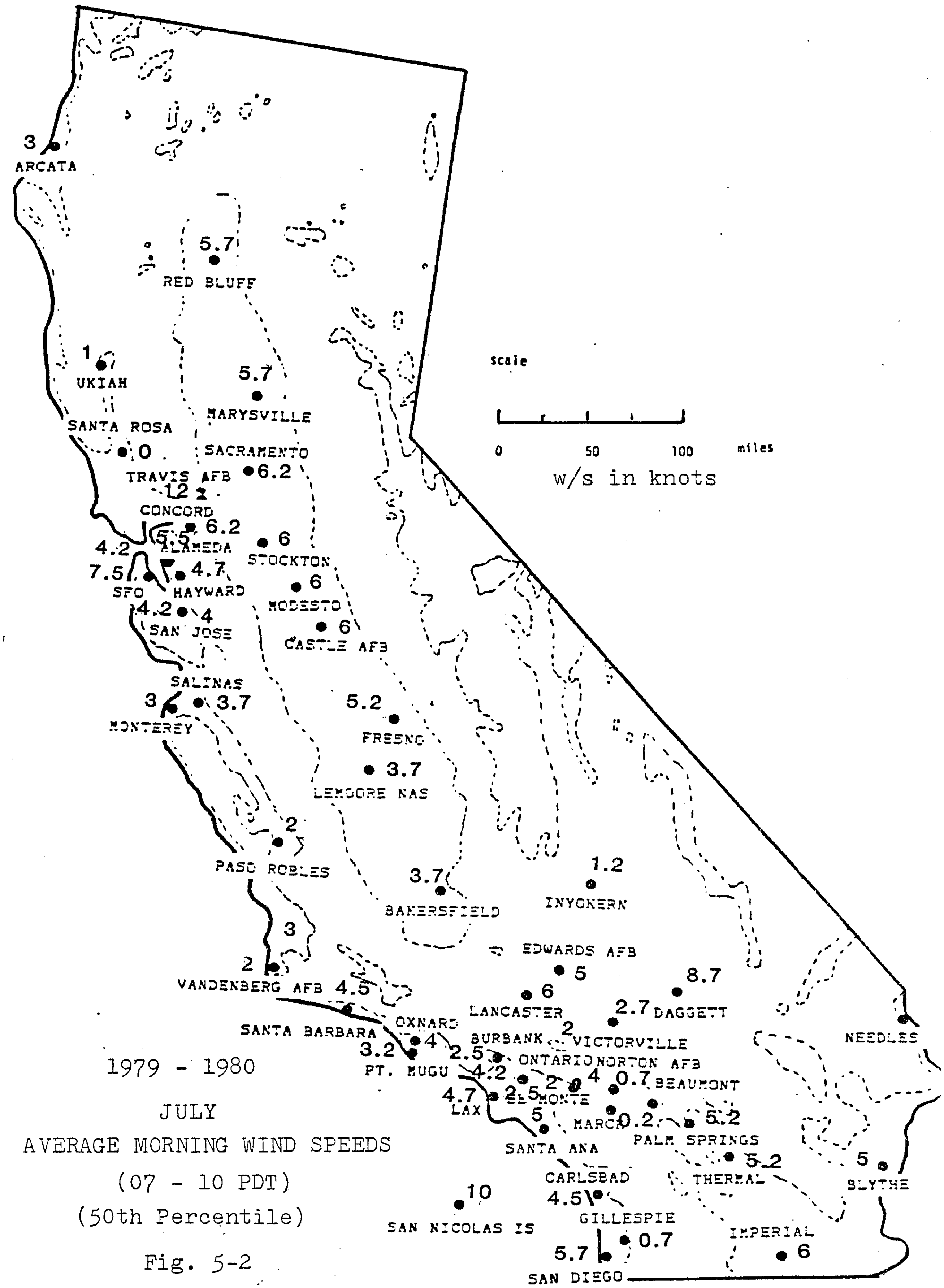
## 5.4 Low Wind Speeds

A major meteorological influence in California on the generation of high pollutant concentrations is the occurrence of light winds during the morning hours. Light winds combined with low mixing heights during morning peak traffic hours permit the build-up of high concentrations which subsequently are transported downwind.

Significant accumulation of pollutants occurs with a protracted period of low wind speeds. Indications of regions susceptible to accumulation were obtained by examining the distribution of average morning wind speeds at each location. For the purposes of the present study the average morning wind speed was considered to be the arithmetic average of the 07, 08, 09 and 10 PDT values for each day. The 50th percentile values for each location are plotted in Fig. 5-2 for July.

In Fig. 5-2, the map of 50th percentile values shows four regions of light, morning wind speeds. These are the Ukiah/Santa Rosa area, the March Field/San Bernardino area, Gillespie Field and the Inyokern area. All of these show average wind speeds (07-10 PDT) of less than two knots on a 50th percentile basis. The coastal areas, the Central Valley and the remainder of the Mojave Desert all show average wind speeds generally 2-4 times the averages for the low wind speed areas.

The tenth percentile data indicate, in addition to the above low wind speed areas, that the Salinas Valley, the South Coast Air Basin and much of the Mojave Desert experience low morning wind speeds on some days. The morning wind speeds in the Central Valley average 2-3 knots on a tenth percentile basis which makes the potential for morning pollutant accumulation somewhat less than experienced in other parts of the state.




