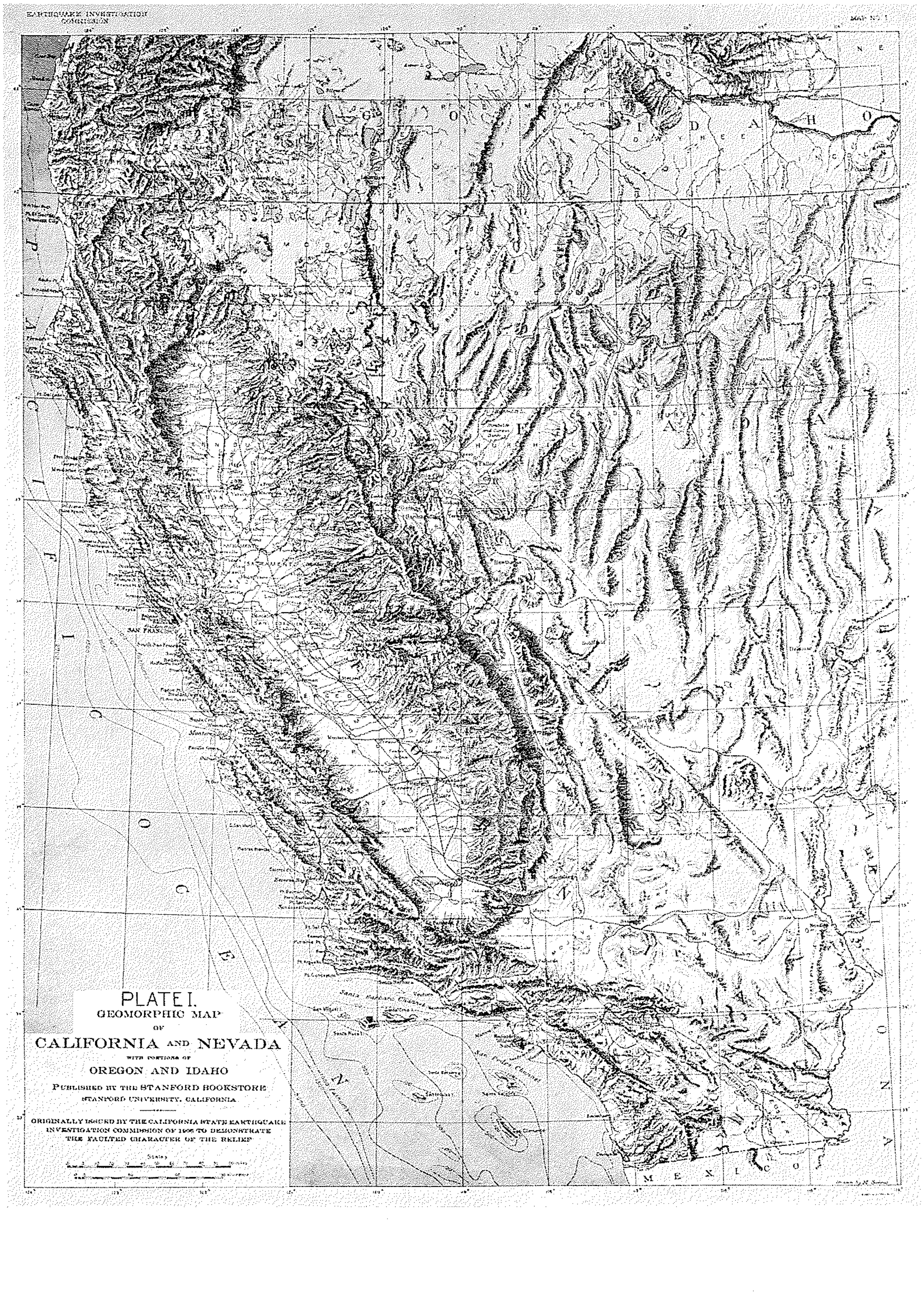
EARTHQUAKE INVESTIGATION
COMMISSION
MAP NO. 1
OREGON
IDAHO
NEVADA
SACRAMENTO
SAN FRANCISCO
PACIFIC OCEAN
MEXICO
ARIZONA
PLATE I.
GEOMORPHIC MAP
OF
CALIFORNIA AND NEVADA
WITH PORTIONS OF
OREGON AND IDAHO
PUBLISHED BY THE STANFORD BOOKSTORE
STANFORD UNIVERSITY, CALIFORNIA
ORIGINALLY ISSUED BY THE CALIFORNIA STATE EARTHQUAKE
INVESTIGATION COMMISSION OF 1906 TO DEMONSTRATE
THE FAULTED CHARACTER OF THE RELIEF
Scales

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
METEOROLOGICAL PAPERS, VOL. I, NO. 2

CHARACTERISTIC WEATHER PHENOMENA OF CALIFORNIA

A Regional Analysis Based on Aeronautical Weather Observations

BY

HORACE R. BYERS

WITH A CHAPTER ON WINTER FOGS BY

WILBUR M. LOCKHART, Lieutenant-Commander, U. S. N.

CAMBRIDGE, MASSACHUSETTS
1931

PREFACE

THE appearance of this California regional study as a publication of the Massachusetts Institute of Technology should perhaps be explained. Professor C. G. Rossby, in charge of the Meteorological Course, organized and directed the aeronautical weather service in California for the Daniel Guggenheim Fund. The organization was later placed in the hands of the Federal Government. The author was engaged in the routine operation of this service as an assistant to Professor Rossby and later under the supervision of Major E. H. Bowie, meteorologist of the U. S. Weather Bureau. The daily work of this rapidly growing weather-reporting system allowed little time for a thorough investigation of the meteorological phenomena, and it was not until 1930, while studying at the Massachusetts Institute of Technology, that the author could undertake an analysis of the great mass of observational material.

Lieutenant-Commander Wilbur M. Lockhart, who has contributed the chapter on the winter fogs, assisted greatly in the work of this publication. His experience in Navy aerological work on the Pacific Coast has placed him in a position to deal understandingly with the weather phenomena of this region. The author is indebted to him for compiling and analyzing the data for the situation of December 9 to 12, 1928, appearing in the first part of Chapter IV.

The authors wish to express their appreciation of the assistance and advice given by Professor Rossby, who supervised the investigation. Officials of the U. S. Weather Bureau, the Navy Department and the Lick Observatory of the University of California kindly provided copies of their records and observations. The values for reducing the barometric readings (aneroid) to sea level were determined by Mr. D. M. Little of the Oakland office of the Weather Bureau.

CONTENTS

Chapter I

INTRODUCTION

During the fiscal year beginning July 1, 1928, the Daniel Guggenheim Fund for the Promotion of Aeronautics maintained an experimental meteorological service for the benefit of air transportation between San Francisco and Los Angeles. The system was designed as a first approach toward a model weather reporting organization for air traffic. Its main feature was the gathering of simultaneous weather observations from about 35 stations in Southern and Central California covering an area of, roughly, 65,000 square miles. The observation hours were 6.30 a.m., 8 a.m., 9.30 a.m., 11 a.m., 12.30 p.m., and 3.30 p.m., 120th meridian time. The regular Weather Bureau observations furnished additional data for 5 a.m. and 5 p.m. A description of the organization has been published by E. H. Bowie.[1]

Since the service was organized strictly for the purpose of informing airplane pilots of weather conditions over their routes and not with a view of furnishing a fertile field for meteorological investigations, certain instrumental readings which are important in meteorological research were not provided. Thus humidity observations are lacking, except as subsequently obtained from the few but more thoroughly equipped stations of the U. S. Weather Bureau, the U. S. Navy and the University of California.

A series of airplane ascents made at the Naval Air Station at San Diego provided pressure, temperature and relative humidity observations from the upper atmosphere for part of the period investigated. Three pilot balloon stations were established by the Fund to supplement those of the Government, so that ample free air wind data are available.

Non-professional part-time observers were employed at most of the stations. For this reason, inaccuracies are likely to have lessened the value of the reports. These errors occurred chiefly in the determination of cloud forms. When the uncertainties of cloud classification and the difficulties it presents even to the trained meteorologist are fully appreciated, the errors in these observations are not surprising. It is the opinion of the authors that the cloud forms herein recorded are for all practical purposes correct.

During the year in which this service was conducted by the Fund, some interesting data were collected to add to the knowledge of meteorological conditions in California. This applies particularly to the movement of fronts and the development, distribution and dissipation of the persistent and frequent fogs in the area. Some of these results will be presented below.

Peculiarities of the Region

Physical Features. To make the discussions in this paper clear it is necessary to call attention to the general physical features of California and the region about it. (Plate I.) Neglecting Southern California and the desert regions, California consists mainly of two large valleys, the San Joaquin and the Sacramento, draining toward each other into San Francisco Bay to form one great, continuous basin; bordered on the west by the Coast Ranges with their narrow valleys and on the east by the high and massive Sierra Nevada. The Tehachapi Mountains in the south and the Siskiyous in the north make the seclusion of the Great Valley com-

[1] Bowie, E. H., Weather and the airplane, publication of *The Daniel Guggenheim Fund for the Promotion of Aeronautics, Inc.* New York (1929).

plete except for the relatively narrow, steep-sided strait leading into the northern end of San Francisco Bay. The valley is very flat, rising imperceptibly toward the surrounding foothills. The Sierra forms a barrier which is on the average 6000 to 8000 feet high with somewhat lower points at the northern and southern extremities. The Coast Ranges are for the most part 2000 to 5000 feet high and lowest about San Francisco Bay. They consist of steep-sided mountain ranges with narrow valleys between, all running in a northwest-southeast direction. There is no coastal plain.

In Southern California the structure is different. South of San Luis Obispo the Coast Ranges give way to a series of high, more irregular ranges running east and west in a system joining with the Tehachapi and San Bernardino Mountains. South of Los Angeles the ranges again turn parallel to the coast. Beyond them to the east and northeast lie the broad deserts.

East of the Sierra in Nevada and western Utah is the Great Basin, the floor of which, for the most part, is about 4000 feet above sea level. The Colorado Plateau, a high, relatively flat region, lies to the north of it in eastern Oregon and southwestern Idaho.

Weather and the Climate. It will be difficult for the reader to gain a thorough understanding of the weather conditions in California without some knowledge of the peculiar influences at work in this region, particularly those caused by the rugged relief. A brief description of the climate emphasizes to what extent these modifications make themselves felt.

The California climate is mainly of Mediterranean and steppe type, characterized by long, dry summers and a marked maximum of rainfall in winter. In general, exclusive of the mountains and deserts there are two major climatic provinces — the coast and the interior valley.[2] There is very little difference in temperature between coast and interior in winter, but in summer the contrast is very marked, ranging from 30 to 50 degrees Fahrenheit difference in midday temperature during most of the warm season. As would be expected, the coastal region has more abundant rainfall than the interior. San Francisco receives about ten inches more precipitation in a year than stations in the same latitude in the interior valley. Proceeding southward, one finds arid conditions approaching nearer to the coast. The coast has "high fog" nearly every day during summer and dense surface fogs of different origin are frequently observed for long periods of time in the interior valley in winter.

The semi-permanent Pacific anticyclone, the counterpart of the Azores HIGH of the Atlantic Ocean, has a profound influence. In summer it generally lies to the northwest at about lat. 40°, and in winter it is displaced southward towards lat. 30°. During the warm season it is continually feeding fresh maritime air into the thermal low pressure areas of the hot, dry regions of the Southwest. In winter, when radiation cooling produces over the land another region of high pressure, there are often two anticyclones, one over the plateau and one over the ocean, to the southwest. The plateau, or Great Basin, anticyclone is not of the stationary, semi-permanent type. It is frequently replaced by cyclones. However, this HIGH is known to remain tenaciously stationary during long periods of time.

Practically all of the cyclones of California come by way of the Aleutian Islands. They move down along the Pacific Coast accompanied usually by occluded or rapidly occluding fronts. Obviously, such an extended southward movement is not the normal development. It is only when cold air over the Canadian prairies prevents the normal southeasterly passage that storms are forced as far south as California. Therefore, this is chiefly a winter phenomenon.

As a result of these pressure distributions, on-shore winds are in great preponderance in summer, northwest to west directions prevailing. In winter, on the other hand, almost any

[2] For a complete classification of the climates, see:
Russell, R. J., Climates of California, *University of California Publications in Geography*, vol. 2, pp. 73-84, October, 1926.

direction is possible, and a considerable variation in the prevailing winds from year to year is observed.

The California climate in many respects is unproductive of interesting and diversified meteorological phenomena. Fronts pass over the region relatively infrequently; rapid changes in the weather are seldom observed; and the "cold wave" common to most of North America is unknown. Owing to the influence of ocean currents in summer and to the stagnation of maritime air masses in winter, the region is one of frequent and persistent fogs.

The Influence of the Mountains. An examination of the relief map immediately impresses one with the mountainous character of the California landscape. These irregularities of relief stand out more than anything else as modifying factors in the climate and weather. Without an understanding of the effects of these mountain ranges, the work of the meteorologist in analyzing the weather situations is hopeless. Therefore, the writers feel that it is necessary to explain in some detail the influences exerted by the mountain barriers.

The mountain effects may be classed as follows:

(1) Damming.
(2) Diversion of air flow.
(3) Forced condensation and precipitation.
(4) Dynamic heating — the Föhn.

It is hardly necessary to point out that these effects are not independent of each other. The classification is introduced merely to facilitate the discussion.

(1) The damming effect occurs wherever high and extensive mountain ranges exist. The inrushing sea fog resting against the coastal mountains offers a very good example. Another case in point is furnished by the frequently observed steep pressure gradient across the mountains. This gradient does not give rise to the high wind velocities which would ordinarily be expected. The pressure gradient is meaningless except that it demonstrates the existence on either side of the mountains of two masses of air of different weight. They are not in contact with each other at the lower levels and therefore their potential energy cannot be set free. An analogous situation can be created artificially in the laboratory by placing two liquids of different density in an open container so that they are separated by a thin vertical wall. If both sections of the container are filled to the same level, there will be a pressure gradient between them in the partition, but there will be no flow. Such complete independence between two neighboring air masses can seldom be realized in the earth's atmosphere, but it is closely approximated at lower levels under conditions such as those found on the Pacific Coast.

(2) The question of the diversion of air flow by the mountains in many cases becomes very complex. To understand it thoroughly requires an intimate knowledge of the relief. The most striking example of the domination of the air flow by the relief is perhaps afforded by the narrow coastal valleys, such as the Salinas Valley, where only two wind directions are possible — northwest and southeast. It is a well-known fact that stable air will move around obstacles whereas unstable air will pass over the mountains. The northwest winds are generally more stable in the summer than during the winter. Therefore, the directing influence of the mountains is greater in summer. Another illustration is afforded by the summer stream lines shown in plate VIII. Here, however, enters in the additional effect of valley breezes acting in response to a horizontal temperature gradient. Throughout the summer the winds blow along the California Coast from the northwest, sometimes shifting to west. The air movement is generally so unchanging in direction that one can, without great error, assume the mean values to be representative of instantaneous conditions. It will be noted that a crazy

pattern of wind direction is followed. In the valleys north of San Francisco Bay the northwest wind turns around into the opposite direction.[3] In many other regions there are similar peculiar trends, but upon examination of the relief, the reason becomes obvious.

In summer, the innermost portions of the valleys are warmer than their lower reaches. In response to this temperature distribution the air will move up the valleys regardless of their orientation. With the possible exception of the Sacramento Valley, a horizontal sea level pressure gradient is nowhere discernible which would cause the winds to change about from their original northwesterly direction. These summer winds decrease in velocity with altitude. In winter, when northwest winds may occur with velocities increasing with altitude, the pressure gradients are strong enough to prevent the development of mountain and valley breezes. Besides, the local differences in temperature are less marked at this time of the year.

(3) All of the mountains of the Pacific Coast play an important rôle in producing clouds and precipitation. Much of the rainfall of the area is due in part to orographic influences. The coastal mountains are very effective in precipitating the moisture and allowing the interior valley little or no rain. On the western side of the valley, in the lee of the mountains, the result is especially marked, this section showing up as a belt of deficient rainfall both on our weather maps and in the climatological data. Vertical movements set up by the mountains also account for considerable cloudiness on the western slope of the Coast Range as normally would be expected.

(4) Perhaps no phase of mountain influence is felt more profoundly in California than the Föhn. No body of air can pass from the plateau region down into the valleys of California without being heated at least 20° F. For this region, the movement of air from the continent, except when unusually cold at its source, generally means unseasonably warm weather. The well-known "cold wave," characteristic of the greater part of North America, often develops into a "heat wave" over most of California. In geographical and climatological literature, many writers have accounted for the mild winter as an effect of the maritime location. An equally significant explanation for the warm winter is the adiabatic heating due to mountains of the air from the only possible cold air source, namely the interior of the continent. Blake[4] has observed that in the vicinity of Los Angeles, movement of air from the land brings high temperatures at any season.

The Air Masses of California

California is not invaded by as many different types of air masses as regions in its latitude farther eastward. As far as the writer's investigations have gone, only three main classes are discernible. Since it is convenient to refer to different types by special names, a classification of air masses will be helpful. At the Massachusetts Institute of Technology a system for classifying the air masses of North America has been outlined and essentially the same nomenclature, an adaptation of Bergeron's system,[5] will be used in this paper.

Since we are dealing with weather situations of a local character, the definitions of the air masses in the following paragraphs are based upon their properties as observed in California, and refer to this region only. Some transition types are recognized here which for lack of data must be overlooked on our general North American synoptic charts.

[3] The directing influence of the mountains was pointed out in 1902 by F. H. Bigelow in Barometry of the United States, Canada, and the West Indies, *Report of the Chief of the Weather Bureau,* 1900-1901, vol. 2, p. 16. Washington (1902).

[4] Blake, D., Temperature inversions at San Diego, as deduced from aerographical observations by airplane, *Monthly Weather Review,* vol. 56, pp. 221-224, June, 1928.

[5] Bergeron, T., Über die dreidimensional verknüpfende Wetteranalyse, *Geofysiske Publikasjoner,* vol. 5, no. 6 (1928).

The air masses are as follows:

Polar Continental (Pc). Air masses originating (i.e., acquiring their principal characteristics) over the tundra and ice cap between Hudson Bay and Alaska. In winter they are characterized by extremely low temperature and specific humidity. This air has a very stable lapse rate in winter, usually with a marked temperature inversion, the result of pronounced radiation cooling and perhaps also subsidence. As it moves southward and especially as it moves down the mountains into California, the low surface temperatures disappear unless renewed by strong nocturnal radiation. A considerable pressure gradient is usually required to bring this highly stable air across the Sierra Nevada. The resulting strong wind and turbulence usually prevents marked nocturnal cooling. In midwinter, this air produces temperatures along the northern part of the Pacific Coast sometimes near freezing, but at other times of the year it is very warm and, most characteristic of all, very dry. It should then properly be called Transitional Polar Continental Air (Npc). Its occurrence in California is infrequent.

Polar Pacific (Pp). Air masses of polar origin which move southeastward over the North Pacific Ocean. In winter, owing to its course over the relatively warm ocean, this air is never very cold, but usually moist and conditionally unstable. In the interior, radiation cooling will eliminate the instability in the surface layers. As it reaches the coast a fresh outbreak of this air will produce showery weather in the winter season. In summer it is very cool, and usually stable as it reaches the coast, and has a marked temperature inversion due to passage over a cold water belt lying off the California Coast. This effect does not appear in winter time since the ocean temperatures then are more uniform. In summer, air of this type is rapidly heated in moving inland, but on account of its dryness does not produce showers except in the high Sierra Nevada.

Transitional Polar Pacific (Npp). Polar Pacific air modified by either of the following processes:

(1) Modified over the ocean (Nppm). Polar Pacific air which has passed for a great distance and far to the south over warm seas and thus has become warm and moist throughout a fairly deep layer. After passing to the southward it frequently returns northward and has properties somewhat resembling those of the true tropical maritime air defined below.

(2) Modified over land (Nppc). Polar Pacific air which has had a sufficiently long existence over land so as to become cold in winter from radiation and to show a slight decrease in specific humidity. In winter, the characteristic unstable lapse rate of Pp is then replaced by a stable one usually with a temperature inversion. This modifying influence generally does not become noticeable until the Pp air has passed beyond the Sierra-Cascade range. Most currents of air from the continent moving into California are of this land-modified, maritime type.

Tropical Pacific (Tp). An air mass originating in the northern part of the trade-wind belt between Lower California and the Hawaiian Islands. It is warm and moist and frequently conditionally unstable. Its movement northward is contrary to the prevailing circulation and therefore occurs infrequently, and only in winter.

It is possible, especially in the fall, that air from the deep tropics may reach the extreme southern part of California, by means of northward-moving tropical hurricanes. One such case has been recently observed at San Diego.[6] However, on account of its infrequent occurrence this air mass will not be considered here.

While the air masses of the Middle West and the East have sharply differentiated properties, the characteristics of the air masses in California are often poorly defined. For that reason the interpretation of the synoptic situations from the point of view of the Norwegian School

[6] Blake, D., A tropical hurricane in Southern California, *Monthly Weather Review,* vol. 57, pp. 459-460, November, 1929.

does not always appear so obvious as it does in most of North America and Europe. The methods of air mass analysis were developed from a study of Northwestern European weather. Naturally, in California, a large portion of which is in the same latitudes as Morocco and Algiers, the numerous and distinct types of air masses and fronts observed in Norway are not found. One must not assume from this that there is any weakness in the Norwegian system of analysis. The discussions of this paper will only serve to strengthen the theory by showing how it applies in the frontier region of the extra-tropical domain.

