U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
OFFICE OF SYSTEMS DEVELOPMENT
TECHNIQUES DEVELOPMENT LABORATORY

TDL OFFICE NOTE 83-12

DEVELOPMENT OF AUTOMATED SANTA ANA FORECAST GUIDANCE - PHASE I

Lawrence D. Burroughs

August 1983

DEVELOPMENT OF AUTOMATED SANTA ANA FORECAST GUIDANCE - PHASE I

Lawrence D. Burroughs

1. INTRODUCTION

The Santa Ana has been written about often, but usually with a view to the associated fire weather danger. Rarely has anyone viewed it as a potential marine weather problem. In this Office Note, I will describe what a Santa Ana is, how it can affect marine interests, and what criteria determine its existence. I will diagnose conditions leading to the development of Santa Ana conditions along the southern California coast and to their demise, and I will describe progress toward developing automated forecast guidance and plans for completing the project.

A. Background

In October 1976, the Techniques Development Laboratory (TDL) was sent a set of proposals by the National Weather Service Western Region Headquarters covering a number of wind forecasting problems along the southern California coast. Among these was one about Santa Ana winds of sufficient strength to create damaging waves at Avalon Harbor (AVC) on Santa Catalina Island (see Fig. 1). For a variety of reasons, TDL was unable to begin work on the problem until mid-1979. Since then, our effort has varied depending on the availability of resources and personnel.

B. Establishment of Criteria

The Glossary of Meteorology (Huschke, 1959) defines a Santa Ana as a "hot, dry, foehn-like desert wind, generally from the northeast or east, especially in the pass and river valley of Santa Ana, Calif., where it is further modified as a mountain gap wind...". Actually, all of southern California is affected. Wind speed and direction at the coast depend on synoptic scale events (primarily surface pressure gradient and cold air advection aloft), interaction of the Santa Ana circulation with the sea breeze circulation, and topography (primarily canyon orientation and structure). Intensity and duration are also dependent on synoptic forcing and mesoscale interaction.

Over the years, many criteria have been developed to forecast or nowcast the presence of Santa Ana conditions at the surface. Richardson (1973) gives an excellent summary of these criteria. They take into account many of the phenomena observed during Santa Anas, such as temperature rise, humidity decrease, and wind direction, speed, and gustiness. Most of the criteria were developed for inland stations where fire danger is maximized by the conditions. Few authors have discussed Santa Ana conditions at the coast. Fosburg et al. (1966) describe some aspects of these winds at the coast and over the Santa Barbara and San Pedro Channels (see Fig. 1). Edinger et al. (1964) show wind patterns over the Los Angeles basin as far as the coast, but not over water. Rosenthal (1972) gives an excellent summary of Santa Ana conditions as they affect the Naval Air Station, Point Mugu, Calif. (NTD) and the Naval Air Facility, San Nicolas Island (NSI) (see Fig. 1). Rosenthal's statistics are based on the following criteria: 1) wind from northeast quadrant, 2) speed $\geq$ 12 kt, 3) at least one hourly observation meeting criteria 1 and 2, and 4) significantly lower humidities than in the preceding several hours. These criteria exclude: 1) moist, cyclonic Santa Anas, 2) very weak Santa Anas, and 3) Santa Anas of less than 1 hour in duration. Using other unpublished studies from the Pacific Missile Range at NTD, Rosenthal describes another set of criteria which would include some cases in the classes excluded by his criteria. They include : 1) northeast winds, but 2) reduce the speed to $\geq$ 10 kt, and 3) specify the relative humidity to be < 50 percent.

In my own study, I initially chose the following criteria: 1) wind in the northeast quadrant and 2) wind speeds $\geq$ 18 kt. Later in the study these criteria were modified several times, and these modifications are discussed in Section 4. My purpose was to forecast when Santa Ana winds could endanger boating or shipping in the Santa Barbara and/or San Pedro Channels. These criteria restrict the study to the more intense Santa Ana situations.

2. SYNOPTIC FORCING, MESOSCALE INTERACTION, AND TOPOGRAPHIC EFFECTS

Complete details about synoptic forcing, mesoscale interaction, and topographic effects are given by Rosenthal (1972) and Richardson (1973). Additional details, particularly about the vertical structure of Santa Anas are given by Fosberg et al. (1966). Following Rosenthal, I will give an overview of the synoptic forcing involved in setting up the general Santa Ana conditions, the mesoscale interaction of the general Santa Ana circulation with the sea breeze circulation at the coast, and the modifications in wind direction and speed at the surface due to topographic effects. At NTD, Santa Anas generally occur during the months of October through March. They have occurred as early as mid-September and as late as mid-June. With little variation, this is so throughout southern California.

A. Synoptic Forcing

There are three major synoptic events which, when they occur simultaneously, normally give rise to Santa Ana conditions over southern California. These are the development of high pressure over the Great Basin (see Fig. 2), the passage of fronts through southern California, and development of a 500-mb ridge and trough set centered near the west coast of the United States. There is a fourth synoptic event which rarely occurs, but which gives rise to some of the most intense Santa Ana winds at the coast. This event is the development of a surface low off the southern California coast in addition to the above conditions. The resulting Santa Ana is often called a "moist" Santa Ana.

Great Basin High

The Great Basin is the area between the Sierra Nevada/Cascade Range and the Rocky Mountains, encompassing southeastern Oregon, southern Idaho, and all of Nevada. The building of high pressure over the area is a primary factor in creating Santa Ana conditions. The high may originate in three ways: as a Pacific maritime high, as a continental polar high from Canada, or *in situ*. Development *in situ* occurs because of cold advection, subsidence, and ridging aloft over the basin. When the Great Basin high originates as a Pacific maritime or continental polar high, it moves over the basin, becomes quasi-stationary and builds due to surface cooling and subsidence aloft. The higher the central pressure, and the colder the air mass, the more likely offshore flow will occur in southern California.

Fronts

The onset of Santa Ana conditions usually follows the passage of a cold front. Onset may occur anywhere from a few minutes to as much as 48 hours after passage depending on frontal orientation and movement with respect to southern California. Fronts oriented from northeast to southwest and moving toward the southeast usually result in Santa Ana conditions 24 to 48 hours after passage. Fronts oriented east to west and moving south usually result in Santa Ana conditions within 6 to 18 hours of passage, while fronts oriented southeast to northwest or north to south and moving west ("backdoor" fronts) usually result in Santa Ana conditions almost immediately upon passage. Timing depends on how long it takes to establish and build the Great Basin high sufficiently to produce offshore flow in southern California. For a "backdoor" front, the high is already established and building, so when the front passes, the Santa Ana usually begins almost immediately.

500-mb Patterns

Associated with nearly all Santa Anas is a strong 500-mb ridge aloft just off the west coast. It is usually centered between 130° and 140° west longitude with a deep trough between 100° and 110° west. Airflow around the ridge into the trough subsides and warms adiabatically. This helps to maintain and build the Great Basin high. The more persistent the pattern, the stronger the Santa Ana. The strength of the Santa Ana winds is also related to the amount of cold air advection aloft and the amplitude of the wave pattern. The strongest Santa Anas, especially over marine areas, occur with a deepening, retrograding trough over southern California and the southwestern United States. See Figs. 3 and 4 for a typical surface and 500-mb Santa Ana pattern.

"Moist" Santa Anas

Occasionally, a large amplitude 500-mb ridge builds strongly into the Pacific northwest, and the downstream trough becomes sharp enough to form just off the coast of southern California. As a result, a surface low forms in the border area of California, Arizona, and Mexico.

As with other Santa Anas, a strong Great Basin high exists. The closer the surface low is to southern California, the more cyclonic, wetter, and unstable the weather is likely to be. Sometimes the pressure gradient between the high center and the surface low is strong enough to cause northeast winds of gale or even storm force over the San Pedro and Santa Barbara Channels. Aronovitch (1969) gives a good case study of such a storm.

There has been some controversy over whether this is a "true" Santa Ana or not. One can argue against using cases of this type; however, since the affect on the maritime environment is so drastic and since our criteria are met in most of these cases, we have included them in our study.

B. Mesoscale Interaction

Along the coast, Santa Anas exhibit diurnal variations which are also seasonally dependent. The onset of Santa Ana conditions can occur at any time; however, near the coast, variations in wind speed and wind direction are introduced by the interaction of the Santa Ana circulation with the sea breeze circulation. The Santa Ana is weakest at the coast in the afternoon, when opposed by the sea breeze circulation. These variations are also seasonally dependent. Near the coast, Santa Ana conditions usually become apparent after midnight during the winter and just after sunrise during the fall and spring. Santa Ana conditions become less apparent or disappear entirely by mid-day. The time of disappearance is more variable in winter than in spring or fall. When Santa Ana conditions exist, the sea breeze is generally weaker, drier, and of shorter duration than under normal circumstances. Figure 5 gives a schematic of the interaction of the sea breeze with the Santa Ana circulation. According to Fosberg et al. (1966), the Santa Ana is primarily a lee wave phenomenon, and air flow is nearly isentropic. When the amplitude of the waves is large, they surface; when the amplitude is small, they don't. There are periodic and antiperiodic components in the surfacing. The periodic components are associated with the interaction of localized circulations, such as the sea breeze, with the mountain waves. The antiperiodic effects are determined by the static stability and wind structure upwind of the mountain barrier and are the prime factor in the surfacing.