1979 - 1980

JULY

AVERAGE MORNING WIND SPEEDS

(07 - 10 PDT)

(50th Percentile)

Fig. 5-2

## 5.5 Low Wind Speeds vs. Low Mixing Heights

It has been pointed out that low morning wind speeds and low mixing heights both contribute to increased air pollution potential. Low wind speeds in the morning permit the accumulation of pollutants during the morning traffic hours which then react photochemically as they are transported downwind during the afternoon. Low mixing heights in the morning contribute to the pollutant accumulation but tend to occur simultaneously with low wind speeds and hence do not provide a strong independent relationship. Low mixing heights in the afternoon, however, tend to maintain higher pollutant concentrations in the mixed layer and therefore provide additional information to evaluate the potential impact of the morning wind speed conditions.

Low morning wind speeds (10 percentile values) and low afternoon mixing heights (10 percentile) have been plotted in Fig. 5-3 to indicate how these two parameters occur in combination at the various sounding locations.

In the left portion of the diagram are all of the coastal locations where afternoon mixing heights remain relatively low, regardless of morning wind speeds. Locations such as Vandenberg AFB and Pt. Mugu (low morning wind speeds and low afternoon mixing heights) have a potential for pollution problems but do not generally have the upwind emission sources which could be transported onshore in the afternoon. The Salinas Valley, however, has a major emission source upwind at the coast line.

At the far right of the diagram are the desert and Central Valley locations where strong surface heating provides deep mixing layers during the afternoon. This mixing serves to dilute the pollutants during the afternoon, regardless of the wind speed in the morning.

Between these two extremes in the diagram are locations such as Rialto/San Bernardino, El Monte and Ukiah where morning wind speeds are very low and where afternoon mixing depths are intermediate between the coastal and interior areas. It is in these areas where many of the primary pollutant problems in the state occur.

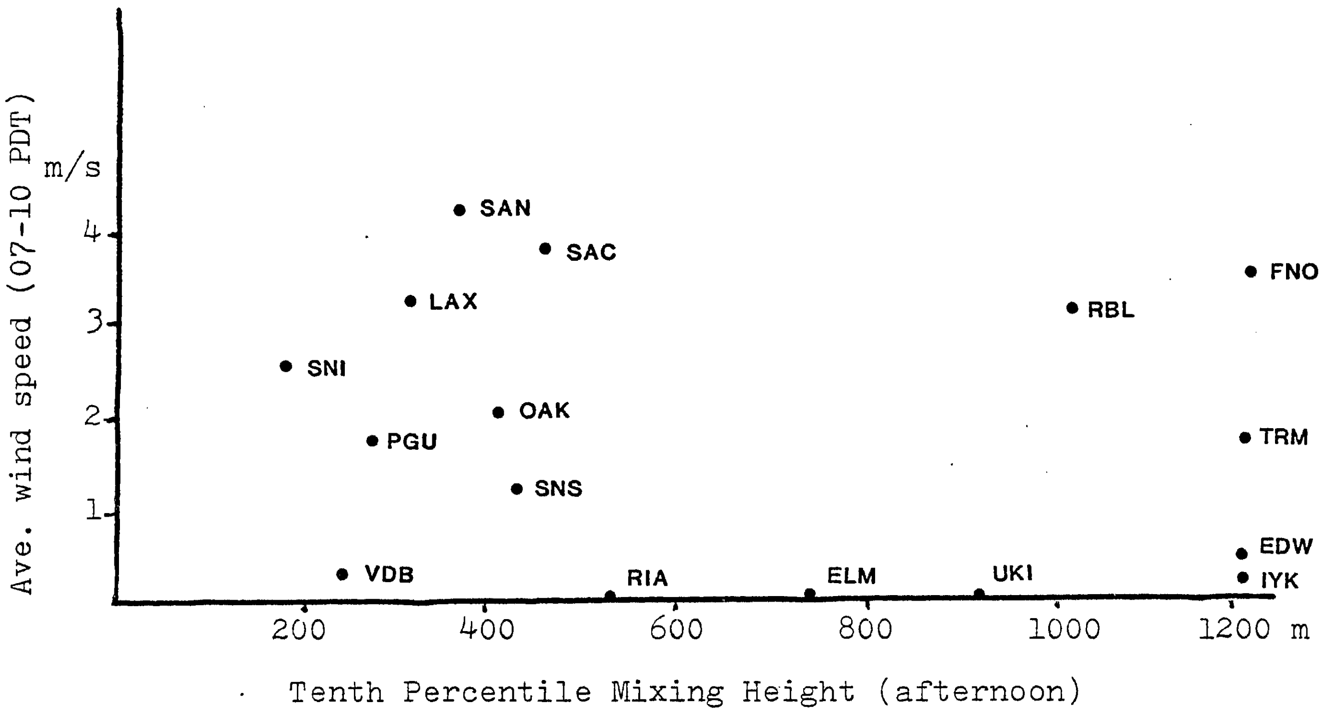



Fig. 5-3 VARIATIONS IN MORNING WIND SPEEDS AND AFTERNOON MIXING HEIGHTS

July 1979-1980

Legend

EDW - Edwards AFB
ELM - El Monte
FNO - Fresno
IYK - Inyokern
LAX - Los Angeles AP
OAK - Oakland
PGU - Pt. Mugu
RBL - Red Bluff
RIA - Rialto
SAC - Sacramento
SAN - San Diego
SNI - San Nicolas Is.
SNS - Salinas
TRM - Thermal
UKI - Ukiah
VDB - Vandenberg AFB