On the western shores of the major continents around 30 degrees from the equator are the coastal deserts. They occupy a large transition zone between extra-tropical and tropical circulation. The southern part of California is very near this cyclone-less belt. One needs travel but a short distance southward from San Diego into Lower California before encountering a region where only one or two cyclones may pass in several years. Similarly, as one travels southward along any part of the Pacific Coast of the United States, regions of less and less cyclonic activity, and of decreasing air movement are reached until in Southern California one has nearly passed beyond the extra-tropical régime.

Bergeron[7] has pointed out that the Pacific Coast is a region of what he calls "frontolysis," that is, a region of divergent air flow and consequently frontal dissipation and occluded and dying cyclones. Accordingly, a strong interaction of air masses of different temperature would not be expected.

In selecting situations for discussion, the authors have taken front passages which are sufficiently well marked to permit a reliable analysis. However, they are typical and well representative of what takes place in this area. They demonstrate the similarities in the air masses and also furnish good examples of the differences by which the air masses can be recognized.

[7] Bergeron, op. cit. in fn. 5.

Chapter II

A WINTER FOG IN THE INTERIOR

By W. M. Lockhart, Lt.-Comdr., U. S. N.

The synoptic situation under discussion in this chapter was selected to illustrate the winter fogs in the San Joaquin and Sacramento Valleys. This type of fog is very persistent and occurs repeatedly in the region mentioned during the winter months for considerable periods of time, sometimes as long as two weeks. It affords an almost ideal example of High Inversion Fog,[8] since the physical seclusion of the region brings about almost complete freedom from outside atmospheric influences and reduces the number of controlling factors to an extent seldom realized except in laboratory experiments.

Our material covers Central and Southern California and therefore includes only that part of the "Great Valley" which lies south of Sacramento. However, the analysis is no doubt applicable also to the Sacramento Valley. The following discussion embraces a detailed study of the fog period, December 20 to 24, 1928. The weather conditions previous to this period will be considered in a general way so as to give an understanding of the causes leading up to the fog formation.

Distribution and Duration of the Fog

On the morning of December 20, fog is reported at all stations on the east side of the San Joaquin Valley, from Modesto southward to Bakersfield, with low ceiling and poor horizontal visibility. It is impossible to estimate the depth of this fog, but judging from later reports, it is rather limited in vertical extent and lies close to the ground. As the day progresses and the temperatures in the valley rise, this fog is gradually dissipated. The dissipation begins along the outer limits of the fog area, and slowly progresses inward toward the center. At 3.30 p.m. (plate II) clear weather, with unlimited ceiling and fair horizontal visibility, is reported by all valley stations. The winds at the surface remain light and variable — below 6 miles per hour.

During the following night, fog again forms, so that the morning map on the 21st (plate III) shows fog at all stations on the east side of the valley, from Sacramento to Bakersfield. It thins out along the western edge so that Tracy and Los Banos have only light fog. This fog does not extend to the southwestern rim of the valley, which is somewhat higher. Coalinga, Lost Hills and Taft report clear skies. By 9.30 a.m. Tracy and Los Banos are clear, while Sacramento has only light fog, indicating, as before, that the fog is dissipating along its outer boundaries. Later reports confirm this development, and by the late afternoon only a small area, extending from Merced to Visalia, has fog. Winds at the surface remain variable and light, or calm, over most of the valley.

By 6.30 a.m. on the 22nd (plate IV) the entire valley is again engulfed in fog, with the exception of the higher stations along the southwestern edge. This fog persists throughout the day, with the exception of a period from 9.30 a.m. until 12.30 p.m. at Bakersfield. The winds are light and variable.

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[8] For a definition of this term and a complete classification of fogs see:
Willett, H. C., Fog and haze, their causes, distribution and forecasting, *Monthly Weather Review*, vol. 56, pp. 435-468, November, 1928.

The fog continues during the night and throughout the following day, December 23. As may be seen from plate V, the fog area has increased somewhat in vertical and horizontal extent, for it includes Coalinga, which is located at the foothills of the Coast Range, and has spread into the Livermore Valley as well as into the other small valleys in this region. Coalinga later becomes clear and the fog dissolves at Livermore and Concord during the day.

Practically no change is apparent in the early morning of the 24th, the valley still being fog-bound. By 9.30 a.m. (plate VI) the situation begins to change and rain is reported in the San Francisco Bay region. Sacramento reports light fog only and a slight increase in wind velocity. Later reports show that the rain is moving inland and at the same time, the fog becomes lighter and finally disappears. This dissipation takes place quite slowly, as usual, beginning along the outer edges of the fog belt. By 3.30 p.m. (plate VII) only one station (Lost Hills) reports fog, while over the rest of the valley not covered by the rain belt, the ceiling is reported as unlimited. (The term "unlimited ceiling" applies also to cloud decks at an estimated altitude of 10,000 feet or more.)

Formation of Subsidence Inversions

The Great Basin anticyclone plays a major rôle in the formation and continuance of the fog in the Sacramento and San Joaquin Valleys. Therefore a discussion of some of the properties of stationary anticyclones and of the Great Basin anticyclone in particular will be helpful in explaining the fog.

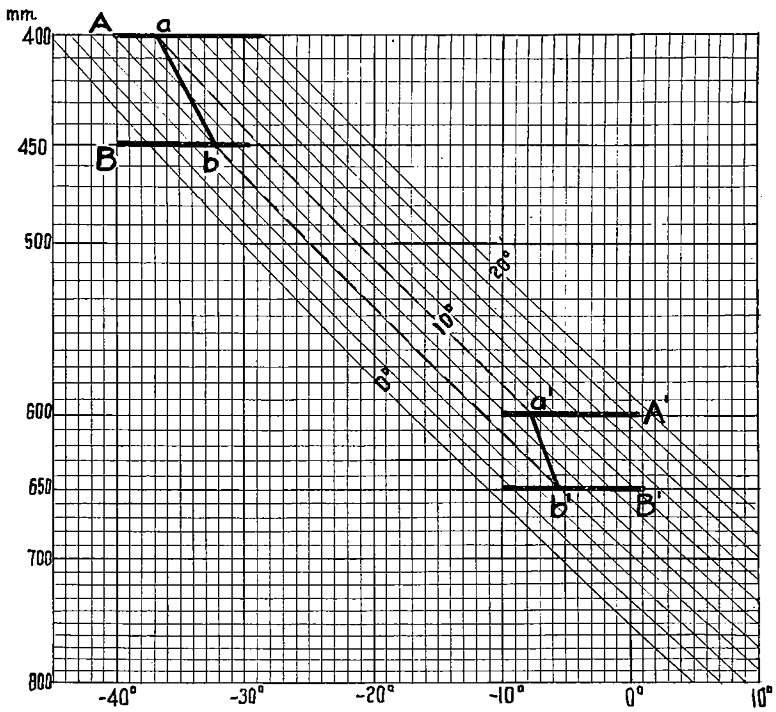

Fig. 1a

It is an accepted fact that the air in stationary anticyclones is slowly settling. Sir Napier Shaw[9] on one occasion calculated the rate of descent in the Azores High as being 86 meters per day, and, for an anticyclone over the British Isles, he obtained a rate of 264 meters per day. This downward displacement of air results in a slow temperature increase within a large part of the anticyclone and in a decrease of the vertical temperature lapse rate. Generally one or several well-marked temperature inversions develop, especially along the borders of the subsiding anticyclone.

The formation of these inversions has been treated analytically by a number of writers.[10]

[9] Shaw, N., The air and its ways, p. 77. Cambridge (1923).

[10] Especially:
Exner, F. M., Dynamische Meteorologie, 2te. Aufl., pp. 58, 85. Vienna (1925).
A simplified explanation of subsidence is given in:
Rossby, C.-G., On the effect of vertical convection on lapse rates, *Journal of the Washington Academy of Sciences*, vol. 20, No. 3, February, 1930.

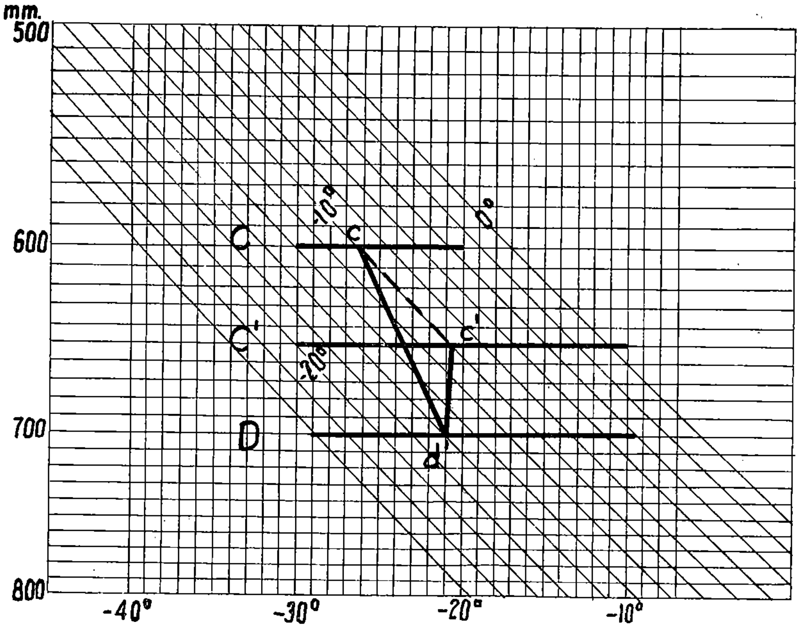

FIG. 1b

We shall follow below a simple, unpublished, graphical method developed by Prof. C.-G. Rossby, to illustrate the effect of subsidence on lapse rates. For this demonstration an ordinary adiabatic chart (temperature-log pressure diagram) is needed (figs. 1, a, b, c).

We consider first (fig. 1-a) a limited layer "AB" — 50 mm. of mercury in thickness — with pressures of 400 and 450 mm. at its upper and lower boundaries respectively, and assume that this layer has a temperature distribution corresponding to the line "ab" (stable, less-than-adiabatic lapse rate). This layer is now forced to descend, without change in horizontal cross section, until the pressures at the upper and lower boundaries become 600 and 650 mm. respectively (position "A'B'"). During the descent the individual particles are heated by compression and we shall assume this heating to take place adiabatically. Their temperatures will therefore be displaced along the lines of constant potential temperature. Thus, a particle at the upper boundary of the layer with an original temperature "a" will, during the descent, be heated and its temperature will follow the adiabatic "aa'"; a particle at the lower boundary will follow "bb'". The layer "AB" with the temperature curve "ab" will therefore reach the final position "A'B'" with a temperature curve which may be represented by the line "a'b'". A comparison of the temperature distribution before and after the descent shows that the layer in its new position has become more stable;

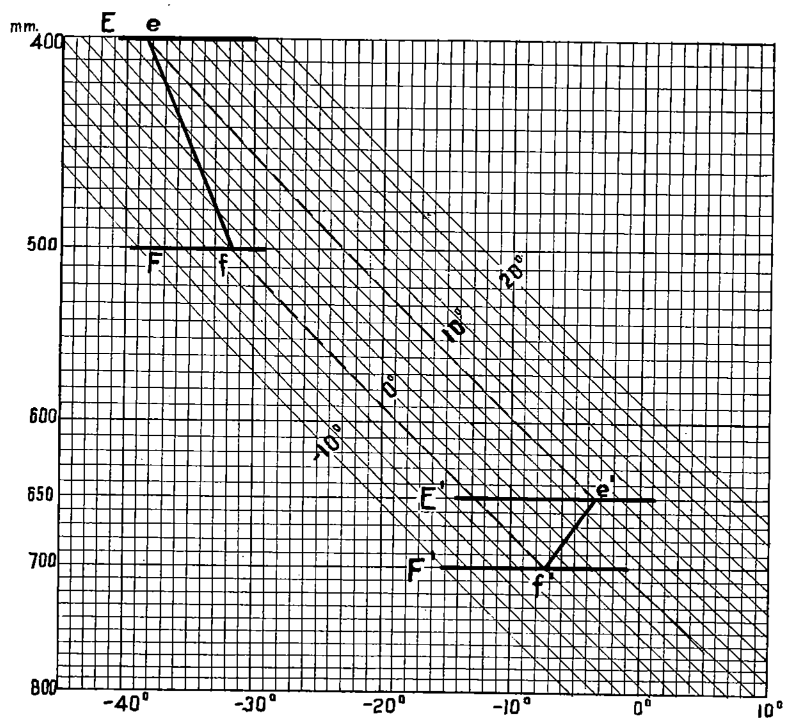

FIG. 1c

in the figure the original temperature drop of 5° C. has decreased to about 2.5° C.

In a similar manner, it may be shown that the spreading out of a layer will also increase the stability, provided the initial stratification was stable. In fig. 1b the layer "CD" has an initial depth of 100 mm. of mercury (the two boundary pressures being 600 and 700 mm.). It is then permitted to spread out until its horizontal cross section is doubled. For the purposes of this discussion we shall assume that the lower boundary of the layer remains at the 700 mm. level. Then the top surface must sink to the 650 mm. level, and the original temperature curve "cd" is transformed adiabatically into the curve "c′d′". Fig. 1c illustrates the combined effect of sinking and lateral spreading of the air; in the figure an original temperature drop of about 6.5° C. changes into an inversion of about 3.5° C. Since altitudes are roughly proportional to logarithms of pressure, the adiabatic chart permits also a quantitative estimate of the changes in lapse rate which accompany these adiabatic displacements.

The above discussion shows that a mass displacement downward tends to increase the stability of the various air layers in a stagnant anticyclone. It may be readily seen that such a movement will also decrease the relative humidity, even though the absolute amount of water vapor present in the air remains unchanged, for relative humidity, being a function of temperature, will decrease when the temperature rises.

Such a sinking and spreading out of the upper layers of a stagnant anticyclone usually produces a series of subsidence inversions in the free atmosphere above a resting layer close to the ground, and a sliding out of the air along the periphery of the anticyclone. These layers have been variously named—"subsidence inversion" being the generally accepted English term.

The preceding discussion explains the initial formation of isothermal or inversion layers at higher levels but does not explain why fog forms in the layer below these inversions, nor does it explain why the largest inversions are usually concentrated relatively close to the ground. Willett[11] has investigated high inversion fog in Europe. He finds that its formation is dependent upon the previous history of the air mass. It occurs particularly in stagnant maritime polar air outbreaks. This air has passed sufficiently far over the sea to have acquired a moderate amount of water vapor in the lower layers and hence a higher relative humidity than when it left its source. When this cold maritime air reaches the continent its movement will slow down or cease, and a gradual subsidence will take place.

Below the level of maximum subsidence, turbulence will tend to maintain a fairly steep lapse rate. Turbulence will favor the transportation of dust, smoke and moisture upward to the base of the lowest inversion layer, which will act as a blanket, effectively limiting the height of turbulence. Thus the dust, smoke and moisture are trapped and there is formed directly below the inversion layer a layer of air which gradually increases in water content, dust, etc. (In typical cases over Europe, the relative humidity may vary from 60-70 per cent at the ground to 90-100 per cent directly below the inversion.) The inversion layer therefore becomes a well-marked surface of discontinuity also with respect to relative humidity. Below it is a layer in which the relative humidity is increasing, while above, the relative humidity remains low and the skies clear.

During the night this moist layer beneath the inversion will rapidly lose heat by radiation toward space since the dry air above the inversion is highly transparent. The ground below will likewise radiate towards space, but part of the heat lost will be retained and re-radiated downward by the lower moist layers. The effective radiating surface is thus displaced from the ground up to the top of the moist layer immediately below the inversion. If the loss of heat at this surface is sufficiently large, condensation will take place and stratus or high fog will form

[11] Willett, op. cit. in fn. 8.

at the base of the inversion. For fog formed in this way the term "high inversion fog" has been introduced.

After sunrise, the high albedo of the new cloud layer will, to a certain extent, prevent a normal heating of the moist layers below and consequently slow down or prevent the evaporation of the fog. The fog is also protected from mechanical dissolution by the strong inversion above it, for, due to the high stability of this inversion layer, the turbulence in the upper rapidly moving layers is prevented from diffusing downward. Below the inversion, in the absence of high wind velocities and especially in enclosed basins like the interior valley of California, turbulence is just sufficient to keep the air well stirred, and is thus less detrimental to the fog. If these effects continue, the layer below the inversion is cooled to such an extent that the fog, after a few days, extends down to the ground.

In the following paragraphs we hope to be able to show that the winter fog in the interior valley of California represents a good example of "high inversion fog."

Inflow of Maritime Air

In order to establish the fact that the air mass in the valley during the period under discussion is of recent maritime origin, it is necessary to review the meteorological conditions during the days preceding this analysis and to select some means of identifying this air mass or any other air mass which may enter the valley. To do this, specific humidity has been selected as being perhaps the most conservative air mass property available.

The period December 10-14 was one of cyclonic activity over California. Following this period, an anticyclone made its appearance on December 14 off the coast of Washington, centered somewhere to the northwest. This anticyclone moved slowly southeastward during the next three days, giving northwest and north winds along the California coast and bringing into the Great Valley a relatively cold air mass. As may be noted from fig. 2, the specific humidity at Fresno reached a low value of 4.0 grams per kilogram at the 5 a.m. observation of December 15. Nevertheless this value is decidedly higher than that characteristic of Polar Continental (Pc) air (about one gram per kilogram in February) and we conclude that this air mass was of Polar Maritime origin (Pp).

The weather map of the 17th shows the anticyclone centered over eastern Washington, and on the following two days it continues its southeastward movement so that by December 19 it is located over southwestern Idaho. There it stagnates. During these two days the general pressure distribution has been such that the previous flow from the north and northwest into California has been cut off and replaced by a flow from the Great Basin, with winds from the easterly quadrant. This flow from the Great Basin takes place at upper levels due to the shielding effect of the Sierra Nevada. This is brought out by the pilot balloon observations from California for this period. They show winds of moderate velocity from the northeast and east at levels between 4300 and 10,000 feet. Below the mountains, in the Great Valley and in the San Francisco Bay region, the winds are light and variable in direction and no inflow of air from higher levels down into the valley can be detected. At the same time, the observations indicate that no air movement takes place in the lower layers from the Pacific Ocean. These conclusions are verified by the constancy of specific humidity at Fresno during the period and by the continued low temperatures which prevail in the valley as compared to the higher temperatures recorded at all mountain stations. Intermittent fog, dissipated soon after sunrise, is reported by a great number of valley stations during this time.

It should again be emphasized that at no time during this period is it possible to find any indication that the air mass which is in the valley at midnight on December 19 is other than that which we know to have moved into the valley December 14-15.

Thus it may be stated that due to the meteorological conditions and physical features of the surrounding region, as well as those of the valley itself, Polar Maritime air has been trapped in the interior of California and has not been renewed from any source.

The Ultimate Results of the Stagnation

As a result of the previous investigations we may state that the shutting off of the Polar Maritime air in the valley probably occurred around December 17. The weather map for December 20 shows the anticyclone still stagnant over southwestern Idaho, but the pressure at its center has increased from 30.6 to 30.8 inches since the preceding day. This indicates that the anticyclone is still building up and that subsidence has not yet developed, as shown by the pilot balloon observations obtained in California during this time. They show light to moderate west and northwest winds at levels above 9800 feet. Below this level, and down to the mean elevation of the mountain ranges, the winds continue light and from the easterly quadrant. Thus one would not yet expect to encounter a well-marked inversion aloft but rather a normal rate of decrease of temperature and specific humidity with elevation. In the absence of free air soundings over this region, the most reliable indication of the conditions at higher levels is furnished by the data obtained at Mount Hamilton, at an elevation of 4209 feet. From this and similar data for San Francisco and Fresno, curves of temperature and specific humidity have been prepared (figs. 2 and 3). In addition, the following table has been compiled, giving the upper air movement as determined by pilot balloons:

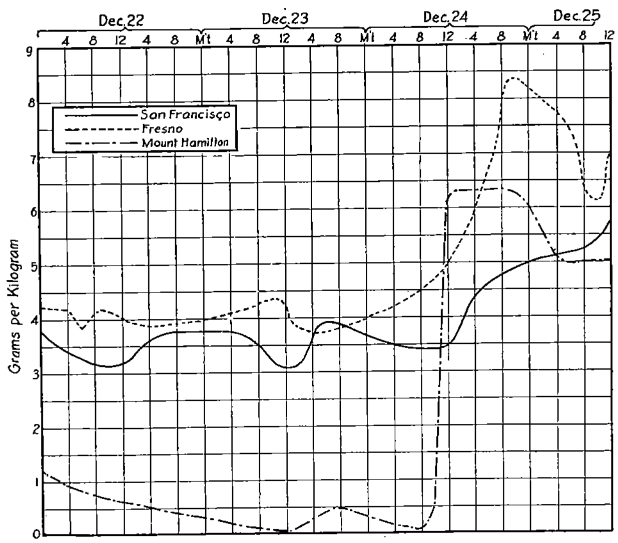

Fig. 2
Specific humidity curves, December 22-25, 1928.

Table 1
Pilot Balloon Observations, Morning of December 20, 1928

*Altitude**	*Oakland*		*Hollister*		*Lebec*		*Los Angeles*	
(Feet)	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*
Surface	E	10	Calm				N	9
800	ENE	11	E	3			ENE	3
1400	E	15	E	3			SSE	2
2000	E	16	SE	6			ESE	4
2600	ESE	13	SE	14			NNE	3
3200	ESE	12	SE	14			NW	7
3800	ESE	12	SSE	7	S	11	W	8
4300	SE	9	SSW	6	SE	12	WSW	8
5000	SE	6	SW	7	E	19	WSW	3
6200	SE	7	SSW	8	ENE	8	NNE	5
7400	S	3	ENE	4	N	8	NNE	16
8600	E	7	WSW	2	NW	18	N	17
9800	ENE	4	W	5	NW	13	NNW	22
11,000	W	4	WNW	11	W	17	NNW	18
12,100			WNW	9	W	16	NNW	16
13,200			WNW	10	WNW	18	NW	20

* Altitudes in feet above sea level.