To distinguish between the general Santa Ana conditions and the surfacing of Santa Ana winds, the following definitions, attributed to Lea by Rosenthal (1972), are made:

Santa Ana Burst - A single period of continuous Santa Ana surface winds.

Santa Ana Regime - An overall synoptic episode consisting of one or more bursts separated by not more than 24 hours.

According to Rosenthal (1972), the average length of a regime is about 36 hours, while that of a burst is 6 to 8 hours. If a regime consists of more than one burst, the first burst is the longest and strongest, having the greatest average wind speeds and gustiest winds. Each succeeding burst becomes progressively weaker, shorter, and less gusty. The most frequent sustained maximum wind speeds are 15 to 19 kt with gusts of 25 to 29 kt.

During strong Santa Ana conditions, NSI, AVC, and NUC (see Fig. 1) are affected by Santa Ana winds, and humidities are somewhat lower. Wind speeds usually fall off with distance from the mainland. Since NSI and NUC are 51 and 154 m above sea level respectively, it is difficult to assess whether the Santa Ana winds reach the surface through the stable maritime inversion along the coast or not. Rosenthal (1972) documents a case where satellite photographs seem to show evidence of Santa Ana surface winds out to 100 n mi offshore.

C. Topographic Effects

Figure 6 shows the local topography of southern California. The mountain ranges act as barriers to flow out of the Great Basin region. When flow is perpendicular to the mountain ranges, and the static stability and wind shear upstream of the ranges is favorable, mountain waves form. In addition, the air is forced to flow around the San Gabriel mountains and through the major passes. Wind speeds tend to be enhanced through the passes because of venturi effects, and wind direction tends to be oriented along canyon and valley axes.

3. AVAILABLE DATA

Several types of data were used during the course of these studies. These include: surface observations, upper air observations, grid-point data from surface pressure analyses, and grid-point data from 700-mb analyses. The data were generally used for two purposes: diagnosis and prediction. Most of the data were obtained from the National Climatic Data Center, but some data were obtained from other sources which will be pointed out later.

A. Data for Diagnostic Purposes

I compared cases developed with my criteria and those developed with criteria from the Fire Weather Service Office (FWSO) in Los Angeles. I used a data set provided to TDL by Leo Serguis when he worked for FWSO Los Angeles. He was primarily interested in the effect of the Santa Ana conditions on fire danger in the interior. His criteria for determining the existence of a Santa Ana were simple. When the sea level pressure gradient between the Weather Service Forecast Office at Los Angeles, Calif. (LAX) and the Federal Aviation Administration's Flight Service Station at Tonopah, Nev. (TPH) was 3 mb or more for 24 hours or more and when there was northeast flow at the Weather Service Meteorological Observatory at Sandburg, Calif. (SDB)(see Fig. 1), a Santa Ana existed. SDB is northeast of LAX along the ridgeline of the San Gabriel Mountains. For the period November 1957 to June 1964, these data included 175 cases. Sergius' data included:

1) Beginning time (year, month, day, hour [L.S.T.]),
2) Ending time (month, day, hour),
3) Duration (tenth of days),
4) Maximum sea level pressure gradient between LAX and TPH (tenths of mb),
5) Time of maximum sea level pressure gradient between LAX and TPH (day, hour),
6) Maximum wind (speed [mph], day, hour, station),
7) Maximum wind at SDB (speed [kt], day, hour),
8) Position of high pressure center at time of maximum sea level

pressure gradient between LAX and TPH (latitude, longitude, central pressure [mb]),

9) Minimum relative humidity (percent, station),

10) Mean temperature between 850-mb and 700-mb at time closest to maximum sea level pressure gradient between Las Vegas (LAS) and LAX (degrees C), and

11) Mean temperature between 850-mb and 700-mb at time closest to the beginning of Santa Ana conditions between LAS and LAX (degrees C).

Rosenthal (1972) explains a parameter which he attributes to H. Harvey called the thermal support parameter (TSP) which combines the effects of 700-mb temperature advection and surface pressure gradient into a single value. The 700-mb temperature advection is parameterized by the absolute value of the difference between the 700-mb temperatures (in °C) at the Air Force Bombing Range, Yucca Flats, Nev. (UCC) and Vandenburg Air Force Base, Calif. (VBG) (see Fig. 1). The surface pressure gradient is given by the pressure difference (in mb) between TPH and LAX. The sum of the two gives TSP. For example, if the 700-mb temperature at UCC is -15°C and at VBG is -2°C, and if the surface pressure at TPH is 1028 and at LAX is 1023, then TSP = -15 - (-2) + (1028-1023) = 13 + 5 = 18. According to Rosenthal (1972), if TSP $\geq$ 12, conditions are favorable for a Santa Ana. I examined TSP to show how it varies prior to inception of a Santa Ana. Radiosonde data from UCC and VBG were used for this study. The surface pressure gradient was determined by taking sea level pressures for LAX and TPH from microfilm prints of the National Meteorological Center's (NMC's) North American surface pressure charts. TSP was computed for each case developed from our criteria for the years 1957 through 1977.

B. Data for Forecast Derivations

The forecast equations were derived with a multiple linear regression technique. The predictand and predictor data are described below.

Predictand Data

Wind speed and direction at 6-h intervals were obtained for these places: NTD; the Marine Corps Air Facility, Santa Ana, Calif. (NTK); NSI; and NUC (see Fig. 1). Periods of record extend from 1945 through 1977, 1945 through 1978, 1946 through 1977, and 1960 through 1977, respectively. Computed predictand data will be discussed in Section 4.

Predictor Data

Surface pressure data were obtained from NMC's North American surface pressure charts for cases between October 1972 and mid-1977. Grid-point sea-level pressure data for a 63-point subset of the Limited-area Fine Mesh (LFM) grid were taken from each chart used (see Fig. 7). Similarly, grid-point 700-mb temperatures and height data were obtained from NMC's 700-mb height analyses for each case from October 1972 through mid-1977. The surface pressure data were at 6-h intervals, while the 700-mb data were at 12-h intervals. To obtain 700-mb data at 6-h intervals, a linear interpolation in time was done. This provided data at both levels (surface and 700-mb) at each synoptic hour (0000, 0600, 1200, and 1800 GMT).

4. DATA ANALYSIS

A. Modification of Criteria and Analysis of TSP Patterns From Observations

In Section 1.B., I discussed the development of criteria for establishing Santa Ana cases along the southern California coast. The data for NTD and NTK were searched, and only the data that met those criteria were kept. For NSI and NUC, the same direction criterion was used, but the wind speed criterion was lowered from 18 kt to 6 kt. Using the definitions for Santa Ana regimes and bursts, I attempted to match the Sergius cases with my own. I soon discovered how localized Santa Ana winds can be, even when restricting them to higher wind speeds. Many of Sergius's cases had no coastal counterpart; likewise, some coastal cases didn't match Sergius's data. Further, though only 100 km from each other "as the crow flies," many cases at NTD didn't match cases at NTK and vice versa. Very often Santa Ana winds at the coast were not apparent at the offshore islands. In addition, there were gaps in the data.

Modification of Criteria

To overcome some of the mismatches at the coast, the criteria were modified to the following:

1. Wind direction north through east at NTK and NTD,
2. Wind speed at least 6 kt at both NTK and NTD,
3. Case begins when wind speed is at least 18 kt at either NTD or NTK, and
4. Case terminates when the wind speed at both sites decreases to 18 kt or below.

The criteria were developed this way to ensure the Santa Ana regime affected the entire area of interest. Criteria 3 and 4 meant that in many cases the first and last observation of the case were the same. With these criteria, we were able to isolate 172 cases from 1957 through 1977.

TSP Patterns From Observations

Of the 172 cases selected, a subset of 105 cases had TSP values. The other cases had data missing. I made a table of TSP versus time with zero being the time the wind speed first reached 18 kt. Values of TSP were available at 12-h intervals from -72 to 0 hours. Since I was interested in the pattern of TSP leading to inception of 18-kt winds during Santa Ana conditions, 11 cases were eliminated from the subset where only singular values of TSP were available. I assumed TSP should increase to some maximum value at or near the hour where Santa Ana winds reached 18 kt. Three more cases were removed from the subset because this pattern wasn't observed. Two basic patterns in TSP emerged: one showing a continuous rise in TSP to time zero (profile 1) and one with TSP peaking 12 to 23 hours prior to inception of 18-kt winds (profile 2) (see Fig. 8). Because there were gaps in the data which made profile definition impossible, the subset of cases used in this TSP study was reduced to 79 cases.

