Some Characteristics of the Three-Dimensional Structure of Santa Ana Winds

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Foreword

In March 1962 a contract was made between the Office of Civil Defense, now in the Office of Secretary of the Army, and the Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, to carry out a study of critical fire weather patterns and their relationship to synoptic patterns and to topography. The general objective of this study was to determine, region by region, the major synoptic scale weather patterns creating conditions under which large area ignition would result in high intensity, fast spreading fires; to determine the frequency of occurrence of these patterns and aids for predicting their occurrence; and to analyze and measure major topo- and mesoscale weather patterns creating critical fire weather in selected target areas.

The first two parts of this objective were described in two previous reports "Synoptic weather types associated with critical fire weather" (Schroeder et at. 1964) and `"Critical fire weather patterns—their frequency and levels of fire danger" (Hull, O'Dell, and Schroeder 1966). Two other brief reports, "Probability of effective post-attack fire fighting in wildlands" (Chandler and Schroeder 1965) and "Monthly fire behavior patterns" (Schroeder and Chandler 1966) have indicated ways in which data from this study can be reoriented for application to specific problems.

The mesoscale fire-weather pattern selected for investigation was the Santa Ana wind of southern California. Similar foehn-type winds affect many areas of the mountainous West. One previous report, "Surface wind patterns in the Los Angeles Basin during 'Santa Ana' conditions" (Edinger, Helvey, and Baumhefner 1964) presents the results of an analysis of 7 years of Santa Ana wind situations in both statistical terms and in streamline presentations of individual situations. A second report, "The structure of thermal convection in the lower atmosphere" (Myrup 1965) deals with the more general and basic problem of the way in which heat introduced at the bottom of the atmosphere is carried upward and thus modifies air masses.

This report describes the measurement of the three-dimensional wind flow and temperature structure in the lower atmosphere during Santa Ana conditions. Although the study of Santa Ana wind flow is by no means complete, this is the final report for the Office of Civil Defense under the present contract. Forest Service plans call for further field studies of the structure and variations of Santa Ana wind flow.

The work reported in this paper was performed by the Forest Service, U. S. Department of Agriculture, for the Office of Civil Defense, Office of the Secretary of the Army, through the U. S. Naval Radiological Defense Laboratory, San Francisco, California, under Contract OCD-PS-65-27 (Subtask 2535A)

Acknowledgments

The field portion of this study required the participation of other projects and agencies. Richard M. Ogden and Donald V. Lust, of the U. S. Weather Bureau, and William Innes, of the California Division of Forestry, assisted in field observations. Further observations were made by personnel from the Pacific Southwest Forest and Range Experiment Station's Forest Fire Laboratory in Riverside, Calif. The Weather Bureau staffs at San Diego, Santa Monica, and Las Vegas took extra rawinsonde observations for the study, as did the U. S. Navy at the Pacific Missile Range. Dr. J. G. Edinger, the University of California at Los Angeles, obtained pilot balloon observations in the Los Angeles basin. Meteorology Research Inc., of Altadena, Calif., obtained—under contract—aircraft and radar observations. Personnel at Edwards Air Force Base, Cuddeback Lake Naval Test Site, and 29 Palms Marine Corps Station in California provided data routinely taken but not normally available. We also appreciate the National Meteorological Center data and analyses provided by the Los Alamitos Naval Air Station. The Los Angeles and Riverside Air Pollution Control Districts provided data from their special networks. The California Division of Forestry aided by securing permission from private and public landowners to set up the field equipment.

Contents

The Authors

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MARK J. SCHROEDER is responsible for forest meteorology studies at this Station. Native of Edgar, Wisconsin, he was graduated from Wisconsin State University (1936) and did graduate work in meteorology at the University of Chicago. He has been on assignment to the Station from the U. S. Weather Bureau since 1955, and headquartered at the forest fire laboratory since 1963.

Fire behavior is affected by many meteorological elements. The two most influential elements are wind speed and relative humidity. During foehn activity, the lee slopes of mountain ranges experience both high winds and low humidity. When winds up to 50 meters per second combine with relative humidity of 5 percent, fire danger reaches a critical stage. In southern California, the foehn is known locally as the Santa Ana. Together with the low relative humidities, it produces the most extreme fire danger found anywhere in the world.

The synoptic features producing Santa Ana winds are reasonably well understood and can be forecast. But their mesoscale and smaller characteristics produced by mountain waves are less well understood. The behavior of large wildland fires is affected by variations in the mesoscale Santa Ana of such features as foehn islands, surfacing, and intensity of outflow. These characteristics would similarly affect mass fires resulting from nuclear attacks.

The purpose of this study was to determine the three-dimensional structure of the Santa Ana so that the mesoscale morphological behavior could be understood. Data were collected during two cases of Santa Ana winds—each 48 hours long—in December 1963 and January 1964. This paper describes the procedures and results of the study, and suggests implications as well as recommendations for future research.

Early Studies

The major portion of research on foehn winds has been done in the Inn Valley of Austria. The foehn phenomena of descending air, adiabatic warming (Defant 1951; Godske et al. 1957), and low humidities along a mountain slope and the adjacent valleys have been partially understood since the 1800's. Hann (1866) proposed the thermodynamic explanation of the warming as a release of latent heat on the windward side and adiabatic warming on the leeward side of a mountain range during the descent.

Ficker and Rudder (1943) summarized the large scale aspects of foehn occurrence. Their explanation is that pressure must be low on the lee side of the mountain range. If the air current is cold, it piles up to the top of the range and spills over. The descending air is warmed adiabatically and shows the foehn characteristics only after the adiabatic modification has changed the cold air characteristics to such an extent that it is warmer and dryer than the air it is replacing. If the air flow is warm, it assumes foehn characteristics much higher on the lee slope. In general, the factors determining the foehn type are the synoptic situation, the orientation of the mountain range, and the air mass properties.

Four factors—mechanism of descent, foehn islands, surfacing along the lee slope, and the diurnal fluctuations—have been identified as related to a mountain wave phenomenon (Gutman and Tebuev 1961; Holmboe and Klieforth 1954; Lyra 1943).

The Santa Ana wind of southern California was first identified as foehn flow by Carpenter and Gorthwaite (1914). The *Riverside Daily Press* of December 24 and 30, 1901, suggested that the air was warmed adiabatically. The synoptic aspects of Santa Ana winds (Sergius 1952) require an anticyclone in the Great Basin and a surface low pressure trough off the California coast. Because the Great Basin anticyclone has a cold core, gradient flow at the ridge top associated with the resultant upper Low is nearly perpendicular to the San Gabriel and San Bernardino Mountain ranges. This is an ideal situation for the development of lee waves (Colson 1952). Because the anticyclone in the Great Basin is more often cold than warm, most of the Santa Ana winds are of the cold type described by Flicker and Rudder (1943). During early fall, however, the warm type is often observed.

Analysis of theoretical work on lee waves yields the following factors that influence the amplitude of the waves (Corby and Wallington 1956):

1. Amplitude will increase if the wind speed increases with increasing height, or the stability decreases with increasing height. The amplitude is more responsive to the wind profile than to the stability.

2. Largest amplitude waves occur when the critical conditions for airstream characteristics for wave formation are just barely reached.

3. Adiabatic mixing near the ground decreases the amplitude.

4. Large amplitude waves are more likely in airstreams having a shallow layer of great stability rather than a deep layer of moderate stability. Foldvik and Wurtele (1964) suggested that the stable layer is a result of and not an *a priori* condition for wave formation. Corby and Wallington (1956) also indicated that the wave-length is increased by adiabatic mixing near the ground.

Meso and local analysis of the Santa Ana has been somewhat neglected; only papers by Sergius (1952) and Edinger, Helvey, and Baumhefner (1964) describe the climatology of the surface winds, temperatures, and humidities associated with the Santa Ana. The salient features of these studies are:

1. A wind shadow perpendicular to the flow is cast by the mountain range. This shadow is so effective that a sea breeze or pseudo-sea breeze pervades the shore every day.

2. The sea breeze or pseudo-sea breeze is characterized by low humidities and is probably foehn air that has been over the ocean only a short time.

3. The areas of strong winds are well defined. The strongest winds blow out of the passes, particularly on the flanks of the San Gabriel range, and occasionally have preferred channels on the plain, such as along the Santa Ana River bed.

4. Humidities are found to be low (less than 20 percent) throughout southern California during a Santa Ana, with a slight tendency to be as high as 30 percent in the mountain top areas.

5. Fuel moisture tends to have minimum values in sheltered and semi-sheltered areas and maximum values at high elevations and along the axes of the strongest winds. In a case study, Fosberg (1965) found that the descending flow was complicated by the interaction with the mountain and valley winds.

The line along which the Santa Ana separates from the mountain, the spotty descent—both in time and in space—the interaction with more local winds—such as mountain and valley winds and the sea breeze—and the spectrum of lee waves produced by the complex nature of the mountains are difficult to determine from surface data.

If the Santa Ana separates from the mountain at a high elevation, only the normal thermal winds are found at lower elevations on the lee side. The behavior of wildfires occurring under such conditions is controlled by the local winds. If, however, the Santa Ana surfaces and scours out the lee canyons, a fire can be carried down slope and into heavily populated areas. This wind action occurred in such California fires as the Malibu fires in 1956, the Bel Air fire of 1961, and the Coyote fire in 1964, when many expensive homes were destroyed.

The major objective of the work reported in this paper was to determine the three-dimensional structure of the Santa Ana winds from analyses of wind, temperature, and moisture fields. To determine this structure, such characteristics as the areal extent, spatial variations, and relation to the synoptic pattern were examined. The influence of the mountains and the basic wind and thermal structure also had to be separated in order to determine which wave characteristics were due to the mountains and which were due to the static stability and the wind profile. To further describe the Santa Ana we had to answer such questions as: 1. Are foehn islands strongly related to both the downwind topography and to the wave characteristics or does topography play a dominant role? 2. What is the life history of the Santa Ana? 3. Does the sea breeze penetrate as a cool marine surge during the decay stage of the Santa Ana? Condensation is not involved in the Santa Ana to any appreciable degree, yet in the European foehn, condensation is quite important. 4. What difference does the lack of release of latent heat produce in the Santa Ana?

Procedures

Field Study

The area selected for study covers the Los Angeles Basin, the San Bernardino Valley, and the mountains to the north and east. Our principal effort was in the latter two areas.

Originally, 20 recording weather stations were installed to obtain surface weather information (fig. 1). Considerable difficulty was encountered in keeping the stations operating so that data acquisition was not complete. For this reason, only 10 stations were installed for the second case study. The sites were selected to provide area coverage

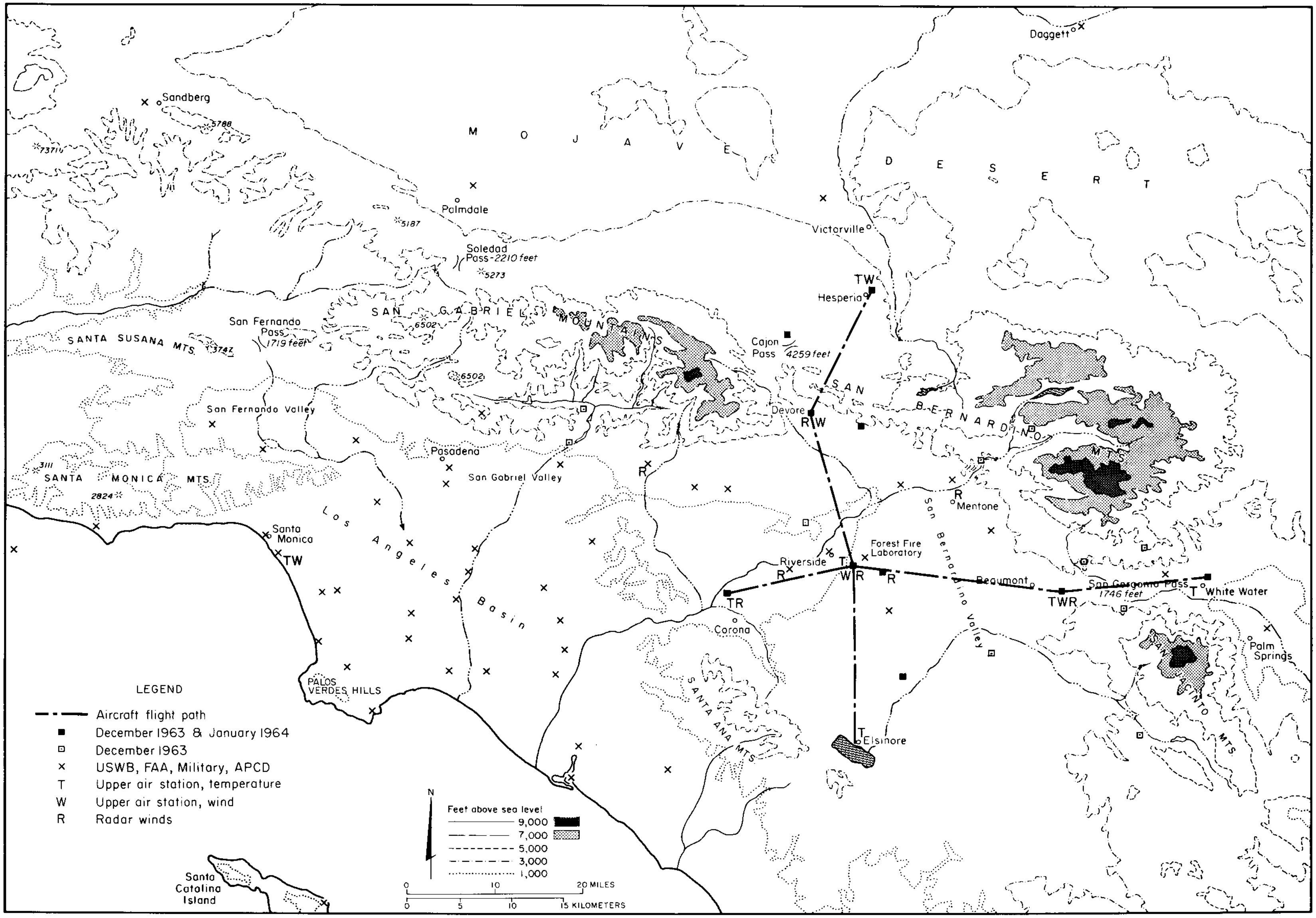

Figure 1.—*Map of southern California showing major topographic features, station locations, and aircraft flight paths.*

and data for cross sections through Cajon Pass and San Gorgonio Pass. Surface observations included wind speed and direction, and dry- and wet-bulb temperature. Surface pressure readings were made at some stations, but the measurements were not accurate enough to be useful in the analysis.

The recording stations were placed in their sites well in advance of the study periods. Participating personnel remained on call until a Santa Ana situation was forecast. On the basis of the forecast, all personnel were then sent into the field to take upper-air observations. Observations were continued until the Santa Ana winds showed signs of diminishing. In each of the two cases the study period lasted 2 days.

Double-theodolite winds aloft observations were made at 3-hour intervals—0100, 0400, etc.—at Devore, Hesperia, and Beaumont. Thirty-gram balloons were used with a free lift giving a normal ascension rate of 180 meters per minute. Runs were ended after 18 minutes.

Radiosonde observations were taken at the Forest Fire Laboratory at Riverside, California, to coincide with upper-air wind observations, except for 0100 P.s.t. observations. Standard procedures were used.

Meteorology Research, Inc., operated an M-33 tracking radar on Box Springs Mountain and tracked aluminum foil targets attached to balloons. At Riverside a target was attached to the radiosonde train, and wind profiles were obtained by tracking. Wind profiles were also obtained by tracking targets on 30-gram balloons released from Corona (December 1963 case), and near Riverside Airport (January 1964 case) as soon after the 3-hour observation time as possible, and from the Forest Fire Laboratory at 0100 P.s.t. when a radiosonde was not released.

Trajectory balloons with targets were released for radar tracking at Devore, Beaumont, Mentone, and Cable. Two balloons were attached to a single target. One was filled with a free lift of 3 grams and the other was given a free lift of 30 grams, but a slow leak was provided by punching a hole in the neck. The object was to allow the two balloons to rise to about 300 m. and then have them take off on a constant altitude course. In practice the balloons and targets usually ascended at a slow rate. The release times of the trajectory targets were coordinated with the radar to fit into the radar schedule. Releases were about 0200 and 1400 from Cable; about 0500 and 1700 from Devore; about 0800 and 2000 from Mentone; and about 1100 and 2300 from Beaumont.

The radar provided a graphical track of the balloon target, giving its position in terms of range, azimuth, and height. By measuring the track between 1-minute plots, it was possible to deduce the direction and speed of the wind at balloon level.

Although winds aloft information was obtained from most of the balloon releases, considerable gaps in the winds aloft record occurred because radar could not distinguish between return from the balloon target and ground clutter. Balloon releases made far from the radar were difficult to acquire since the widening of the radar beam width with distance allowed for more interfering returns to mask the target. At close-in points, when the balloon could be sighted visually at release, the target could be tracked optically until it rose above the ground clutter. The radar could then be locked on it. This generally occurred at about 500–600 m. above the surface.

In general the trajectory balloons failed, chiefly because (a) it was virtually impossible to fly the balloons at a given level, and (b) whenever the balloons were flying at altitudes close to the surface, they were lost in the ground clutter.