Comments on other portions of the state where detailed sounding information are not available follow:

1. Ukiah/Santa Rosa - Both Ukiah and Santa Rosa exhibit very low morning wind speeds during the summer and fall. Mixing heights at Ukiah during July afternoons are relatively high and provide moderately good dilution of the morning pollutant accumulation. Maximum temperatures at Santa Rosa, however, are some 10$^{o}$F lower than at Ukiah and it would be expected that the mixing heights might also be less. The Santa Rosa end of the Russian River Valley may therefore have a higher pollution potential than indicated for Ukiah.

2. San Jose/Hayward/San Carlos - The southern end of the San Francisco Bay Air Basin shows tenth percentile average morning wind speeds of 0-1 knot. Information on mixing heights, however, is not available. The area should be partially under the influence of the lower afternoon mixing heights along the coast. Maximum temperatures at San Jose are comparable to those at Santa Rosa.

3. San Bernardino/March AFB - Low average morning wind speeds occur in this area, even at the 50th percentile level (0.7 and 0.2 knots, respectively). Afternoon mixing heights in the area are somewhat uncertain due to the limited height of the San Bernardino soundings. For this reason, the August mixing height value for Rialto was used in Fig. 5-3 together with the wind speed from Norton AFB. At times, the coastal mixing layer moves as far east as San Bernardino and Riverside, resulting in restricted vertical mixing.

4. San Diego Air Basin - The immediate inland areas of the San Diego Air Basin (e.g. Gillespie Field) show very low morning wind speeds in spite of the stronger velocities along the coast. Again, the inland extent and characteristics of the afternoon coastal mixing layer are uncertain. The coastal plain of the San Diego Air Basin is not as wide as in the South Coast Air Basin. Otherwise, similarities in air pollution potential could be expected due to accumulation opportunities in the morning and restricted vertical mixing in the afternoon.

5. Salinas Valley - Low coastal mixing heights are present at the northwestern end of the Salinas Valley. Downwind, to the southeast, the mixing layer increases in height with increased surface temperatures. The characteristics of the mixing layer variations downwind are not well documented.

## 6.0 SPECIAL TOPICS

The terrain of California and the dominance of the ocean - land interface lead to a variety of phenomena which significantly influence the air quality environment in the state. Some of these phenomena are outlined in the following sections:

### 6.1 Eddy Structures

There are several areas in the state where horizontal eddies exist in the surface wind patterns on a scale of 100-150 miles diameter. In each case, the eddies result from a combination of terrain and vertical stability influences. Marked stability in the layers below the top of the terrain prevents the transport of air over the terrain and results in the deflection of the low-level flow into an eddy circulation.

Principal among the areas where eddy circulations have been observed are:

1. Schultz Eddy - During the early morning hours, on many summer days, an eddy exists in the southern portion of the Sacramento Valley. Southerly winds occur on the east side of the valley with northerly winds on the west. The northern edge of the eddy is generally in the vicinity of Marysville/Oroville.

2. Fresno Eddy - A large horizontal eddy develops in the southern San Joaquin Valley between 21 PDT and 11 PDT on most summer nights. The eddy begins in the Bakersfield area but the northern edge of the eddy extends as far north as Fresno by morning. Southerly winds occur on the eastern side of the valley with northerly winds on the west side.

3. Santa Barbara Eddy - A similar eddy often appears to develop at night in the Santa Barbara Channel to the west of Ventura. Westerly winds in the Channel are unable to pass over the mountains to the east of Ventura if the low-level nocturnal stability is sufficiently strong. In such cases the westerly flow is deflected to the north and south along the Ventura coast, resulting in an apparent eddy structure in the Channel.

The importance of these flows to the air quality environment is that pollutants trapped in the surface eddies can be recirculated throughout the eddy dimensions and be transported to otherwise unaffected receptor areas.

## 6.2 Slope Flows

Some of the principal air basins in California (Sacramento, San Joaquin, North Central Coast, South Central Coast, South Coast and San Diego) are bordered by significant mountain ridges. When appropriately located, the slopes may be heated, resulting in the generation of a significant transport of air upslope. In the areas affected by the summer marine inversion the upslope flow provides a mechanism for the transport of pollutants from below the inversion to above. In areas such as the South Coast Air Basin this transport provides one of the the more effective methods of removing pollutants from the Basin.

In areas which are immediately downwind of significant emission sources the upslope flow may transport ozone and other pollutants to high elevations in the mountain areas. Lake Gregory in the San Bernardino Mts. (elev. 4500 ft.) is immediately downwind of the San Bernardino area and frequently reports ozone values as high or higher than any in the South Coast Air Basin. Ozone scavenging by fresh emissions of nitric oxide is generally low in mountainous areas and ozone development may continue well beyond the boundary of the emission regions. Mt. Baldy and Mt. Wilson in the San Gabriel Mts. also experience high ozone concentrations as a result of the upslope flow (Smith et al, 1983a).