Since the TSP values were at 12-h intervals and the wind observations at hourly intervals, the time at which the wind speed reached 18 kt could be up to 11 hours later than the nearest TSP value. Therefore, TSP was put into temporal classes of 0 to 11, 12 to 23, 24 to 35, and 36 to 47 hours prior to the commencement of 18-kt winds. The classes are labeled S - 6, S - 18, S - 36, and S - 42 hours, repectively, on Fig. 8. TSP was stratified by profile class and averaged for each class to produce mean profiles. The mean profiles are shown in Fig. 8. In addition, a mean profile for all data is shown. The sample size for each point in the profiles is given in parentheses near the points. Of the 79 profiles, only 15 resemble profile 2.

Recall that the buildup of the Great Basin high occurs three ways: a maritime Pacific high moves into the area, becomes stationary and builds; a continental polar high from Canada moves down over the area, becomes stationary and builds; or a high builds over the area due to cold advection aloft and radiational cooling at the surface. In the first two, fronts passing through southern California generally precede the building of the high. This leads to a profile which resembles profile 1. In the last, the building of the high precedes the passage of the front and leads to a profile similar to profile 2.

B. Final Modification of Criteria and Analysis of TSP Patterns From Grid-Point Data

A number of factors influenced the modification of the criteria. These factors include: the amount of time required to produce grid-point data, the gustiness of Santa Ana winds, the availability of LFM model output data, and differentiation between Santa Ana regimes and bursts.

The criteria developed in Section 4.A. isolated 172 Santa Ana cases from 1957 through 1977. This set of cases included three classes: 1) winds $\geq$ 18 kt at NTD, 2) winds $\geq$ 18 kt at NTK, or 3) winds $\geq$ 18 kt at both NTD and NTK. Additionally, the criteria were very restrictive in that most of the cases isolated Santa Ana bursts rather than Santa Ana regimes.

I had decided to use the perfect prog technique (Klein and Glahn, 1974) to develop forecast equations and to use the grid-point data as potential predictors. When I estimated the time necessary to produce grid-point data for all the cases, I found it would be prohibitive. I decided to modify the criteria and use only cases that occurred after the LFM model came into existence. I also determined that the sustained winds at either NTD or NTK should be in the small craft advisory range and that winds at the other station should be gusting into that range. This would limit my sample to the strongest cases.

Rosenthal (1972) points out that Santa Ana winds are typically gusty, but that gustiness depends on how long the Santa Ana regime has existed, the time of day, and the season of the year. The gust factor typically runs from about 1.2 to about 1.9 times the sustained wind. The average is about 1.6.

Sustained winds of 18 kt or greater are necessary for small craft advisories; therefore, I concluded at least one coastal station should have sustained winds of 18 kt or more at some time during a Santa Ana regime and the other should have wind gusts well into that range. With a gust factor of 1.6, sustained winds of 15 kt give gusts of 24 kt; therefore, I settled on having sustained winds of at least 15 kt at the other station at some time during a regime.

The LFM model became operational in October 1972, and wind data were available through 1977. These dates were the limits I imposed for deriving the forecast equations. To capture a Santa Ana regime from beginning to end, I relaxed the criteria in Section 4.A. The criteria in their final form are given below:

1. During Santa Ana bursts, wind is from the northeast quadrant including light winds;
2. For the entire Santa Ana regime, relative humidity $\leq$ 50 percent;
3. Wind speed at NTD or NTK $\geq$ 18 kt for at least one observation during the Santa Ana regime and $\geq$ 15 kt for at least observation at the other station;
4. To be included in a regime, bursts must < 24 hours apart;
5. A case is defined when criteria 1, 2, and 4 are met at both NTD and NTK for a majority of observations and criterion 3 is met; a case begins when criteria 1 and 2 are met at either station and ends when critera 1 and 2 or 4 are no longer met at either station.

These criteria focus on the stongest cases and cover regimes, not just bursts. Criterion 5 accounts for the fact that a regime may affect one station before another and longer than another. Twenty-three cases were identified from October 1972 through December 1977 which met these criteria. To each case, grid-point data were added at 6, 12, 18, and 24 hours prior to the start of a case and at 6, 12, 18, and 24 hours after a finish of a case. These data were added to the regime data and used to develop a prediction equation to forecast the existence of a Santa Ana regime.

For the 23 cases, I computed TSP from grid-point data. The grid points nearest LAX and TPH were used for the pressure difference, and the grid-points nearest VBG and UCC were used for the 700-mb temperature. Then, average values of TSP for all cases were computed at each synoptic hour. The results are shown in Fig. 9. The pre-regime times are shown by the S - times; the intra-regime times are shown by S + times, and the post-regime hours are shown by the E + times. S + 0 is the beginning of the regime, and E + 0 is the end of the regime. The number of intra-regime times shown is limited to 42 hours because there were too few observations beyond that point. The break between the intra-regime times and the post-regime times shows that some cases exceed 42-h in length. The pre-regime values in Fig. 9 are smaller than those of Fig. 8 since grid-point data do not specify gradients as well as station specific data. The pre-regime pattern in Fig. 9 is like profile 1 or the mean profile in Fig. 8. In the mean, TSP peaks 6 hours into the Santa Ana and generally declines in value to the end of the Santa Ana regime. The pattern can be explained as follows. A high passes into the Great Basin following a frontal passage in southern California. Cold air advection and pressure gradient build to a maximum at or shortly after inception of a Santa Ana. From 6 to 42 hours the pressure gradient relaxes and cold air advection decreases. Finally, the upper level pattern moves out of the area taking with it the Great Basin high and abruptly cutting off the Santa Ana regime.

5. PREDICTION TECHNIQUE

The perfect prog technique was used. In this case, historical records of sea-level pressure, 700-mb height, and 700-mb temperature at LFM grid points were related via regression to wind components (u and v) and wind speed (s) at several southern California stations and to the presence or absence of a Santa Ana regime as defined. The derived relationship was then applied by using model output for the predictor data.

A. Equation Development

A screening regression procedure was used to develop equations for forecasting the existence of a Santa Ana regime and for forecasting u, v, and s at three locations in southern California. Analyzed sea-level pressure and 700-mb height and temperature data interpolated to the locations of the 63 LFM grid points shown in Fig. 7 were used as predictors.

Regression Procedure

The predictors were screened in a series of steps; the equations used for the first n steps are:

1. $\hat{Y} = A_1 + B_1X_1$

2. $\hat{Y} = A_2 + B_2X_1 + C_1X_2$

3. $\hat{Y} = A_3 + B_3X_1 + C_2X_2 + D_1X_3$

$\vdots$

n. $\hat{Y} = A_n + B_nX_1 + C_{n-1}X_2 + D_{n-2}X_3 + \ldots + M_1X_n,$

where $\hat{Y}$ is the estimate of the predictand, Y. $A_1, A_2, \ldots, A_n$ are constants; $X_1, X_2, \ldots, X_n$ are predictors; B_1 $B_2, \ldots, B_n, C_1, C_2, \ldots, C_{n-1}, \ldots, M_1$ are regression coefficients; and n is the number of the step. The procedure selects the potential predictor (X_1) having the highest correlation with Y first. At each following step, the potential predictor ($X_2, \ldots, X_n$) yielding the highest partial correlation with Y, after the effect of the previously selected predictors was removed, is selected. This process is continued until the desired number of 20 predictors is included.

Wind Forecast Equations

Separate equations for the u (west) and v (south) wind components have been derived for each station. The wind speed (s) can be developed from the unbiased estimates of u and v, but Glahn (1970) has shown this underestimates the wind speed. Therefore, a separate equation for s has been derived. Equations were developed from predictand and predictor data at 6-h intervals. For the 18 Santa Ana cases chosen, there were 127 observations available with which to derive the equations.

Santa Ana Regime Equation

To derive an equation for forecasting the existence of a Santa Ana regime, the pre-, post-, and intra-regime data were used. In general, four 6-h observations were added before and after the regime observations. The non-Santa Ana data were identified with a 0 and the Santa Ana data with a 1. Then these binary data were regressed against the same set of predictors used to derive the wind forecast equations. For the same 18 cases, the data sample was increased to 272 observations by the addition of the pre- and post-Santa Ana data.

B. Testing and Evaluation

To test the forecast equations, I used an independent data set consisting of five Santa Ana cases. A total of 58 observations were available to test the u-, v-, and s- equations, and 96 observations were available to test the Santa Ana regime forecast equation. Equations with 10, 12, 14, 16, 18, and 20 predictors were tested.