We tried to obtain wind information at aircraft level by using radar to track the airplane's path as it flew past the radar site. The plan was to derive the wind vector by solving the wind triangle. From the aircraft the true air speed and heading were obtained, while the radar track provided the true course and ground speed. The difference between these two sets of readings would be the wind affecting the airplane. Unfortunately the first priority requirement of tracking balloons almost fully occupied the radar so that little time remained for extensive experiments with this technique.

Aircraft observations were made by Meteorology Research, Inc., in a twin-engined Piper Apache instrumented to record pressure, temperature, humidity, turbulence, compass reading, and true air speed. The aircraft was based at Cable. The flight pattern consisted of a sounding from near the surface to 3100 m. at Corona, a traverse at that altitude eastward through San Gorgonio Pass to Whitewater, descent to near the surface at Whitewater, a low-level traverse westward to Beaumont, and sounding to 3100 m. at Beaumont. The aircraft then proceeded to Hesperia, descended near the surface, then proceeded southward through Cajon Pass at an intermediate elevation to near

Lake Elsinore. There, it made a sounding to 3100 m., and then returned to Cable.

Flights were started about 0200, 0800, 1400, and 2000 P.s.t. Each flight took 3 hours so that the originally-planned, additional probings of the mountain wave crest could not be conducted within the scheduled flight-time limitations. However, data acquired in the course of the various soundings and the traverses between sounding points did provide a partial picture of the extent of the wave phenomenon associated with these Santa Ana winds.

Data Reduction

Surface Data

The surface data were recorded on Esterline Angus milliameter strip chart recorders. A programer was used to cycle through the various sensor signals. The charts were read and data recorded manually using calibration scales.

Upper-air Data

Theodolite readings for the pilot balloon observations were placed on punchcards along with other pertinent data. Computations were made by electronic computers. Besides the horizontal wind speeds and direction, the computer program provided the vertical component by subtracting the normal vertical displacement from the measured displacement. The program also computed the north-south and east-west components of the wind. In this study the components along the cross sections through Cajon Pass and through San Gorgonio Pass were desired. These components were near enough to north-south and east-west, respectively, so that it was not necessary to rotate the coordinate system.

Data for significant levels on the radiosonde run were also placed on punchcards and the computations were made by computers.

Radar Wind Data

Data were obtained from the original radar plot of the targets. These data were plotted on a series of upper-air charts (in 305-m. intervals, from 1000 to 3100 m.) at the geographical locations of the observational points as determined from the radar.

Aircraft Data

The various data obtained during the aircraft soundings and traverses were plotted against height (above mean sea level). The soundings were identified with the point on the ground over which the aircraft circled during the course of the sounding. Data from aircraft traverses were plotted on cross sections—the data points corresponding to the actual points on the aircraft's flight path.

Air temperature, obtained in degrees Celsius, was later converted into potential temperature in degrees absolute to put the data in a form convenient for the determination of vertical motion patterns in the airflow.

Subjective turbulence reports by the aircraft pilot were displayed on the cross sections.

Analysis

Analysis of the data collected during the two case studies was designed to accomplish two goals: (a) to obtain the three-dimensional structure in such a way that the physical processes could be understood; and (b) to obtain information on the interaction of the local outflow of foehn air and the synoptic patterns in such a way that the intensity of the foehn could be understood.

The analyses of surface and constant pressure charts, vorticity, and vertical motion by the National Meteorological Center were taken as a *prima facie* description of the structure of the atmosphere. Only when the data coverage was at least one order of magnitude greater per unit area, was the NMC analysis modified and then only in sub-synoptic scale detail.

The second analysis scale was at the mesoscale, covering the Southwestern United States. The analysis area can be described by lines running east and south from San Francisco and north and west from Yuma, Arizona. Horizontal analysis at this scale was at 50-mb. intervals from 1000 mb. to 500 mb. on constant pressure surfaces where geopotential height, vector winds, temperature and mixing ratio were analyzed. Isentropic analyses, at the 280° A, 290° A, and 300° A surfaces, of mixing ratio, pressure and vector wind were also performed. These three surfaces are in the outflow boundary layer, the transition layer and smoothed outflow, and gradient flow level. Vertical cross sections from the surface to 300 mb. were also analyzed from San Francisco to San Diego and from Las Vegas to San Nicolas Island (an offshore Navy station in the Gulf of Santa Catalina) to provide information on longwave gravity flow. The time period between analyses at this scale was 6 hours, just half that of the synoptic scale. The base map at this scale was 1 to

3 million and included surface contours.

For the surface analyses a 1 to 250,000 base was used to obtain enough detail of the local outflow. Data analyzed at this scale were mixing ratio, vector wind in scalar form, and temperature reduced adiabatically to sea level. Vertical cross sections of vector wind, potential temperature, aircraft flights, radiosondes and subjective turbulence reports were analyzed in an east-west cross section from Whitewater to Corona and a north-south cross section from Hesperia to Elsinore. These cross sections had a 16.7 to 1 vertical exaggeration.

Results

The two cases, 10–12 December 1963 and 7–9 January 1965, are described in this section. Little attempt was made to draw or define common characteristics or to synthesize the data into a single descriptive model here, but a synthesis and model are given in the next section. All times reported in these two case studies are in Pacific Standard Time.

Case of 10-12 December 1963

The synoptic features of this case are typical of those encountered in the development of a Santa Ana (fig. 2). A high pressure area of maritime origin moved into the Great Basin from northwest Canada. Concurrently, the short-wave trough deepened until 1600 P.s.t., 11 December. The surface High and upper trough had reached their most intense stage and began to weaken, although the system remained quasi-stationary through the twelfth. A surface low pressure area over northern Mexico remained quasi-stationary throughout the Santa Ana, but by 2200 P.s.t. on the tenth, a surface trough began to develop parallel to the coast and out of the Mexico Low. This trough line was apparently associated with a weak front that had passed through southern California 2 days before and was now stationary. The surface Low offshore and the Great Basin High provided a 1.8 x 10^{-2} mb./km. pressure gradient between the Great Basin High and the offshore trough. The mountain ranges ringing southern California have a maximum elevation of near 3000 m. so the 700 mb. charts provide a good basis to examine the wave development criteria. The air was stable, temperature decreased 16° C. in 200 mb. Although no direct computation of Scorer's (1949) l^2 stability parameter was made, it is safe to say that l^2 decreased with height. This decrease is a necessary condition for the formation of lee waves, but the waves formed would not have a large amplitude. At higher levels, around 600 mb., where the flow is more nearly geostrophic, the flow was from the northwest and not the optimum condition for Santa Ana waves (fig. 17). In this respect, this case is not a perfect example of Santa Ana structure.

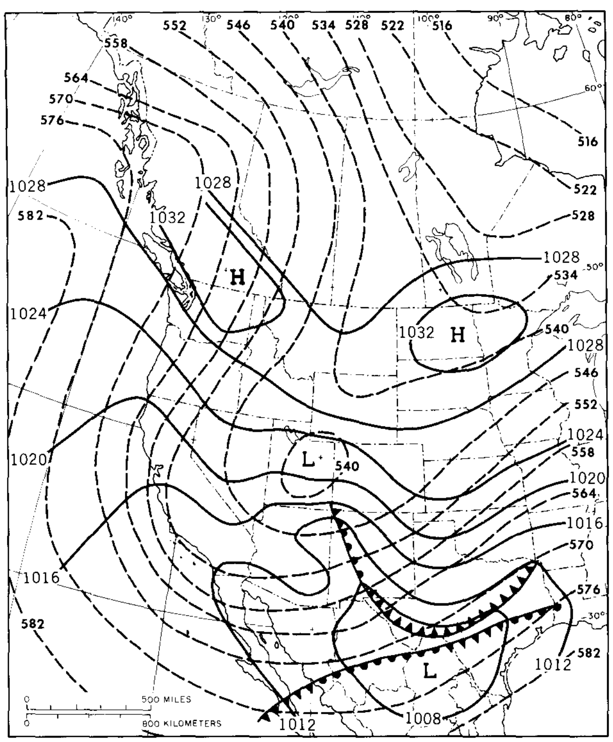

Figure 2.—*NMC analysis of synoptic features at 1600 P. s. t., 10 December 1963. Dashed lines are 500 mb. contours, solid lines are surface isobars.*

By the afternoon (1600 P.s.t.) of the eleventh, the flow had veered to north in the upper levels and northeast at 700 mb. The wind shear had decreased, but the shear of the perpendicular to the ridge had increased. And the conditions for large amplitude waves became more favorable. The period of optimum wave formation was short-lived as the vertical wind shear decreased by 0400 P.s.t. on the twelfth. In summary, this case developed more slowly than normal, maintained

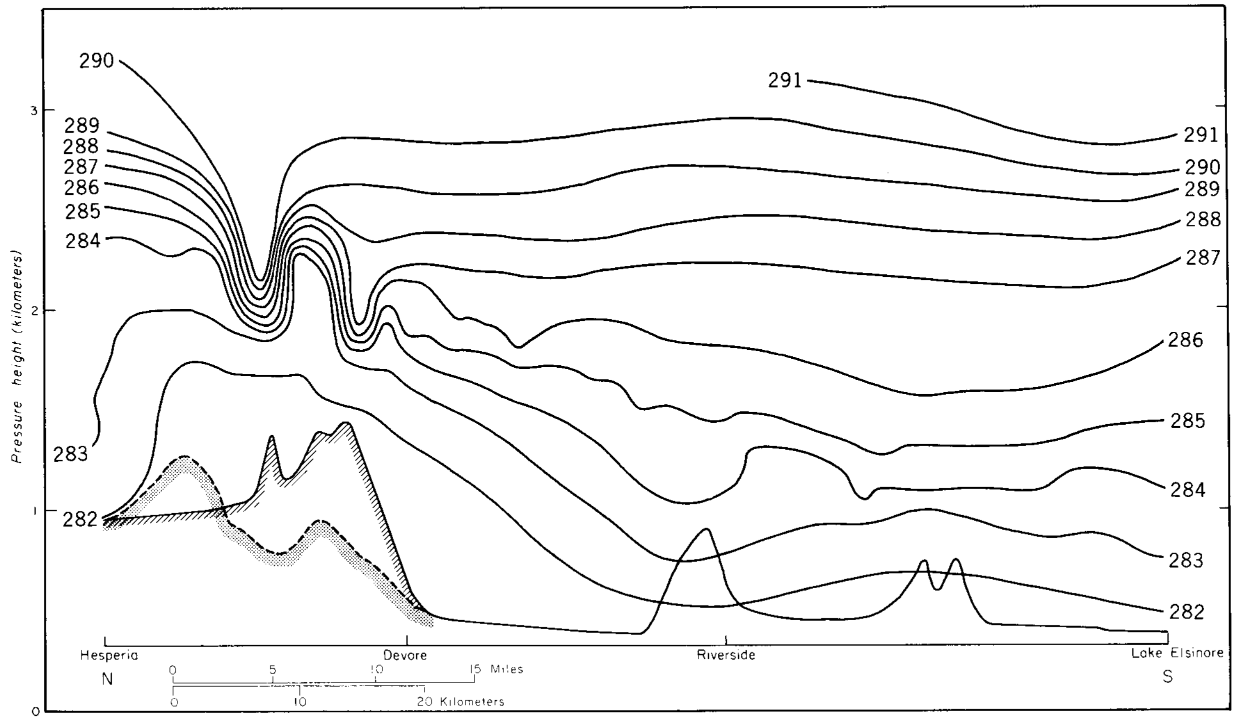

Figure 3.—*North-south potential temperature cross section. Hesperia to Elsinore 2159 P. s. t. to 2303 P. s. t., 11 December 1963. Short waves are dominant at this scale, the long wave is indicated by general downslope of isentropes to the lee of the mountains. Dotted terrain is through Cajon Pass. Hashed terrain is along flight path of aircraft 2 to 3 km. east of Cajon Pass.*

maximum intensity only for a short time, then dissipated in a near normal manner.

The detailed local features of the Santa Ana are best seen in the surface analysis of streamlines and the vertical cross sections of potential temperature. Several overwhelming features are clearly evident in the vertical cross sections (fig. 3). The first, and perhaps single most important feature of the Santa Ana, is the lee wave train set up downward from the mountains. The wave train sloped downward on a much longer wave, with apparently few or no wave lengths between the small waves set up by individual ridges and the large wave set up by the mountain range.

The outflow of the Santa Ana both in the mountains and on the plains appeared to be influenced most by the long waves (figs. 4-9). The term outflow, in general, refers to the easterly offshore flow observed in and immediately above the planetary boundary layer during a Santa Ana. Particular features, such as strong winds, foehn islands, eddies, etc., are not identified in detail by the term. The usefulness of this "outflow" concept comes from the fact that the driving force of the Santa Ana is in the free atmosphere rather than in the planetary boundary layer. The variability of the outflow in the mountains depended on the characteristics of both the long wave and the short waves. However, the outflow on the plain seemed to be nearly independent of the short waves. The Santa Ana outflow showed a strong dependence on local topographic features. The predominant paths of outflow in the mountains were through the major passes (Cajon, Soledad, and—to a secondary degree—San Gorgonio). Winds through the passes were strong (10 to 20 m. sec. $^{-1}$). Near the coast, even such minor obstructions as the Palos Verdes Hills in Los Angeles deflected the outflow (fig. 7).

North of the major range of mountains, the surface flow was southerly (figs. 4-7), suggesting an eddy with a horizontal axis and downward motion along the north slope.

Since true European foehn conditions of high temperature and low humidities were not observed in this case, the definition of foehn islands might be modified in such a way as to emphasize the areas of strong outflow that are observed as isolated cells. From this standpoint, the foehn islands occur primarily on the northern end of the Santa Ana Mountains (figs. 4, 5, 8) and are related primarily to elevation rather than to the lee waves.

The life history of this case showed an initial weak invasion of foehn air to the western portion of Los Angeles, where it was stopped by the sea breeze (fig. 4) at 1900 P.s.t., 10 December 1963. As the foehn became stronger, the sea breeze was rapidly pushed offshore. The offshore push was aided by the nocturnal cooling over the land (figs. 5, 6) throughout the night and morning. Until 1300 P.s.t., 11 December (fig. 9), there was no onshore flow, and the outflow behaved as in the general description given above. At 1300 P.s.t., 11 December 1963 (fig. 9), the sea breeze made a futile attempt to penetrate the coastline at Santa Monica and along the coast opposite the Santa Ana Mountains. By 1600 P.s.t., (fig. 10) the sea breeze had invaded a narrow strip all along the coast, but further offshore the winds were again easterly foehn flow. This feature, along with the moisture content of the onshore flow of 4 to 6 gm./kg. mixing ratio (compared to 1–3 gm./kg. in the unmodified foehn air) suggests that this is not a true sea breeze (when the normal moisture content is of the order of 10 gm./kg.), but foehn air that has had only a short trajectory over the sea. This return flow is probably from an eddy with a horizontal axis. In contrast, at 0100 P.s.t., 12 December 1963 (fig. 11), an eddy with a vertical axis was responsible for onshore flow. Since a sea breeze is not expected at this time of night, the flow is exclusively returning foehn flow. The onshore flow during the daytime is undoubtedly aided by the surface heating over the land. The decaying stages of the Santa Ana, from 0100 P.s.t., 12 December 1963 on (figs. 11, 12) showed a gradual weakening of offshore flow. Subsequently flow returned to normal.

The temperature field associated with the Santa Ana was dominated by descending air and adiabatic warming. This characteristic was evidenced by weak temperature and potential temperature gradients at the surface. Surface heating played a minor role—indicated by relatively small diurnal surface temperature changes during the Santa Ana period.

The mesoscale charts and cross sections indicate a strong tie between the local features and the synoptic features. Each set of meso maps showed a smooth transition from the large scale flow pattern observed at 500 and 700 mb. to the local outflow patterns observed in the detailed surface maps. The transition first became noticeable at 750 mb. when the mountains began to deflect the flow around their flanks and set up a mesoscale eddy on the leeward side (fig. 13). The eddy tilted out to sea and was apparently associated with a lee trough set up from the conservation of absolute vorticity. At 900 and 950 mb. (figs. 14, 15) the flow was similar to the surface flow in the Los Angeles Basin. One of the striking features of the transition layer is an apparent conversion of potential energy to kinetic energy immediately downwind of the San Gabriel Mountains. As the wind at ridge top level veered to the northeast, the transition layer dropped to near 800 mb. and the lee eddy became less pronounced (fig. 16) . The major change in the trough appeared to be in the winds rather than the thermal field.

The dissipation stage of the Santa Ana appeared to have less coupling through the meso field than the forming and mature stages. The dissipation apparently resulted from a decreased pressure gradient brought on by the eastward migration of the synoptic features.

Isentropic analysis of the mesoscale features showed the interaction clearly. The airflow in the Santa Ana is nearly isentropic. At the transition level (fig. 17) (290A surface) the influence of the mountains was particularly noticeable. The airflow upstream closely followed that observed on constant pressure analysis. The flow was strongly deflected by the mountain barrier—a trough in the isentropic surface formed upstream, and a ridge formed to the lee of the mountain range. (Although the analysis on the isentropic surface is in terms of pressure, we refer to ridges and troughs in terms of height rather than pressure so as to be consistent with the terminology used on vertical cross sections of potential temperature.) A lower isentropic surface would show a ridge over the mountain range and a broad trough to the lee side because of the vertical shrinking of the air layer over the mountains and vertical stretching on the lee side (Haltiner and Martin p. 357, 1957).