Similar problems exist in the Sierra Nevada Mts. to the east of Fresno, Bakersfield and Sacramento. Miller, McCutchan and Milligan (1972) and Williams, Brady and Willson (1977) have documented high ozone concentrations in the Sequoia National Forest and have attributed these to the urban area of Fresno. Unger (1978) and Duckworth and Crowe (1979) have described the impact of the Sacramento urban sources on the Sierra Nevada slopes to the northeast of Sacramento.

### 6.3 Layers Aloft

The unique combination of terrain and meteorological conditions in California contribute to a high frequency of pollution layers aloft. There are a number of different mechanisms for producing such layers:

1. Upslope Flow - As described in the previous section, upslope flow transports pollutants to elevations above the top of the mixed layer from which the pollutants originated. Given a strong stable layer in the inversion the pollutants flatten out into a layer aloft which is then transported by the winds within the inversion layer.

Such layers have been observed in the South Coast, San Diego, South Central Coast, San Joaquin Valley, Southeast Desert, San Francisco Bay, North Central Coast and over the near-offshore coastal waters.

2. Convergence Areas - In some areas of the state, surface wind patterns converge and pollutants from the surface layers are transported aloft. (See Section 6.4)

3. Marine Air Intrusion - Along the immediate coast a marine layer often undercuts the coastal pollutant layer bringing cleaner air to the surface layers but leaving a pollutant layer aloft. (See Section 6.5)

4. Transport into the Stable Layer - Active vertical mixing in the mixed layer during the afternoon transports pollutants into the inversion layer, primarily by convective processes. As soon as the surface temperatures begin to decrease and the convective action becomes somewhat less vigorous, the pollutants in the inversion layer become separated from the lower levels and become a layer aloft.

5. Plumes from Stationary Sources - Heated, isolated sources frequently deliver plumes into the inversion layer where they may become separated from the mixed layer and constitute a layer aloft.

The importance of the layers aloft lies in the potential for mixing downward on the same day or the following day as the surface-based mixing layer grows upward due to surface heating. This process has been observed in the South Central Coast Air Basin (Smith et al, 1983b) and in the Sacramento Valley (Lehrman et al, 1981). However, little is known at present about the impact of these layers on surface concentrations.

6.4 Convergence Zones

In several areas of the state convergence zones are formed by the confluence of opposing surface wind flows. The confluence of the flows requires strong terrain influences which can channel the winds into interacting flow patterns. Several of the recognized zones in the state are:

1. Elsinore Zone - This zone is formed along a line from Hemet to Elsinore by northwesterly winds passing through the Riverside area interacting with southwesterly winds arriving from Orange County. The upward currents in the zone are frequently used by sailplane enthusiasts.

2. El Mirage Zone - A flow through Cajon Pass, turning northwestward, frequently meets a westerly flow passing through Palmdale. The interaction is often in the vicinity of El Mirage where it is also utilized in summer by sailplane pilots.

3. San Fernando Valley Zone - A flow from the Ventura coastal plain into the western San Fernando Valley often interacts with a southeasterly flow in the eastern portion of the Valley to form the San Fernando Valley Convergence Zone (Edinger and Helvey, 1961).

4. Coachella Valley Zone - The penetration of marine air through San Gorgonio Pass into the Coachella Valley is often opposed by a southeasterly flow in the Valley, resulting in a convergence zone which moves southeastward during the late evening.

5. Ventura Zone - At night (summer and fall) the wind flow in the Ventura coastal plain frequently consists of an easterly drainage wind from the hills to the east of Ventura. This flow interacts with the westerly flow in the channel in a convergence zone which is located near or slightly offshore of the Ventura coast.

The importance of the convergence zones is twofold. First, they serve to restrict the transport of pollutants from one area into adjacent regions. Second, they provide a mechanism for ventilating surface pollutant concentrations to higher levels where they may be carried away by upper level winds.

## 6.5 Mixing Layer Structure in the Coastal Areas

### 6.5.1 Impact of Surface Heating

Under meteorological conditions of pollutant interest there is typically a strong surface temperature gradient directed from the immediate coast to the inland areas of California. Maximum surface temperatures between LAX and San Bernardino in summer, for example, differ by over 20$^{o}$F. These temperature differences lead to variations in the depth of the mixed layer as a function of distance from the coast.