Referring to figs. 2 and 3, it may be noted that on December 20 no marked temperature differences are apparent between the mountain station and lower stations; that the value of the specific humidity at Mount Hamilton has slowly increased during the day to a value of 2.3 grams per kilogram at 4 p.m.; and that during the day (plate II) the fog which was present in the valley during the early morning hours has disappeared. The winds below the level of the mountains and at the valley floor are light and variable and no inflow of air from the Pacific can be detected, the specific humidity at Fresno remaining fairly constant, at an average value of approximately 3.8.

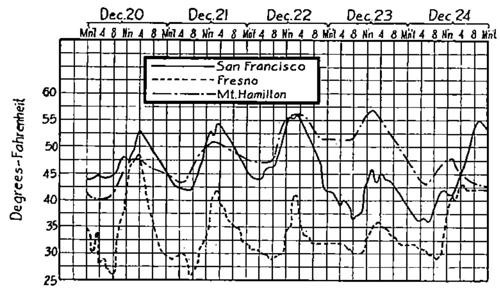

FIG. 3
Temperature curves, December 20-24, 1928.

By the afternoon of the 21st, the winds aloft over the northern stations above 9800 feet have shifted from west and northwest to northeast; while at practically all altitudes over the mountains which form the southern boundary of the valley, winds with an easterly component and slightly increasing velocity are observed. The free air winds are given in the following table:

TABLE 2
Pilot Balloon Observations, Afternoon of December 21, 1928

*Altitude**	*Oakland*		*Hollister*		*Lebec*		*Los Angeles*	
(Feet)	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*
Surface	WSW	6	SSW	3			NW	9
800	ENE	7	WNW	2			NW	7
1400	NE	14	NE	1			NNW	2
2000	NE	9	ESE	5			SSW	2
2600	E	3	ESE	7			SSW	3
3200	ENE	3	ENE	7			W	2
3800	ENE	5	NE	9	ENE	5	N	3
4300	ENE	4	NE	7	SE	3	NE	5
5000	E	3	ENE	3	E	6	ENE	9
6200	NE	2	SSE	5	ENE	26	E	16
7400	WSW	3	SE	3	ESE	16	ESE	18
8600	W	6	ESE	6	ESE	15	SE	23
9800	N	4	NE	5	ENE	11	SE	20
11,000	NNE	5	NE	6	NE	3	ESE	13
12,100	NE	5	NE	6	NNW	1	NE	12
13,200	NE	7	NE	8	NNW	2	NNE	13
33,000	NE	45						

* Altitudes in feet above sea level.

This table indicates that the anticyclone, still stagnant over southwestern Idaho, has begun to subside and should soon show over California the effects of this subsidence. Thus, as previously pointed out, the temperatures aloft should rise; and the relative and specific humidities there should decrease. This is amply verified by our observations. The specific humidity at Mount Hamilton has decreased during the day to 1.2 gm/kg at midnight; while, at the same time, the temperature (see fig. 3) has risen considerably. A comparison shows that the temperature at midnight of the 21st-22nd is only 0.5° F. lower than the maximum recorded on the 20th at 2 p.m. An increasing difference between this high station and the two lower stations — San Francisco with clear skies, and Fresno with fog — is apparent. Thus we see that at midnight, December 21-22, Mount Hamilton is 2° F. warmer than San Francisco and 16.5° F. warmer than Fresno. On this day, then, the subsidence layer formed by the stagnant anticyclone has overspread the Great Valley and the various phenomena which accompany such a subsidence are now coming into play.

On the following day — the 22nd — these conditions are greatly accentuated and, as expected, the fog situation in the valley becomes worse. We note from the pilot balloon soundings that the winds at all elevations above the mountains have increased slightly in velocity. They are from the northeast and east over the southern mountains and from the southeast and south over the mountains of Central California. The specific humidity at Mount Hamilton has continued to decrease and reaches the low value of 0.4 gr/kg at midnight. The temperature has continued to rise; the maximum for the day is 5° F. higher than that of the preceding day and at midnight it is 4° warmer than at midnight the day before. The difference in temperature between Mount Hamilton and San Francisco, which has clear skies, is 10° F. at midnight; while Fresno, with fog, is 20° F. colder than Mount Hamilton. Such abnormal differences in temperature show clearly that the sharpening factors mentioned in the section on anticyclonic subsidence now are at work.

On the 23rd, the anticyclone has decreased slightly in intensity — from 30.9 to 30.7 inches pressure at its center. It has also increased somewhat in area but remains centered over southwestern Idaho. The winds aloft over California are mostly east and southeast over the southern mountains and south over the central part of the Great Valley. The fog in the valley has increased in horizontal extent and remains throughout the day over most of the region. The specific humidity at Mount Hamilton reaches a very low value of practically zero, and the temperature still remains abnormally high. A comparison of temperatures recorded at midnight on this day indicates that San Francisco is 9° F. colder and Fresno is 13° F. colder than Mount Hamilton.

The weather map of the 24th shows that the anticyclone has been displaced into southwestern Wyoming and has further weakened to 30.6 inches. At the same time, there is an area of low pressure approaching the northern Pacific Coast, indicated on the map as northwest of British Columbia, and rain is falling along the coast from Eureka northward. The effects of this displacement of the anticyclone and the appearance of the cyclone to the northwest may be readily seen by examining plates VI and VII and the following table:

TABLE 3

Pilot Balloon Observations, Morning of December 24, 1928

*Altitude**	*Oakland*		*Hollister*		*Lebec*		*Los Angeles*	
(Feet)	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*
Surface	WSW	2	SSE	1			NE	8
800	SSW	3	SE	9			ENE	8
1400	SSW	3	SSE	10			E	11
2000	SSW	7	SSE	7			ESE	12
2600	SW	12	SW	7			ESE	7
3200	SW	15	SW	8			S	4
3800	SW	17	WSW	9	S	14	SSW	7
4300	SW	19	W	9	SE	7	SSW	6
5000	SW	20	W	7	SE	4	SSE	2
6200	SW	19	WSW	16	WNW	12	S	4
7400	SW	17	WSW	13	WNW	13	WSW	3
8600	Entered		W	16	W	10	NW	5
9800	clouds.		W	17	WSW	14	NW	9
11,000			W	21	WSW	16		
12,100					W	16		
13,200					W	21		

* Altitudes in feet above sea level.

Pilot balloon soundings obtained at Oakland at 4 a.m. indicate clearly that during the night, the winds in the upper levels have shifted to the southwest and west and have increased somewhat in velocity. An examination of the specific humidity curve at Mount Hamilton indicates much more clearly the effects of this displacement of the anticyclone. Between 8 a.m. and noon of this day, the specific humidity rose sharply from a value of approximately 0.0 to 6.0 gm/kg, showing plainly that a new air mass of distinctly different characteristics has reached Central California at higher levels. At the same time, the temperature curve indicates a return to a more nearly normal value (see fig. 3). The early morning maps over California show increasing cloudiness over the coastal stations, clouds which in themselves are indicative of a warm front moving in, that is, cirrus, cirro-stratus and then alto-stratus. By 9.30 a.m. light rain of a warm front type is falling in the San Francisco Bay district. All these indications show that the subsidence or inversion layer over the Great Valley has been destroyed during the night or early morning hours. With the destruction of the inversion and the return to a normal lapse rate at higher levels, we should expect that the fog which has engulfed the valley would disappear during the day. Plate VII indicates that with the spread of the rain area southward into the valley and the slightly increased winds, the fog has been dissipated in the valley prior to 3.30 p.m.

While the observations for this day do not cover the period between 3.30 p.m. and 6.30 a.m. of the 25th, it is of interest to note how the specific humidity curves for the various stations indicate the front passage. The warm front, as indicated by the specific humidity and temperature curves, passed Mount Hamilton at approximately 12.30 p.m. on December 24. At the ground, on the other hand, the corresponding curves for San Francisco indicate that the warm front did not pass until 10 p.m. of the 24th. The effects of the warm front were not felt at Fresno, at least not at the ground, until sometime the following day (December 25), when the specific humidity rose to 8.0 gr/kg by the 5 p.m. observation.

Attention should again be directed to the specific humidity at Fresno during the foggy period (fig. 2). During the days immediately preceding the 20th, this value oscillated between 3.4 and 4.8, with an average value of 4.1. On these days ground fog was reported in the early morning hours which later was dissipated. On the 20th and 21st, the value varied between 3.2 and 4.7 (average 3.8). During these days, the fog in the valley was mostly dissipated by the late afternoon. From the 22nd to the 24th of December, the specific humidity varied between 3.1 and 4.0, or an average value of 3.5 gr/kg. On these days there was continuous fog in the valley. It is interesting to note that the low values were obtained in all cases, in the early morning hours, when the fog was thickest, and when the total amount of water vapor and water droplets in the air was considerably more than that registered by the hygrometer or psychrometer.

This curve for the specific humidity indicates clearly that the air mass, previously brought into the valley earlier in the month, has remained stagnant during this entire time and has, as far as we can determine, been neither refreshed nor renewed. The valley has been covered by a subsidence layer which has effectively blanketed it and blocked any ingress of air from the Pacific. Thus we have a situation in which the only possible way for air to enter is from the mountains surrounding the valley. A study of the conditions over the mountains bordering the southern end of the valley shows that the air mass flowing past these mountains has distinctly different characteristics from the air in the valley — a higher potential temperature and distinctly different values of specific humidity. It thus is out of the question that any drainage or flow from these levels into the valley has occurred during the period investigated.

The Effect of Fog on Temperatures

The effect of the fog on the temperatures recorded at Fresno can be easily seen by the following table:

Table 4

Temperatures and Fog Duration at Fresno, December 20 to 24

*Temperature**	*Dec. 20*	*Dec. 21*	*Dec. 22*	*Dec. 23*	*Dec. 24*
Maximum	49° F.	42° F.	41° F.	36° F.	43° F.
Minimum	26	26	29	30	29
Range during the day	23	16	12	6	14
Duration of Fog	Until late afternoon	All day	All day	All day	Until approximately 12.30 p.m.

* Temperatures in degrees Fahrenheit.

The table indicates clearly the effect of this fog layer in equalizing temperatures. As the fog layer continued to enclose the valley and apparently became thicker, the maximum temperature recorded during the day steadily decreased, showing that an ever-increasing fraction of the sun's insolation failed to penetrate to the ground. At the same time, the amount of heat lost by the ground through radiation during the night was reduced. Thus the diurnal temperature range has decreased from 23° on December 20 to 6° on December 23, when the subsidence layer was most marked.

CHAPTER III

THE SUMMER SEA FOGS

THE "high fog" or stratus cloud which lies along the California coast nearly every day in summer is the most distinctive and interesting weather phenomenon of that region. Its climatic importance, as well as its general meteorological interest, would warrant a comprehensive exposition of the subject in this paper. A rather detailed discussion of the question has already been published by the author,[12] and we will therefore confine ourselves to a brief survey of the topic with additional treatment of questions which have arisen since the previous paper was published.

GENERAL CHARACTER

Whether lying at sea level or at some altitude, this formation, for convenience, will be designated as fog. Some serious and well-founded objections have been raised to this nomenclature. In the majority of cases the formation appears over the land as stratus cloud and condensation frequently takes place at the stratus level instead of at the surface, therefore in contradiction to the strict definition of fog. However, the characteristics of the landward-moving air in which the condensation takes place, whether at the surface of the sea or at some height over the land, are originally imparted to it directly by surface conditions over the ocean. In this respect, the condensation can be traced back to surface phenomena, therefore satisfying the definition more fully. Several writers have already classified various low stratus formations as fog, for example the "high fogs" of Georgii[13] and Willett.[14] Since the inhabitants of the California coast designate the summer clouds as "high fogs," the use of this term will be less confusing than any other name. It must be noted, however, that the High Fog of Willett's classification is very different from that of the present discussion. The California coastal fogs fall under the category of Sea Fog according to Willett's definitions.

As was pointed out in the previous discussion, the fog is nearly always present in summer along the outer coast, appearing in the coastal valleys late in the afternoon, retreating back to the ocean before noon of the following day. It is not, of course, an actual retreat in the sense of a reversal of direction of motion, for, to be sure, the wind remains westerly and even increases in velocity as the day goes on. The effect of solar heating causes more rapid evaporation over the land. Thus, at midday, the fog usually remains only on the ocean. The question of the effects of solar heating on the fog will be discussed in a later paragraph.

These fogs occur over the ocean and in a narrow coastal strip of land from Oregon southward to below the Mexican border and along the greater part of the Lower California coast. The region of greatest frequency and persistence is probably between San Francisco and Cape Mendocino, where they are of almost daily occurrence in summer. July and August are the foggiest months, but the summer fogs are usually observed with fair regularity from May to September, inclusive. Similar fogs occur at other seasons, but that their causes of formation are exactly the same is doubtful.

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[12] Byers, H. R., Summer sea fogs of the Central California coast, *University of California Publications in Geography,* vol. 3, pp. 291-338, February, 1930.

[13] Georgii, W., Die Ursachen der Nebelbildung, *Annalen der Hydrographie und Maritimen Meteorologie,* vol. 48, pp. 207-222 (1920).

[14] Willett, op. cit. in fn. 8.

Conditions Favoring Fog Formation

In the first fog study it was shown in considerable detail how the distribution of temperature and pressure over the eastern Pacific Ocean and the adjacent land tends to produce a pronounced on-shore wind movement along the California coast. An anticyclone is centered around latitude 40° N. and longitude 140° W. during the summer, while a thermally produced LOW persists over the interior of California extending into Arizona, Nevada and Mexico. Midday temperatures in the interior are usually about 40° F. warmer than along the coast. The resulting air movement is from northwest to southeast.

It was further shown that as the maritime air passes near the California coast it becomes rapidly cooled. This temperature reduction is caused by cold ocean water lying off the coast. The current, probably induced entirely by wind friction, has an off-shore direction. Such a direction (30 to 45 degrees to the right of the wind) corresponds with theoretical results calculated by Ekman[15] and others for wind-produced ocean currents.

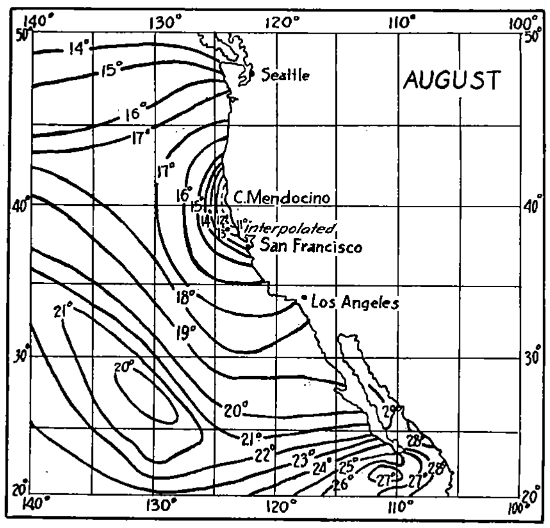

Fig. 4a
Ocean surface temperatures for August, when the cold-water belt is most pronounced. — (From H. Thorade.)

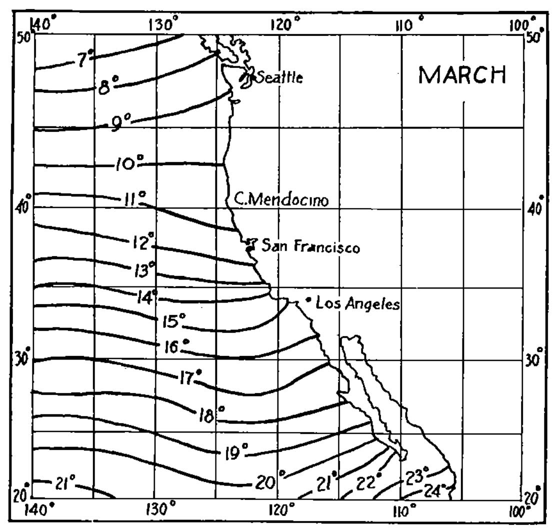

Fig. 4b
Ocean surface temperature for March, when the isotherms follow most closely the parallels of latitude. — (From H. Thorade.)

The work of McEwen[16] and others in applying Ekman's theories in an explanation of the cold water belt off the California coast was cited in the previous discussion. The theory given is that the water displaced outward from the shore leaves a deficit which is compensated by cold water rising from deeper levels. The assumption must be made that the water is homogeneous. The validity of this assumption and of the entire theory of upwelling water in this region will not be known until sufficient observational data are obtained to determine the dynamics of these waters. It is certain, however, that there is a distinct belt of cold surface water along the coast. That is the only essential point for our discussion. The map in fig. 4a shows the surprising fact that in summer the water along the California coast is colder than at points a thousand miles north. Farther west lies relatively warm water.

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[15] Ekman, V. W., On the influence of the earth's rotation on ocean currents, *Arkiv för Matematik och Fysik,* vol. 2, 11 (1905).

[16] McEwen, G. F., The distribution of ocean temperatures along the west coast of North America deduced from Ekman's theory of the upwelling of cold water from the adjacent ocean depths, *International Revue der Gesamten Hydrobiologie und Hydrographie,* vol. 5, pp. 243-286 (1912).

FORMATION OF THE FOG

The northwest wind blowing out of the Pacific anticyclone moves from water having a temperature near 70° F. to colder and colder seas until near the coast it is moving over a surface having a temperature 15 to 20 degrees lower. The resulting temperature reduction produces condensation in the form of fog. It has been shown by Taylor[17] that cooling of this type would be effective only in a very shallow layer if the wind were a very light one. Turbulence is necessary to carry the cooling effect upward from the surface. Mechanical turbulence in a stable air mass depends entirely upon the wind velocity. Therefore, moderate winds are necessary. Records from Point Reyes cited in the previous paper show that moderate to fresh winds prevail on the California coast in summer. The effect of the wind velocity is shown in the results obtained by Taylor in observations aboard the S. S. *Scotia* in 141 cases of fog in the vicinity of the Newfoundland Banks. He found that most fogs caused by cooling of air over the ocean occurred with wind force 2 to 5 Beaufort. There were only three cases with a wind of force 6 and but one with force 7. Three fogs were observed in calms, but they were steam fogs, that is, formed in cold air over warmer waters. In the case of radiation fogs on the land, Taylor has made a careful analysis of data obtained at Kew Gardens, England, and his results are probably applicable in some measure to sea fogs. He found that cooling by molecular conduction in the course of a winter night extends upward only about four feet. Using the coefficient of turbulent conduction, he calculated a much more extensive cooling in the case of a slight wind movement. As a result of these investigations we can definitely conclude that turbulent mixing is necessary to spread the fog upward to an appreciable thickness. On the other hand, if the wind is too strong, there is no localized cooling of the lower strata, but a general mixing so that fog does not form. Hurd[18] has made the same observation with regard to high winds on the California coast.

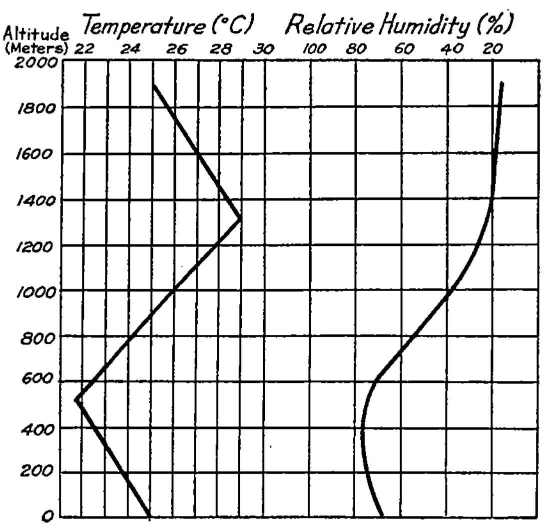


FIG. 5

Vertical distribution of temperature and relative humidity for summer months at San Diego. —(From D. Blake.)

Given a moderate wind, then above a certain limiting height the cooling is not effective and the air remains warm. This results in the temperature inversion which is observed over the land in this region (fig. 5). The fog lies immediately below the inversion surface, which is at a height between 1000 and 3000 feet. It occupies a layer varying in thickness from a few hundred to 2500 feet. It is interesting to note that Taylor did not find many cases of fog more than 600 feet thick over the Newfoundland Banks, whereas most of the well-marked summer fogs of the California coast have a depth of more than 1000 feet. On numerous occasions during the summer of 1928 and 1929 a layer of more than 2000 feet was observed. Taylor has shown that the depth depends upon the distance which the air has traversed

[17] Taylor, G. I., Ice observation, meteorology and oceanography in the North Atlantic Ocean, *Report S. S. Scotia, 1913, to Board of Trade.*

Taylor, G. I., The formation of fog and mist, *Quarterly Journal of the Royal Meteorological Society,* vol. 43, pp. 241-268, July, 1917.