Testing of Wind Direction and Speed Forecasts

I used mean absolute error (MAE) to test s and wind direction (θ) computed from the u- and v-equations, and the mean vector error (MVE) to test the wind vector. The Heidke skill score (Panofsky and Brier, 1963) against chance, percent correct, and bias[1] were also used to test s. The Heidke skill score (H) against chance is given by:

$$H = (R - E_R)/(T - E_R), \text{ where} \tag{1a}$$

$$E_R = (\sum_{i=1}^{n} O_i F_i)/T, \text{ and where} \tag{1b}$$

R is the number of correct forecasts, T is the total number of forecasts, O_i is the total number of observations in the i-th category, F_i is the total

---

[1] Bias = B/C, where B is the number of forecasts and C is the number of observations in a particular category.

number of forecasts in the i-th category, and n is the number of categories. H = 1 when all the forecasts are correct. H = 0 when the number correct is equal to the expected number correct, i.e., $R = E_R$. I used seven categories of wind speed: < 3 kt, 3 to 7 kt, 8 to 12 kt, 13 to 17 kt, 18 to 22 kt, 23 to 27 kt, and > 27 kt. The tests were used to determine how many predictors should be used in the final set of equations and how well the equations did on independent data.

Testing of Santa Ana Regime Forecasts

I used MAE, bias, and the Pierce score to test the Santa Ana regime forecasts. According to Daan (1981), the Pierce score is among the best statistical scores to use for binary predictors where there is no climatological reference available. The Pierce score (P) is given by

$$P = (NA - BC)/[B(1-B)], \qquad (2)$$

where N is the sample size, A is the number of times a Santa Ana regime is forecast correctly, B is the number of times a Santa Ana regime is forecast, and C is the number of times a Santa Ana regime is observed. If P = 1, the forecast is perfect; if P = 0, the forecast has no skill. According to Daan (1981), the Pierce score also has advantages over other scores in the case of rare events. Therefore, I chose it over the Heidke skill score which it most resembles.

Evaluation of Wind Direction and Speed

Table 1 shows the MAE of θ and s, and MVE for NTD for forecasts from equations having 10 to 20 predictors at 2-predictor intervals. Also shown is the bias by category, percent correct, and skill score for s and the sample size. To evaluate which equation set (u, v, s) was better, each result was ranked for a particular statistic from 1 to 6, 6 being worst. Table 2 gives the ranking of the forecast equations. The equation with 14 predictors was first, and I will use that number of predictors for all future developments. The MAE of θ and s and the bias by categories were given a single combined rank for each statistic, so that no one statistic had any more weight than another.

Evaluation of Santa Ana Regime Forecasts

Table 3 shows the MAE, bias, and Pierce score for Santa Ana Regime forecasts. Also shown is the percent correct and sample size. To evaluate which prediction equation was better, each result was ranked for a particular statistic as above. Table 4 gives the ranking of the forecast equations. The equation with 18 predictors was first, so I will use that number of predictors for all future developments.

C. Sample Equations

The experimental equations derived for the wind forecasts at NTD are given below in the order of predictor selection:

$$u = 244.884 + 0.00828p_{14} + 0.20516p_{51} - 0.64882p_{40} + 1.67389p_{42}$$

$$
\begin{aligned}
&- 1.26632p_{35} - 0.63168p_{49} + 2.50849p_{52} - 0.88097p_{59} \\
&- 0.89077p_{18} + 0.39869p_{20} + 0.10194h_{22} - 0.61941T_{29} \qquad (3a) \\
&- 0.04761h_{5} - 0.88245p_{54},
\end{aligned}
$$

$$
\begin{aligned}
v = \quad 315.266 &- 0.40387p_{14} - 0.28979p_{44} - 1.13667p_{39} - 0.17591h_{46} \\
&- 0.35199T_{60} - 0.07741h_{56} + 2.06829p_{62} - 1.60604p_{63} \\
&+ 1.35018p_{37} - 0.04797h_{50} + 0.29943T_{56} - 1.24868T_{47} \qquad (3b) \\
&+ 0.95402T_{48} - 0.44190p_{29},
\end{aligned}
$$

and

$$
\begin{aligned}
s = \quad 240.133 &+ 0.51697p_{14} - 0.33882p_{51} + 0.79508p_{40} + 0.72394p_{15} \\
&- 0.50004p_{32} - 1.13192p_{42} + 1.26094p_{35} + 1.21343p_{48} \\
&- 0.97660p_{60} + 1.28031p_{59} - 0.80380p_{28} - 2.04803p_{52}, \qquad (3c) \\
&- 1.21791p_{43} + 0.99315p_{54},
\end{aligned}
$$

where u, v, and s are in knots; p_i is the surface pressure at point i on the 63-point subset of the LFM grid in mb; and h_i is the 700-mb height in geopotential meters and T_i is the 700-mb temperature in degrees C. These equations will be rederived with all the data and tested on LFM model output before becoming operational.

The experimental equation for forecasting Santa Ana regimes is given below:

$$
\begin{aligned}
SA = -27.779 &- 0.01428p_{14} - 0.02922T_{35} + 0.00784h_{28} + 0.22819T_{56} \\
&- 0.07667T_{49} - 0.20371T_{55} + 0.11004T_{53} - 0.01548H_{11} \\
&- 0.00263h_{1} + 0.20095T_{36} - 0.17400T_{31} - 0.11118T_{43} \\
&+ 0.09594T_{33} - 0.07630T_{42} + 0.05126p_{13} - 0.01872p_{10} \\
&+ 0.02381h_{26} - 0.01584h_{33}, \qquad (4)
\end{aligned}
$$

where SA is a dimensionless number and p_i, h_i, and T_i are the same as for (3). This equation will be rederived with all the data and tested on LFM model output before becoming operational. A Santa Ana is forecast if $SA \geq 0.5$.

6. SUMMARY AND FUTURE PLANS

A. Summary

Using TSP, an average profile has been computed for Santa Anas whose strength is sufficient to affect the coastal areas of southern California. Wind forecast equations have been dervied for NTD, NTK, and NUC, and an equation has been derived to forecast the existence of Santa Ana regimes. These equations have been tested with observed data. They have not been tested with model output from the LFM.

B. Future Plans

Before this technique can become operational, more work is required. The equations need to be rederived with all the data and tested with LFM model output.

The equations will be rederived with data from all 23 cases. The constants for these equations will be adjusted for any biases apparent from using model output. The equations derived in this phase will be recommended for the initial operational system. The output of the system would be a bulletin giving forecasts of when Santa Ana regimes will occur and what the winds for NTD, NTK, NUC will be during those regimes. When no Santa Ana is forecast, a message to that effect would be given with no wind forecasts.

In the next phase, more cases will be added to the developmental sample and wind equations will be derived for NSI. Also, the data will be stratified into two classes: hours of no sea breeze (0600 and 1200 GMT) and hours of sea breeze (1800 and 0000 GMT). This will allow derivation of equations for when Santa Ana winds at the coast are strongest and when they are weakest.

ACKNOWLEDGEMENTS

Many have helped with this project as it has developed and progressed. Special thanks are due Mr. Franklin A. Rosenstein, who did a partial literature search and several case studies, and Mr. Mark S. Solomon, who developed cases for deriving the prediction equations, created computer programs to manipulate the data, and error checked it. I am also grateful to Mr. Robert C. Elvander, Mr. N. Arthur Pore, and Dr. Kurt W. Hess for their helpful comments and critisms during writing and to Ms. Alice T. Baker, Ms. Belinda F. Davis, Ms. Karen D. Brubacher, and Ms. Janice Washington for typing the manuscript.

REFERENCES

Aronovitch, B. B., 1969: Analysis of the southern California Santa Ana of January 15-17, 1966. ESSA Technical Memorandum WBTM WR-42, Environmental Science Services Administration, U.S. Department of Commerce, 10 pp.

Daan, H., 1981: Scoring rules in forecast verification. Memorandum No. 81-10, Royal Netherlands Meteorological Institute, 90 pp.

Edinger, J. G., R. A. Helvey, and D. Baumhefner, 1964: Surface wind patterns in the Los Angeles basin during "Santa Ana" conditions. Final Report, Part 1, Department of Meteorology, University of California at Los Angeles in cooperation with Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture for Office of Civil Defense, Office of the Secretary of the Army, 72 pp.

Fosberg, M. A., C. A. O'Dell, and M. J. Schroeder, 1966: Some characteristics of the three-dimensional structure of Santa Ana winds. U.S. Forest Service Research Paper PSW-30, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 35 pp.

Glahn, H .R., 1970: A method for predicting surface winds. ESSA Technical Memorandum WBTM TDL-29, Environmental Science Services Administration, U.S. Department of Commerce, 18 pp.

Huschke, R. E., ed., 1959: Glossary of Meteorology. American Meteorological Society, Boston, 638 pp.

Klein, W. H., and H. R. Glahn, 1974: Forecasting local weather by means of Model Output Statistics. Bull. Amer. Meteor. Soc., 55, 1217-1227.

Panofsky, H. A., and G. W. Brier, 1963: Some Applications of Statistics to Meteorology. The Pennsylvania State University, University Park, 224 pp.