As the Santa Ana approached dissipation stage the lee ridge became less pronounced (fig. 18). This change was reflected in the boundary layer outflow which also gradually weakened.

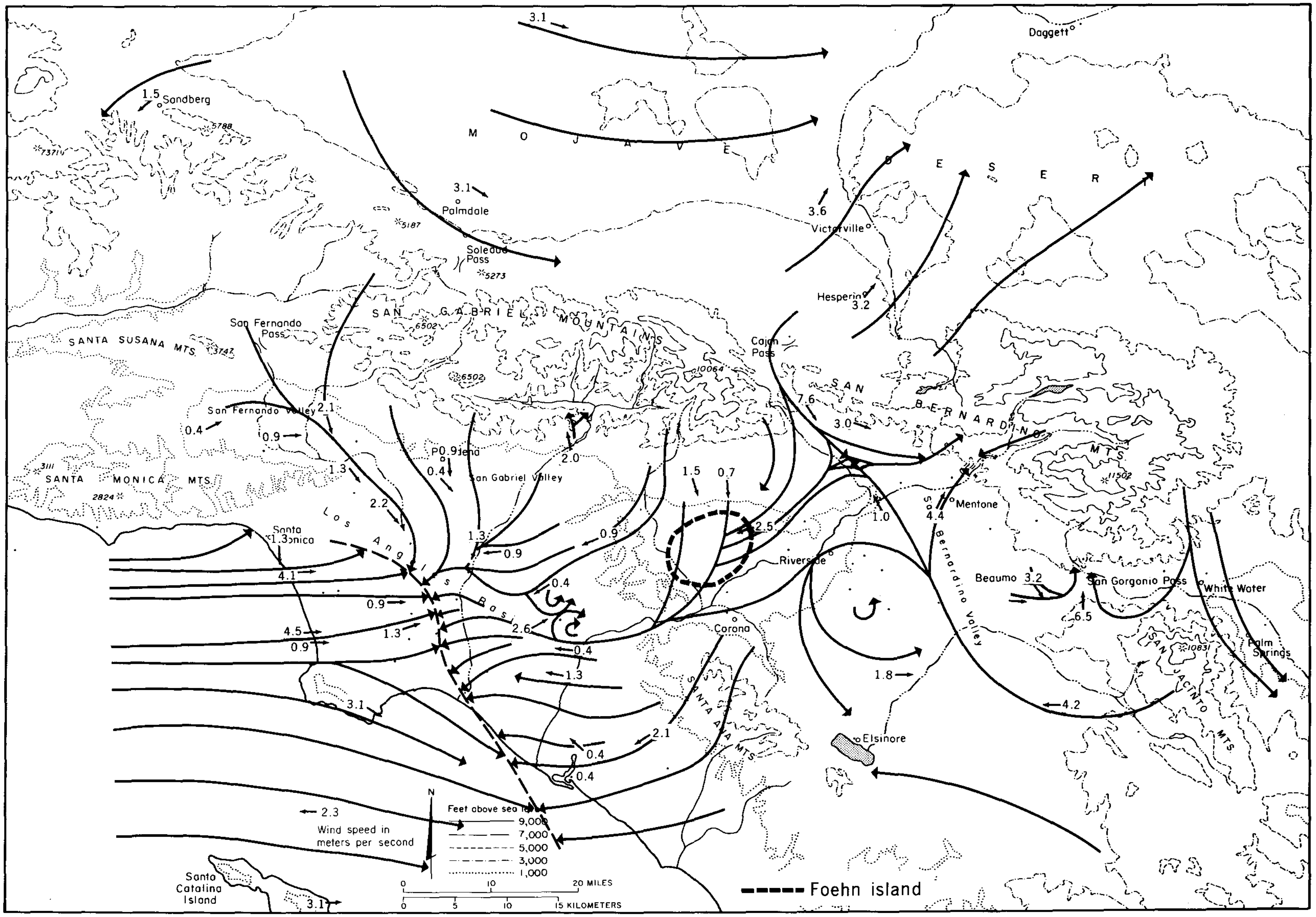

Figure 4.—*Surface streamlines 1900 P. s. t., 10 December 1963. Weak foehn flow is interacting with sea breeze.*

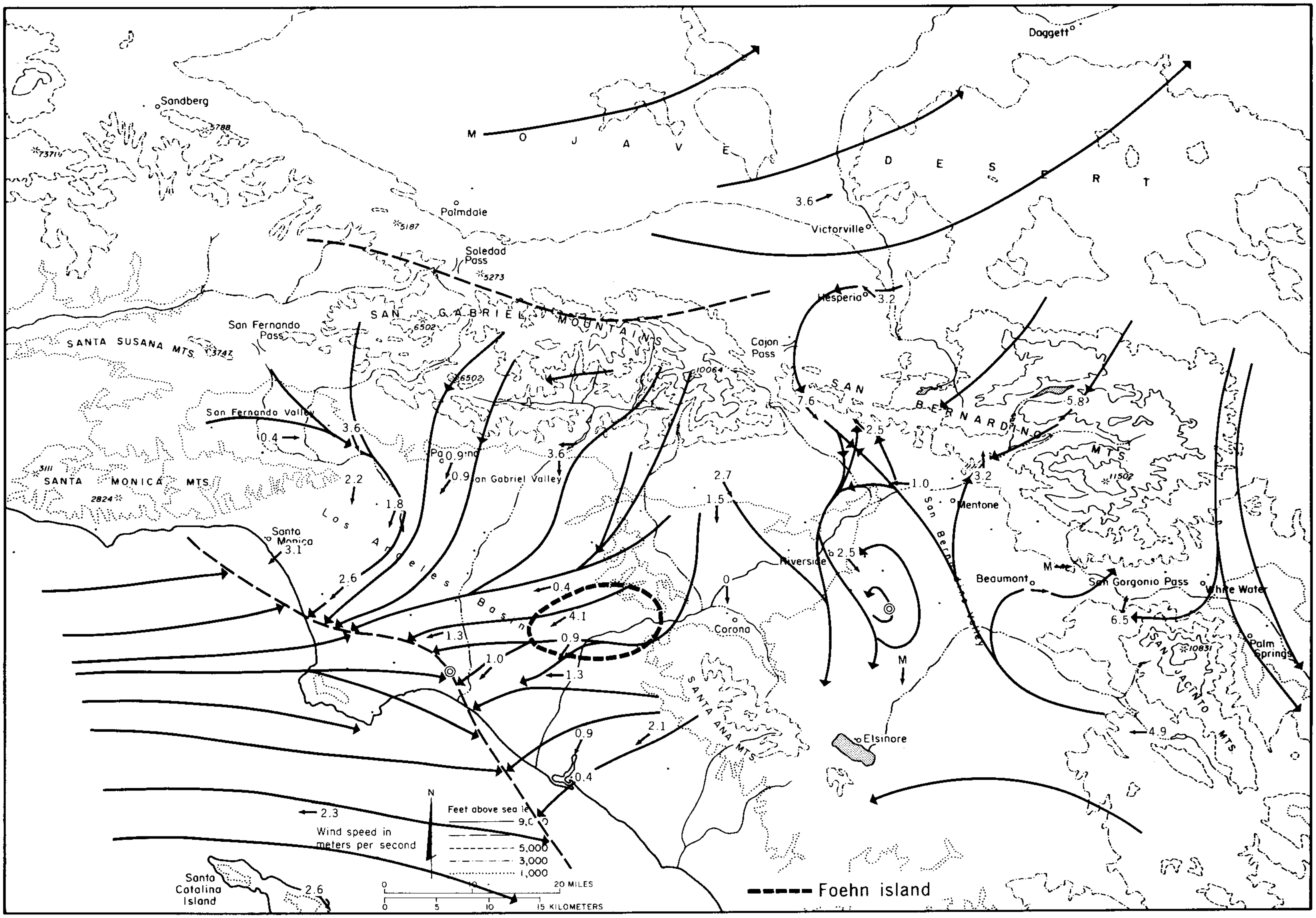

Figure 5.—*Surf ace streamlines 2200 P. s. t., 10 December 1963. Santa Ana is assisted by land breeze.*

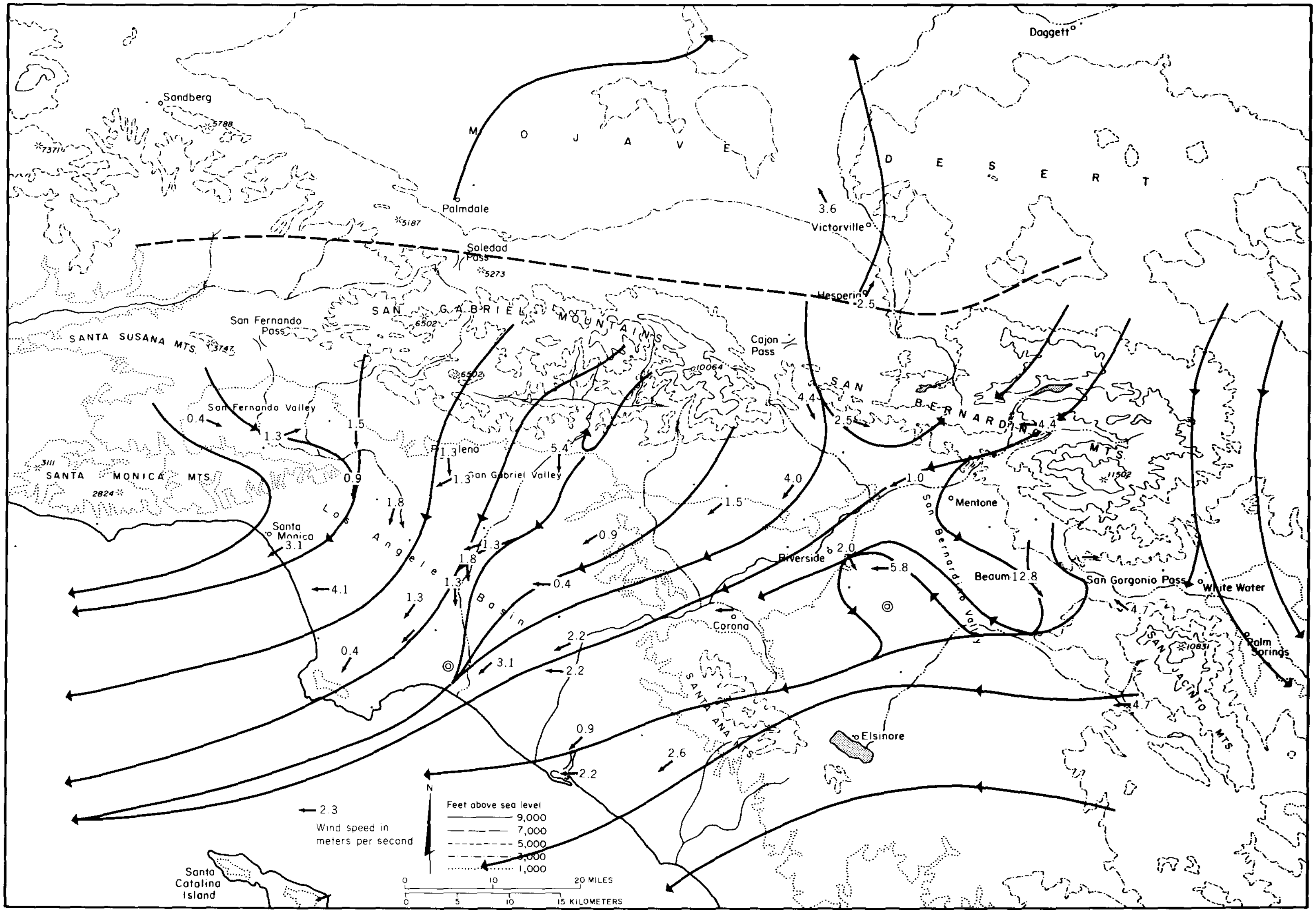

Figure 6.—*Surface streamlines 0100 P. s. t., 11 December 1963, showing general pattern of mature Santa Ana flow. Strongest outflow winds are through the passes. Strong winds may also occur near mountain peaks.*

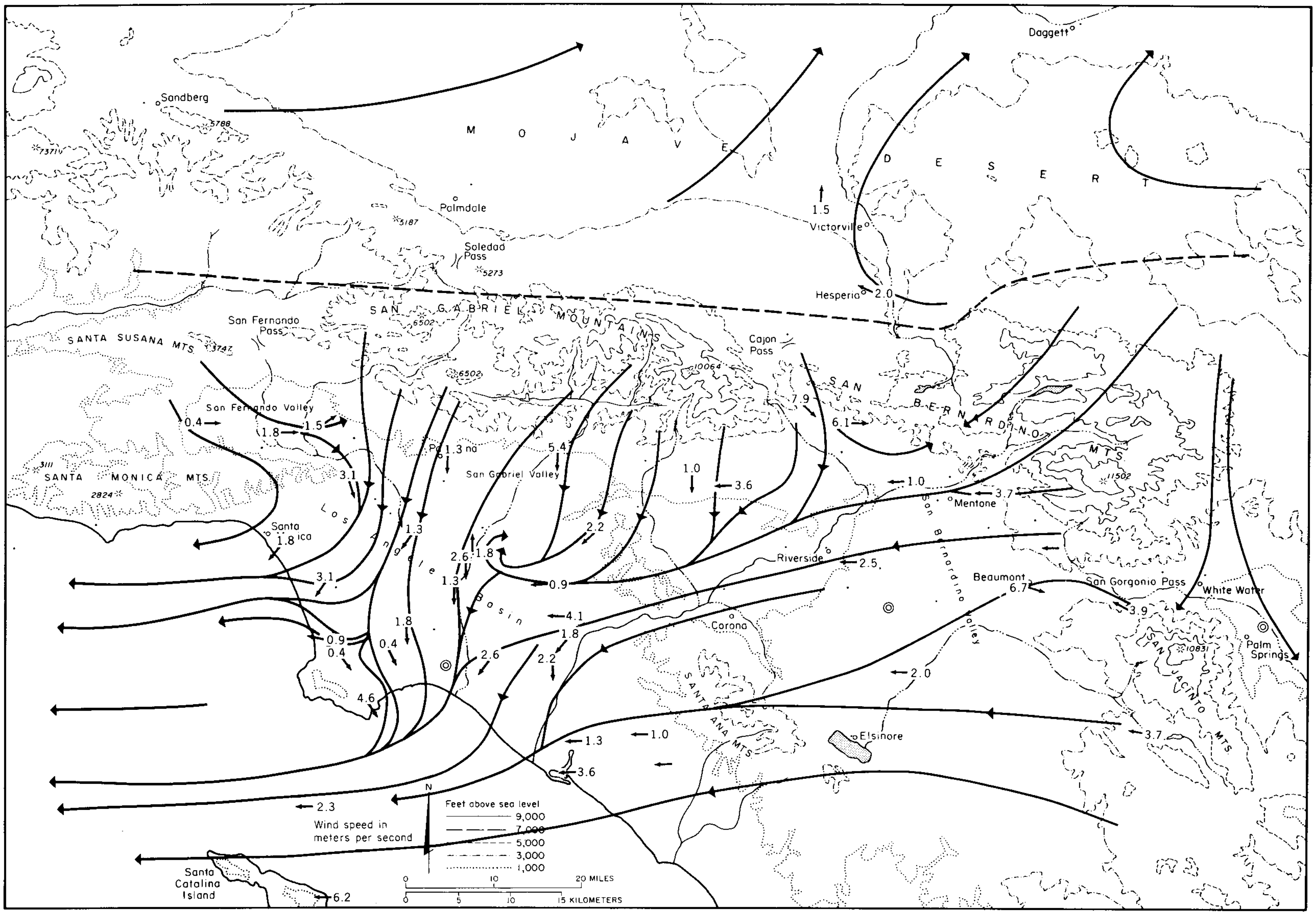

Figure 7.—*Surface streamlines 0700 P. s. t., 11 December 1963. Flow is deflected by Palos Verdes Hills.*