[18] Hurd, W. E., Fog at sea, *U. S. Hydrographic Office, Pilot Chart of the North Atlantic Ocean,* November, 1927.

over water cooler than itself. As shown by his kite observations, in air moving 10 miles an hour with the temperature of the water decreasing at the rate of 1° C. for every 60 miles covered, the temperature inversion extended up to 100 meters when the air had traveled 220 miles. When it had moved 870 miles over the water under these same conditions, the cooling effect extended up to 400 meters. In each case the fog reached about two-fifths of the depth of the inversion. Werenskiold's[19] calculations of the mean monthly air transport in the North Pacific show that the air from the center of the Pacific anticyclone travels between 800 and 1000 miles before reaching the California coast. The average rate of decrease of the ocean temperature is about the same as in Taylor's examples. Therefore a fog about 500 feet thick would be expected, according to his results, with the inversion reaching an altitude of 1200 feet. Actually, however, the fog is usually about 1000 feet thick and the inversion extends through a depth of 2000 feet. This greater thickness of the fog in California than over the Newfoundland Banks is probably explained by the presence of a steady circulation on the Pacific Coast, in which the process of transporting warm air over cold water is continuous and almost unvarying for a whole season, whereas in the region investigated by Taylor the air movement varied considerably from day to day.

In connection with the temperature lapse rate it is well to note that at San Diego, and probably at all points along the shore, the air is not stable in its lower layers, at least during the daytime. Instead, the inversion occurs at an elevation of about 1500 feet, on the average. This height corresponds to the average altitude of the top of the fog as determined from observations at Mount Tamalpais. There are indications that even over the ocean the temperature distribution may be characterized by an inversion beginning at some height instead of at the surface. The observations at S. E. Farallon Island, situated about 30 miles outside the Golden Gate, have been cited, and they show that in only about half of the cases in which ocean fog was visible from Mount Tamalpais was a surface fog recorded at the island station.

This brings up an important question concerning the origin of the fog in which the following possibilities must be investigated: (1) formation between the island and the shore; (2) originating west of the Farallons as a surface fog but soon lifted as a "high fog"; (3) formed at the surface and remaining there until its passage over the land; (4) formation at high levels initially. Records of fog distribution over the ocean are almost completely lacking, but it is very likely that all four modes of formation occur at different times.

Examples of the first type are cited by Wright,[20] who, from the U. S. Weather Bureau station at Mount Tamalpais, has seen the fog form but 20 miles from the land.

The second possibility was discussed to some extent in the previous study. Turbulence transmitting the cooling effect to higher levels would tend to overcome the stability in the lowest layers. Air carried upward by turbulence would expand and cool adiabatically with the result that the coolest layer would lie at the height to which the surface air had been lifted. Above this height the air would still remain stable, that is, inversion would begin at this point instead of at the surface, as originally was the case. Thus, it is seen that there are two effects of turbulence. The first is to transmit the cooling effect through an appreciable depth, and the second is to overcome the stability which was caused by cooling. The fog tends to confine itself to the coolest stratum. This accounts for the "lifting" of the fog while it is still over the ocean.

It is also probable that the water between the Farallon Islands and the Golden Gate is

[19] Werenskiold, W., Mean monthly air transport over the North Pacific Ocean, *Geofysiske Publikasjoner,* vol. 2, 9 (1922).

[20] Wright, H. H., Fog in relation to wind direction on Mount Tamalpais, Cal., *Monthly Weather Review,* vol. 44, pp. 242-244, June, 1916.

warmer than that slightly farther west on account of the action of the tide and river discharge in mixing the sea water with that of San Francisco Bay. If this is so, then the air is heated from below and in this way its stability near the surface is destroyed.

In the third case, the turbulence is insufficient to raise the fog which initially forms at the surface, and the lifting is not accomplished until the air is heated from below upon passage inland.

The fourth possibility, namely the initial formation of the fog aloft, is of frequent occurrence over the land. After the vertical temperature distribution has been altered either by turbulence or heating from below and the coldest stratum is at some height above the surface, then fog may form for the first time. This may be accomplished by the slight cooling of the air after sunset. Until then, the air has not reached the point of condensation, but the necessary temperature for formation is reached by nocturnal cooling. It may occur in the daytime over the ocean when the air is too dry to be immediately affected by the surface cooling but reaches a temperature sufficient to cause condensation only after turbulence has produced a decrease in temperature with increased altitude.

From this, it will be seen that the type of fog formation depends upon turbulence and the initial moisture content of the air. If the turbulence is not very great, the fog will form and remain at the surface. If there is considerable turbulence, such as would be produced by moderate to fresh winds, and the air is initially at saturation, the fog will form on the ocean surface and then lift. If the air is initially somewhat dry, then, under the same conditions, the fog, if formed at all, will originate at a slight elevation above the sea. In the coastal valleys of California, the steepening of the lapse rate is caused by heating from below.

It has been suggested that radiation to space from the cloud level may cause cooling at higher levels and account for the formation of the fog there. Investigations of the winter fogs of the San Joaquin Valley appearing elsewhere in this paper showed this to be true. The evidence tending to show that the same is possible in the summer is not as convincing. In winter, the air above the inversion is sometimes between 20 and 30° F. warmer than that below. In summer, even along the immediate coast, the temperature aloft is hardly 15° warmer than below. These comparisons are made on the basis of mountain observations where the summer temperatures are as a rule much too high to be representative of the particular stratum in question. Therefore, it is probable that the upper air in summer is not as much warmer than that below it as the mountain records would lead us to believe. In the same way, the discontinuity in relative and specific humidity for the summer fogs is not so sharp as in the winter fogs. In the winter, air is sinking in the Great Basin anticyclone. It is very dry air, with a specific humidity of about one gram per kilogram or less as compared with a value of five at the valley stations. At Point Reyes in summer the average specific humidity is 7.75 grams per kilogram. At Mount Tamalpais, immediately above at an elevation of 724 meters, the average specific humidity for summer is 6.23 grams per kilogram. Thus there is no distinct upper boundary to the moist air in summer time, at least not in the San Francisco region, and radiation cooling cannot play such an important rôle as in the case of the winter fogs.

The air which passes over Mount Tamalpais in summer is the air that lies at the same level near the center of the Pacific anticyclone. It is to be expected, therefore, that this air is more moist than land air. The fact that the air at Mount Tamalpais is usually a few degrees warmer than the surface water in the center of the anticyclone, may lead to the conclusion that the air aloft must have been heated over the land. However, as has already been pointed out, the summer temperatures are too high at Mount Tamalpais on account of the heating effect of insolation on the mountain. Pilot balloon data furnish no indications of a return flow aloft.

There frequently occurs in the Los Angeles Basin during the summer a fog of different characteristics. It occurs only at night and in a very light wind. It rests immediately on the ground and is seldom as much as 500 feet thick. It is probably due in a large measure to nocturnal radiation. During the day the damp sea air moves in from the sea, but the temperature is too high for it to contain fog. At night the wind dies down and nocturnal radiation cools the lowest layers and the moist air condenses to form fog. Furthermore, inland from Los Angeles are the true deserts, and the nocturnal radiation over these regions produces a temperature and pressure distribution tending to nullify the sea breeze at night and thus produce the calm weather required for radiation. During July, 1928, there were three days with dense fog at Los Angeles while there were none at San Francisco.

Evaporation of the Fog

In the previous investigation the following observations relative to the evaporation of the fog were pointed out:

(1) Complete evaporation is accomplished nearly every day over the land but not over the ocean.

(2) The cloud layer evaporates from its base rather than from its upper surface.

(3) Leeward slopes become clear early while windward slopes remain cloudy. Hills running parallel to the wind direction are clear early in the day also.

(4) Evaporation of the cloud layer from below occurs even when the sun is completely obscured. After the sun breaks through, the "ceiling" rises very rapidly.

The first observation is confirmed by records of the Mount Tamalpais station and by reports from the sea-coast stations of the Guggenheim Fund's network.

The second, namely the constancy of the elevation of the top of the cloud, is shown by observations at Mount Tamalpais, Mount Hamilton and Mount Wilson.

Both Ångström[21] and Aldrich[22] have arrived at values for the albedo of clouds. Aldrich's figures are based on observations from Mount Wilson made mostly in cases of summer stratus in the Los Angeles Basin. They show that the clouds reflect 78 per cent, while the remainder is transmitted or absorbed by the clouds. Ångström finds a value of 70 per cent. Kimball[23] has made measurements of the short wave diffuse radiation received at the ground through fairly thick clouds and has found it to be approximately 29 per cent of the maximum radiation possible on clear days. These determinations leave a very small percentage for absorption within the cloud. Furthermore, on account of the smallness of the absorption and on account of its non-selective character, it is reasonable to assume that it is fairly uniformly distributed throughout the entire cloud layer. It seems probable, then, that the fog does not evaporate to an appreciable extent from the top, but must evaporate from the bottom under the influence of increased long wave radiation from the earth. Over the water this process will be very slow since the temperature and therefore also the radiation of the ocean remains practically constant throughout the day. This explains why the fog does not evaporate readily over the ocean and possibly may account for the sometimes long duration of the fog over San Francisco Bay.

An attempt has been made to correlate the heating of the land with the rising of the "ceiling." An examination of the records at Mills Field and Oakland Airport shows that in the majority of cases an increase in temperature of 1° F. under a solid cloud cover will raise the base approximately 100 feet. On foggy days, the rise in temperature is usually slow —

[21] Ångström, A., On radiation and climate, *Geografiska Annaler,* vol. 1, p. 126 (1925).

[22] Aldrich, L. B., The reflecting power of clouds, *Smithsonian Miscellaneous Collections,* vol. 69, 10 (1919).

[23] Kimball, H. H., Amount of solar radiation that reaches the surface of the earth, *Monthly Weather Review,* vol. 56, p. 395, October, 1928.

about 1° F. in 90 minutes during the morning. It is only after the sun has broken through in a nearby region that a thick cloud layer can evaporate quickly.

The cloud usually breaks first on the leeward slopes of hills, as was pointed out in the previous paper. This is due to adiabatic warming of the air descending these slopes. On windward slopes turbulence produces the opposite effect. When the fog is stationary or moving parallel to the sides of a valley, the convectional heating from the adjacent slopes will cause the fog to evaporate first along the edges.

Properties of the Sea Air

The marked contrast in temperature between coastal stations and those of the Sacramento and San Joaquin valleys should be emphasized again. For example, Point Reyes, located on the outer coast, has a mean monthly temperature at this season of 52.6° F., while Milton, in almost exactly the same latitude but 55 miles farther inland, has a July mean of 95° F. This represents an average increase in temperature, with distance from the ocean, of about 0.8° F. per mile. Actually, however, this change in temperature takes place almost entirely within the narrow zone occupied by the Coast Ranges, and the differences in the middle of the afternoon are considerably greater than those represented by the mean temperature values. For example, on the afternoon of August 18, 1928, the temperature was 54° F. at Point Reyes, 59° at San Francisco, 95° at Sacramento and 104° at Fresno.

The question immediately arises whether or not the air in the interior valleys of California is of a different air mass classification from that along the coast. Does the rapid transition in temperature across the Coast Ranges represent a frontal zone? Since the local influences are so great, temperature is not a dependable element upon which to base conclusions with regard to the air mass. Only the most conservative properties of an air mass will serve for identification. It has been shown[24] that specific humidity is the most invariant property which we are able to measure in an air mass. Excellent psychrometric observations have been made at Weather Bureau stations. Analysis of these surface records shows that the change in specific humidity is slight as the air is transported from the ocean into the dry interior.

The weather of July 9, 1928, serves as a good example of a typical summer situation. On this day fog or stratus cloud is present along the entire coast. The accompanying table shows the character of the fog.

Table 5

Observations at Coastal Stations, 8 a.m., July 9, 1928

Station	*Wind*	*Cloudiness*	*Ceiling*	*Visibility*	*Temp.*
Crissy Field	SW light	Overcast st.	200 ft.	3 mi.	
Mills Field	W 10	Overcast st.	900	10	56
Palo Alto	SW light	Overcast st.	2000	5	
San Pablo	S mod.	Overcast st.	1500	6	55
Oakland	SW light	Overcast st.	800	5	56 Misting
Concord	SW 21	Clear	Unl't'd	Unl't'd	Low clouds
Livermore	SW mod.	Overcast st.	1500	Unl't'd	63 SW
San Jose	S light	Overcast st.	800	8	58
Gilroy	Calm	Overcast st.	1000	3	
King City	N light	Overcast st.	2000	Unl't'd	
San Luis Obispo	S mod.	Overcast st.	800	1	57
Santa Barbara	Calm	Overcast st.	1500	4	
Vail Field	Calm	Overcast st.	1000	2	
Griffith Park	SE light	Overcast st.	500	1	
San Fernando	S light	Overcast st.	500	2	
Newhall	S 5	Clear	Unl't'd	Unl't'd	63

[24] Earl, K., and Turner, T. A., A graphical means of identifying air masses, *Massachusetts Institute of Technology Meteorological Course, Professional Notes No. 4* (1930).

These observations indicate a fairly widespread distribution of fog. At Mount Hamilton, the sky was clear and the top of the fog below the station was estimated to be about 2000 feet above sea level. At 9.30 a.m. the temperature at the mountain station was 10° F. higher than at San Jose, in the valley below. Reports from Mount Wilson indicate that the top of the cloud over the Los Angeles Basin is at 2800 feet above sea level.

The air movement is light during these morning hours on account of nocturnal cooling in the interior valleys. Later in the day, however, when the contrasts in temperature are greater, the sea air moves into the valleys at a moderate velocity. As this landward movement becomes more accentuated, identification of the various air mass properties should become simpler because there is less chance for local influences to interfere with a fresh flow of air than with a stagnant one. On the other hand, the intensive solar heating during the day has a profound effect in altering the non-conservative air mass properties.

The table reproduced above shows that July 9, 1928, was a typical foggy day. It will be well to investigate the air on this particular day to determine whether or not the interior and the coast are both in air masses of the same origin. Temperatures and relative humidities lead one to suspect that we are dealing with two different air masses. At noon on this date the specific humidity at San Francisco was 7.78 grams per kilogram; at Sacramento, 9.73; at Red Bluff, 7.87; at Fresno, 7.03; and at Los Angeles, 9.42. The increase in specific humidity between San Francisco and Sacramento is probably due to the fact that the air must pass over somewhat extensive bodies of inland water, such as San Francisco and San Pablo bays, Carquinez Strait and the Sacramento and San Joaquin river deltas. Moisture is added to the air by evaporation from these water surfaces. At the same time its moisture holding capacity is increased, due to slow heating. The decrease in specific humidity between Sacramento and Red Bluff and between San Francisco and Fresno may be due to convection, which, with the intense heating of the ground, here very dry, would tend to carry off the moisture to higher levels. Los Angeles, on account of its more southerly location, has a slightly higher specific humidity, as would be expected. This is due to the higher vapor pressure over the ocean caused by higher temperatures and also to the additional possibilities for the air to take on moisture owing to the greater distance it travels over the ocean.

In these humidity observations is contained an explanation for the almost total absence of clouds and thunderstorms in the hot interior valleys. However great heat convection may be in this region, the air is too dry to form clouds. It is only over the high Sierra Nevada that clouds and thunderstorms form to an appreciable extent.

Chapter IV

THE MOVEMENT OF FRONTS OVER CALIFORNIA

Two examples of pronounced interaction between air masses along moving frontal zones will be discussed in this chapter to illustrate the typical California winter storms and also to demonstrate the applicability of the Norwegian system of weather analysis to this region. The periods chosen are the dates December 9 to 12, 1928, and March 8 to 10, 1929. While these two situations have much in common, they are representative of two separate

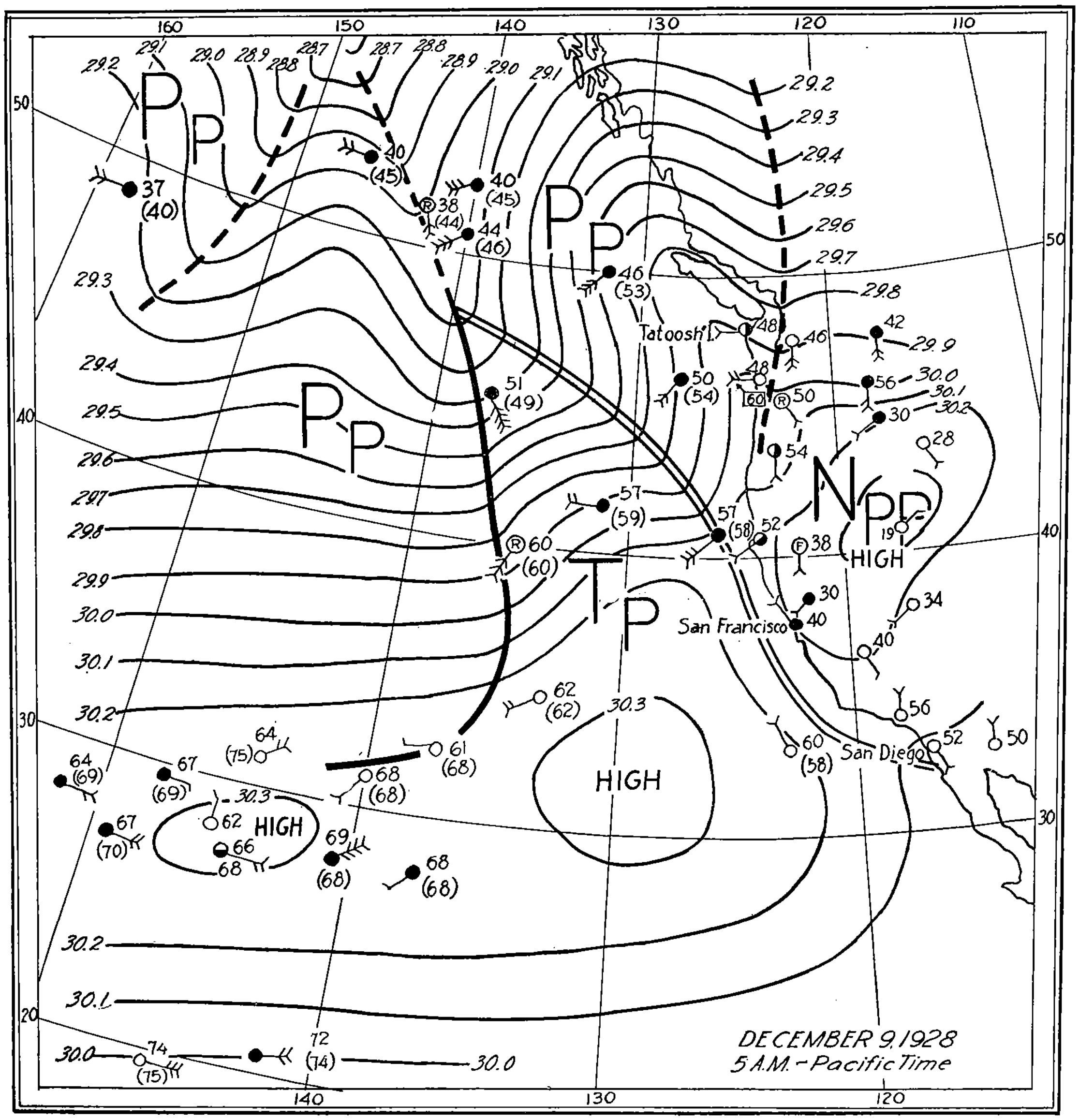


Fig. 6a

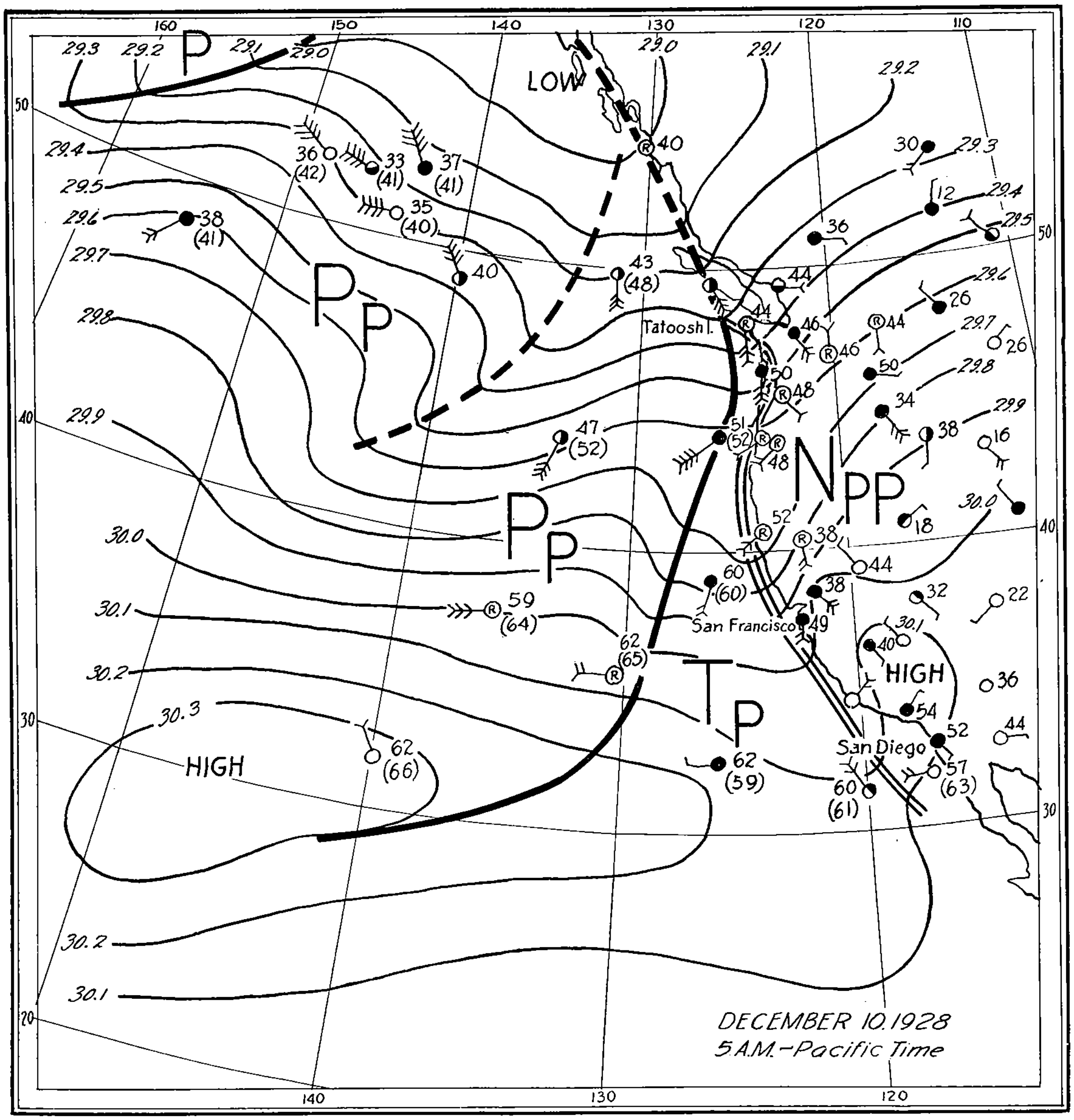


FIG. 6b

seasons, winter and spring, and therefore differ in essential details. The principal difference is in the general character of the polar maritime air which follows the passage of the fronts; for, in the winter case, this normally unstable air quickly becomes stable, whereas in the spring it remains unstable for some time.