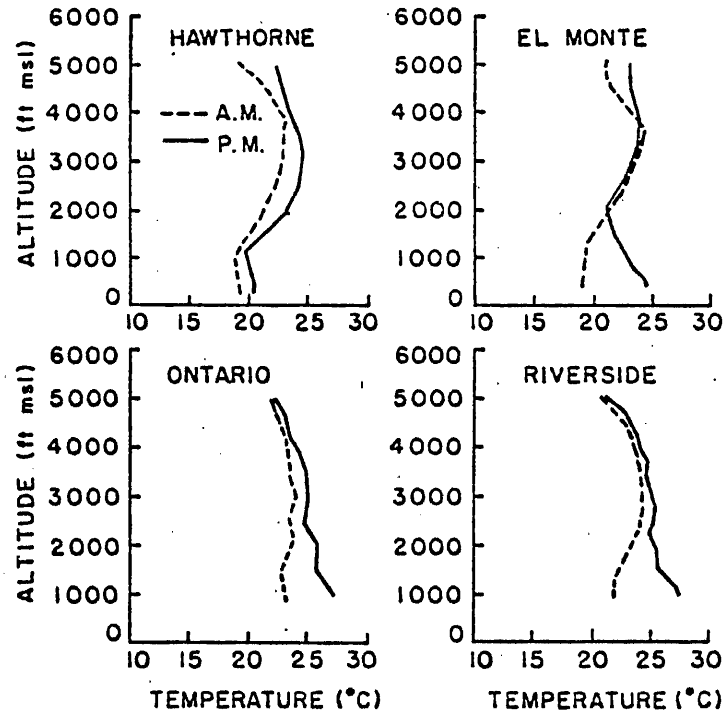
Fig. 6-1 was taken from a paper by Husar et al (1977). The data consist of mean temperature and turbulence soundings made on 24 pollution days in 1972-73 during a CARB-sponsored study of the South Coast Air Basin. Fig. 6-1(a) shows the mean morning and afternoon temperature soundings at four locations. The height of the temperature inversion remains nearly constant at Hawthorne from morning to afternoon but increases markedly in the afternoon in the inland areas. Both Ontario and Riverside show slightly higher inversions than El Monte in accordance with the increased surface heating inland. Fig. 6-1(b) shows the mean turbulence values at the same locations and serves to illustrate the changes in mixing characteristics as a result of the surface heating.

The increased afternoon mixing layer depths as a function of distance from the coast have several important effects on pollutant concentrations:

1) The increased depth permits increased dilution in the pollutant concentrations which are frequently generated by morning emissions and then transported downwind to areas further inland.

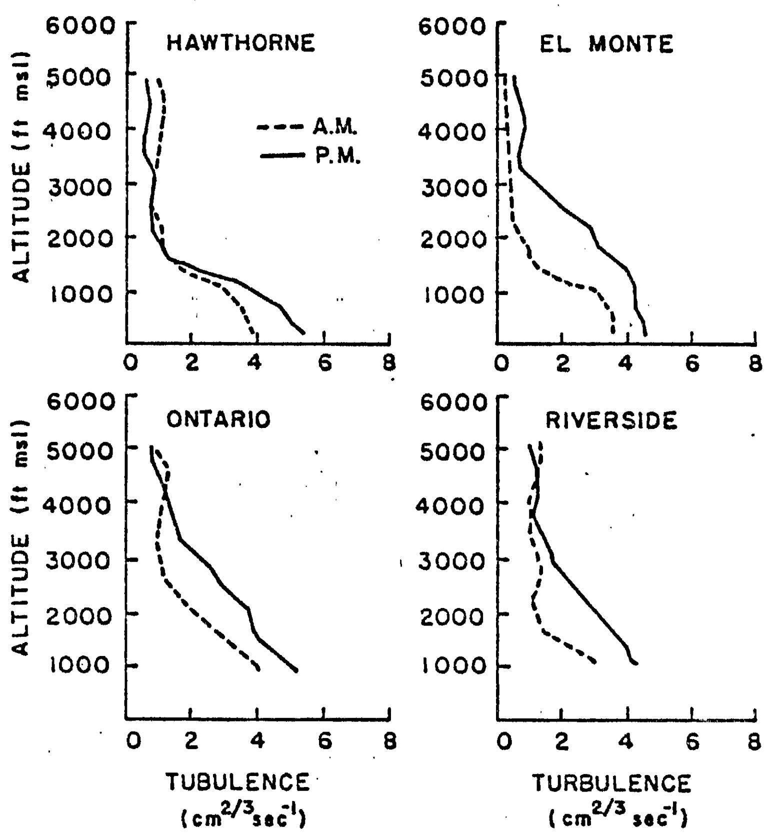
2) The increased depth may incorporate into the mixed layer pollutants aloft which may have resulted from elevated plumes from layers left over from the previous day.

3) Pollutants from elevated sources near the coast may not be brought downward into the surface layers (if at all) for a considerable distance downwind but may be brought downward more rapidly in the inland areas.




a. Temperature Profiles

(after Husar et al,1977)