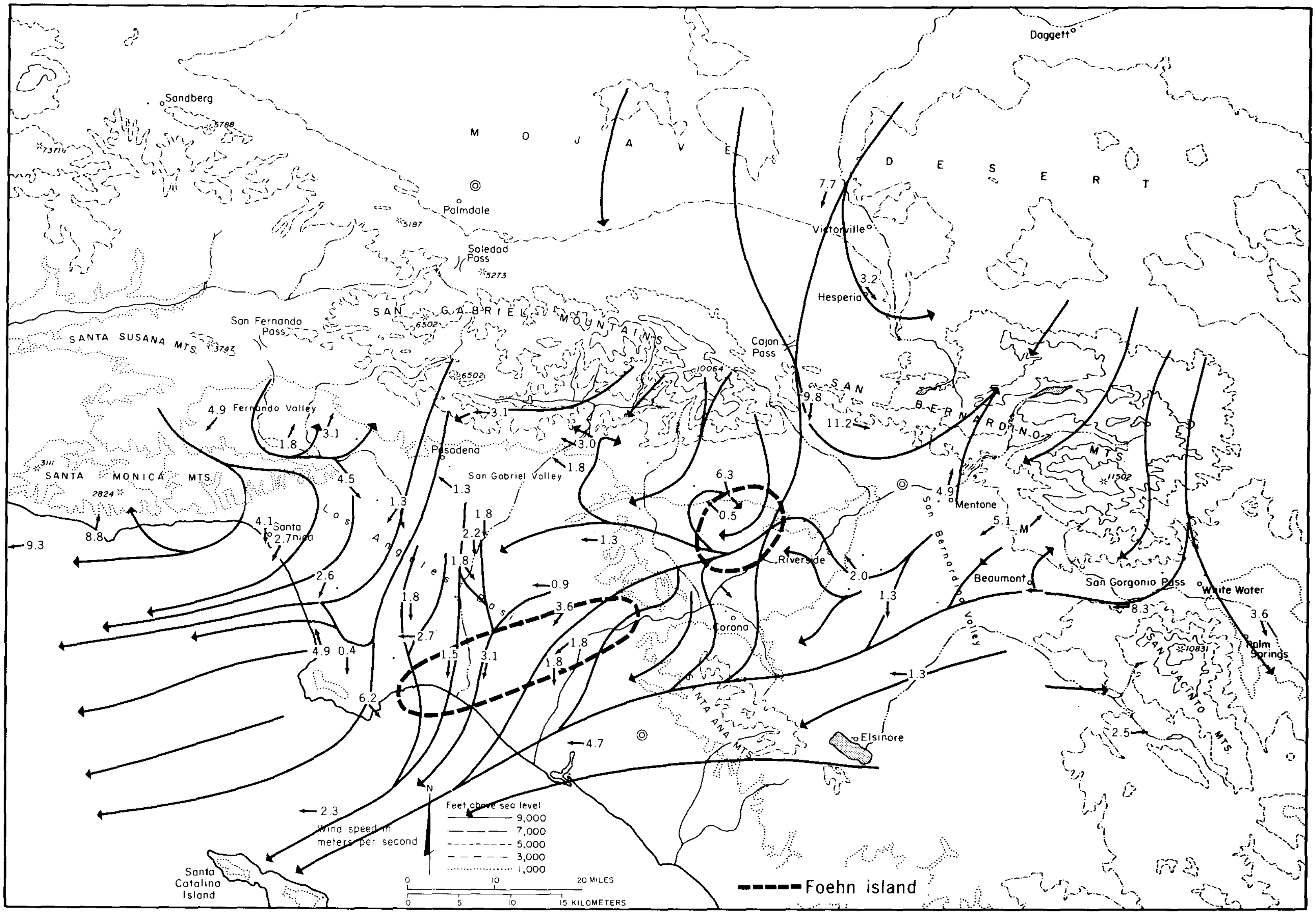

Figure 8.—*Surface streamlines 1000 P. s. t., 11 December 1963. Note foehn island on northern end of Santa Ana Mountains.*

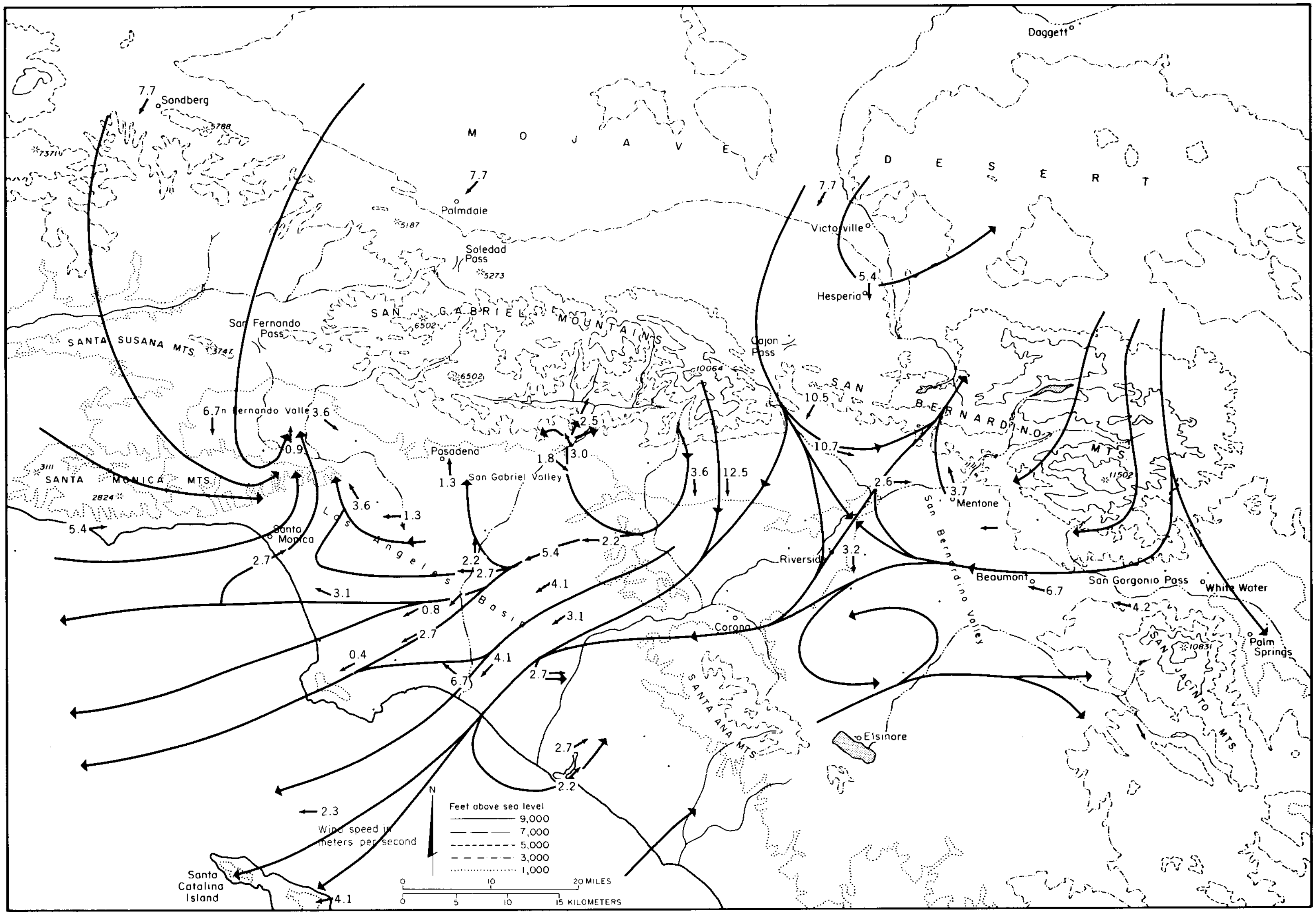

Figure 9.—*Surface streamlines 1300 P. s. t., 11 December 1963, showing beginning of delayed sea breeze along coast.*

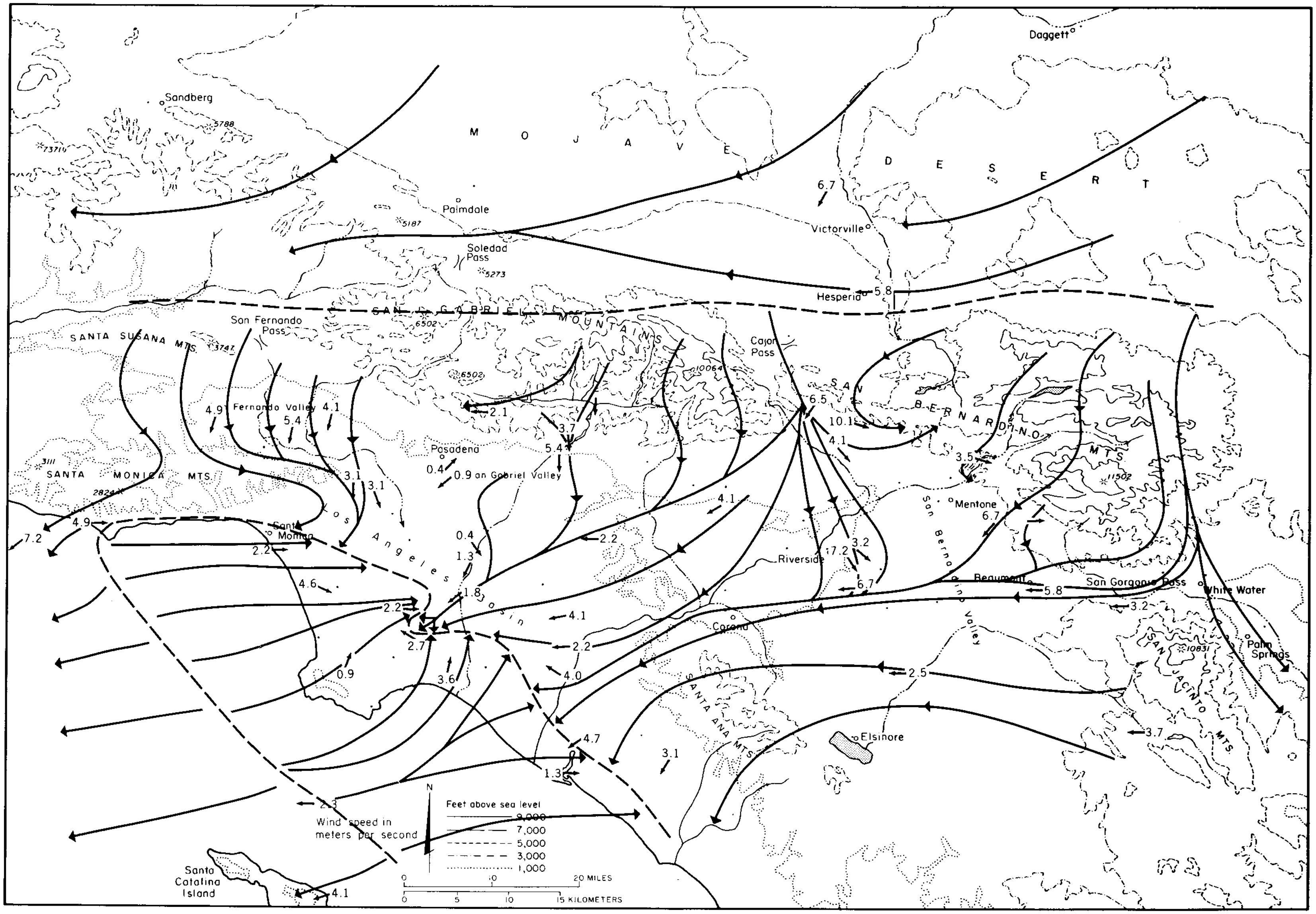

Figure 10.—*Surface streamlines 1600 P. s. t., 11 December 1963, showing extent of sea breeze penetration. Note easterly flow further offshore.*

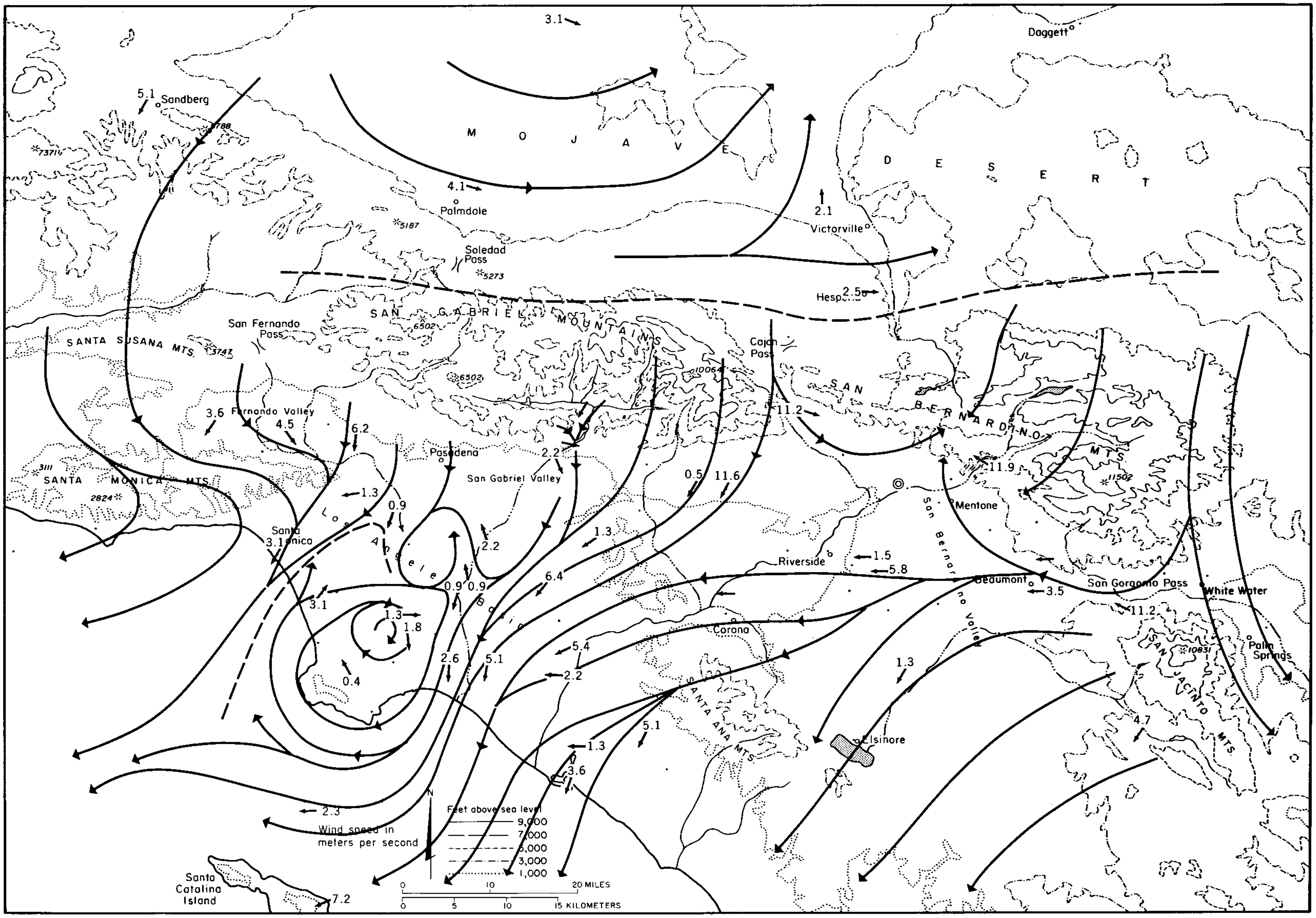

Figure 11.—*Surface streamlines 0100 P. s. t., 12 December 1963. Note onshore flow from eddy.*

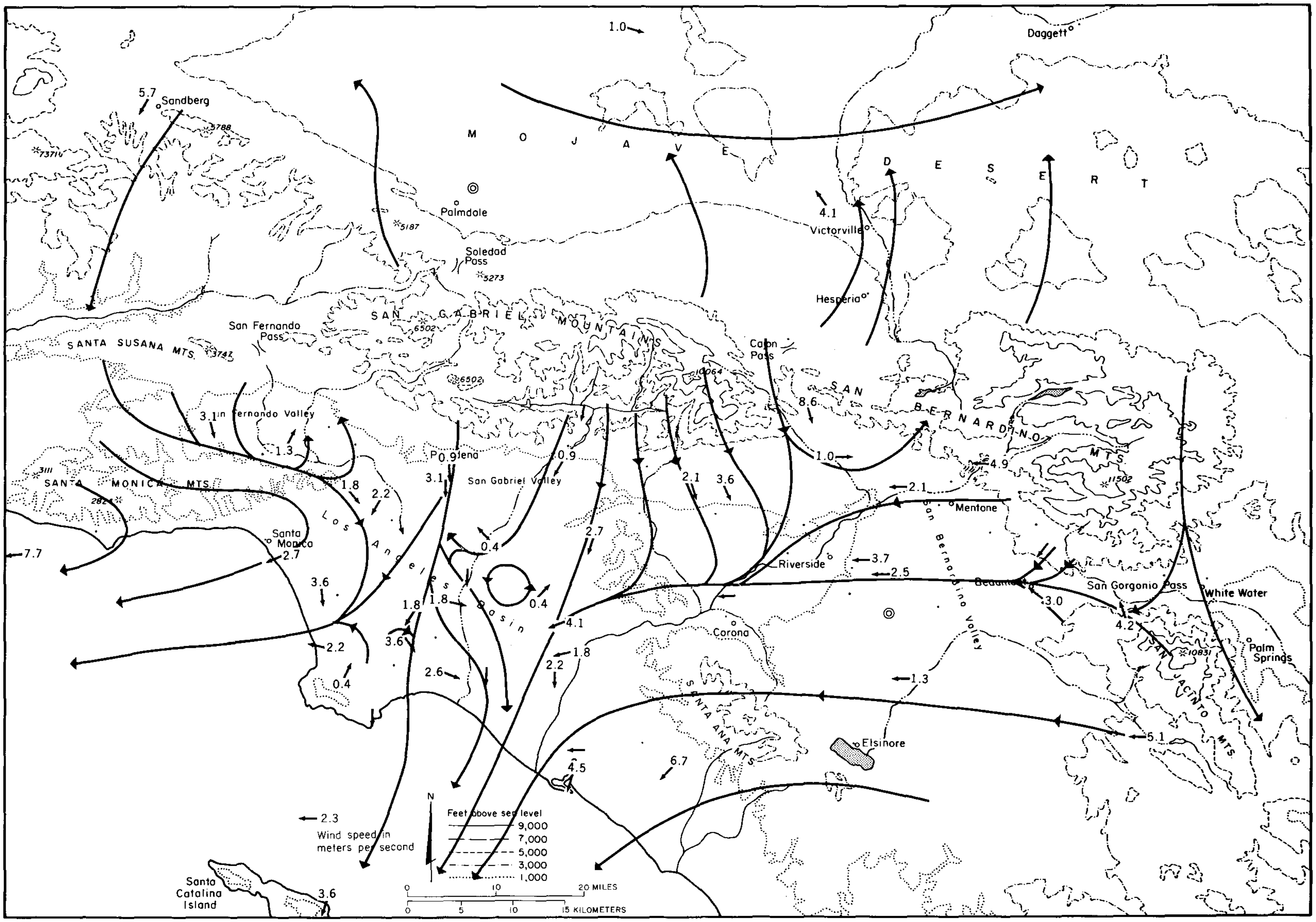

Figure 12.—*Surface streamlines 0700 P. s. t., 12 December 1963, showing decaying stage of Santa Ana.*