I. December 9 to 12, 1928

On the weather map of the eastern North Pacific Ocean and the western quarter of North America for the morning of December 9 (fig. 6), a system of fronts accompanied by a well-marked trough of low pressure is shown approaching the continent from the west. Although the lowest pressure is at Kodiak, Alaska, rain has been observed as far southward as the 30th parallel of latitude. Most of the rain is in advance of the fronts in the northward moving current. The occluded front shown on the map as extending through Oregon, Washington and British Columbia at this time, will have no bearing on the present discussion. The chief disturbance is characterized by strong interaction of three different air masses — Polar Pacific, Tropical Pacific and Transitional Polar Pacific. The Polar Pacific air has moved southward across the ocean from the vicinity of the Bering Sea. The tropical current is from the northern part of the trade wind belt. The warm air is not only followed by Polar Pacific but is also moving against the same type of air ahead of it. In California, however, the air in advance of the warm front is Transitional Polar Pacific. The specific humidity serves as a reliable means of identifying these air masses. In the tropical air, both the steamer *President Taft* and the *Kentucky*, at latitudes 35 and 45 degrees, respectively, have a specific humidity of approximately 7.5 grams per kilogram. During the next 24 hours the specific humidity increases by 2 grams per kilogram, as indicated by observations in the warm sector at San Francisco the following day. Gales and turbulent seas may account for the addition of moisture. Gales are reported by both ship and land stations. At North Head, located at the mouth of the Columbia River, the wind attained a maximum velocity of 72 miles per hour. Observations from ships in the northern part of the ocean show a water vapor content of 3 to 4 grams per kilogram both in advance of and behind the warm sector, indicating that in both cases we are dealing with Polar Pacific air. The air in advance of the warm front over California has been designated as Transitional Polar Pacific. Its specific humidity is between 5 and 6 grams per kilogram. It is Polar Pacific air which has remained nearly stationary over the region and which has been acted upon by both the Great Basin and Pacific anticyclones. In fact, on this date (December 9) these two HIGHS are both fairly well marked. It is between them that the warm front lies. The warm air is moving around the oceanic anticyclone, while the high pressure over the land tends to hold it back. The relative strengths of the two slightly opposed currents may be the determining factor in the movement of the front. It so happens that at this time there is a fairly even balance, for the warm front remains practically stationary off the California coast for more than 24 hours. Meanwhile the cold Polar Pacific air moves in from the northwest and the warm sector narrows until eventually occlusion takes place along the California coast. This displacement of the warm air by the cold occurs just in the region covered by the aeronautical weather service, and we are thus able to obtain a "microscopic" view of the process. The chief value of investigating this type of situation, however, lies in the fact that it is of very common occurrence in California. During the winter 1928-29 there were at least four occlusions of this type observed within the area covered by this study. Had the winter been a normal one with respect to the amount of rainfall and number of storms passing, a greater number of examples probably would have been found.

It is difficult to judge whether the retarding of the warm fronts is caused more by the high pressure area over the plateau or more by the mountains which act as a dam against the flow of warm air at sea level. In the example of March 8 to 10, 1929, the front apparently remained stationary even after the Great Basin anticyclone had shrunk almost to insignificance. This indicates that the mountain effect is strongest. The warm air is retarded only in its lower layers, however, for there is some overrunning of this air above the colder air ahead, as will be shown in the following discussion.

Passage of the Warm Front. The warm front which is shown lying near the California coast on the morning of December 9 is preceded by overrunning air from the warm sector which can be detected at the mountain stations. For example, Mount Hamilton, located about

20 miles inland and having an elevation of 4209 feet, is within the warm air at this time. The temperature at this station is 46° F. at 6.30 a.m., while at San Jose, near its base, the temperature at the same hour is 40° F. At Sandberg, in the Tehachapi Mountains of Southern California, at about the same elevation as Mount Hamilton, the temperature is 48° F., while the temperature at Mount Wilson, elevation 5886 feet, is 40° F. at this time. The air at Mount Wilson can be identified as Tropical Pacific by the specific humidity which has a value of 4.5 grams, a fairly high value for air at this height. Records are not available for the 9th at Mount Hamilton, but on the following morning the specific humidity is even higher than at Mount Wilson, namely 6.22 grams per kilogram, while at the latter station the value still remains at 4.5. At Los Angeles, near the base of Mount Wilson, the specific humidity is nearly the same on the morning of the 9th as at the mountain station — 4.75 grams per kilogram. San Francisco and Fresno each have values very close to 5 grams per kilogram. These temperature and specific humidity values give very definite indication that the mountain stations are in an air mass different from that of the sea level stations. The overrunning is not very strong, as is shown by the light wind velocities within the upper warm air. At Mount Hamilton the air is calm, and the pilot balloon observations at Los Angeles and Lebec show light westerly winds in the upper levels. Another indication of the weakness of the overrunning is the fact that at all the mountain stations clear skies are observed.

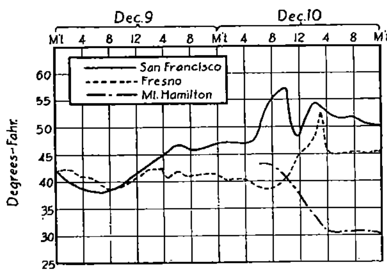


FIG. 7
Temperature curves,
December 9-10, 1928.

There has been fog in the San Joaquin Valley during the preceding days and it still persists on the morning of the 9th, having spread to the Santa Clara Valley and San Francisco Bay region, as well. But it is rapidly breaking up under the influence of an increasing wind. The fog is of the high inversion type discussed in Chapter II, and the dry continental air at upper levels which characterizes this fog has just been displaced by tropical maritime air.

In tracing fronts on the maps we shall confine ourselves to indicating their passage at sea level. To completely represent a warm front moving over a mountainous region would require a very great number of observations and the weather map would appear with many isolated, closed warm sectors scattered over the various mountain peaks and ranges. Therefore, no front will be represented as having passed a mountain station until it has reached stations in the same path in the valley floor below.

After remaining stationary along the coast for 24 hours, the warm front finally begins to move over our region on the morning of December 10. It has already moved into western Oregon and Washington before passing over the California coast line. The reason for its being now set into motion across our region is that the cold Polar Pacific Air from the northwest is pushing in behind it and rapidly forcing an occlusion. The wall of cold air pushes the warm air ahead of it, thus increasing the strength of the overrunning, with the result that a fairly large rain area develops in this upward-gliding warm air. This overrunning air is probably unstable, or at least conditionally unstable. This fact is illustrated by the fairly large amount of rain within this air mass while still over the ocean. Conditional instability combined with rapid overrunning causes heavy rain over the land as the tropical air slides over the Transitional Polar Maritime Air.

With the polar air pushing it along, the velocity of the warm current above Lebec at 6 a.m., December 10, varies from 14 to 34 miles per hour. At Mount Hamilton, where on the previous day the air was calm, it now has a velocity of 20 miles per hour from SSW. There is dense fog on the mountain now. The temperature is 43° F. and the specific humidity is 6.22 gr./kg. In Southern California the action is not as intense as in the northern part of the region, because the cold air has not approached as near. Mount Wilson reports clear skies with a southwest wind of 9 miles per hour and a temperature of 39°. The specific humidity remains 4.5 grams per kilogram.

During the early morning of this day, the temperature and specific humidity at stations in the San Francisco Bay region begin to rise rapidly, indicating the approach of the frontal zone at the surface. The south to southeast winds in advance of the warm front increase in strength until velocities of 30 miles per hour or over are attained. A rapid fall in pressure is noted, amounting to 0.13 of an inch in 90 minutes at Oakland Airport. This rapid pressure decrease occurs between 6.30 and 8 a.m., apparently just before the warm front reaches the station. It is difficult to determine the exact time at which the front passes. Three well-known indices of a front passage are changes in temperature, specific humidity, and wind direction. It has been repeatedly observed that temperature and specific humidity change quite abruptly on the passage of a cold front, but in a warm front the changes are gradual. Thus in the warm front, which we are now considering, the temperatures and specific humidities at the stations in the Bay Region rise for six hours and no sharp discontinuity can be defined. In the case of a front that is moving rapidly, the windshift is abrupt. If the front is stagnant or moving slowly, a long period of calm or light variable winds may accompany its passage. In any event, the windshift should be the most accurate indication that the front has passed. In our case, however, since occlusion is taking place so rapidly, the distance between the warm and cold fronts is slight, and, since both are preceded by southerly winds, the expected windshift does not occur, or, if it does, is not very well marked. On the maps (plate X) we have used a slight shift in the wind to a more westerly component as an indication that the front has passed. Thus the front is considered to have reached Mills Field at 6.30 a.m. and to have extended to Livermore and Oakland by 8 a.m. (At Livermore there was a 13° F. rise in temperature between 6.30 a.m. and 8 a.m.) By 9.30 it has extended to Concord, Tracy and Palo Alto, and so on. As the front moves across the more southerly parts of the region, the discontinuity is more distinct and few further difficulties arise.

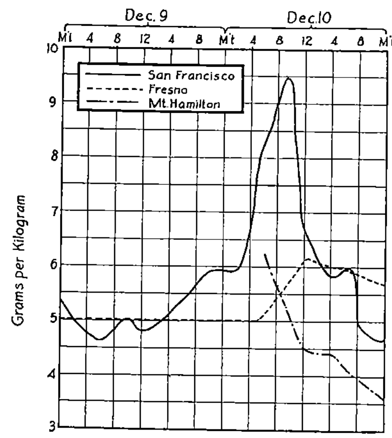


FIG. 8
Specific humidity curves, December 9-10, 1928.

As the warm sector sweeps across the San Francisco Bay region, it has become so narrow that we are able to observe its properties during only a very short period of time. It is characterized by fairly high temperatures, high specific humidity and a moderately steep lapse rate. At San Francisco, the temperature rises about 10° F. after the passage of the warm front, changing from 47° at 5 a.m. to 57° at 10 a.m. The water vapor content at this station increases from approximately 5 grams per kilogram to a maximum of 9.4 grams per kilogram in the warm sector. It is not possible to get a picture of the vertical temperature distribution in the tropical air by comparing the temperature at Mount Hamilton with that of stations directly below, for the cold air is actually overriding the warm air for a distance of perhaps 40 miles or more in advance of the cold front. This will be discussed more fully below. By comparing maximum temperatures at San Francisco with those of Mount Hamilton we are able to judge that the average rate of temperature decrease per hundred meters' altitude is around 0.75° C. within the warm sector.

During the day the warm front did not move much more than a few miles into the San Joaquin Valley before occlusion took place. It never reached Fresno, and at the last observation of the day the warm sector is being displaced by the cold Pp current in the vicinity of Bakersfield. The warm front passed Los Angeles some time during the afternoon and later reached San Diego. In the warm sector, the specific humidity at Los Angeles increased from 6 grams per kilogram to 9 grams per kilogram, while the temperature rose from 56° F. to 62° F.

Passage of the Cold Front. The cold front moved over the San Francisco Bay region at about 10 o'clock — less than three hours after the passage of the warm front. However, two hours earlier the cold air started moving in at upper levels, as indicated by the Mount Hamilton observations. Thus, we are led to the important conclusion that there is overrunning cold air over the warm. While sea-level stations of the San Francisco Bay region are in the warm sector and experience rising temperatures and specific humidity, it is getting continually colder at Mount Hamilton and the specific humidity is decreasing. This decrease in water vapor content is a clear indication that we are dealing with polar air and not with forced ascent in the warm sector in advance of the cold front. Beginning at 8 a.m., the temperature dropped steadily at the rate of 10° F. in four hours. At the same time the specific humidity at this station changes from 6.22 grams per kilogram to 4.5 grams per kilogram. This overrunning cold air produced a steep lapse rate. For example, just before the cold front passed San Jose (11 a.m.), the temperature difference between that station and Mount Hamilton was 19° F., indicating an average temperature decrease with altitude of 0.9° C. per 100 meters. Probably at the boundary between the overrunning cold air and the warm air below it, the temperature falls off very suddenly. This cold air aloft, together with the strong influence of the hills and mountains, accounts for the very heavy rains observed in advance of the cold front.

Unlike the warm front, the discontinuities at the passage of the cold front are pronounced. Heavy rain squalls, a change of wind from south to west or northwest, and a rapid decrease in temperature and specific humidity are experienced. At San Francisco the Polar Pacific air pushes in at about 10 o'clock. The temperature falls 9° F. in one hour, while the specific humidity decreases in two hours from 9.4 grams per kilogram to 6.5 grams per kilogram. A heavy squall occurs just before the wind changes from south to west and northwest. High velocities are characteristic of the southerly wind in advance of the cold front, and these winds exceed 30 miles per hour in the squall. The westerly winds behind the front, however, are only of moderate velocity. A good example of the winds experienced is afforded by the wind record of the *U. S. S. Saratoga* at anchor in San Francisco Bay (fig. 9). At 10.30 a.m. the south wind reaches a maximum velocity of 32 miles per hour. As the squall passes eastward the wind shifts to west, the velocity now being about 12 miles per hour. At 10.45 the squall line passes Oakland Airport. The south wind of 40 miles an hour is changed to a west-northwest wind of 20 miles per hour, and the intense precipitation preceding the front gives way to a lighter rain. It is interesting to note that the visibility greatly improves as the cold air moves in.

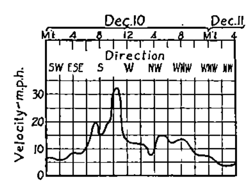


FIG. 9
Variations in wind, *U.S.S. Saratoga,* San Francisco Bay, December 10, 1928.

After 12.30 p.m., when the cold air has entered the Santa Clara Valley, it is possible to obtain an estimate of the lapse rate of this air. The difference in temperature between Mount Hamilton and San Jose ranges from 16° F. to 19° F. This means that the temperature decreases at a rate about eight-tenths of the dry adiabatic lapse rate, certainly an unstable condition.

On the map for 12.30 p.m. (plate XIII), it can be observed that a secondary low pressure center is beginning to develop around the region where occlusion is taking place, that is, where the cold front is overtaking the warm front. By observing the positions of the fronts we are in this way able to attach a real physical meaning to the formation of the low pressure in that particular locality. It is here that the strongest interaction of air masses of different density is taking place.

The map for 3.30 p.m. (plate XIV) shows even more clearly the effect of this interaction. During the three-hour interval since the previous observation, the cold air has spread over a large portion of our region and occlusion has taken place along the Coast Ranges and in the San Joaquin Valley. There remains an open warm sector over Southern California. The center of action where the occlusion is taking place forms a low pressure region which, to be sure, is small, but which is considerably more pronounced than on the 12.30 map. The contrast in conditions between Taft, which lies in the warm sector at this time, and Lost Hills, which has been reached by the cold air, is very striking. At the former station, the strong south wind has stirred up a dust storm, whereas at the latter, heavy rain is falling.

A new occluded front is shown moving over the Coast Ranges at this time. It brings additional showers in the vicinity of San Francisco Bay. Its passage is marked by phenomena similar to those of the passage of the cold front, only much less pronounced, of course. For instance, at San Francisco there is a slight increase in temperature during the afternoon, but as the occluded front passes, the temperature drops again. The wind was southerly for a short time preceding the front, then shifted to west as the discontinuity reached the station. This front is shown on the general Pacific synoptic chart for the morning of December 10 as an occluded front following some distance behind the cold front. During the night of December 10 to 11 it apparently merges with the main front, as it is impossible to trace it further as a separate front.

The Weather of December 11. There are two important characteristics of the weather of the following day which should be noted. In the first place, the Polar Pacific air which was so unstable the previous day has now become quite stable. There is a difference in temperature of only 8° F. between Mount Hamilton and San Jose, indicating that the average rate of temperature decrease is about one-third the dry adiabatic. Fog has formed at several stations in the San Joaquin Valley during the early morning. It is mostly light fog but at two stations, Sacramento and Modesto, later also at Mendota, the visibility is less than 1000 feet and the fog obscures the sky. Except for the fog at these stations, practically the only other clouds in the region on this date are over the mountains, where, on the windward slopes, snow is falling in small amounts. By 3.30 in the afternoon even these clouds clear away. This indicates that the cold maritime air has rapidly become stable. This has been accomplished by cooling from below by radiation. This is characteristic of Polar Pacific air in winter. It is often surprising to the observer to notice how rapidly the originally unstable air becomes stable. If the circulation in this air is light, as is frequently the case in California, fog is likely to form. It has been the observation of the writer that many rainy winter days are followed by fog the next morning in the coastal valleys, as well as in the interior. It is usually of short duration, unless characterized by subsidence as described in the previous chapter. This is the typical maritime fog described by Willett.[25]

[25] Op. cit. in fn. 8.

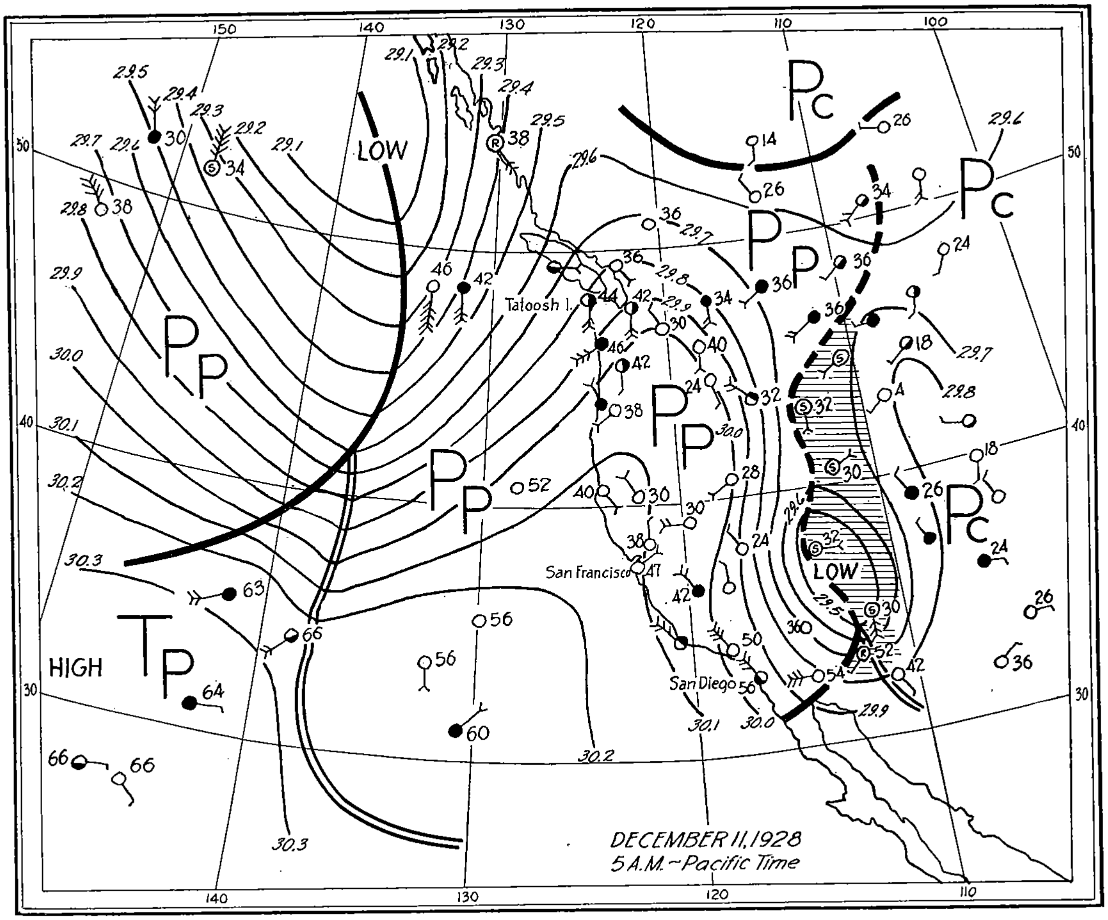


FIG. 10a
Secondary cyclone formed from an occlusion along the California coast. Note the new fronts approaching over the ocean.