b. Turbulence Profiles

Fig. 6-1 VARIATIONS IN MIXING HEIGHTS IN SOUTH COAST BASIN

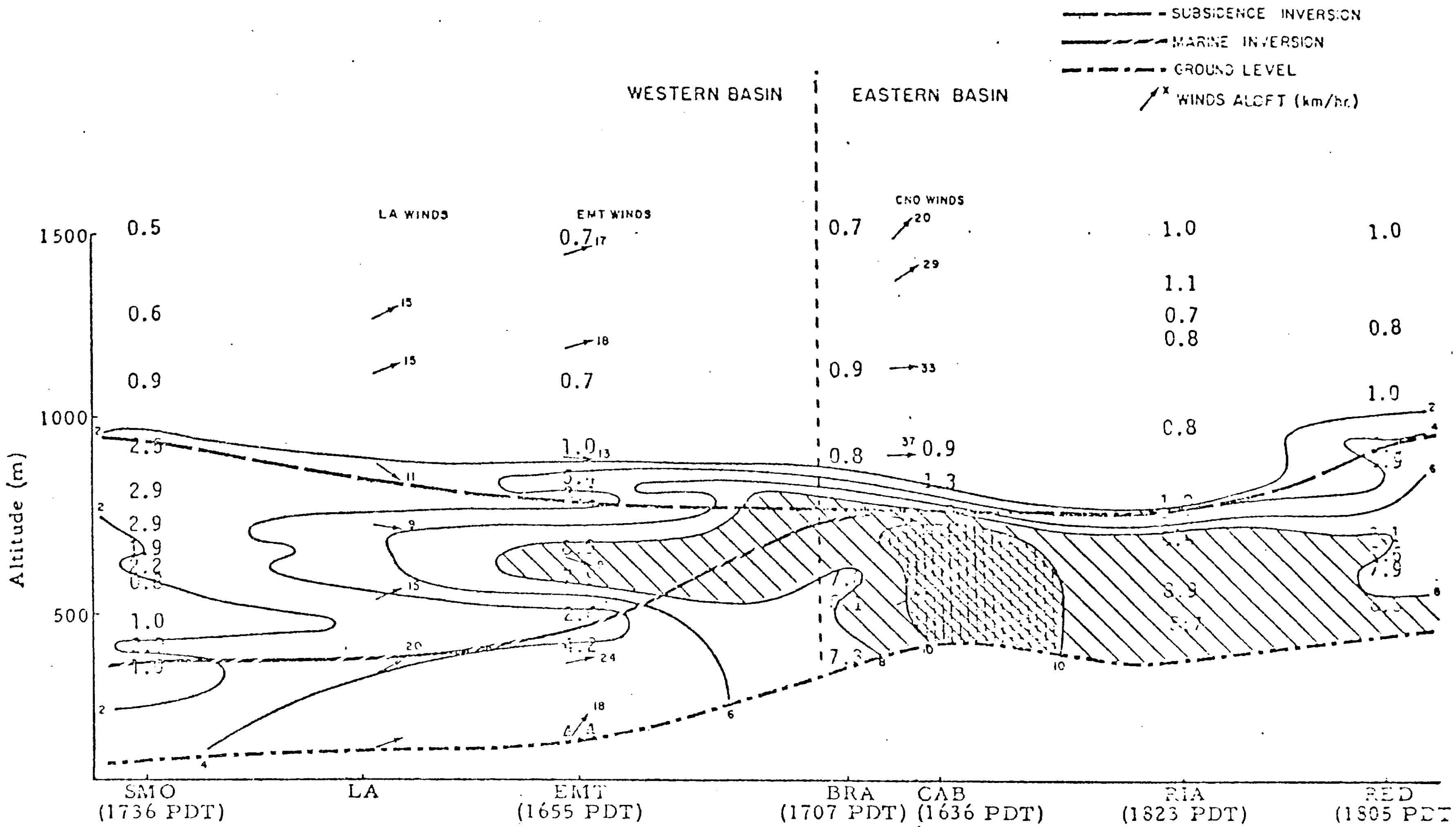
6.5.2 Marine Air Intrusions

The proximity of the ocean to many of the principal emission sources in California has a pronounced effect on the pollutant distribution. A cool layer of air which has come into equilibrium with ocean surface temperatures begins to move inland during the forenoon. Ahead of the marine air may be sizeable concentrations of pollutants which have accumulated during the stagnant wind conditions of the night and early forenoon. These concentrations begin to move inland ahead of the marine air. The sea breeze air moves inland rapidly enough so that accumulations of new pollutants in the marine air are minimized. Thus the high concentrations inland occur ahead of the marine air intrusion.

Fig. 6-2 shows a cross section of $b_{scat}$ from Santa Monica to Redlands (Smith et al, 1976) during the late afternoon. The highest pollutant concentrations have reached Upland (CAB) by 17 PDT and are followed by much cleaner air to the west. Note that the marine air undercuts the pollution leaving a layer aloft.

Similar developments occur in other areas of California. Fosberg and Schroeder (1966) have described the penetration of marine air into Central California on a case study basis. Due to the unique terrain features around the Bay Area the penetration occurs more readily through the Carquinez Straits into the Delta area. The sea breeze front appears to reach Sacramento some time after 14 PST but is delayed in the regions north and south of the Bay Area. Miller and Ahrens (1970) show an example of marine air reaching Livermore about 16 PST with a vertical ozone cross section similar to that shown in Fig. 6-2.

The marine air intrusion is characterized by a cool, shallow layer which maintains its integrity for a considerable distance inland in spite of the surface heating it encounters. In most areas the offshore air which is transported inland has much lower pollutant concentrations than the inland air it displaces. In the South Central Coast Air Basin, however, there are occasionally sufficient concentrations offshore so that the marine air brings in pollutant concentrations which may be even higher than in the air preceding the intrusion.