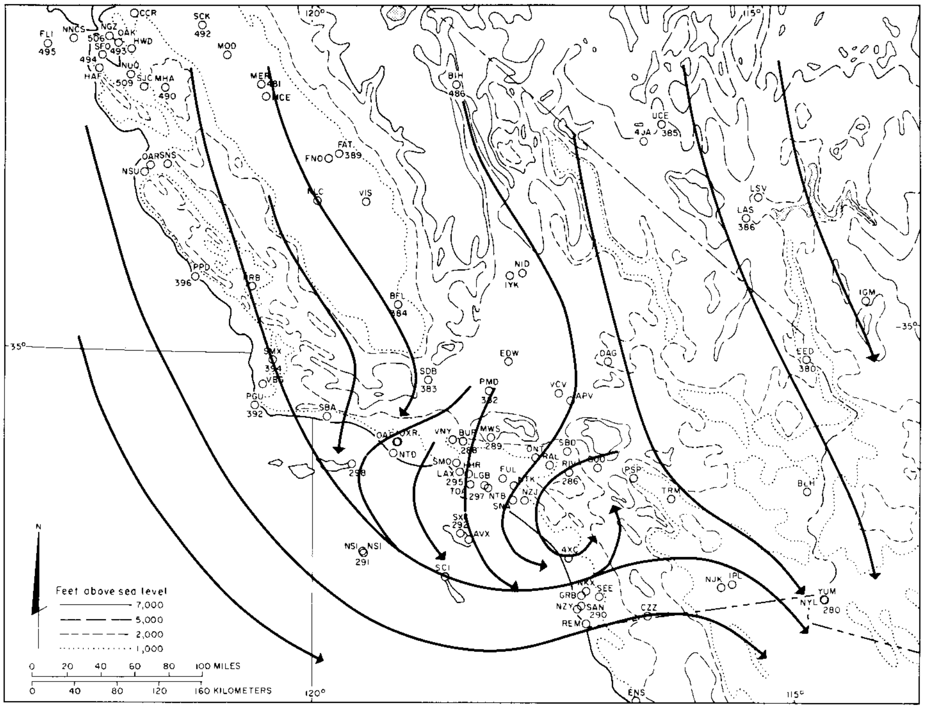

Figure 13.—*750 mb. streamlines 0400 P. s. t., 11 December 1963. Beginning of transition layer between local outflow and synoptic flow. Lee trough is pronounced.*

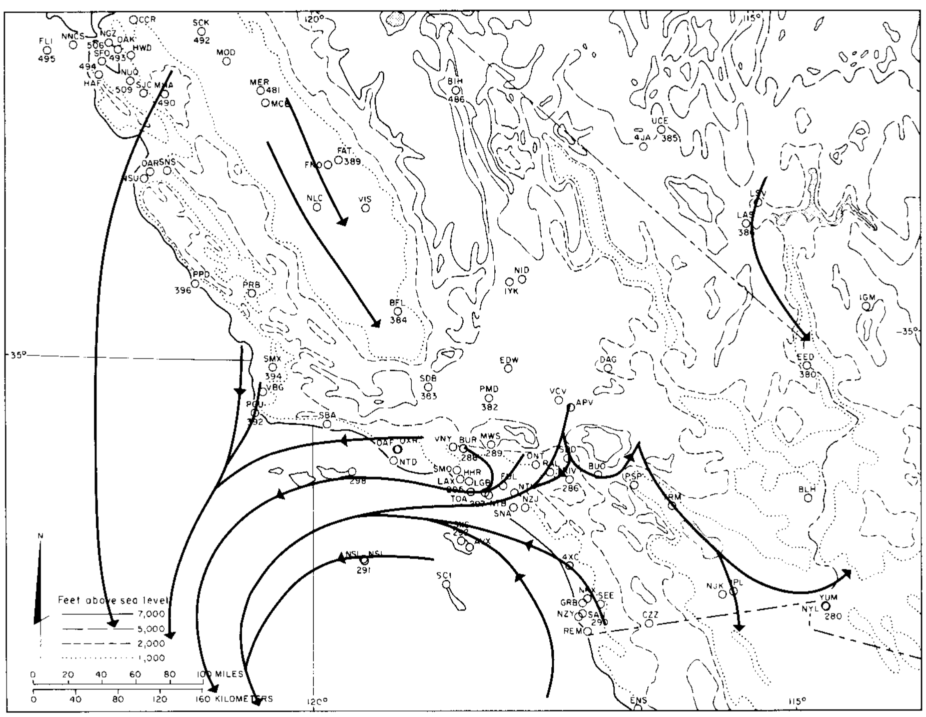

Figure 14.—*900 mb. streamlines 0400 P. s. t., 11 December 1963. This is the mid-level of planetary boundary layer and has appearance of smooth surface map.*

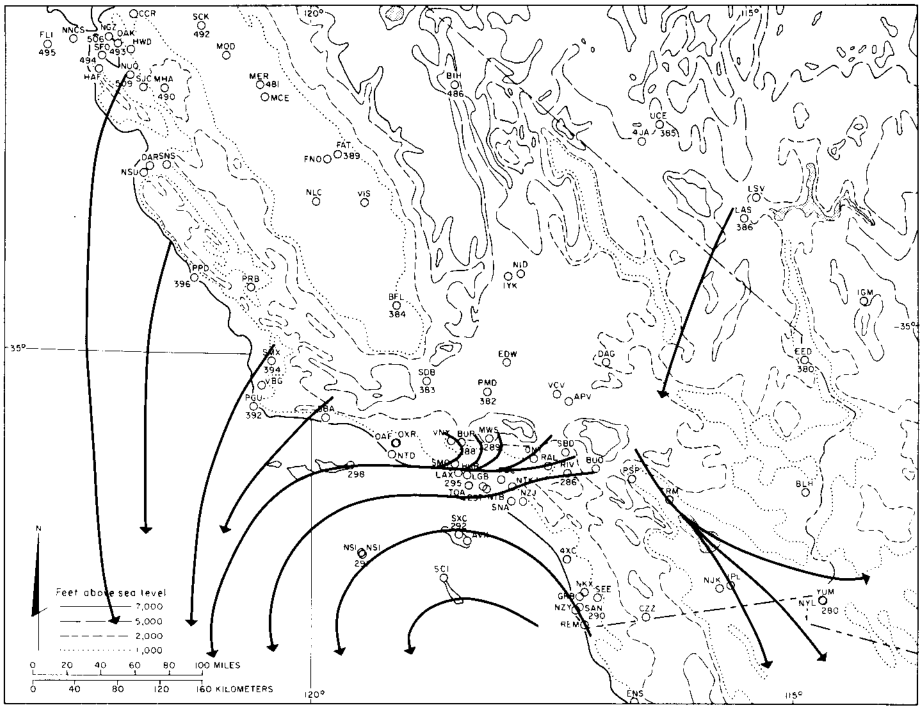

Figure 15.—*950 mb. streamlines 0400 P. s. t., 11 December 1963. Flow approximates that observed at the surface.*

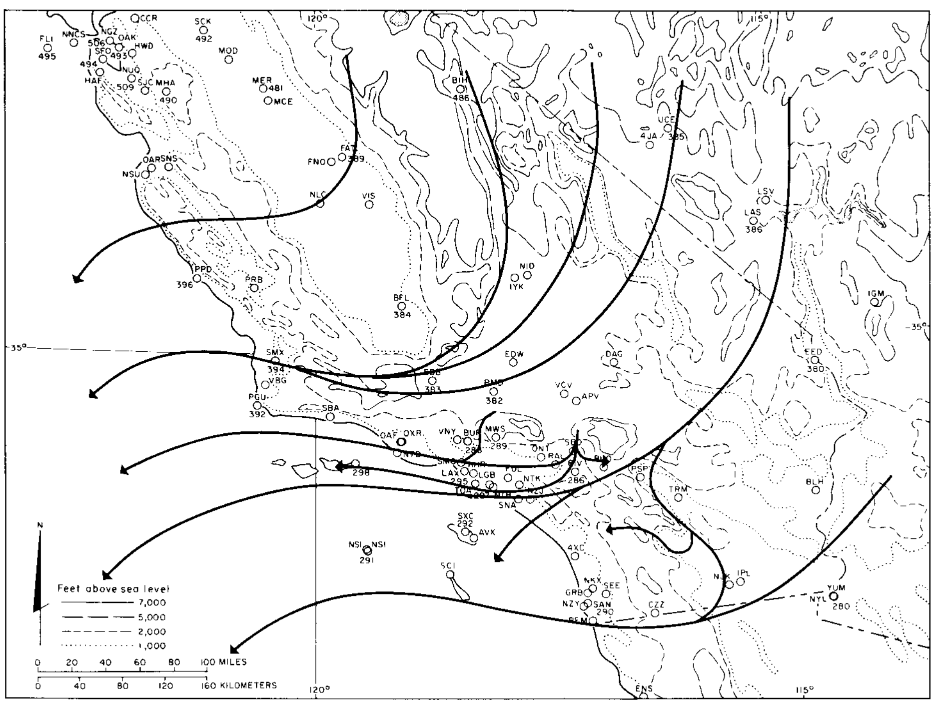

Figure 16.—*800 mb. streamlines 1000 P. s. t., 11 December 1963. The transition layer has lowered as gradient wind veered to north-east.*

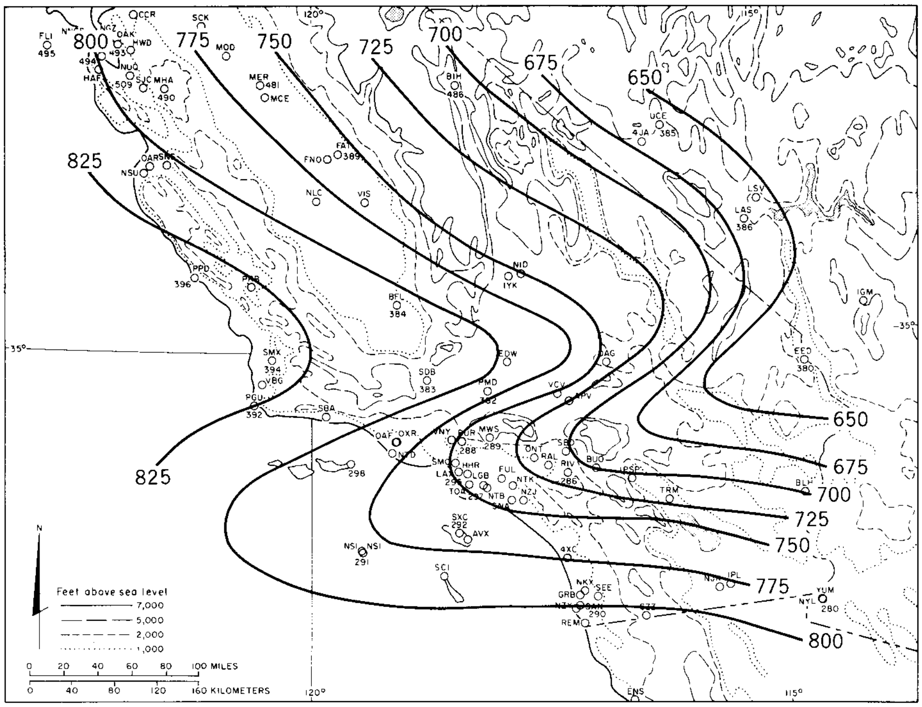

Figure 17.—*290A isentropic surface 0400 P. s. t., 11 December 1963. Flow is isentropic.*

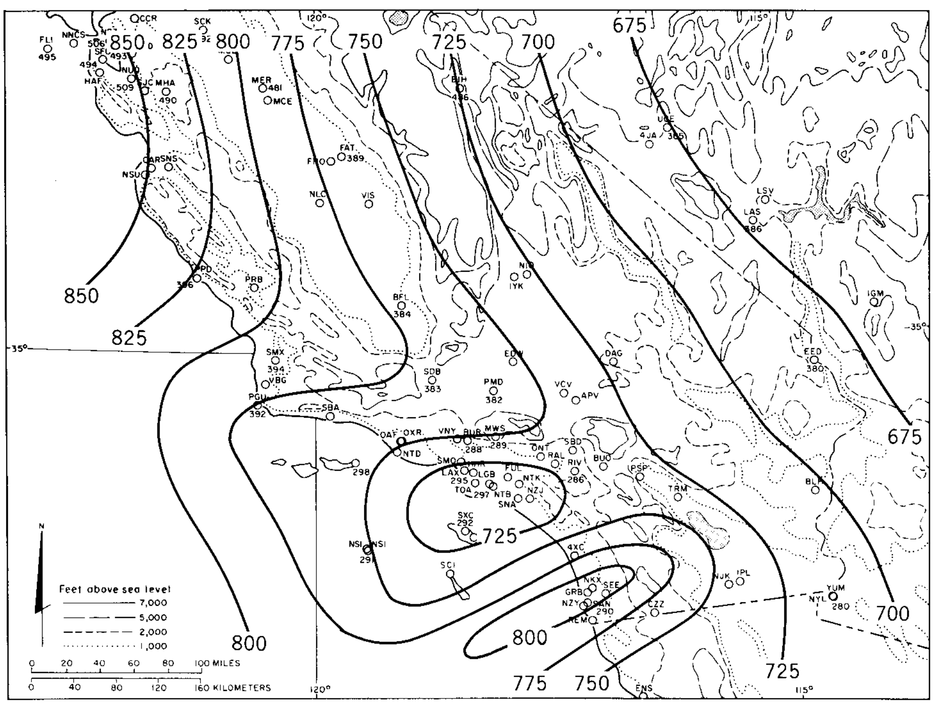

Figure 18—*290A isentropic surface 1600 P. s. t., 11 December 1963. This is the dissipating stage of the Santa Ana.*

Case of 7-9 January 1964

The synoptic development of this case was similar to the December case. An anticyclone moved southward from northwest Canada into the Great Basin late on 7 January 1964 (fig. 19). A trough associated with a weak front extended along the coast (fig. 19) so that the pressure gradient was 1.4×10^{-2} mb./km. The Great Basin anticyclone remained quasi-stationary during the Santa Ana. From 700 mb. up, a small amplitude trough began to deepen so that the winds veered to near north at 700 mb. (fig. 20) and north-northwest from 500 mb. up at 1600 P.s.t., 7 January 1964 (fig. 19). As in the December case the winds increased as height increased, and the static stability was negative so that l^2 decreased above 700 mb. and the synoptic features indicated conditions favorable for the formation of mountain waves. The dissipation stage was brought on by two factors: (a) The surface front and trough migrated eastward decreasing the surface pressure gradient; and (b) a vigorous short-wave trough caused a small amplitude ridging along the west coast.

The detailed local analysis of this case showed nearly the same features as the December case (figs. 21-24). Cajon, Soledad, and San Gorgonio Passes showed the strongest outflow. The wind shadow in the lee of the San Gabriel Mountains was less noticeable during the early stages, but became pronounced toward the end. As in the December case, the pseudo-sea breeze was delayed until 1300 P.s.t. (fig. 23). The sea breeze penetrated only in the wind shadow and was somewhat stronger than the December case. The local upslope winds on the lee side of the San Gabriels assisted in this invasion of onshore winds (fig.