A second important feature to notice in regard to the weather of December 11 is that the secondary, which centered around the zone of occlusion over our region, has now deepened and increased in area. On the morning of December 11 it covers a wide area over the Colorado River region. It is entirely separate from the "mother" cyclone to the north and has a lower pressure than when it passed over our area. Thus it is seen that the occlusion over California was the process in which we witness the formation of a secondary low pressure area. The interaction of the Polar Pacific air and the Tropical Pacific air produces this cyclone. As would be expected, the region of lowest pressure follows the point of the warm sector wedge as it is driven southeastward. This occlusion along the California coast can therefore be responsible for the formation of a type of cyclone which has long puzzled those who have analyzed the situation on the basis of pressure alone. This type of LOW is what is generally known as the South Pacific cyclone,[26] which, of course, should not be confused with the desert "heat LOW." It is a curious fact that on the following day, December 12, a similar condition occurs over California in which an occlusion takes place in almost the same way and on the next day, December 13, there is another Southwest cyclone which takes the place of the former one which has now moved eastward. The position of the Southwest cyclones is shown in fig. 10.

[26] U. S. Weather Bureau, Weather forecasting in the United States, pp. 122-125. Washington (1916).

II. March 8 to 12, 1929

The maps in plates XV to XXII illustrate an occlusion taking place along the California coast under the influence of a strong current of cold maritime air from the northwest.

Our discussion of this situation will begin with the morning observations of March 8, 1929. On this occasion there are present the two anticyclones — the Pacific and Great Basin HIGHS. Between them, extending down the coast from the Aleutian Islands, is a trough of low pressure moving southeast over the ocean. This cyclone is characterized by an occluded front in its northern portion, but to the south there is an open warm sector followed by a well-marked cold front. The location of these fronts is shown in fig. 12. The cold front and the occluded front represent the foremost boundaries of an advancing maritime air mass of recent polar origin (Pp). The source of the warm (Tp) air in the warm sector is the northern part of the trade-wind belt between Lower California and the Hawaiian Islands. The Tp-current is advancing against what probably was originally polar maritime air but which has moved so slowly over the warm southern seas that it has absorbed an appreciable quantity of moisture and heat (Nppm). This transitional air mass and that of the warm sector are carried northward in the circulation in advance of the approaching cold front.

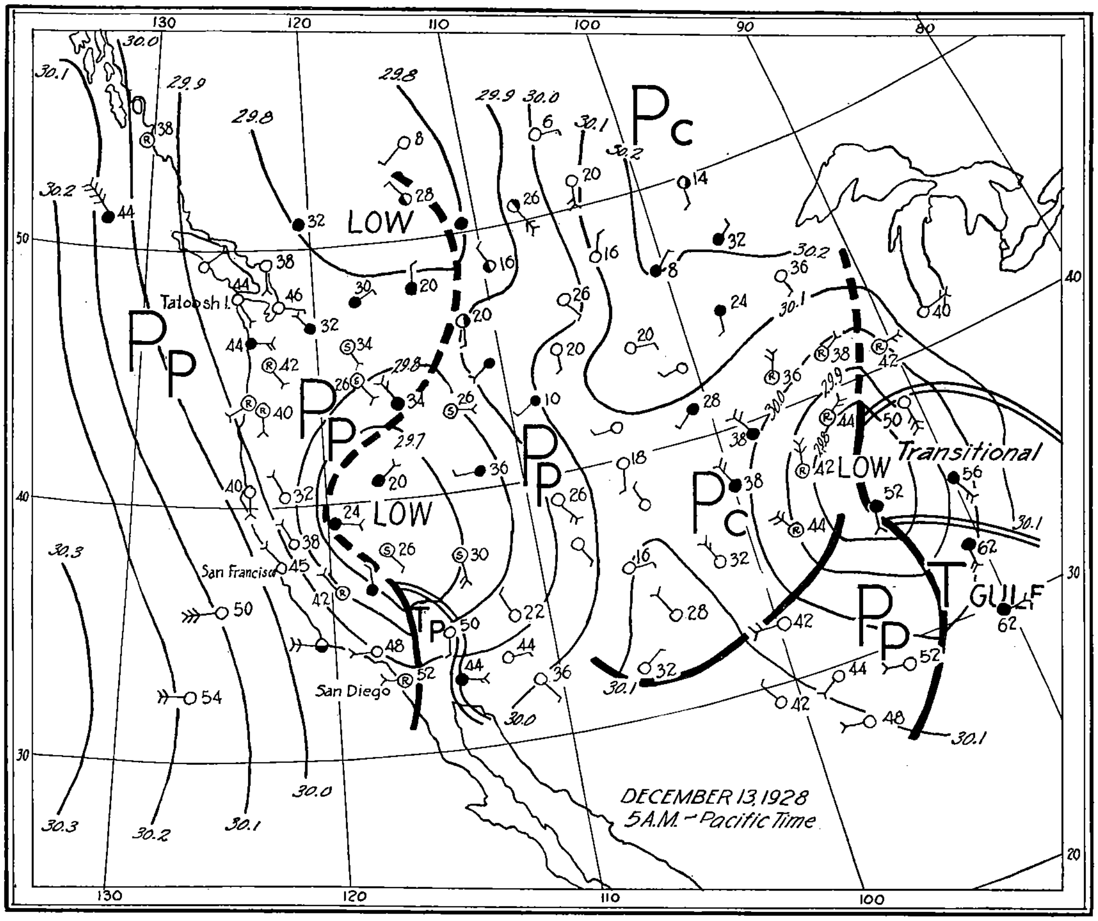


Fig. 10b
The same two frontal systems 48 hours later, showing how the new cold air outbreak formed a secondary LOW the same way as before, by forcing an occlusion along the California coast.

The Conditions in the Coastal Region. The modified polar maritime air (Nppm) covers California on the morning of the 8th and some important transformations are taking place within it. It is characterized at this stage by light, variable surface winds or calm. A heavy blanket of stratus covers the coastal section in the vicinity of San Francisco Bay and the Los Angeles Basin, extending nearly to the ground and obscuring most of the neighboring Coast Ranges. San Jose and Mount Hamilton observations are characteristic of the situation in Northern California. At 6.30 a.m., March 8, these stations reported:

	Wind	*Weather*	*Cloudiness*	*Ceiling*	*Visibility*	*Temperature*
San Jose	NW 2 m.p.h.	Light fog	Overcast, St.	1000 ft.	1 mi.	52° F.
Mount Hamilton	SE 15 m.p.h.	Dense fog	Overcast, Fog	0 ft.	300 ft.	38° F.

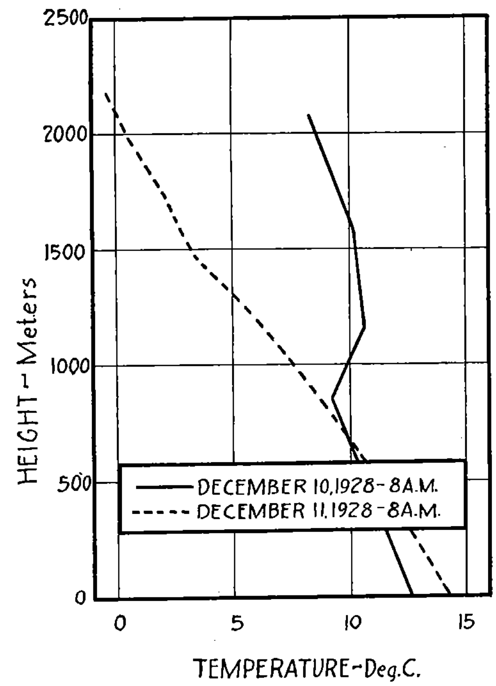


FIG. 11
Vertical distribution of temperature at San Diego before passage of cold front (Dec. 10) and after its passage (Dec. 11).

These two observations indicate that the cloud is at least 3000 feet thick, since the Mount Hamilton station is 4000 feet above San Jose and the distance between them is only a few miles. In other parts of the Bay Region the ceiling observations agree fairly closely, justifying our assumption that the Mount Hamilton and San Jose observations are representative for the area. The southeast wind observed at Mount Hamilton agrees fairly well with the pilot balloon observation at Hollister, in the valley at the southern end of the Mount Hamilton Range, according to which the winds are SSE to SSW from the surface up to an altitude of 13,000 feet, the highest velocity (21 miles per hour) being recorded in a south wind at 6200 feet. The air is virtually calm at the surface and in the layer between 10,000 and 13,000 feet altitude.

There are no clouds in the coastal region southward from Hollister to the Los Angeles Basin, or in the greater part of the San Joaquin Valley. Stations in the northern part of the valley report low alto-cumulus, and at Sacramento the clouds are taken to be strato-cumulus. Farther south, at Fresno, Bakersfield and San Luis Obispo, for instance, cirrus and cirro-stratus clouds are observed. There is some fog in certain parts of the San Joaquin Valley.

On the general synoptic charts for March 8 (morning and evening) a weak occluded front is shown passing over the coast of Washington, Oregon and Northern California. Most of our area lies too far south to come under its influence, but there is some evidence of its passage over the San Francisco Bay region. The clouds in the northern part of the area and the light rains which fell during the day may be ascribed to this front. Its passage is marked by a shift in wind from south to southwest or west and a series of light showers in the San Francisco Bay region occurring around midday.

The cloudiness in Southern California may have been caused by warm, dry air returning inland after cooling and absorbing moisture over the ocean. The dryness of the air above the

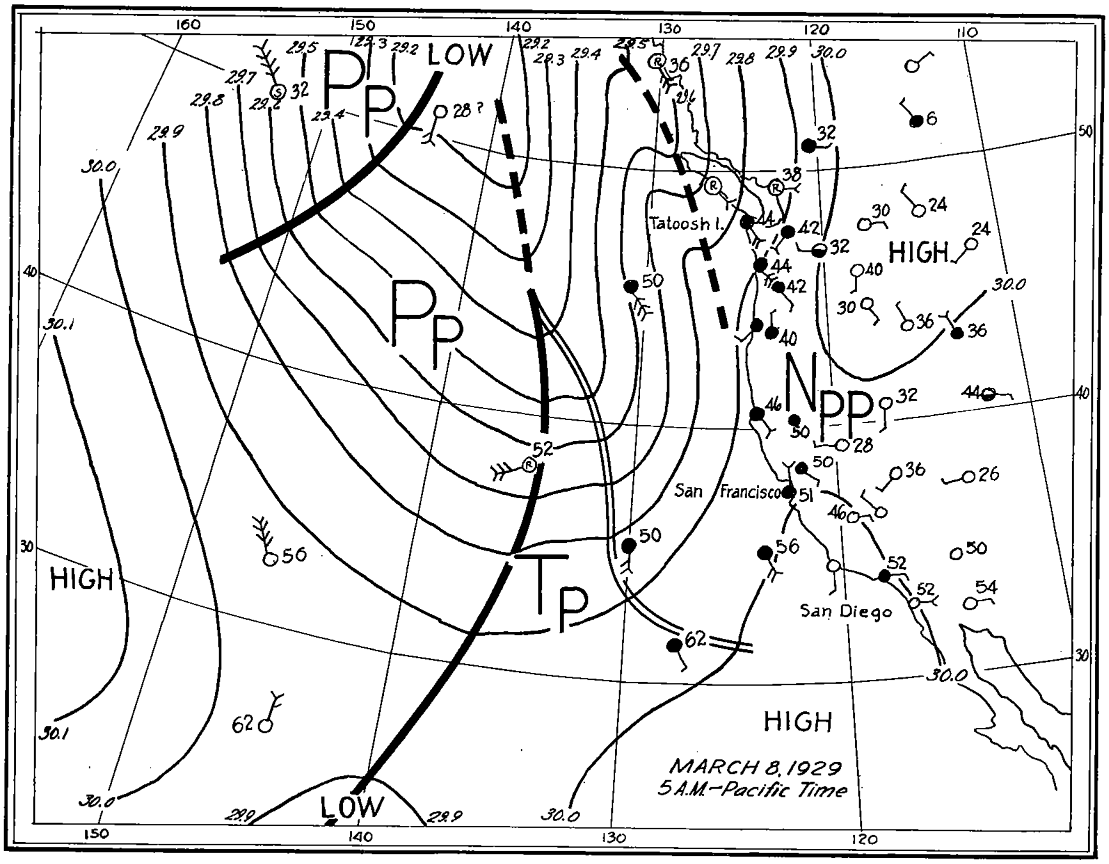

LOW
HIGH
HIGH
HIGH
HIGH
LOW
Tatoosh I.
San Francisco
San Diego
MARCH 8, 1929
5 A.M.—Pacific Time
29.5
29.7
29.8
29.9
30.0
30.1
160
150
140
130
120
110
50
40
30

Fig. 12

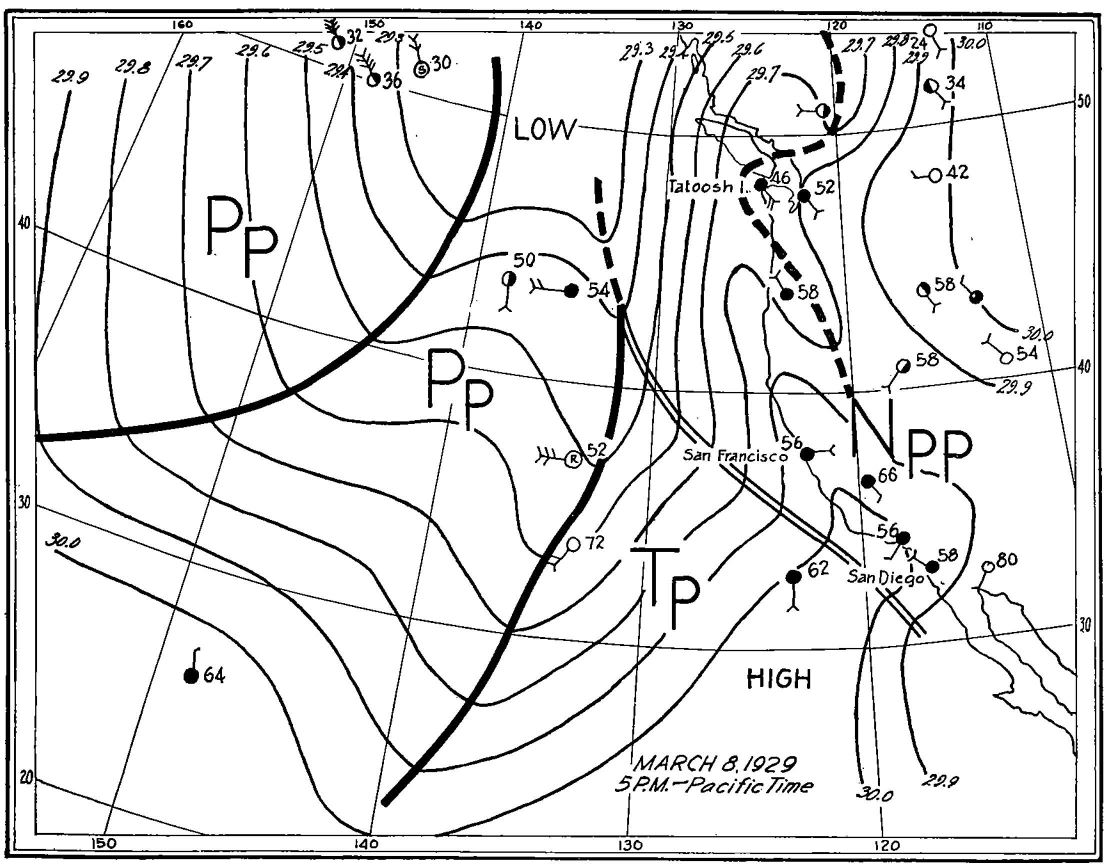

LOW
HIGH
Tatoosh I.
San Francisco
San Diego
MARCH 8, 1929
5 P.M.—Pacific Time
29.9
29.8
29.7
29.6
29.5
30.0
160
150
140
130
120
110
50
40
30
20

Fig. 13

inversion over San Diego on this day (fig. 15) indicates that it either has moved offshore from the dry continent and returned with a west wind or is air which has been sinking in the Pacific anticyclone. We will not attempt a further analysis of this situation on account of insufficient data. However, it might be added that conditions were favorable for the passage of air off the continent and its return onshore, because for several days prior to March 6 there had been a strong offshore Föhn current of air from the continent (Nppc). This was replaced

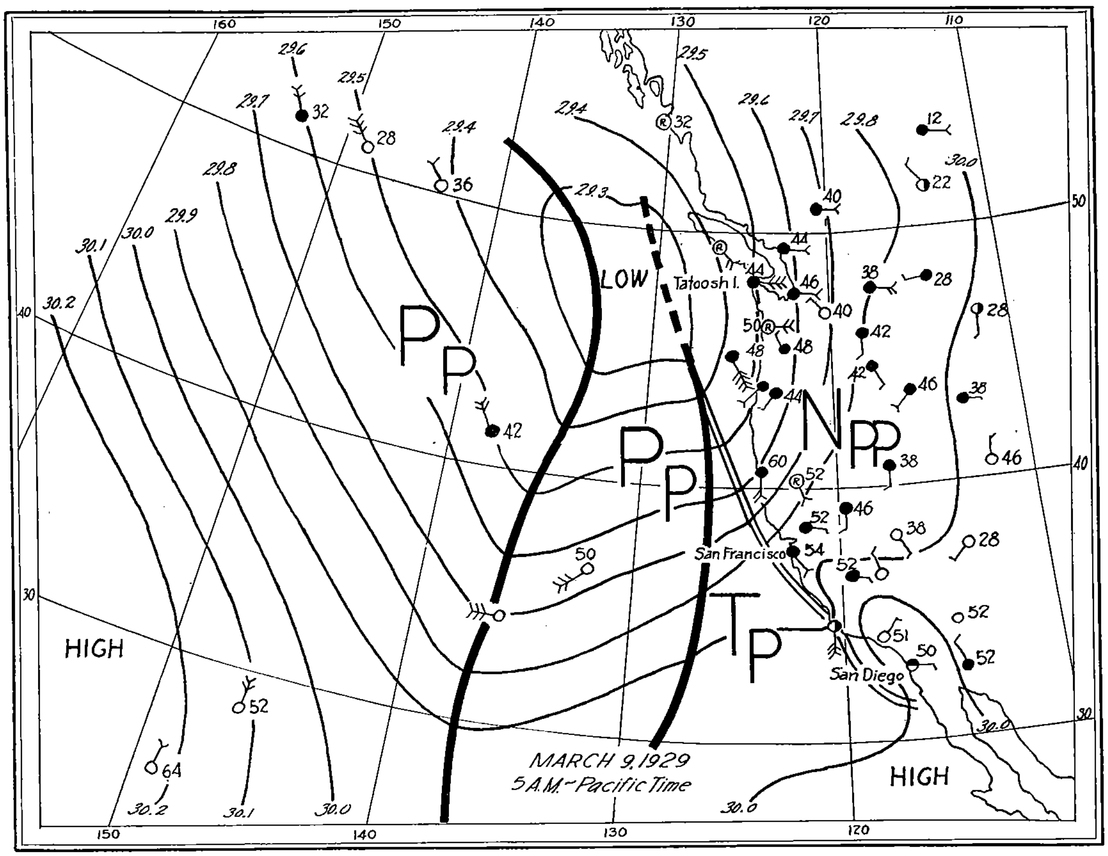


FIG. 14

by the more moist transitional maritime (Nppm) air from the west, but in this westerly current there still remains dry, warm air at higher levels, shown not only in the San Diego sounding but also in the mountain and, indirectly, in the pilot balloon observations over Northern California. Dry air moving from the ocean is observed at Mount Hamilton on the 6th, but on the 7th this is completely replaced at this station by cooler, more moist air. The following observations from Mount Hamilton and Hollister demonstrate the upper air conditions over the northern part of the area March 6 and 7. The similarity between the observations on March 6 at these two stations and the results of the San Diego soundings on March 8 is rather striking, indicating that the particular current under discussion at first appeared in Northern California and then spread southeastward.

TABLE 6

Mount Hamilton 6.30 a.m. Observations

Date	*Wind* (m.p.h.)	*Weather*	*Cloudiness*	*Specific Humidity* (noon)	*Temperature*
Mar. 6	S 15	Fog below	10 A-St	2.53	44
Mar. 7	S 10	Dense Fog	Overcast	6.22	36

Winds over Hollister

Altitude (Feet)	*Mar. 6, 2.30 p.m.* *Dir.*	*Vel.* (m.p.h.)	*Mar. 7, 7.30 a.m.* *Dir.*	*Vel.* (m.p.h.)
Surface	WNW	14	E	1
1000	W	19	S	3
1375	W	20	SSE	8
2050	W	14	SSE	14
2650	W	8	SSE	11
3150	W	4	S	8
3760	SW	5	SSW	9
4300	WSW	6	SW	16
5000			SW	22

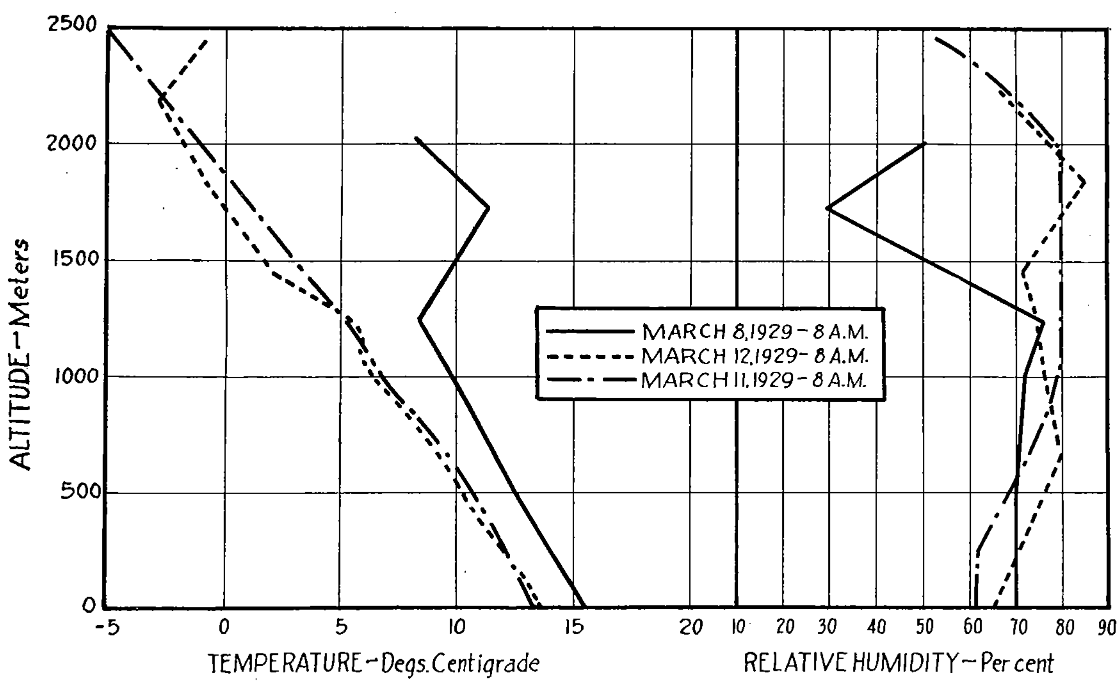


FIG. 15

Vertical distribution of temperature and relative humidity at San Diego before passage of cold front (solid lines) and after its passage (broken lines).