VERTICAL CROSS SECTION OF $b_{scat}$ FOR AFTERNOON OF JULY 25, 1973 (Units are $10^{-4}$ $m^{-1}$)

Fig. 6-2

## 7. CONCLUSIONS

1. There are frequent occurrences of calm winds (less than 3 knots) throughout the state at the 10th percentile limit. These conditions permit the accumulation of pollutant concentrations with reduced dilution.

2. Terrain exerts a strong control over wind flow patterns in the state, particularly during the summer. In Central California a major terrain feature at the Carquinez Straits permits air to pass from the coastal regions into the interior valley. In the south the major openings are several passes from the South Central Coast, South Coast and San Diego Air Basins. In the balance of the state flow from the coastal area is blocked by the coastal mountain range.

3. Interbasin transport has been documented between the following air basins:

   a. San Francisco Bay to Sacramento Valley and the North Central Coast Air Basin
   b. Sacramento Valley to the Mountain Counties Air Basin
   c. San Joaquin Valley to the Southeast Desert Air Basin
   d. South Central Coast to South Coast Air Basin
   e. South Coast to South Central Coast, San Diego and Southeast Desert Air Basins
   f. San Diego to Southeast Desert Air Basin.

4. Air pollution estimates can be formulated from a variety of parameters or combinations of parameters:

   a. 850 mb Temperature
   b. Holzworth Potential
   c. Ventilation Factor (defined as mixing height times wind speed)
   d. Maximum Surface Temperature
   e. Low morning wind speeds
   f. Low mixing heights

Evaluating these parameters against peak daily ozone concentrations, the highest correlations were obtained through the use of surface maximum temperatures. These proved to be slightly better than the 850 mb temperature. Correlations using the ventilation factor were lower and less consistent than with the temperature relationships.

Use of the Holzworth potential produced the lowest correlations and the least consistent values. It is suggested that the use of both ventilation and the Holzworth potential suffer from the difficulties in estimating mixing heights.

5. Time of ozone maximum vs. time of peak temperature at the same location yields useful information on receptor/source areas. Source areas tend to have an ozone maximum before the surface temperature maximum while receptor areas have later ozone maxima with respect to the temperature maximum.

6. Average wind speeds (average from 7 to 10 PDT) were used to estimate the areas of the state where accumulation of pollutants during the morning was most favored. These areas turned out to be Ukiah/Santa Rosa, the Mojave Desert (Edwards, Inyokern), the San Bernardino/March Field area and some inland sections of the San Diego Air Basin. Although low wind speeds are not accurately measured these areas all appeared to have average wind speeds of 1.5 knots or less during the morning hours on a median basis.

7. Several flow patterns which are characteristic of California air pollution meteorology are described. These are:

a. Eddy Structures - Horizontal eddies of the order of 100 - 200 miles in diameter develop in at least three areas of the state (southern Sacramento Valley, San Joaquin Valley and the Santa Barbara Channel. These eddies form as the result of blocking of the flow by terrain or opposing winds. They serve to redistribute the pollutants in the lower layers over the horizontal extent of the eddy.

b. Slope Flows - Heated slopes during the afternoon produce upslope flow which transports pollutants from the mixed layer to levels above the mixed layer. The mechanism is effective in most parts of the state but is probably most significant along the southern slopes of the San Gabriel and San Bernardino Mts. in the South Coast Air Basin. High ozone concentrations have been observed at Lake Gregory, Mt. Baldy and Mt. Wilson.

c. Layers Aloft - Pollutant layers aloft form as a result of several different processes, upslope flow being one of the most productive methods. The layers are separated from the surface during a part of their lifetime. In the afternoon they may be incorporated into the mixing layer and bring additional pollutants to the surface. The layers have been observed in many parts of the state.

d. Convergence Zones - Terrain and regional pressure gradients combine to produce areas where the surface wind flows converge. The most significant of these are the Elsinore and San Fernando Valley Zones although others exist in the state. The zones prevent pollutant material from being transported into certain areas and generate an area of upward currents that remove pollutants from the surface layer.

e. Variations in Coastal Mixing Heights - Maximum surface temperatures increase markedly between the coast and the inland areas (e.g. over 20°F increase from LAX to San Bernardino). These high inland surface temperatures serve to raise the mixing layer depth and dilute the pollutant concentrations within the layer.

The sea breeze flow, beginning in the morning, transports a shallow layer of cooler air inland during the afternoon. The layer generally undercuts the existing mixing layer and creates a layer aloft out of the top of the existing mixed layer. In most areas the marine air intrusion brings cleaner air from offshore which results in a marked improvement in visibility. In the South Central or South Coast Air Basins the layer may bring in recirculated pollutants from offshore which contribute to a second peak in ozone concentrations in the inland areas.

8. The primary source of uncertainty in defining meteorological air pollution potential in the state lies in the description of mixing height behavior, particularly in the coastal areas where mixing height changes significantly with distance inland. Areas where better mixing height statistics are needed are Santa Rosa, the Salinas Valley, the southern portion of the San Francisco Bay Basin, San Bernardino/Riverside and the inland areas of the San Diego Air Basin.

## 8.0 REFERENCES


Aron, R., 1983; Mixing Height - An Inconsistent Indicator of Potential Air Pollution Concentrations, Atmos. Env., 17, 2193-2198.