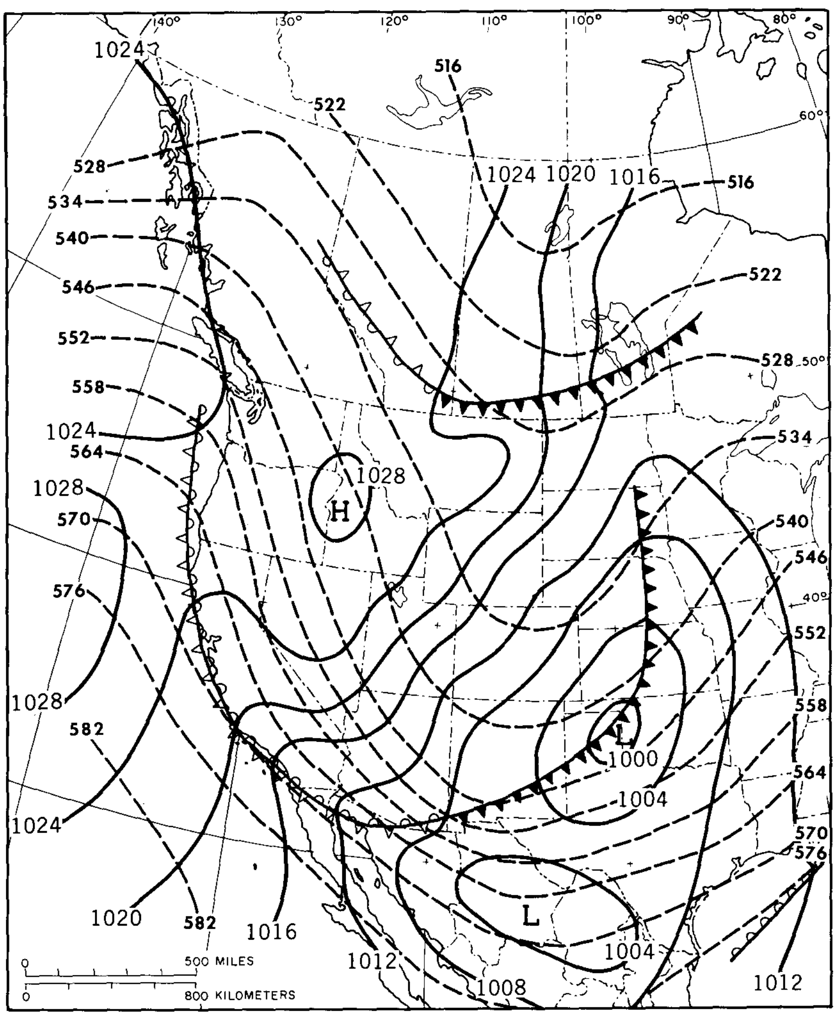

Figure 19. — *NMC analysis of 2200 P. s. t., 7 January 1964 surface features and 1600 P. s. t., 7 January 500 mb. synoptic features. Dashed lines are 500 mb. contours, solid lines are surface isobars.*

24). The outflow over the plain was about the same strength, but contained many more transient eddies from deflection around small obstacles and from convergence of different airstreams.

The local vertical cross section of wind and potential temperature illustrates the series of short waves downstream from the mountains and the long single wave of the lee trough (fig. 25). The importance of these two dominant wave lengths cannot be overemphasized. The short waves tended to behave as linear solutions; the long wave was produced by the conservation of potential vorticity. Again, as in the December case, the mesoscale analysis of constant pressure charts showed the tie between the synoptic features and the local outflow. The lee trough over the Los Angeles Basin was less pronounced in this case than during the December case (figs. 26-29). The mesoscale vertical cross section also showed the gradual weakening of this lee trough. The vertical displacement of the foehn air was on the order of 3 km. at the lower levels (below 700 mb.) and about 1.5 km. above that level (fig. 30), verifying the vertical stretching and conservation of potential absolute vorticity to form the mesoscale lee trough.

Since the small scale features and the synoptic scale pattern show a close relationship, this may account for the difference in intensity of Santa Anas. The differences between the two cases are slight, but there was some indication that the January case was somewhat less intense. The transition from large scale smooth flow to the gravity wave outflow was near 750 mb. for the entire case (fig. 26). The smooth transition was more marked, perhaps because the large scale flow was predominantly from the northwest. Only in the low levels was the flow perpendicular to the mountains.

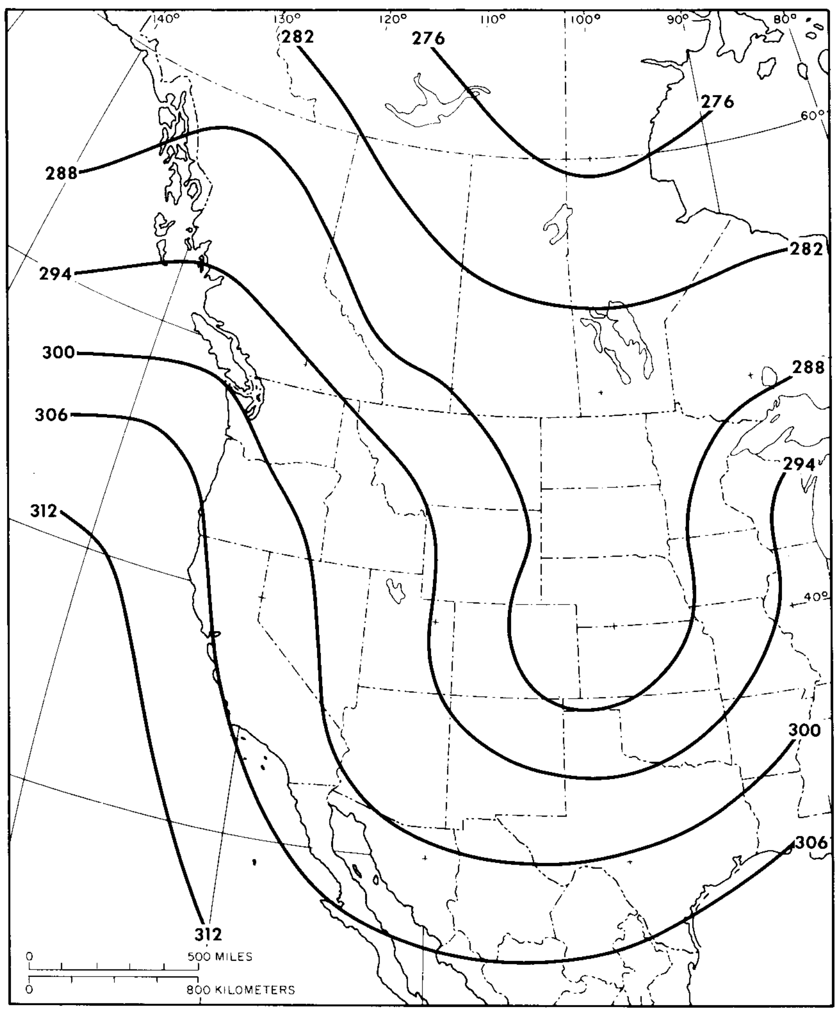

Figure 20.—*NMC analysis, 700 mb. chart for 1600 P. s. t., 7 January 1964, showing the beginning of Santa Ana synoptic conditions.*

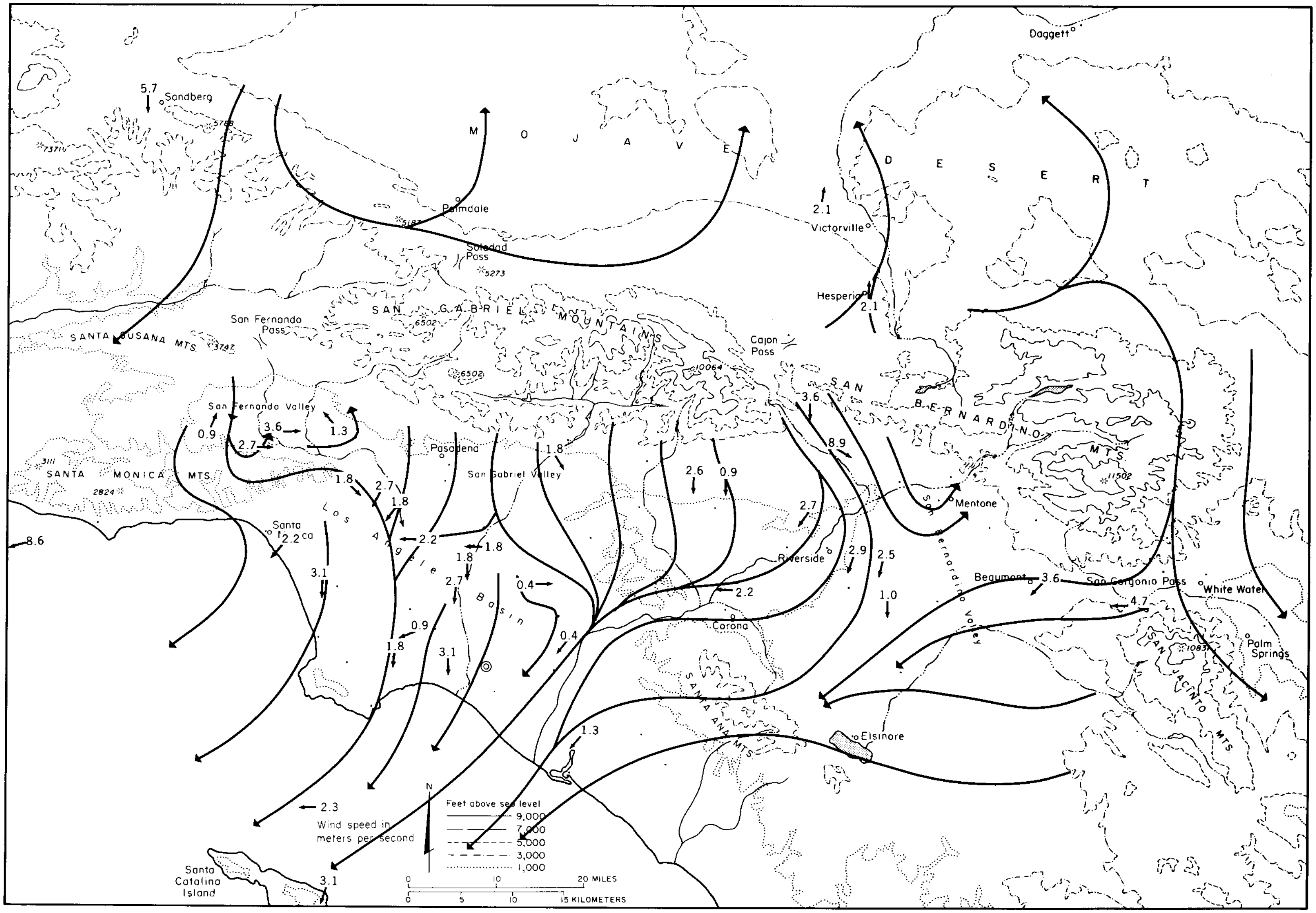

Figure 21.—*Surface streamlines 0100 P. s. t., 8 January 1964. Strongest flow is in the passes as in the December case.*

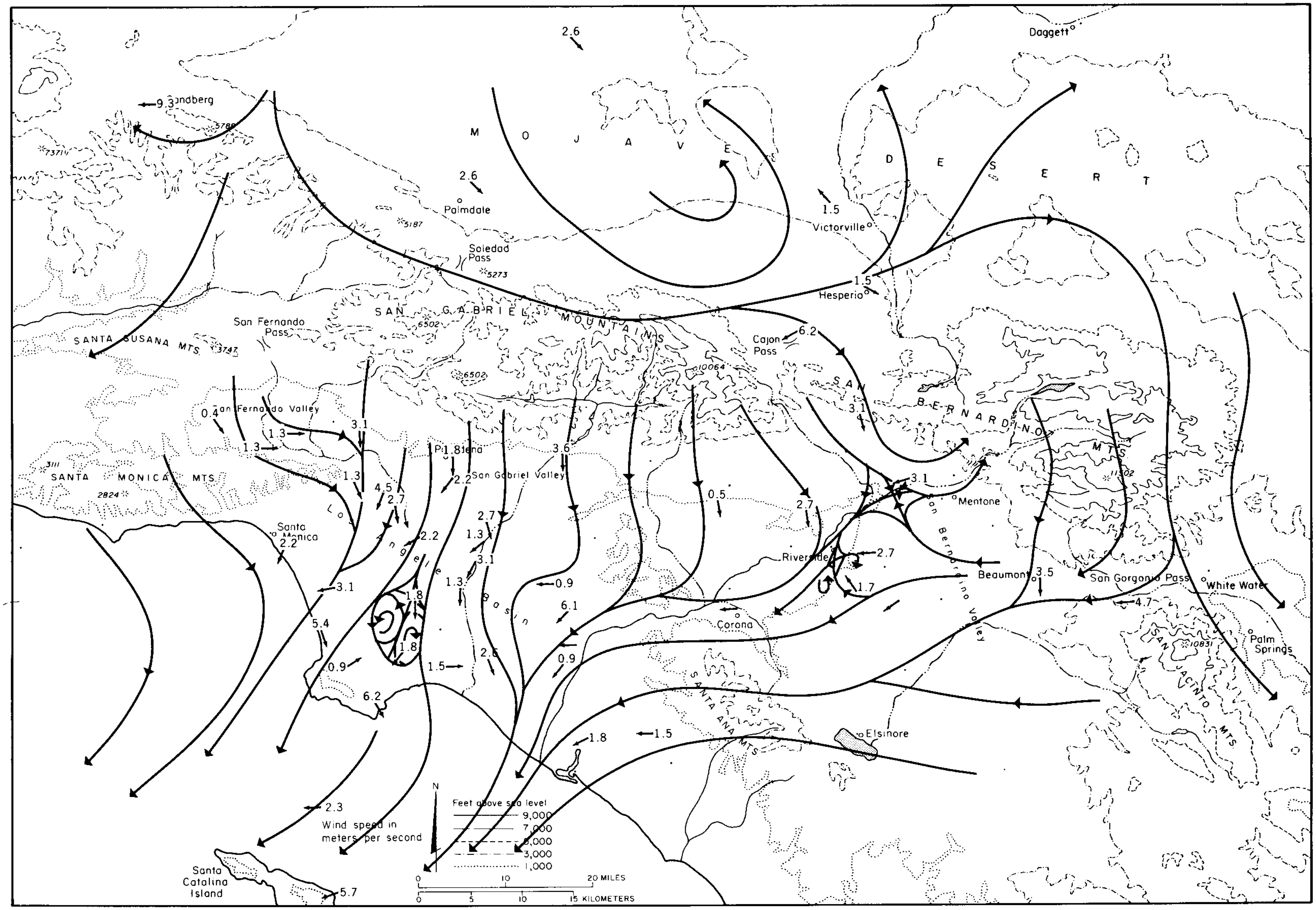

Figure 22.—*Surface streamlines 0700 P. s. t., 8 January 1964. Wind shadow is not pronounced at this time.*

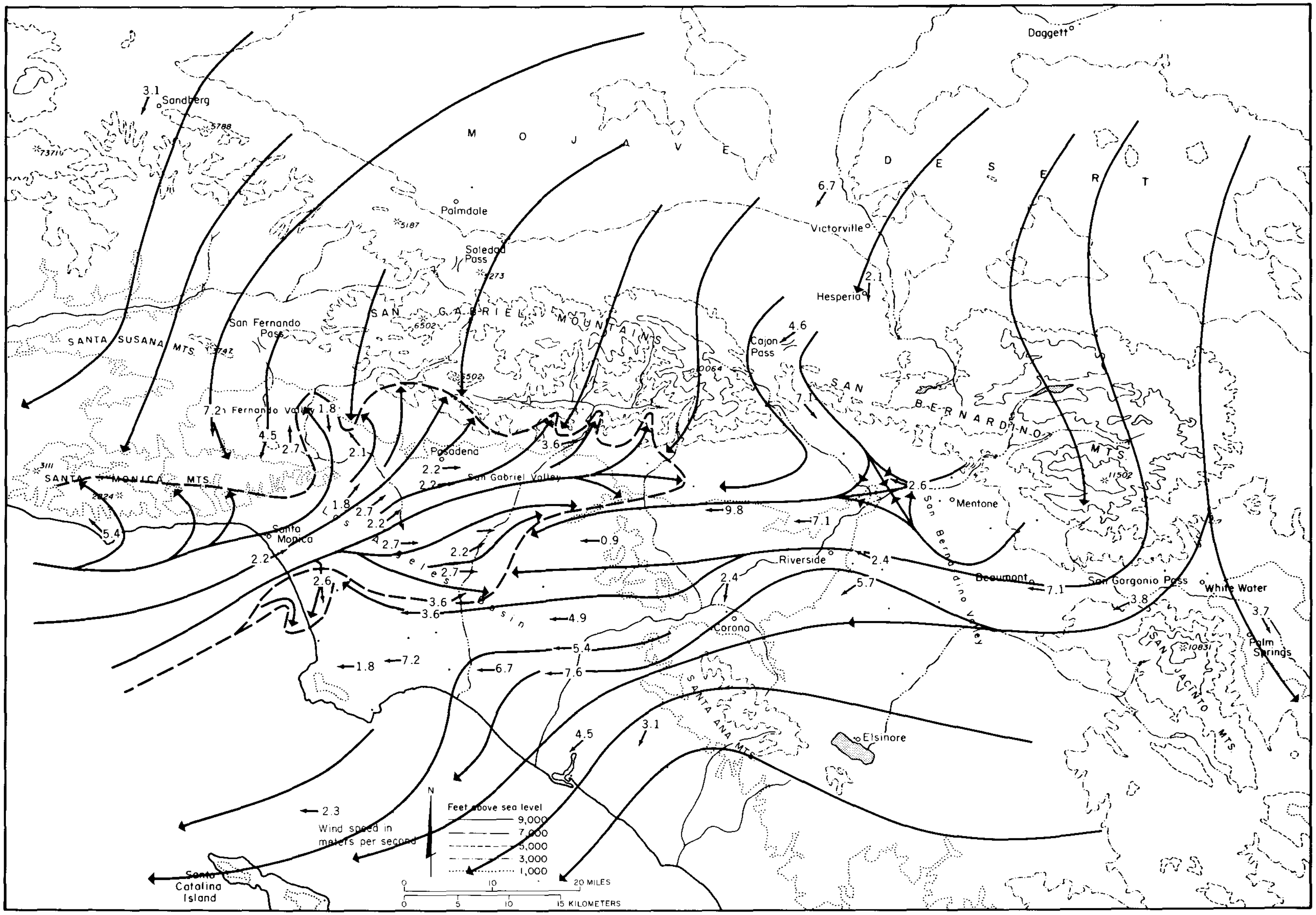

Figure 23.—*Surface streamlines 1300 P. s. t., 8 January 1964, showing the beginning of sea breeze penetration.*