The most striking contrast revealed in these observations is in the specific humidity at Mount Hamilton. On the 6th this station was above the fog in the dry, returning continental air. That evening a change of wind direction brings in a different air mass, Transitional Maritime Polar Pacific air, Nppm. The windshift is clearly shown in the Hollister pilot balloon observations. In addition, at Mount Hamilton the new air mass is 8° F. cooler than the old.

The Situation in the Valley. During this time some fog is also observed in the San Joaquin Valley. On the morning of March 8 the lower part of the valley has what is apparently a ground fog, that is, a fog which forms due to radiation cooling combined with poor air drainage in the lowest layers of the atmosphere. In this case, drainage probably plays an important part. The winds at Fresno are very light east to southeast at all low and moderately high levels, indicating a possible drainage into the lower parts of the valley lying to the west. Mendota, in the bottom of the valley a few miles west of Fresno, is the only station to report the fog thick enough to obscure the sky. The horizontal visibility is but 100 feet. Dense fog is observed at Modesto, but blue sky is visible through it. Light fog is recorded at Tracy and Los Banos.

A considerable amount of radiational cooling in the valley has favored this fog. At most of these interior stations on this date the temperature at 6.30 a.m. is slightly more than 20° F. lower than on the previous afternoon at 3.30 p.m. At 6.30 a.m. Modesto is 11° colder than Oakland, whereas the afternoon before it has been about 10° warmer. This amount of cooling was sufficient to produce a fairly widespread blanket of fog. It is interesting to note that the early dissipation of this fog was accompanied by a cessation of the easterly drainage winds at Fresno and a shifting to southerly at all levels.

The Approach of the Warm Front. During the day (March 8) the warm front has moved from the southwest toward the California coast. The reports of the steamer *Calawaii,* bound for Los Angeles from Honolulu, indicate that the front has so moved that the vessel has followed immediately behind it during the day. The *Manukai,* steaming in the opposite direction, has met the front at some time during the day and is in the warm sector at 5 p.m., while the *Tecumseh,* further north and bound eastward, apparently is passed by the occlusion during the day. The difference in temperature in the air masses is appreciable as shown in the map, fig. 14.

With the closer proximity of the front, the observations at our California stations show a steady increase in cloudiness, particularly A-Cu and A-St — typical occlusion and warm front clouds. By midday they cover practically the entire area. Light occasional rain occurs in the vicinity of San Francisco around noon. This is probably due to the passage at this time of the weak occluded front characterized by the formation of broken cumulus mentioned before.

As was previously stated, the air over the valley has now been caught in the circulation of the approaching cyclone. However, at San Diego, the pilot balloon observations show that this change of wind has not occurred in Southern California during the day, for the west and northwesterly current still prevails. At Lebec, the major movement in the free air at 3 p.m. is from west-southwest, indicating a gradual transition toward the southerly dominance which has been observed farther north.

On the synoptic charts for this day there appears a wedge of high pressure extending up the Southern California coast in advance of the low pressure trough. Its position is such as to produce a gradient which would account for the difference in wind direction between Northern and Southern California. The isobars in this HIGH have a distinct bend at the northernmost end. On one side of this bend are the southerly winds and on the other, the west and northwest winds of Southern California. This high pressure area appears in practically every case of a front approaching from the west. It is usually an eastward extension of the South Pacific anticyclone, and is of considerable importance to the forecaster. It acts as a distinct shield from the approaching storm to those stations lying on its eastern edge. After the "spearhead" of this HIGH passes a station, southerly winds immediately set in and rain is likely in a very short time. A sudden southward retreat of the HIGH has the same effect. The difficulty for the forecaster is in predicting how this anticyclonic wedge will act. This behavior is not only true for California, but also has been observed for the entire Pacific Coast. In summer, the wedge is usually strong enough to maintain itself and force all cyclones around its head into the Canadian interior. In winter, however, its action is more erratic. It is because of the protection of this HIGH that on this day the weather in Southern California, particularly the wind direction, seems to be so independent of developments over the ocean.

The weak occluded front which passed over the Pacific Coast and caused rain in San Francisco at noon, was not felt over most of our region because of the northerly location of the front. We have gathered some data from Eureka, a station in the northwestern corner of California, which shows a noticeable effect produced by this occluded front. The front passage took place early in the morning of the 8th, probably at 6 or 7 a.m. The air in the wake of this front is apparently of polar origin, as shown by its low specific humidity. As it occurs at Eureka, however, it is too warm to be directly classified as polar air. Since it does not move over Eureka from the ocean, the only other way it could reach this station is by passage down the mountains from the higher interior in the northeast. It would therefore undergo adiabatic heating which would account for the high temperatures (50 to 60° F.). The occluded front was a very weak one, and it produced only slight precipitation. On the following morning it is impossible to trace it farther. The effect of this front in bringing air of low specific humidity to Eureka accounts for the non-agreement with specific humidity values of San Francisco.

Appearance of the Warm Front over Southern California. On the following morning, March 9, light rain of pronounced warm front character is falling in the northwestern part of our region and is rapidly spreading down the coast and into the interior valley. Unfortunately, no steamships reported from within the warm sector at the 5 a.m. observation, but a few hours later we obtain definite proof of the existence of the warm sector when it passes inland.

The early morning observations indicate that the area around Los Angeles still has not come under the influence of the cyclonic circulation, but lies behind the protecting wedge of high pressure. Fog is observed in most of the Los Angeles Basin — at March Field (Riverside), Vail Field, Griffith Park and Newhall, with "high fog" at San Fernando. The air is either calm or moving lightly from northeast. In the afternoon of the 8th the sea breeze has filled the coastal valleys of Southern California with moist air which is now calm. There has been sufficient radiational cooling to reduce the temperature at Los Angeles and San Diego to values three to six degrees lower than at San Francisco and San Jose, stations 500 miles to the north. San Diego, with a maritime exposure similar to that of San Francisco, cools 14° F. during the night while the latter has only a 2° drop. Scattered observations show that the night was clear in Southern California before the fog formed. The specific humidity is around 7 grams per kilogram, about the same value as in the southerly current at San Francisco and Fresno.

There is a significant difference in vertical temperature lapse rate between the cyclonic region and the high pressure wedge, if the mountain observations can be taken as criteria. A comparison of the temperatures at San Jose and Mount Hamilton indicates an average decrease of 0.65° C. per 100 meters, while the temperature differences between Los Angeles and Mount Wilson show an average of 0.42° C. for Southern California. Mount Wilson is 500 meters higher than Mount Hamilton and is several miles inland from Los Angeles. This lower lapse rate in Southern California would seem to indicate that the inversion observed in the San Diego sounding on the previous day still persists south of the Tehachapi Mountains.

It is interesting to note that at 5 a.m. Los Angeles, in the protection of the HIGH, has a very light northeast wind, while Point Arguello, some miles west of Santa Barbara, is in the full sweep of the cyclonic circulation with a south wind of 5 Beaufort.

During the early morning hours it is impossible to find any sign of the warm front at our stations. In the light of later observations, however, we know that some time before 9.30 a.m. it passed over the coast in the vicinity of San Luis Obispo, despite the fact that during this time the temperature at San Luis Obispo remained relatively low (52° F.). How could the warm air slip by this station without raising the temperature? For an explanation we must consider the physical features of the landscape.

San Luis Obispo lies in a small protected valley which, except for a narrow outlet to the northwest and an even narrower, more winding one to the south, is completely surrounded by hills. Its seclusion from the sea is about as complete as is geomorphically possible in such a short distance and consists mainly in a formidable spur of the Coast Ranges to the southwest separating it from the ocean. It is possible and probable that the warm air moving in from the southwest runs over this station without penetrating down to the valley floor. We have already shown other instances of the isolation of a mass of relatively cool air in the various valleys of California. Our first evidence of the presence of the warm sector over the region on this day is at 9.30 a.m., when it appears over a wide area at the upper (southern) end of the San Joaquin Valley. Coalinga, Lost Hills, Bakersfield, Taft and Grapevine have all come within the warm front between 8 o'clock and 9.30 a.m. This can best be shown by the following table of observations.

TABLE 7

Observations Indicating Passage of Warm Front, March 9, 1930

8 a.m.

Station	*Wind*	*Weather*	*Cloudiness*	*Temperature*
Coalinga	S 10 m.p.h.	Light rain	Overcast Nb	56°
Lost Hills	S light	Cloudy	Overcast A-Cu	54°
Bakersfield	E 5 m.p.h.	Fair	Partly Ci-St	56°
Taft	Calm	Fair	Clear	48°
Grapevine	SW Strong	Fair	Few Ci	53°

9.30 a.m.

Station	*Wind*	*Weather*	*Cloudiness*	*Temperature*
Coalinga	SW 8 m.p.h.	Cloudy	Overcast Nb	61°
Lost Hills	SW light	Cloudy	Overcast A-Cu	58° (raining in SW)
Bakersfield	SW 5 m.p.h.	Cloudy	Broken A-Cu	63°
Taft	Calm	Cloudy	Overcast St-Cu	56°
Grapevine	SW strong	Cloudy	Broken A-St	61°

The rise in temperature is well marked at most of these stations. Other evidences are change in wind direction and the cessation of the rain at Coalinga. The rain in the warm sector southwest of Lost Hills is in the mountains. The local map (plate XV) shows a marked discontinuity in temperature, wind direction and rainfall area. The temperature changes at the above stations in comparison with those at stations not reached by the warm air give very good evidence of the passage (fig. 16).

The character of a warm front is such that in a mountainous region like ours, the overrunning warm air will reach the high elevations long before being observed at the ground. To attempt to trace the front on the flanks of all the mountains would, as has already been pointed out, be an exceedingly difficult task and would, no doubt, require a great amount of interpolation and guess-work. Therefore, we have considered flat areas near sea level only in drawing the warm front. That is, no mountain station is included in the warm sector ahead of stations on the plain immediately below.

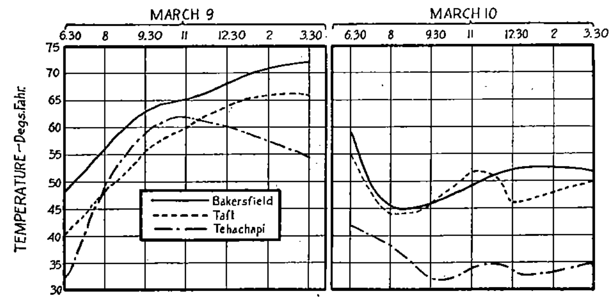


Fig. 16

Daytime temperature curves for southern end of San Joaquin Valley, March 9 and 10, 1929.

The question immediately arises as to why the warm air moves in at this point of the coast and no other. Apparently the warm front lies close to shore along the entire California coast early in the morning. We have good evidence of its passage at Eureka about noontime, followed two hours later by the cold front. Probably the damming effect of the Coast Ranges hindered the progress of the warm front, forcing it to remain almost stationary off the California coast while the polar maritime air was pushing in more strongly from the northwest. Our observations indicate that the open warm sector was very narrow in the northern part of the region, widening out in the south. The coast south of San Luis Obispo is part of a rather boldly exposed outward projection of the land. Here, too, the mountain chains parallel to the coast which are characteristic of the region to the north give way to ranges with axes running more east and west. In addition, these mountains are not so high as those immediately to the north. In this way, there is afforded a more exposed entrance into the interior valley than is found farther north. It is not so that the ultimate height of the mountain barrier over which the air must pass to get into the San Joaquin Valley is lower or even as low as in several places around San Francisco Bay. However, the slope is more gradual on account of the direction in which the valleys lie. A slope of 5000 feet in 50 miles presents less of a barrier than 1500 feet in three or four miles, as is the case around San Francisco Bay. The leeward mountain slope to the west of Taft and Lost Hills is relatively steep, so that the warm air does not have a tendency to spread out over the lowlands at once. That explains why the appearance of the warm air is more gradual at these western San Joaquin stations than at Bakersfield.

In the mountainous regions between San Luis Obispo and Monterey Bay our only stations are in the Salinas Valley, protected to the west and southwest more than any other part of the California coast. These stations are of no assistance to us in detecting the warm front, because it is almost impossible for a southwest wind to penetrate to the valley floor. For the sake of continuity, we have assumed the front to have passed over this area somewhere, but scarcely beyond it. We have, in this instance, chosen the trough of lowest pressure to guide us in tracing the front. In the vicinity of San Francisco, the records show definitely that the warm air did not approach very near. Otherwise one would expect to see evidence of it first at Mount Hamilton, but such is not the case.

At 11 o'clock there has been only a slight change in the position of the front, except that at Bakersfield it has actually retreated. Under the influence of an easterly wind, Bakersfield is again in advance of the front, and a heavy rain is falling at this observation. The front has pushed northward through the valley, however, and has just about reached Visalia, judging from the sudden increase in temperature at that point. The overrunning warm current now lies fairly low on the Sierra Nevada and the Tehachapi Mountains. Tehachapi (elevation 4000 feet) is now within the warm air.

At Eureka, about this time, there is a slight rise in temperature accompanied by a rapid increase in specific humidity, evidence of the passage of the warm front. At 5 a.m. the specific humidity was 4.62 grams per kilogram; at noon it had risen to 8.21 grams per kilogram. This is a value in excess of any observed at Fresno and San Francisco and indicates air of tropical origin. Later we shall observe that this same air (Tp) has a specific humidity of 10 grams per kilogram at Los Angeles. The difference in latitude of the two stations and the fact that the warm sector in Northern California is only a very narrow tongue, might account for the lower value at Eureka. The narrowness of this warm belt is strongly emphasized in the temperature and especially the specific humidity curves for Eureka (figs. 17, 18). No continuous record of relative humidity is kept at Eureka, but we have available psychrometric readings at 5 a.m., noon and 5 p.m. However, from the character of the temperature trace, the warm front seems to have reached this station shortly after noon, and before 5 p.m. the cold air behind the warm sector is already pushing in. Therefore it is also possible that the specific humidity of 8.21 grams per kilogram observed at noon does not represent the warm sector but a transition in the frontal zone, and that in the warm sector the specific humidity may have risen as high as 10 grams per kilogram.

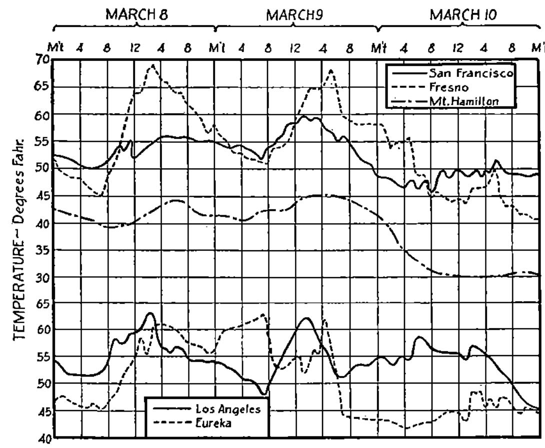


FIG. 17

Temperature curves, March 8-10, 1929.

The map for 12.30 p.m. shows relatively little advance of the warm front. Apparently the Sierra Nevada has checked its movement. However, a shift of wind to east in the Los Angeles Basin indicates proximity to the front. At the 11 a.m. observations the Los Angeles area came into the cyclonic circulation.

By the 3.30 p.m. observation, Bakersfield again comes within the warm sector, and the rain which has been falling since before 11 o'clock has stopped, accompanied by a shift of wind to southwest, a tendency toward clearing and an increase in temperature. Los Angeles is in the doubtful region immediately along the front with a specific humidity of 8.38 grams per kilogram, very similar to that at Eureka at noon in the frontal zone. Preceding the front the wind in the Los Angeles Basin has been from the east, and its desert origin and Föhn heating produce high temperatures. Consequently the temperature at Los Angeles is falling during the afternoon with the approach of the front and is still falling at 3.30, despite the fact that the wind has shifted to west. There has already been an increase of two grams per kilogram in the specific humidity. The temperature and psychrometric readings show that the warm front did not actually pass until about 7 o'clock in the evening, when the temperature begins to rise and increases all night until at 5 a.m. on the 10th there is a temperature of 59° and a specific humidity of 10.02 grams per kilogram as compared with 51° and specific humidity of 6.84 at the same time the previous day.

Source of the Tropical Air. It has already been stated that tropical air is uncommon in most of California. It rarely occurs in the northern part of the state, except along the immediate coast, such as at Eureka, Point Reyes, etc. It does not originate deep in the tropics, but is air which has stagnated in the northern part of the trade-wind belt as the South Pacific Anticyclone has weakened and retreated. The air is caught up in the southerly wind in advance of the cold front and is carried toward the California coast. Either on account of the light circulation which is generally found over the ocean south of California or on account of the damming effect of the mountains, occlusion takes place rapidly and is usually almost complete by the time the California coast is reached. Furthermore, the supply of the warm air is very limited and the air can be easily displaced from below by the cooler air. The value of 10 gr/kg for the specific humidity which we found at Los Angeles is not very high for a station in its latitude when compared with conditions in the tropical air masses of the Eastern United States, where values of 12 gr/kg or more are observed as far north as New England. The difference is that the tropical Atlantic air has swept through the trade-wind belt perhaps all the way from the Azores, while the tropical Pacific has come recently from the north as Polar Pacific air, and then retraced its path. It may not have been as close as 25 degrees from the equator, while the tropical Atlantic air generally comes from south of 20° N. One instance of a tropical hurricane which struck the west coast of Mexico and moved up the coast of Lower California, bringing air from the deep tropics to San Diego, attracted widespread attention during the fall of 1929. Blake[27] has written a brief description of this storm. His records show a much higher specific humidity. However, as Blake points out, a situation of this kind is exceedingly rare, due to the strength and tenacity of the South Pacific HIGH.

Over the eastern Pacific Ocean there is no complete exchange of air between the tropics and the pole. There is an almost continuous feeding of polar air into the trade winds, but the return flow from the south consists of this same air which has been heated and has added moisture while over southern waters, sometimes sufficiently enough to form a distinct advancing warm sector and sometimes not.

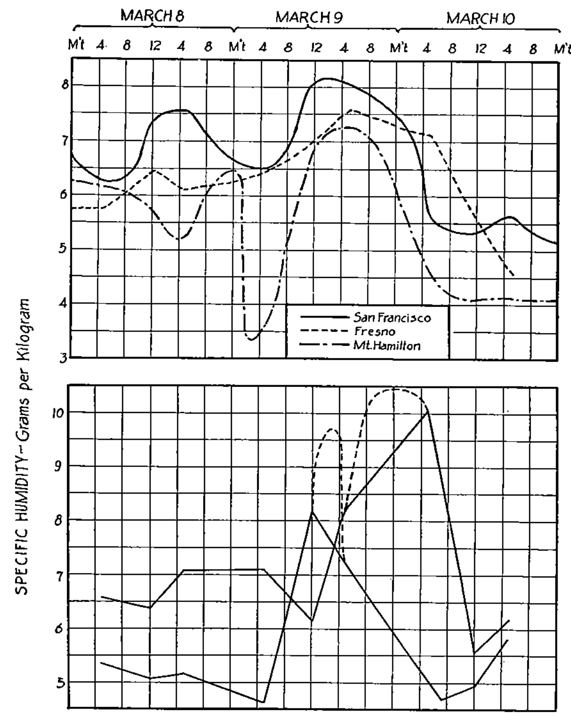


FIG. 18

Specific humidity curves, March 8-10, 1929. Above — Fresno, San Francisco and Mount Hamilton. Below — Los Angeles (upper curve) and Eureka (lower curve). The dotted lines in the lower figure represent values probably attained but which are not recorded owing to lack of a continuous record.

The Occlusion. A complete picture of the occluded and cold front moving over our area is not given, owing to its passage across a considerable part of the coastal region during the night when no observations are made at the stations comprising the network. Therefore, in passing from the conditions of the afternoon of the 9th to those on the morning of the 10th,

[27] Blake, op. cit. in fn. 6.

we have left a large gap unfilled. However, the temperature and specific humidity curves indicate that the cold air reached Eureka at 4 p.m. on the 9th, San Francisco around midnight and Fresno at 5 a.m. on the 10th. The discontinuity is especially well defined at Fresno. At 5 o'clock the wind shifted from south to northwest, the temperature dropped 10° F. in one hour and there was a sharp drop in specific humidity from 7.15 gr/kg at 5 a.m. to 5.3 at noon. (There may have been a sharper drop but no continuous record of humidity is available for this station. See fig. 18.) At Mount Hamilton the specific humidity in advance of the cold front was 7.16 grams per kilogram and after the front passed it was 3.77.