Richardson, R. T., 1973: The continental contribution to the climate of southern California. Ph.D. Dissertation, University of Oregon, 202 pp.

Rosenthal, J., 1972: Point Mugu forecasters handbook. Pacific Missile Range Technical Publication PRM-TP-72-1, Geophysics Division, Pacific Missile Range, Department of the Navy, 426 pp.

Table 1. Comparison of results for wind forecast equations at Point Mugu, Calif. having from 10 to 20 predictors.

Number of Predictors	Sample Size	Bias							Percent Correct	Heidke Skill Score	MAE		MVE
		< 3 kt	3-7 kt	8-12 kt	13-17 kt	18-22 kt	23-27 kt	≥ 28 kt			θ (°)	s (kt)	
10	58	2.00	1.20	1.08	1.15	0.43	0	0	41	0.179	28	3.7	6.2
12	58	2.00	1.60	1.04	1.00	0.43	0.67	0	40	0.164	26	4.0	6.2
14	58	3.00	1.00	1.25	0.92	0.14	0.67	0	47	0.242	26	3.8	6.3
16	58	4.00	1.50	1.13	0.77	0.14	0.33	0	41	0.186	29	4.2	6.6
18	58	0	0.80	1.17	1.38	0.29	0.67	0	48	0.262	31	3.9	6.9
20	58	0	0.90	1.08	1.38	0.43	0.67	0	47	0.247	32	4.1	7.4

Table 2. Ranking of the wind forecast equations developed for Point Mugu, Calif. Equations were ranked on a scale of 1 to 6 (6 being worst) from the results of Table 1.

Number of Predictors	Scoring factors					Cumulative Score	Rank
	Bias	Percent Correct	Heidke Skill Score	MAE	MVE		
10	1	3	5	1	1	11	2
12	1	4	6	2	1	14	4
14	2	2	3	1	2	10	1
16	4	3	4	4	3	18	6
18	3	1	1	3	4	12	3
20	2	2	2	5	5	16	5

Table 3. Comparison of results for Santa Ana Regime forecast equations having from 10 to 20 predictors.

Number of Predictors	Sample Size	Bias		Percent Correct	Pierce Score	MAE
		No	Yes			
10	96	1.21	0.86	71	0.409	0.404
12	96	1.11	0.93	71	0.397	0.400
14	96	1.29	0.81	66	0.317	0.389
16	96	1.29	0.81	68	0.359	0.397
18	96	1.26	0.83	73	0.458	0.390
20	96	1.34	0.78	72	0.452	0.390

Table 4. Ranking of the Santa Ana Regime forecast equations. Equations were ranked on a scale of 1 to 6 (6 being worst) from the results of Table 3.

Number of Predictors	Scoring Factors				Cumulative Score	Rank
	Bias	Percent Correct	Pierce Score	MAE		
10	2	3	3	5	13	4
12	1	3	4	4	12	3
14	4	5	6	1	16	5
16	4	4	5	3	16	5
18	3	1	1	2	7	1
20	5	2	2	2	11	2

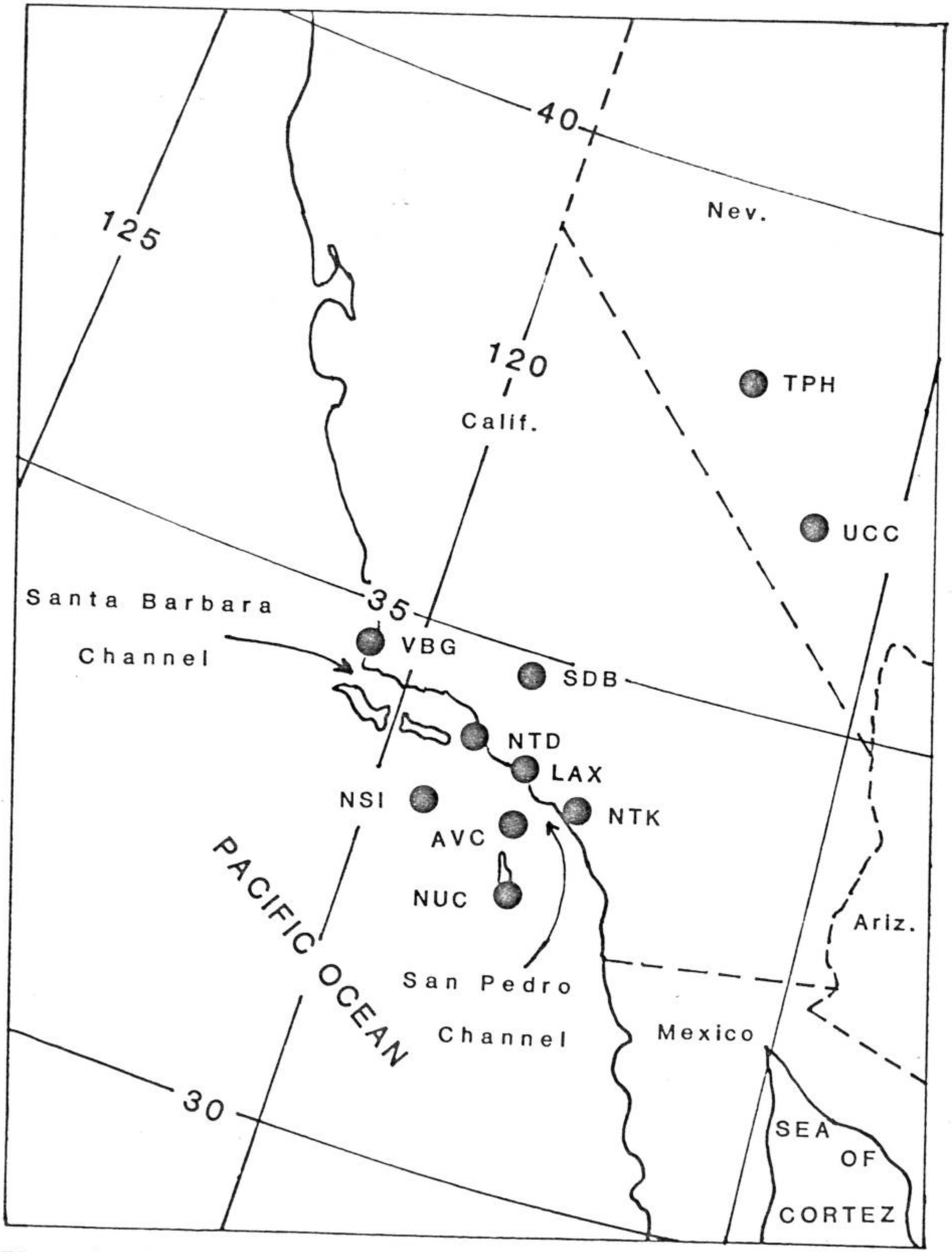

Figure 1. Station locations in southern California and Nevada.