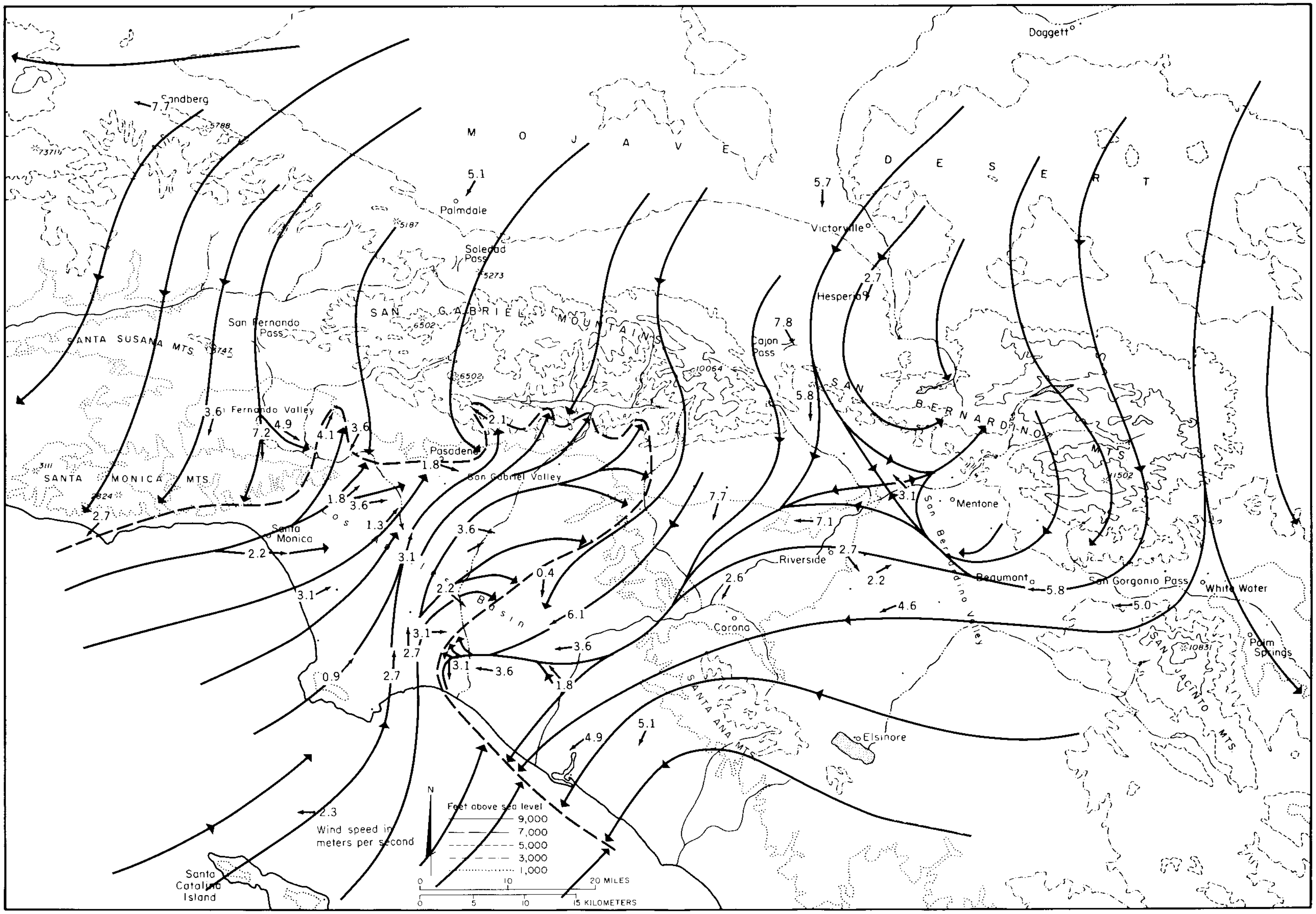

Figure 24.—*Surface streamlines 1600 P. s. t., 8 January 1964. Sea breeze has penetrated only in wind shadow of San Gabriel Mountains. The flow contains numerous small eddies.*

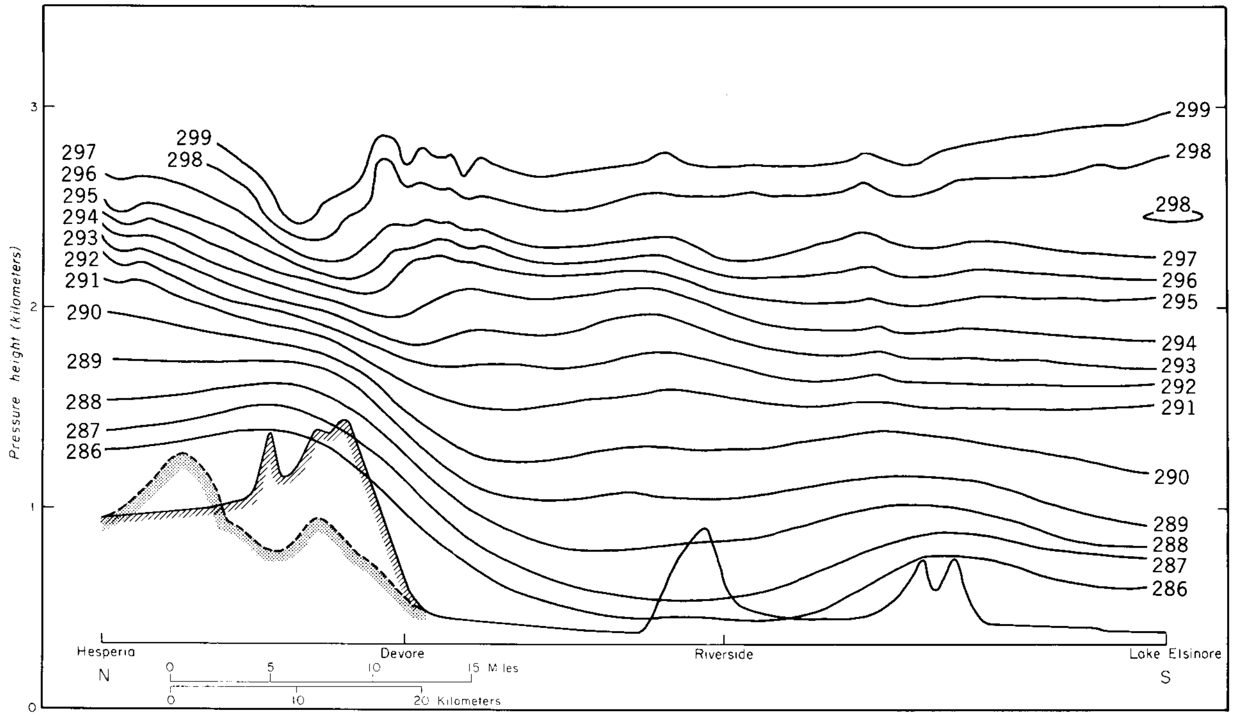

Figure 25.—*Vertical cross section of potential temperature Hesperia to Elsinore, 0420 to 0519 P. s. t., 8 January 1964. Bispectral wave pattern is strongly indicated. Dotted terrain is through Cajon Pass. Hashed terrain is along flight path of aircraft 2 to 3 km. east of Cajon Pass.*

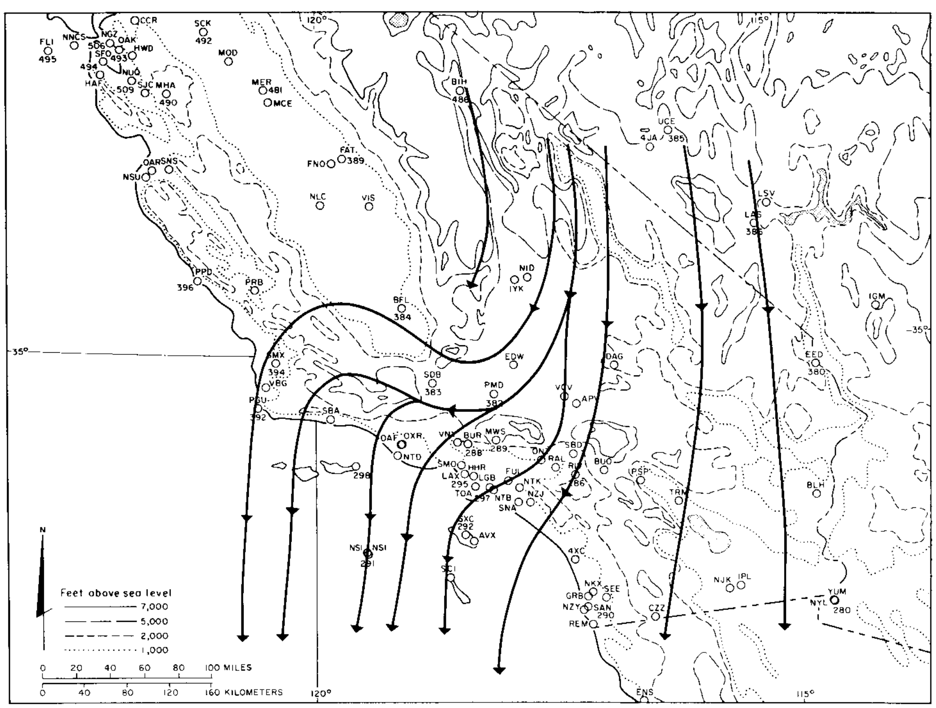

Figure 26.—*750 nib. streamlines /000 P. s. t., 8 January 1964. This is the top of the transition layer for the entire case. Deflection around flank of mountain is evident. The lee trough is less pronounced than in the December case.*

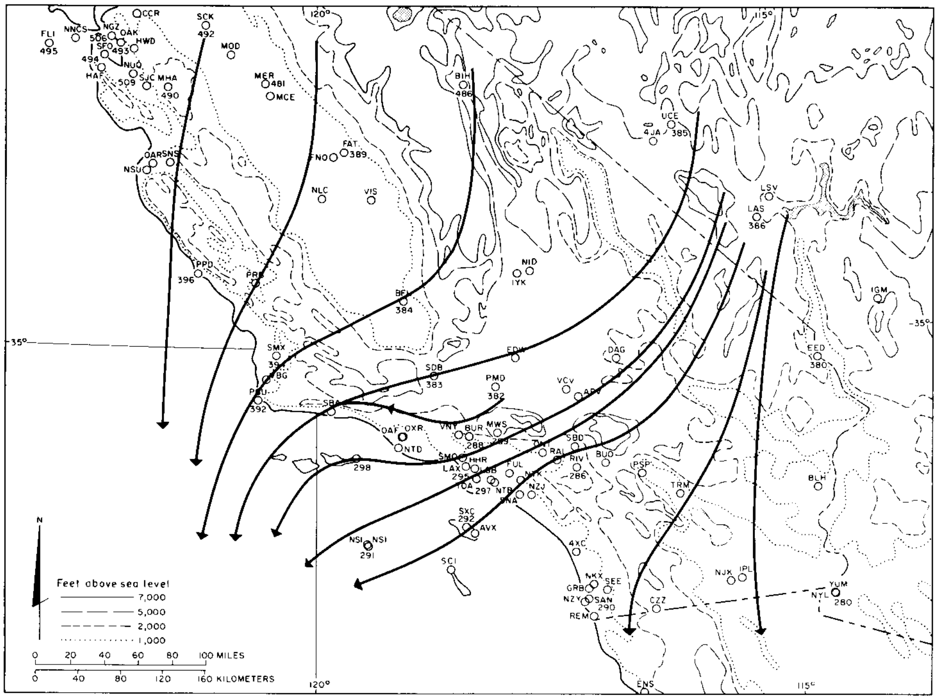

Figure 27.—*850 mb. streamlines 1000 P. s. t., 8 January 1964. There is only a slight hint of the lee trough.*

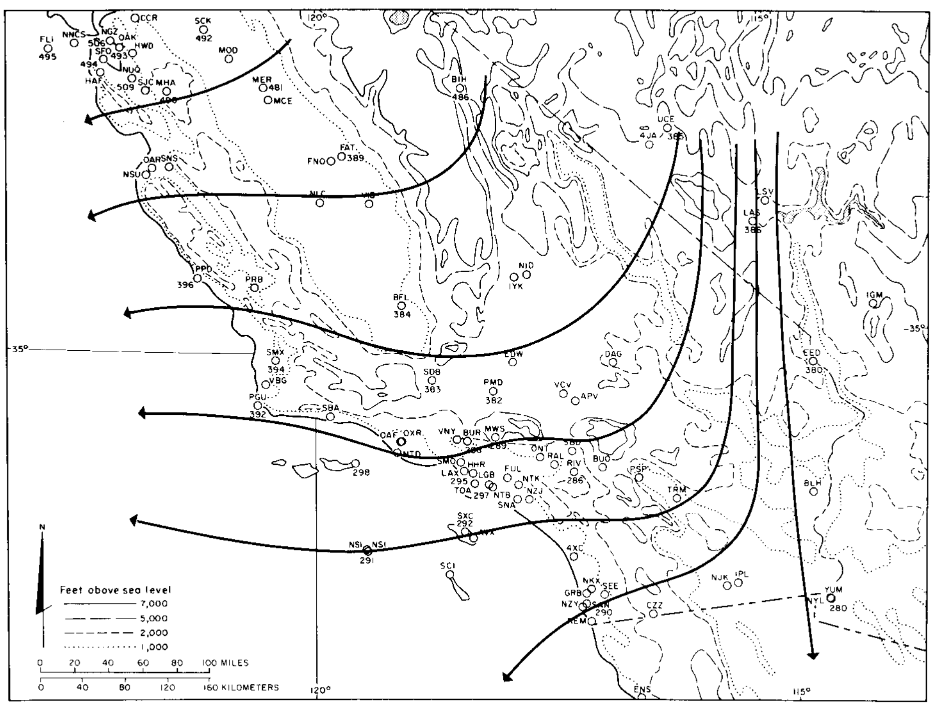

Figure 28.—900 *mb. streamlines 1000 P. s. t., 8 January 1964. Flow at this level approximates that observed at the surface.*

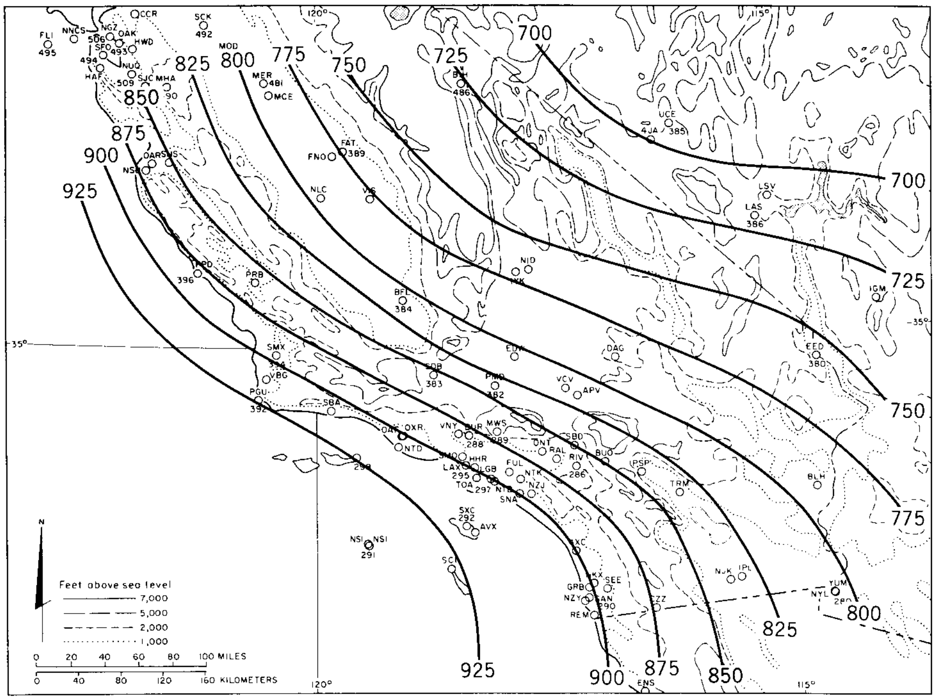

Figure 29.—*290A isentropic surface of 8 January 1964, 1000 P. s .t. Flow is nearly isentropic. Lee trough is not pronounced, supporting surface data to suggest a weak foehn.*

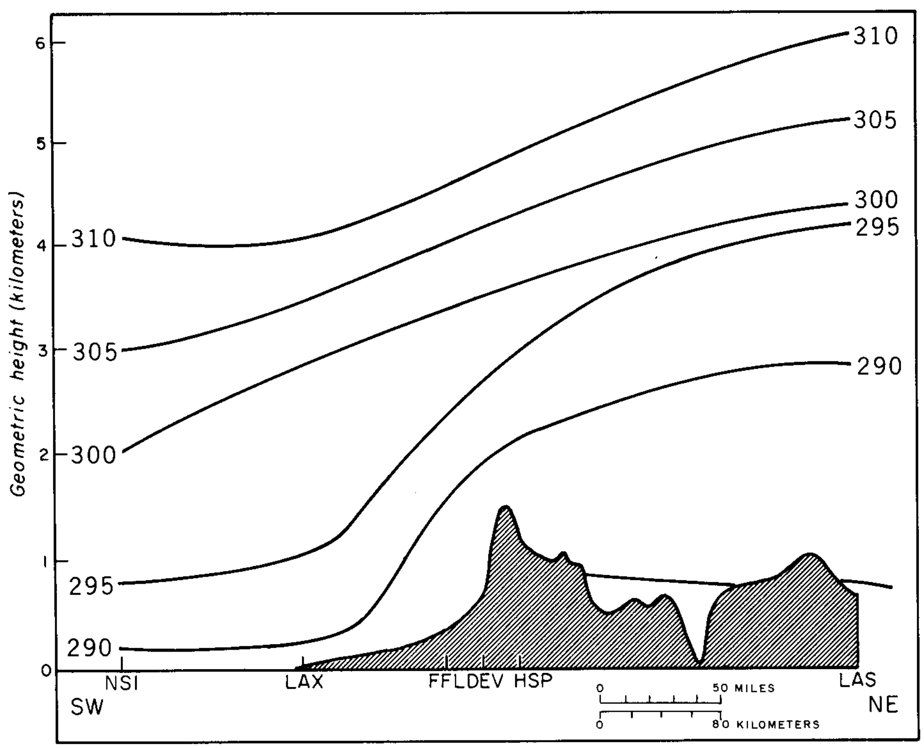

Figure 30.—*Vertical cross section of potential temperature Las Vegas to San Nicolas Island for 7 January 1964, 2200 P. s. t. Lee trough is well illustrated. Short waves have been smoothed out. Major source of outflow air is from the mid and upper troposphere.*

Implications

The simplest and perhaps most useful way to summarize the two case studies is to suggest a schematic structure of the Santa Ana (figs. 31-33). Apart from the synoptic patterns associated with the foehn flow, the most significant features of the Santa Ana are:

- The flow is nearly isentropic.
- Lee waves are responsible for nearly all of the observable features.
- The strength of the outflow of the Santa Ana appears to be determined by the thermal structure. Strong surface outflow occurs when there are strong quasi-horizontal reinforcing temperature gradients at the meso and synoptic scales.