Bell, G. B. 1958; The Uses of Meteorological Data in Large-Scale Air Pollution Surveys, SRI Rept. to Calif. Dept. Public Health, 110 pp.

CARB Staff, 1974; Meteorological Parameters for Estimating the Potential for Air Pollution in California, Rept. by Evaluation and Planning Division, 62 pp.

Dabberdt, W., 1983; Ozone Transport in the North Central Coast Air Basin, SRI Rept. to CARB, Proj.: 1898 and 4637, 314 pp.

Duckworth, S. and D. Crowe, 1979; Ozone Patterns on the Western Sierra Slope, Tech. Services Rept., CARB.

Edinger, J. G. and R. A. Helvey, 1961; The San Fernando Convergence Zone, Bull. AMS, 42, 9, 626-635.

Fosberg, M. A. and M. J. Schroeder, 1966; Marine Air Penetration in Central California, J. Appl. Met., 5, 573-589.

Hayes, T. P., J. J. R. Kinney and N. J. M. Wheeler, 1984; California Surface Wind Climatology, CARB Rept. by Aerometric Data Division.

Holzworth, G. C., 1972; Mixing Heights, Wind Speeds and Potential for Urban Air Pollution throughout the Contiguous United States, EPA Publ. No. AP-101, 118 pp.

Husar, R. B., D. E. Patterson, W. H. White, D. L. Blumenthal and T. B. Smith, 1977; Three-Dimensional Distribution of Air Pollutants in the Los Angeles Basin, J. Appl. Met., 16, 1089-1096.

Kauper, E. and B. Niemann, 1975; Los Angeles to Ventura Over Water Ozone Transport Study, Final Rept. to CARB, Metro Mon. Svcs.

Kauper, E. and B. Niemann, 1977; Los Angeles to San Diego Three Dimensional Ozone Transport Study, Final Rept. to CARB, Metro Mon. Svcs., 43 pp.

Kinosian, J. and S. Duckworth, 1973; Oxidant Trends in the South Coast Air Basin 1963-72, CARB Rept.

Lamb, B., A. Lorenzen and F. H. Shair, 1978; Atmospheric Dispersion and Transport within Coastal Regions - Part I, Tracer Studies of Power Plant Emissions from the Oxnard Plain, Atmos. Env., 12, 2089-2100.

Lehrman, D., T. Smith, D. D. Reible and F. H. Shair, 1981; A Study of the Origin and Fate of Air Pollutants in California's Sacramento Valley, MRI/Caltech Final Rept. to CARB.

Miller, A. and D. Ahrens, 1970; Ozone within and below the West Coast Temperature Inversion, Tellus, XXII, 3, 328-339.

Miller, P. R., M. H. McCutchan and H. F. Milligan, 1972; Oxidant Air Pollution in the Central Valley, Sierra Nevada Foothills and Mineral King Valley of California, Atmos. Env., 6, 623.

Reible, D. D., J. R. Ouimette and F. H. Shair, 1982; Atmospheric Transport of Visibility Degrading Pollutants into the California Mojave Desert. Atmos. Env. 16, 3, 599-613.

Shair, F. H., E. Susake, D. Carlan, G. Cass, W. Goodin, J. Edinger and G. Schacher, 1982; Transport and Dispersion of Airborne Pollutants Associated with the Land Breeze - Sea Breeze System, Atmos. Env., 16. 2043-2053.

Smith, T. B., S. L. Marsh, W. H. White, T. Jarskey, R. Lamb, P. Durbin and J. Killus, 1976; Analysis of the Data from the Three-Dimensional Gradient Study, MRI FR-1395 and SAI EF 75-84 to CARB.

Smith, T. B., H. Giroux and W. Knuth, 1977; Impact of Industrialization of the California Delta Area, MRI 77 FR-1484 to CARB.

Smith, T. B., D. E. Lehrman, D. D. Reible and F. H. Shair, 1981; The Origin and Fate of Airborne Pollutants within the San Joaquin Valley, MRI/Caltech Rept. to CARB.

Smith, T. B., D. Lehrman, F. H. Shair, R. S. Lopuck and T. D. Weeks, 1983a: The Impace of Transport from the South Coast Air Basin on Ozone Levels in the Southeast Desert Air Basin, MRI/Caltech Rept. to CARB.

Smith, T. B., W. D. Saunders and F. H. Shair, 1983b; Analysis of Santa Barbara Oxidant Study, MRI Rept. to CARB, Agreement A2-086-32.

Smith, T. B. and J. G. Edinger, 1984; Utilization of Remote Sensing Data in the Evaluation of Air Pollution Characteristics in the South Coast/Southeast Desert Air Basins, Final Rept. to CARB, Agreement No. A2-106-32.

Unger, C. D., 1978; Transport of Photochemical Smog in the Central Valley and the Sierra Nevada Mountains of California, Rept. by Planning, Div., CARB.

Unger, C. D., 1983; Analysis of Air Quality Data Using Empirical Kinetic Modeling Approach (EKMA) in California Res. Div. Rept., CARB.

Williams, W. T., M. Brady and S. C. Willison, 1977; Air Pollution Damage to the Forests of the Sierra Nevada Mountains of California, JAPCA, 27, 230-234.