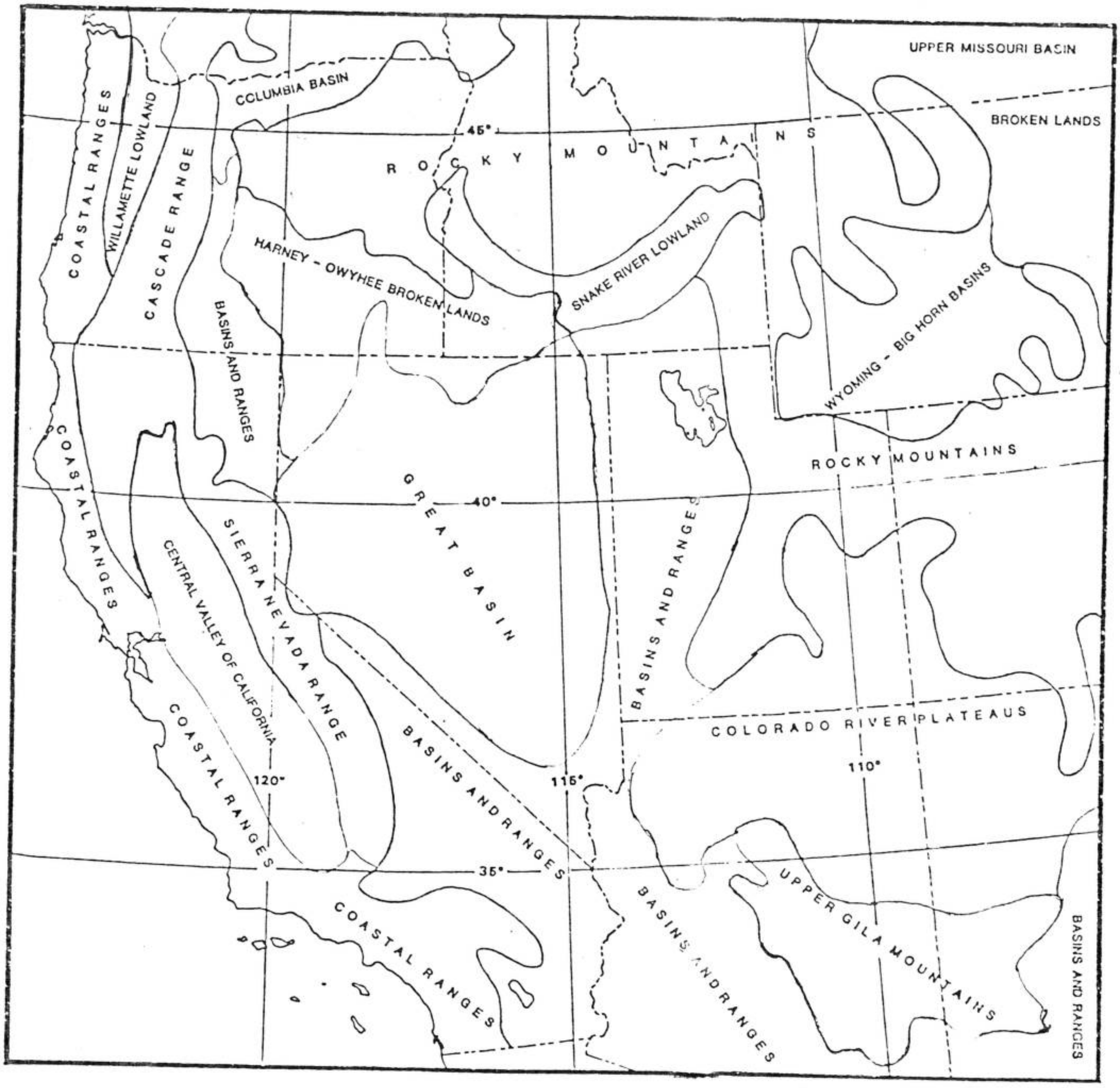

Figure 2. Geographical divisions and subdivisions in the region where synoptic forcing for Santa Ana generation takes place.

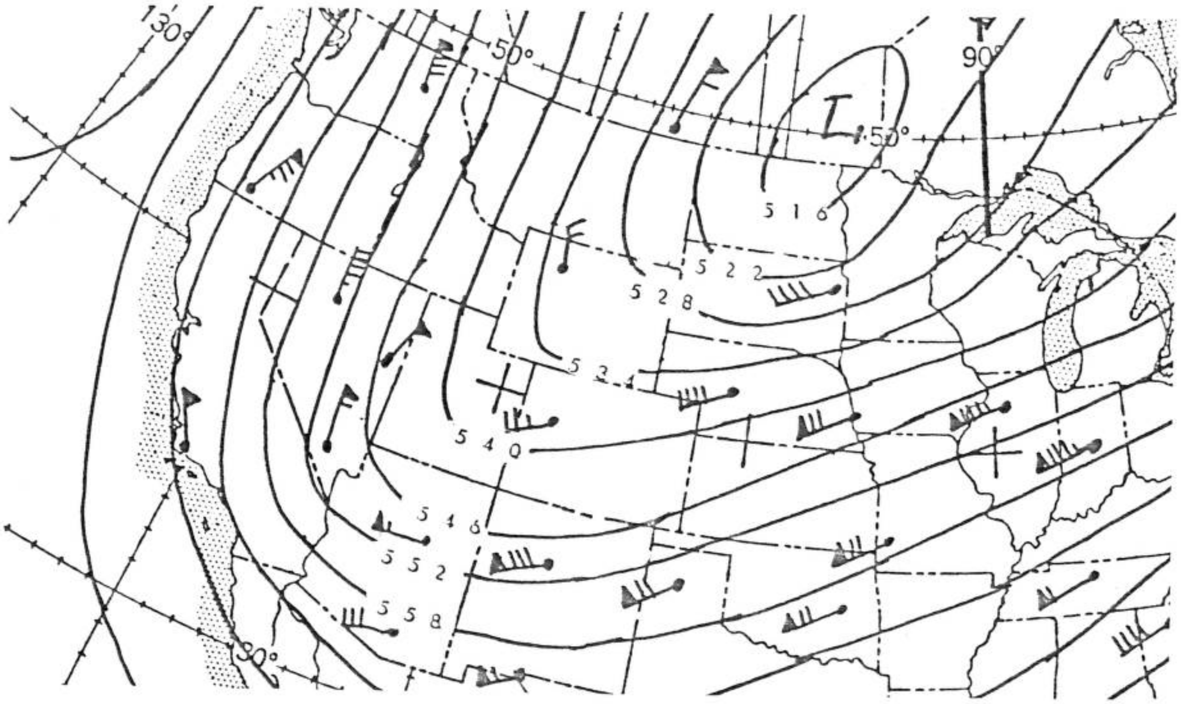

Figure 3. A typical 500-mb pattern during a Santa Ana regime. This chart is for 1200 GMT 27 November 1976.

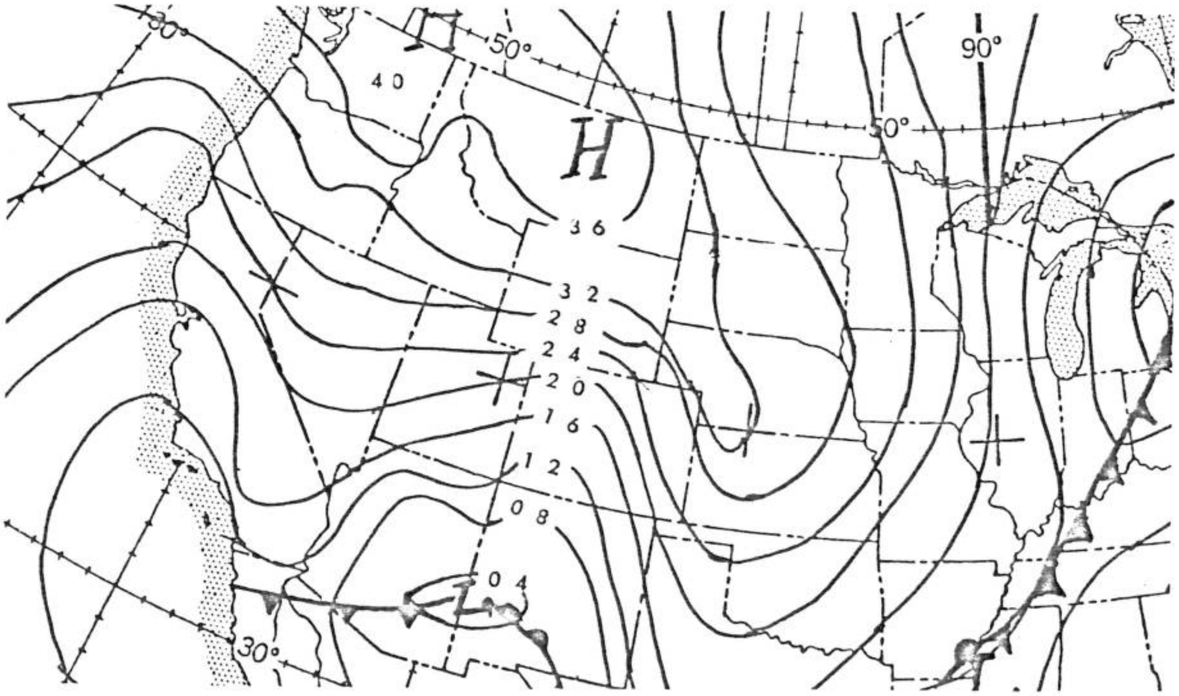

Figure 4. A typical surface pressure pattern for a Santa Ana regime after a cold front has moved through southern California from the north. This surface pressure chart corresponds to the 500-mb chart in Fig. 3.