A consistent and physically meaningful method of presenting the schematic structure is through isentropic analysis.

On an isentropic surface an increase in pressure corresponds to an increase in the Montgomery stream function. Therefore, flow on the surface is "baric" by definition because the pressure force and coriolis force are opposed.

Airflow is baric cyclonic about the cold dome of air in the Great Basin at all levels above the planetary boundary layer (fig. 31). As the flow reaches the San Gabriel Mountains, it is deflected predominantly to the east, but there is some non-isentropic flow to the west, particularly in the planetary boundary layer (fig. 32). The eastward deflection is reflected by a trough in the Lagrangian coordinate system as shown on the 290A and 286A surfaces (figs. 31, 32). Above and immediately downwind of the mountains, a lee ridge is formed by the conservation of absolute vorticity and vertical stretching. The flow in this ridge is isentropic and closely parallels the surface outflow of Santa Ana air. In this lee ridge the air flow is baric cyclonic on the north side as it flows offshore, but becomes baric anticyclonic as the Montgomery stream function turns onshore and forms an eddy between Los Angeles and San Diego. At a higher level—away from the frictional influences—the flow is baric cyclonic in the ridge at all levels. This lee flow is represented in a vertical cross section as a smooth field of potential temperature sloping down toward the coast in the low levels and upward in the higher levels (fig. 33). The major foehn islands are related to this lower mesoscale lee trough. As the outflow air impinges on small topographic obstacles, a foehn island is created. This type of foehn island is observed only in the outflow area over the plain.

Surfacing of the foehn both over the plain and in the mountain areas is determined by the static stability and the magnitude of the potential vorticity. With large amplitude waves, the Santa Ana surfaces and scours out the lee slope canyons. If the waves have a small amplitude, they separate from the lee slope near the ridge top, and normal up- and downslope winds are observed below the separation point. There are both periodic and antiperiodic components in the surfacing. The periodic component is a secondary factor. A 24-hour periodic component is introduced by the interaction of the large and small waves with the mountain and valley winds, and—in the wind shadow—with the sea breeze. The dominant component is antiperiodic and is determined primarily by the static stability and wind structure upwind of the mountain barrier. The intensity of the Santa Ana is determined by the gradient of the Montgomery stream function on the isentropic chart. The influence of latent heat, absent in the Santa Ana, but common in the European foehn, is relatively simple. It does not alter the dynamics of flow, but acts simply to increase the temperature of the foehn.

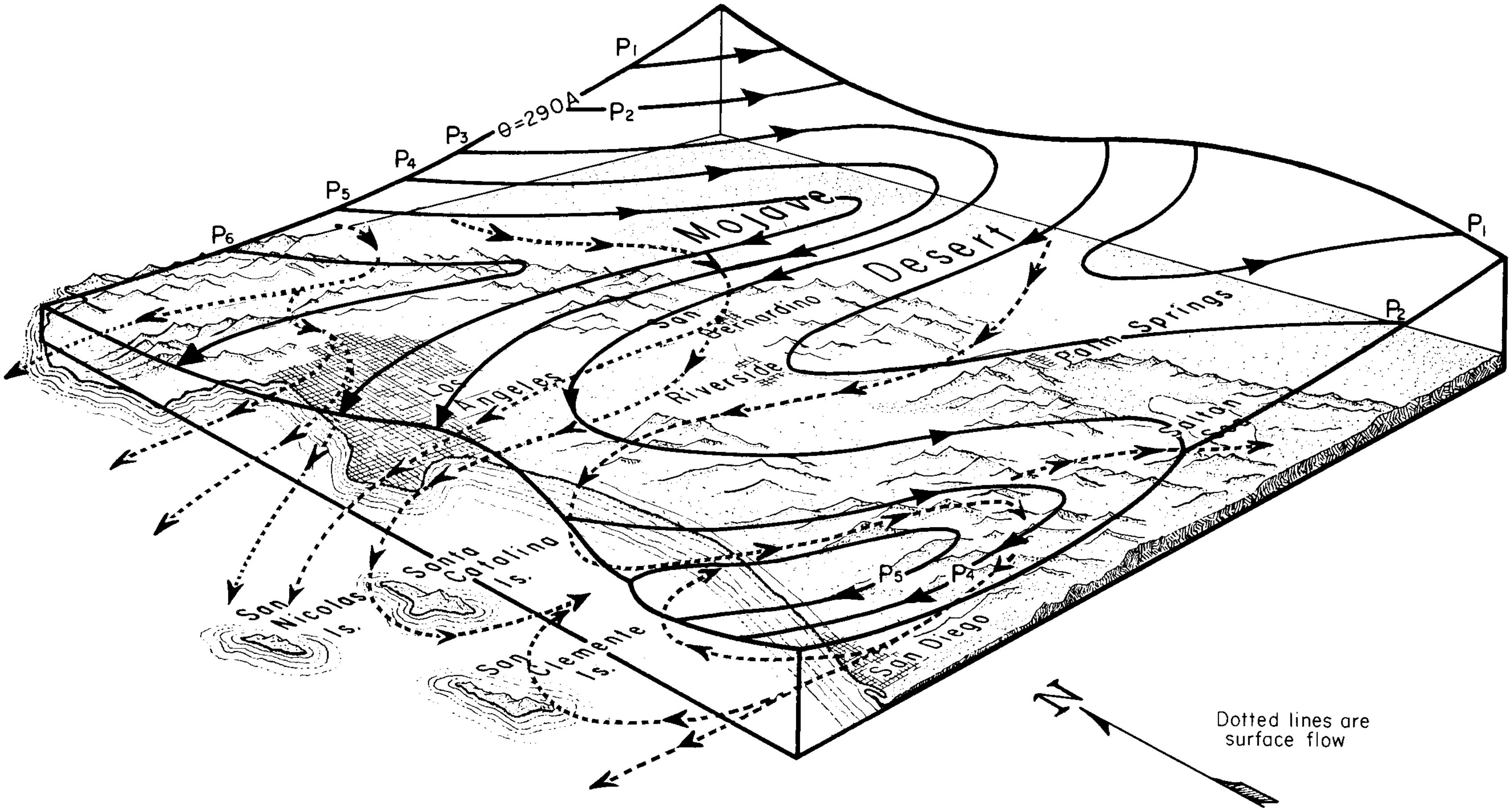

Figure 31.—*Descriptive model of Santa Ana illustrates a mature, intense Santa Ana with a well developed lee ridge. Isobars on isentropic surface indicate pattern of Montgomery stream function. The 290A surface is in the mid troposphere upstream of the mountains at the transition level over the mountains and in the outflow on the lee side.*

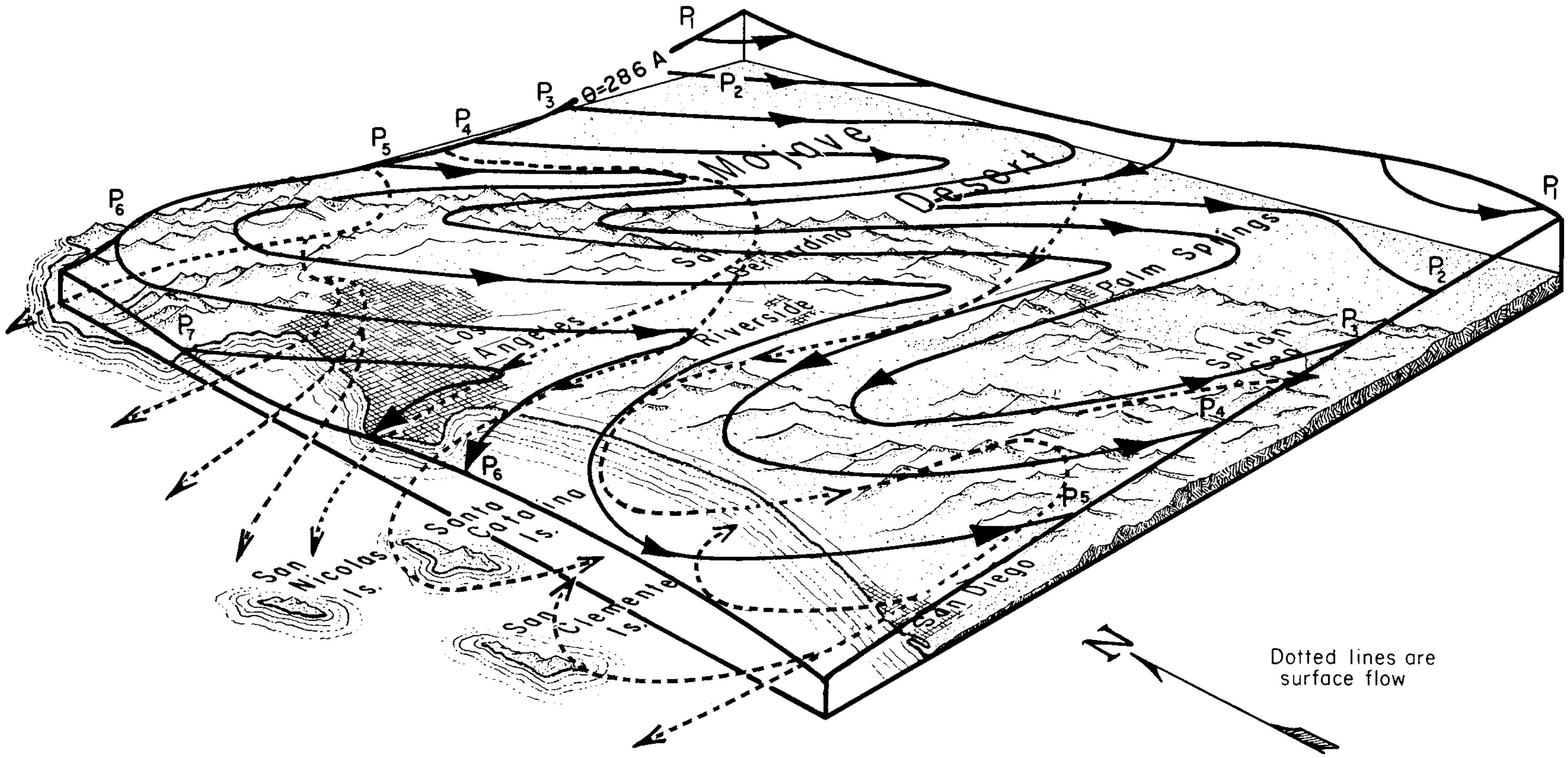

Figure 32.—*Descriptive model of Santa Ana within planetary boundary layer. Ideal case illustrated—a mature, intense Santa Ana, with a well developed ridge over the mountains and a trough to the lee of the mountains—is the same model as in figure 31. But in figure 31 the upper surface was the 290A surface, whereas in this figure it is the 286A surface. The 286A surface is in the transition layer over the mountains and in the outflow on the lee side.*

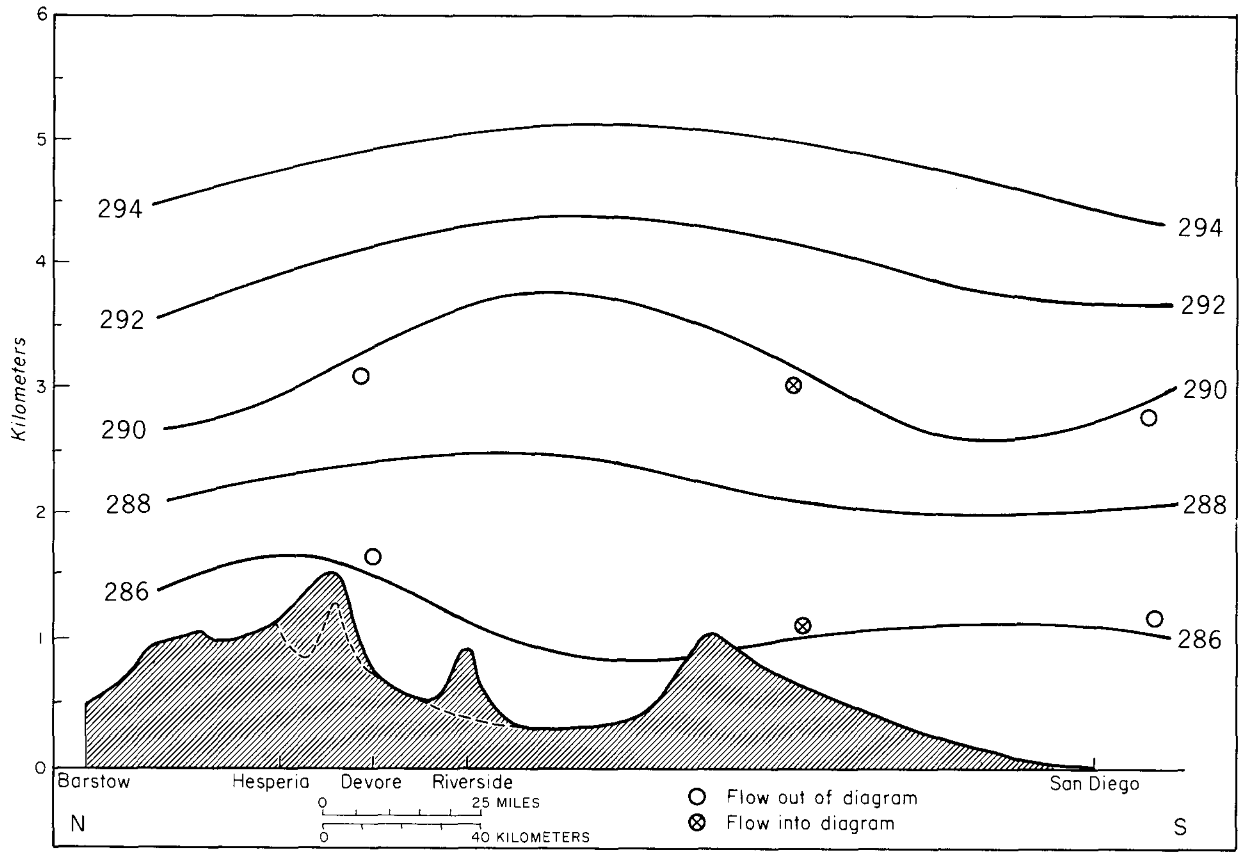

Figure 33.—*Ideal model of Santa Ana vertical cross section illustrates the long-wave characteristics of the higher and the lower level flow, and the vertical stretching to the lee side of the mountains.*

Recommendations

Most features of the schematic model are based on observations of the two case studies, features pointed out in the literature, and an application of meteorological theory. There are, however, two important features obtained by internal consistency of the model which need to be evaluated through additional studies. The interaction of the Santa Ana with the mountain-valley wind system and the land-sea breeze system should be examined in more detail. The second interaction of the synoptic, meso, and local scales needs further study. The intensity of the foehn, energy transfer processes from the synoptic scale to the local scale, and the development of the outflow can be examined by numerical analysis of the mesoscale energy properties on isentropic surfaces.

The data for analysis at this 1 to 250,000 scale has been loaned to the Department of Meteorology at the University of California at Los Angeles for further analysis of detailed outflow. We have retained the mesoscale data, at 1 to 3,000,000 scale, for numerical analysis of the energy properties, interaction, and intensity.

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