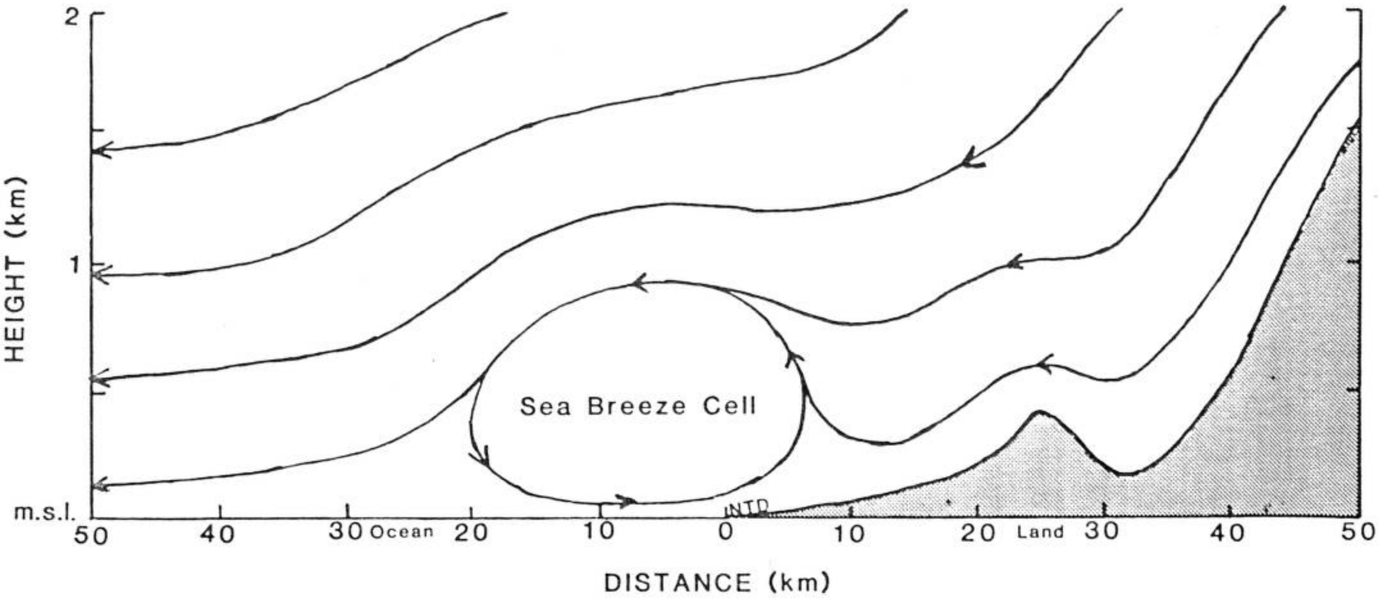

Figure 5. An idealized streamline pattern showing the interaction of the Santa Ana circulation with the sea breeze circulation. The land elevation is for a cross-section which is perpendicular to the coast at NTD.

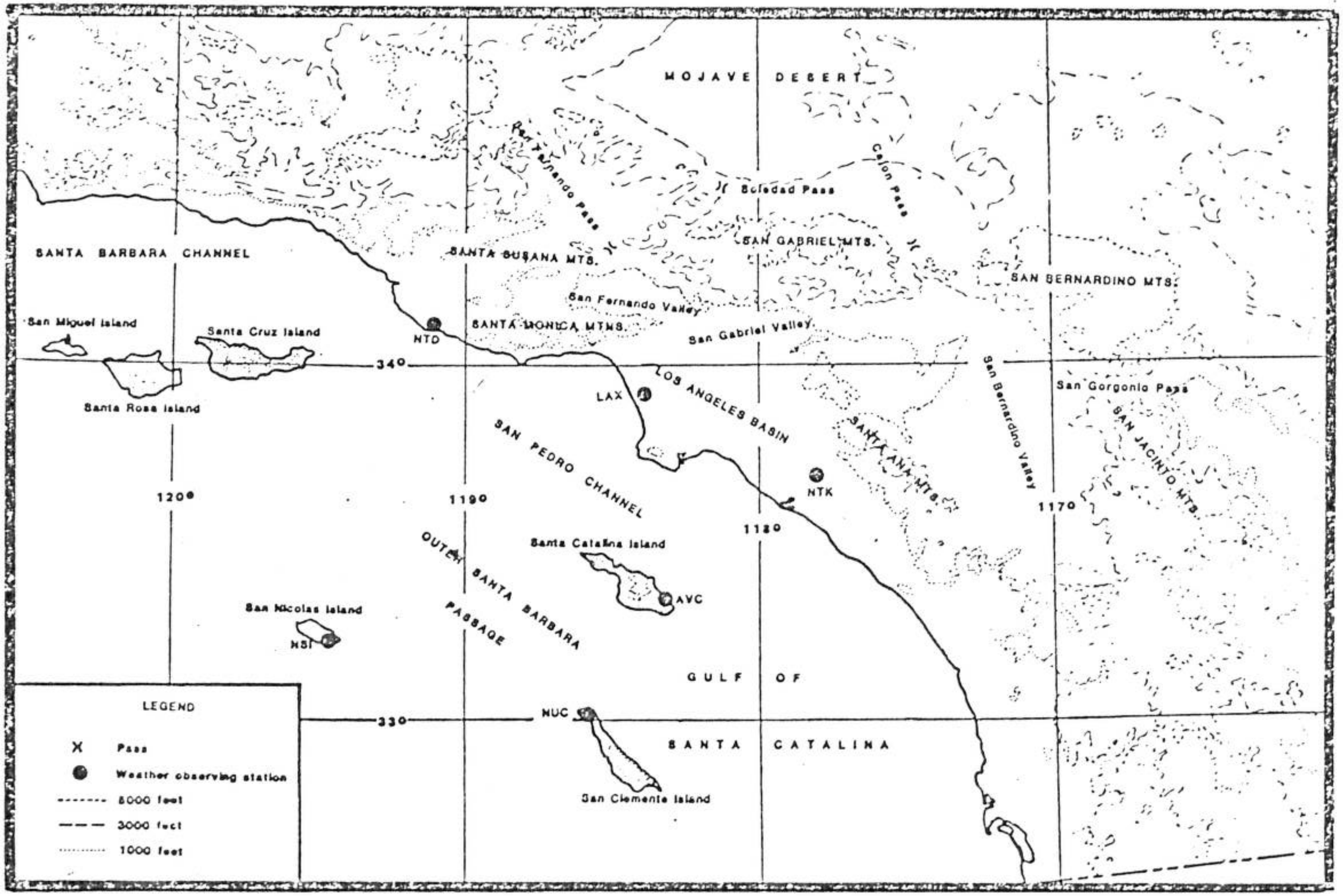

Figure 6. Regional topography of southern California.

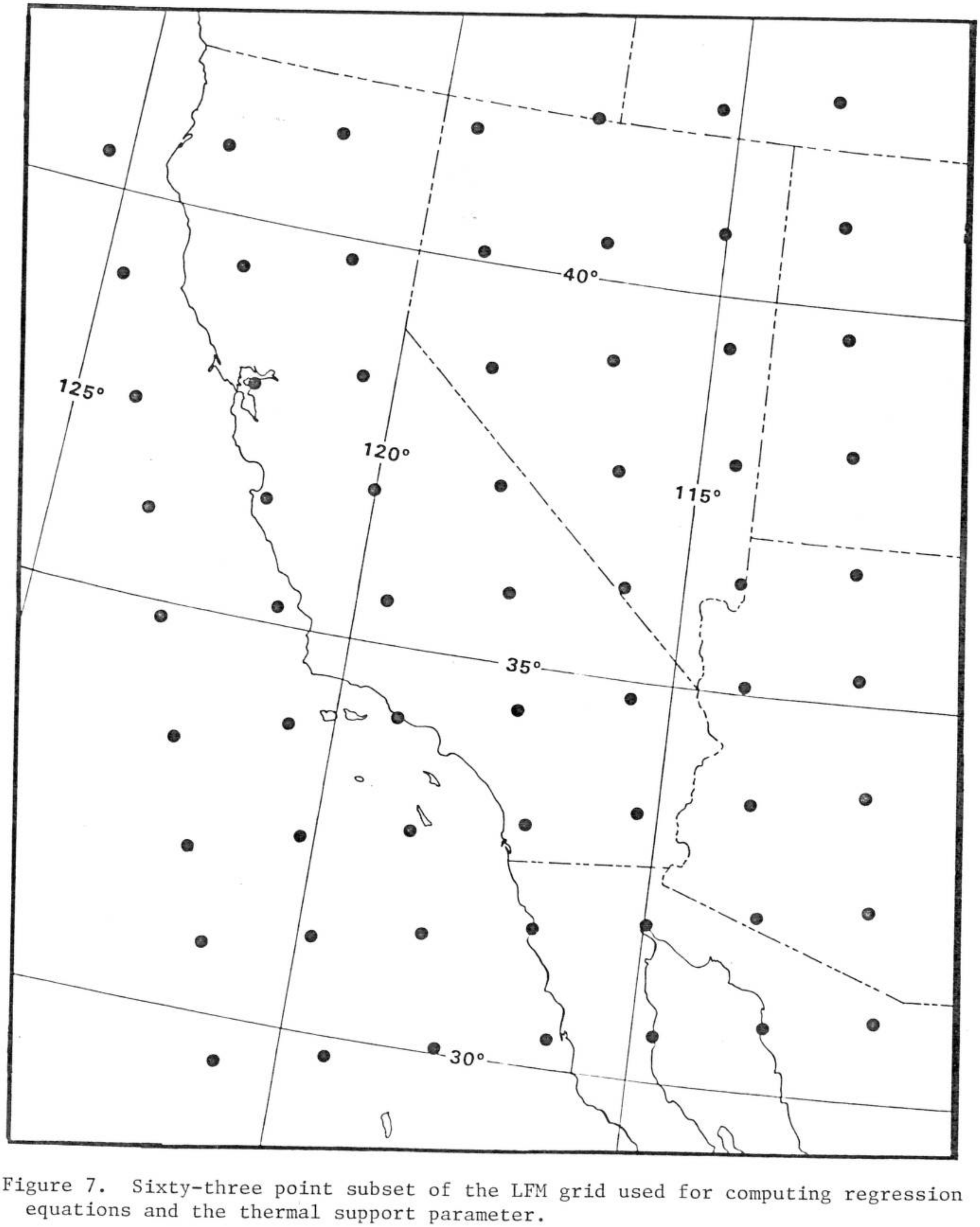

Figure 7. Sixty-three point subset of the LFM grid used for computing regression equations and the thermal support parameter.

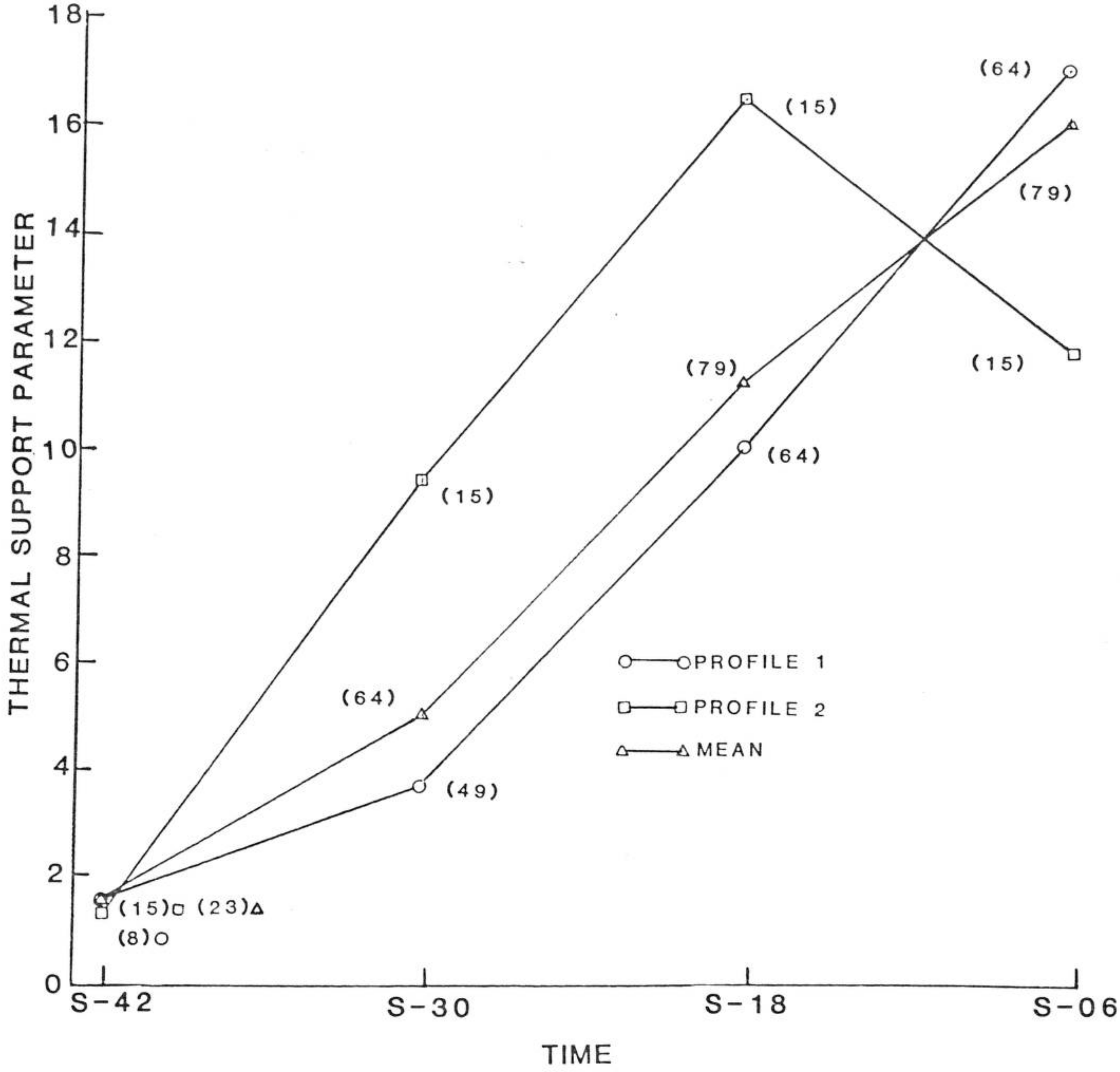

Figure 8. Composite patterns for the thermal support parameter (TSP) in the hours preceeding the inceptions of Santa Ana winds of 18 kt or greater. Surface data at stations LAX and TPH and 700-mb data at stations VBG and UCC were used to compute TSP. The sample size at each point is given in parentheses.

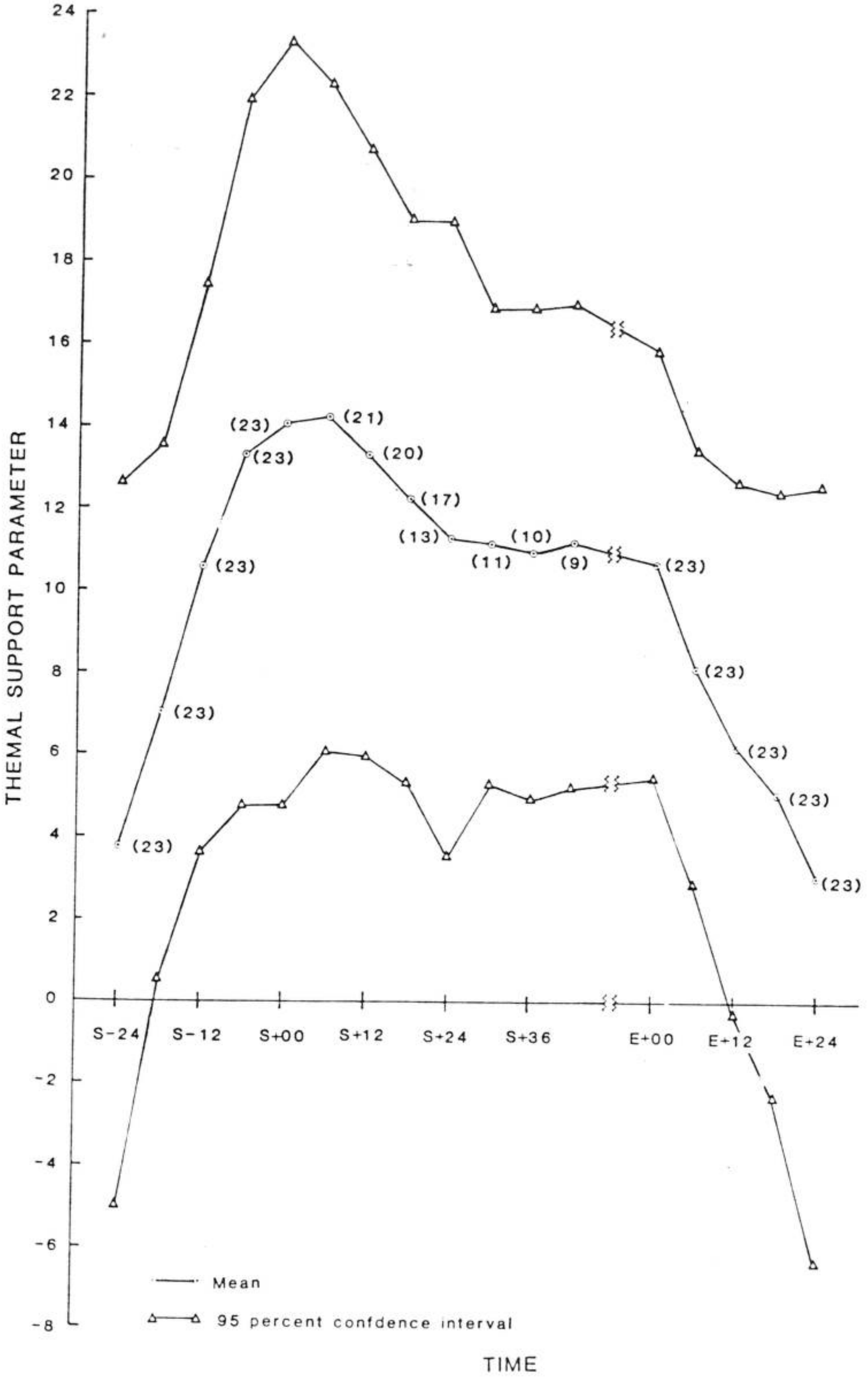

Figure 9. Composite pattern for the thermal support parameter (TSP), computed from grid-point data, for the period 24 hours prior to the beginning of a Santa Ana regime at S + 00 to 24 hours after the ending of the regime at E + 00. The curves on either side of the composite define the 95 percent confidence interval. The sample size for each point is given in parentheses. The break in the curves shows that some cases extended beyond 42 hours in length, but there were too few to composite.