A comparison of temperatures between Mount Hamilton and San Jose again enables us to estimate the vertical lapse of the invading air. At 6.30 a.m. on the 10th, the temperature at San Jose is 46° F., while Mount Hamilton has dropped to 30° F. The average decrease of temperature with elevation is therefore 0.74° C. per 100 meters. This new, cold air mass must therefore be conditionally unstable. There are other evidences of this instability. Large cumulus and cumulo-nimbus clouds with instability showers and, at later observations, hail, thunder and lightning, give striking examples.

There is a distinct open warm sector over Southern California, but it is rapidly occluding along the flanks of the Sierra Nevada as the cold air pushes down the San Joaquin Valley. Already the warm air has been displaced at Coalinga and Lost Hills. A distinct secondary low pressure center has formed between Bakersfield and Visalia, where the strongest interaction of the warm and cold air masses is taking place. The absence of heavy cloud layers in the warm sector is striking. At Lebec, our mountain pilot balloon station, which at 6.30 a.m. still lies in the warm sector, it has been possible to obtain a pilot balloon observation. The result is as follows:

TABLE 8

Pilot Balloon Observation at Lebec, 7 a.m., March 10

Altitude (Ft. above sea level)	*Direction*	*Velocity* m.p.h.
Surface (3570)	S	30
4300	SSW	25
5000	SW	22
5600	SSW	40
6200	SW	46
7400	SW	72
8600	SW	62
9800	SW	52
10,400	SW	49

The cold air passed Bakersfield shortly before 8 a.m., as this station reports a squall and strong northwest wind at this hour. The front is also approaching Lebec (about 50 miles southeast) at the same time, since this latter station then reports rain (prefrontal?) with clouds reaching the ground and a 4° F. drop in temperature since 6.30 a.m. and a change of wind from south 30 m.p.h. to southeast 8 m.p.h. That Lebec by 6.30 a.m. was in the warm sector seems fairly well established by a comparison of its temperature at 6.30 a.m. on this and the two preceding days and on the following day. They are 39°, 40°, 46°, 33°.

The pilot balloon observation within the warm sector at Lebec illustrates a condition found to exist on many occasions in the Tehachapi Mountains. The gales at moderate altitudes above this station are not extraordinary for such a situation. Winds as great or greater in force may occur at any time over these ranges when a fairly steep pressure gradient exists. The effect is produced by the crowding of stream lines as the air flows over these elevated regions. The upward bulge of the stream lines is flattened out at some distance above the ground, depending upon the vertical stability of the air. A crowding of the stream lines means a decrease in the cross-sectional area through which the stream must flow and thereby increases the velocity.

Between 6.30 and 8 o'clock there has been rapid action. The cold air has moved in rapidly, having now passed Taft, Santa Barbara and Bakersfield, and is about to move over Los Angeles. The secondary low pressure area has moved southward and now lies over the Tehachapi Mountains. Its southward movement follows the narrowing warm sector which we have not attempted to trace on the map owing to lack of data over the Mojave Desert. Heavy rain has broken over the Tehachapi Mountains where it was only partly cloudy 90 minutes before. The observations at Bakersfield are typical of the southeastward movement of the polar air. When the cold front displaces the warm sector over this station the wind shifts from southwest to northwest as a heavy squall line sweeps down. The wind increases from 13 to 23 miles per hour and the temperature drops from 59° to 45°. The ceiling lowers from 4000 feet to 1000 and the visibility decreases from unlimited to two miles. Instability showers with fresh to strong west and northwest winds are observed at several stations behind the cold front.

By 9.30 a.m. the Pp air has reached Los Angeles and has passed over the Tehachapi Mountains, leaving heavy rains and snow in its wake. Vail Field, Los Angeles, reports a wind of gale force with heavy showers. The secondary has moved southeastward along the line of occlusion and it is probable that by this time no open warm sector remains.

The 11 o'clock observations show that the cold front has passed all of the stations and is moving over the Sierra into the Great Basin. It is interesting to note on the remaining maps the characteristic instability. It may be raining or snowing at a station and an hour later the sky will be practically clear. Hail, with thunder and lightning, is observed at Mendota at noon, indicating the instability which is accentuated by the mountains.

At 12.30 p.m. a comparison of observations at San Jose and Mount Hamilton shows the following:

	Wind	*Weather*	*Cloudiness*	*Temperature*
San Jose	NW light	Raining	Broken St.	49
Mount Hamilton	NW 10	Snow	Overcast fog	31

If these temperatures can be taken as an indication of the lapse rate, the air is fairly unstable, having a decrease of 0.82° C. per 100 meters, well in excess of the saturation adiabatic lapse rate.

The movement in the free air is shown by the following pilot balloon observations taken on the afternoon of the 10th:

TABLE 9

Free Air Winds, Afternoon, March 10

Altitude	*Hollister*		*Los Angeles*		*San Diego*	
(Feet)	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*
Surface	WSW	8	WSW	25	NW	20
800	W	25	WSW	23	WNW	25
1400	W	27	WSW	16	WNW	26
2000	WNW	23	W	18	WNW	32
2600	WNW	22	W	22	WNW	40
3200	WNW	25	W	24	WNW	43
3800	WNW	25	W	27		
4300	WNW	25	W	28		
5000	WNW	25				

An airplane sounding was made in this Pp air at San Diego on the following morning and also on the 12th. The results are plotted in fig. 15. The temperature decreases at a practically constant rate of approximately seven-tenths of the dry adiabatic up to the highest altitude attained, which is 2565 meters. It is interesting to note that the cold Pp air has displaced, at all altitudes, the dry, warm air observed over this station on the 8th and that no upper boundary to the Pp air current can be detected. It should also be noted that this fresh polar current is characterized by high relative humidities.

CHAPTER V

THE FÖHN

DURING the autumn, winter and early spring, when cold air with its accompanying high pressure sets in over the Great Basin and Columbia Plateau, conditions become favorable for the movement of air out of these regions and over the mountains down to the coast. During the descent to sea level, the air is heated adiabatically and appears at such stations as San Francisco as a warm, dry wind. Winds of this character which have been heated in blowing down mountain slopes are generally known as Föhn winds, a name given to them by the Germans, who first observed the phenomenon in the vicinity of the Alps. The name "Chinook"[28] has also been applied to this type of wind in the Rocky Mountain region of the United States. Their occurrence in California is frequent and in many cases very well marked.

In the discussion which follows, no attempt will be made to present a complete dynamic picture of the Föhn as it occurs in our region. Obviously, to do so requires a close study of conditions in the free air. Since the necessary air soundings are not available, it is necessary to confine the discussion to a presentation of the conditions as observed on the ground. The observations are for stations only on the leeward side of the Sierra.

Several German writers[29] have given good descriptions of the Föhn as it occurs in Europe. Their discussions of the physical processes are probably applicable also to the California Föhn.

During the year in which the Guggenheim Fund's meteorological service was conducted, opportunity was afforded to study the California Föhn in more detail than had previously been possible. An especially interesting example was observed on March 3, 1929. Record high temperatures were reported at stations in the San Francisco Bay region, in many cases exceeding 80° F.

THE FÖHN OF MARCH 3, 1929

On March 2, following the passage over the Pacific Coast of an occluded front, Polar Pacific air flows inland, particularly in the region of the Columbia River. The front is not very well pronounced in the southern part of the United States, and there is little, if any, inflow of polar air into the southern part of our region. Consequently the air remains relatively warm in that vicinity. The result is a pressure gradient directed southwestward from the Columbia Plateau.

The high pressure region which accompanies the polar air first appears as an eastward extension of a widespread anticyclone lying over the Pacific Ocean. The isobars on the morning of March 2 run in a north to south direction and the winds over California at this time are N and NNW, moderate and fresh above 3000 feet. By the evening of the 2nd the winds are NNE and NE.

A well-defined wedge of high pressure extends over Nevada and Utah on the morning of March 3, and it is then that the northeast Föhn wind becomes pronounced along the California coast. At the morning observation (5 a.m.) a temperature of 22 degrees is observed at

[28] How this name originated is not known to the author. A Chinook tribe of Indians occupied the Columbia River region and it is probable that the name originated there.

[29] Especially:
Lammert, L., Der mittlere Zustand der Atmosphäre bei Südföhn, *Veröffentlichungen des Geophysikalischen Instituts der Universität Leipzig,* vol. 2, pp. 261-322 (1920).

Winnemucca, Nevada, while in the same air mass there is a temperature of 64° at San Francisco. This does not necessarily mean that the air has been heated adiabatically in moving down from the plateau as much as 44° F. The temperature at Winnemucca is probably characteristic of only the lowest levels where radiation cooling is strongest.

It is evident that San Francisco Bay is the only sea-level region that has been reached by the Föhn, probably because it is the only place sufficiently far removed from high mountains. Los Angeles has a temperature of 50° F., San Diego, 48° F. and Fresno, 52° F. The wind is from the northeast with a velocity of 10 miles per hour at San Francisco, while other parts of the region have light, variable winds or calms.

The temperature mounts rapidly in the San Francisco Bay region under the influence of this dry, warm northeast wind and the clear skies accompanying it. Late in the afternoon, the land breeze dies down and by 5 o'clock a northwesterly breeze has started. At the 5 p.m. observation San Francisco reports a temperature of 78° F., while at Los Angeles it is 66° F.; San Diego, 62°; and Winnemucca, Nevada, 58°.

The Sierra Nevada and also the Coast Ranges afford protection from the wind to the stations in the valleys below. The San Joaquin Valley and the coastal valleys are entirely unaffected by the Föhn. For example, when the land wind first starts on March 2, the temperature at San Jose is only 5° F. higher than at Mount Hamilton. The winds of the upper air tabulated in Table 10 illustrate this effect. It is only after some altitude is reached above the valley stations that easterly winds are encountered. In the San Joaquin Valley the protection of the mountains is not evident until March 3. On the second the winds are N and NNW. Air moving from this direction passes down the mountains at the northern end of the Sacramento Valley and blows south and southeastward, parallel to the valley's axis. Thus it has a long sweep in which to reach low levels and does so, in the same way as the air coming from the east finally reaches sea level at San Francisco after it has swept down from the mountains 100 miles distant.

TABLE 10

Pilot Balloon Observations, 7 a.m., March 2 and 3, 1929

	March 2				*March 3*			
Altitude	*Fresno*		*Hollister*		*Fresno*		*Hollister*	
(Feet)	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*	*Dir.*	*Vel.*
Surface	ESE	6	Calm		NW	6	NE	1
1000	NNE	6	ESE	3	NW	2	ENE	4
1375	NNW	11	SE	4	ESE	5	NNE	9
2000	NNW	11	NNW	7	SE	8	NNE	15
2600	NNW	10	NNW	12	SE	7	NNE	20
3200	NNW	10	N	14	SE	7	NE	28
3800	NNW	7	N	17	E	7	NNE	33
4300	N	6	N	17	ENE	7	NNE	32
5000	N	8	N	19	NNE	7	NNE	28
6200	NNW	17	N	22	NE	24	NNE	26
7400	NNW	21	N	26	NE	37	NNE	33
8600	NNW	26	NNW	26			NNE	32
9800	NNW	28	NNW	30			NNE	30
11,000	NNW	36	NNW	29			NNE	24
12,100	NNW	35	NNW	32			NNE	23
13,200	NNW	40	NNW	30				

The protection afforded by the mountains is shown in the observation at Fresno for March 3. At this station, it is only above 6000 feet that the seaward moving current is pronounced. At Hollister, the Föhn would probably have reached sea level just as at San Francisco, were it not for the Coast Range mountains immediately to the east which cut off the wind from the levels below 2600 feet.

The similarity which this situation bears to the typical winter fog conditions discussed in Chapter II is evident. For example, the San Joaquin Valley air seems to be isolated from the Föhn system. Below the 6000-foot level, the movement is light and somewhat variable. Except for the period during the middle of the day when solar heating exerts a strong influence, the air above is warmer than that below. Mount Hamilton reports a temperature of 50° F. at 6.30 a.m., while at Fresno at the same time the temperature is 41° F., and at Mendota it is as low as 38° F. In spite of this, fog does not form in the valley.

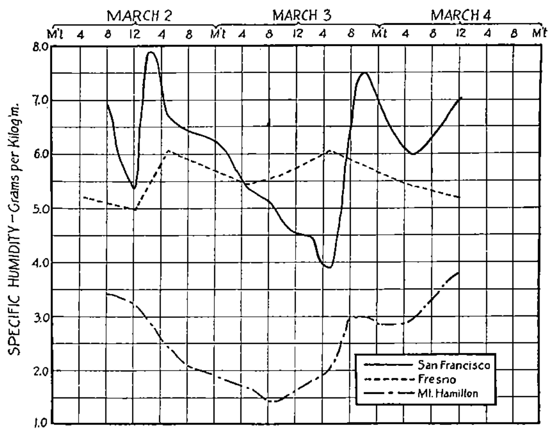


FIG. 19
Specific humidity curves, March 2-4, 1929.

The explanation of the absence of fog in this situation is probably to be found in the fact that we are dealing with a moving anticyclone rather than a stagnant one. The anticyclone described in Chapter II remained stationary over the plateau for several days, all the time subsiding. Then, after the San Joaquin Valley had been cut off from its circulation, this subsiding air spread out over California. In the present case, whatever subsidence has taken place has not been prolonged, for the air is just moving in from the ocean and continuing across the country without showing signs of stagnation. There has been no long-continued tendency to produce a subsidence inversion. Therefore, there is no loss of heat by radiation from the moisture and dust-laden air which lies immediately below an inversion of that type. A further difference between this case and that of the fog formation is that the air which flows into the interior valley on March 2 is Föhn-heated air which descends from the mountains at the northern end of the Sacramento Valley, while in the fog situation the only movement into the valley was from directly off the ocean.

The Mount Hamilton records show that the air moving out above the interior valley on March 3 is not as dry as that which was observed during the December fog. The specific humidity is now between one and two grams per kilogram, while in the winter fog it reached almost zero. The decrease in specific humidity with elevation shown by the difference between Mount Hamilton and sea level (fig. 19) is not very great. It is probable that this decrease is continuous and that there is no sharp discontinuity in moisture content. At noon, there is a temperature difference between San Francisco and Mount Hamilton of 14° F., signifying a lapse rate approximating the dry adiabatic. This would seem to indicate that the two stations are in the same current of air.

The vertical temperature distribution at San Diego for March 1 and 4 (fig. 20), while not representing conditions at the time when the Föhn was at its peak, nevertheless is indicative of the general character of the air which is moving off the continent. Above an elevation of 1000 meters, the movement from the land prevails, and it will be seen from fig. 20 that in

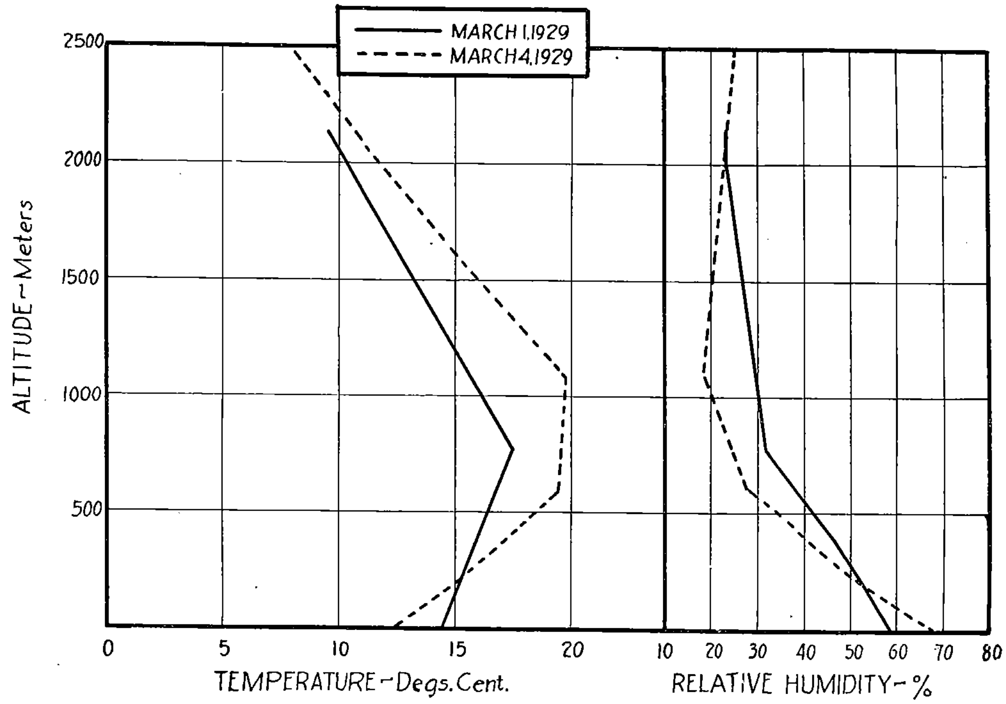


FIG. 20
Vertical distribution of temperature and relative humidity, San Diego, March 1 and 4, 1929.

this westward-moving air the lapse rate is very close to the dry adiabatic. This indicates that the air must have been in almost adiabatic equilibrium at its origin. If the air had been stable to begin with, subsidence would have made it more so.

PLATES

EXPLANATION OF SYMBOLS USED ON MAPS

Heavy solid line — cold front.

Heavy broken line — occluded front.

Double line — warm front.

Wind force represented by number of feathers on arrows as follows:

One — light (1-10 m.p.h.).
Two — moderate (10-20 m.p.h.).
Three — strong (20-30 m.p.h.).
Four — gale (over 30 m.p.h.).

(In the general synoptic charts appearing in the text the feathers on the arrows represent Beaufort wind force.)

R — Raining at observation.

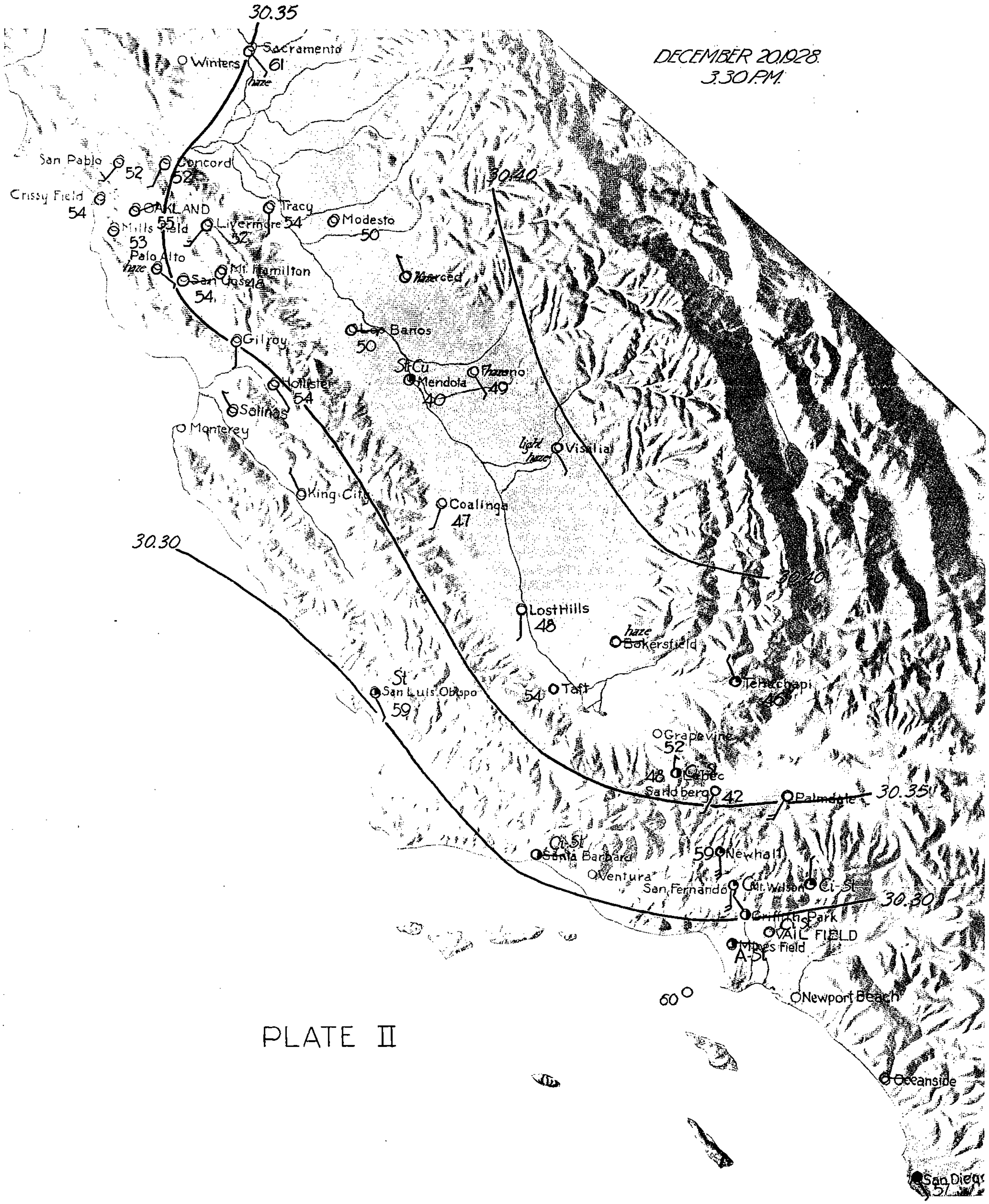
Rs — Showers since last observation, not raining now.

R△ — Hail.

S — Snowing.

F — Foggy.

The figures appearing at each station give the temperature in Fahrenheit degrees.



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3.30 P.M.
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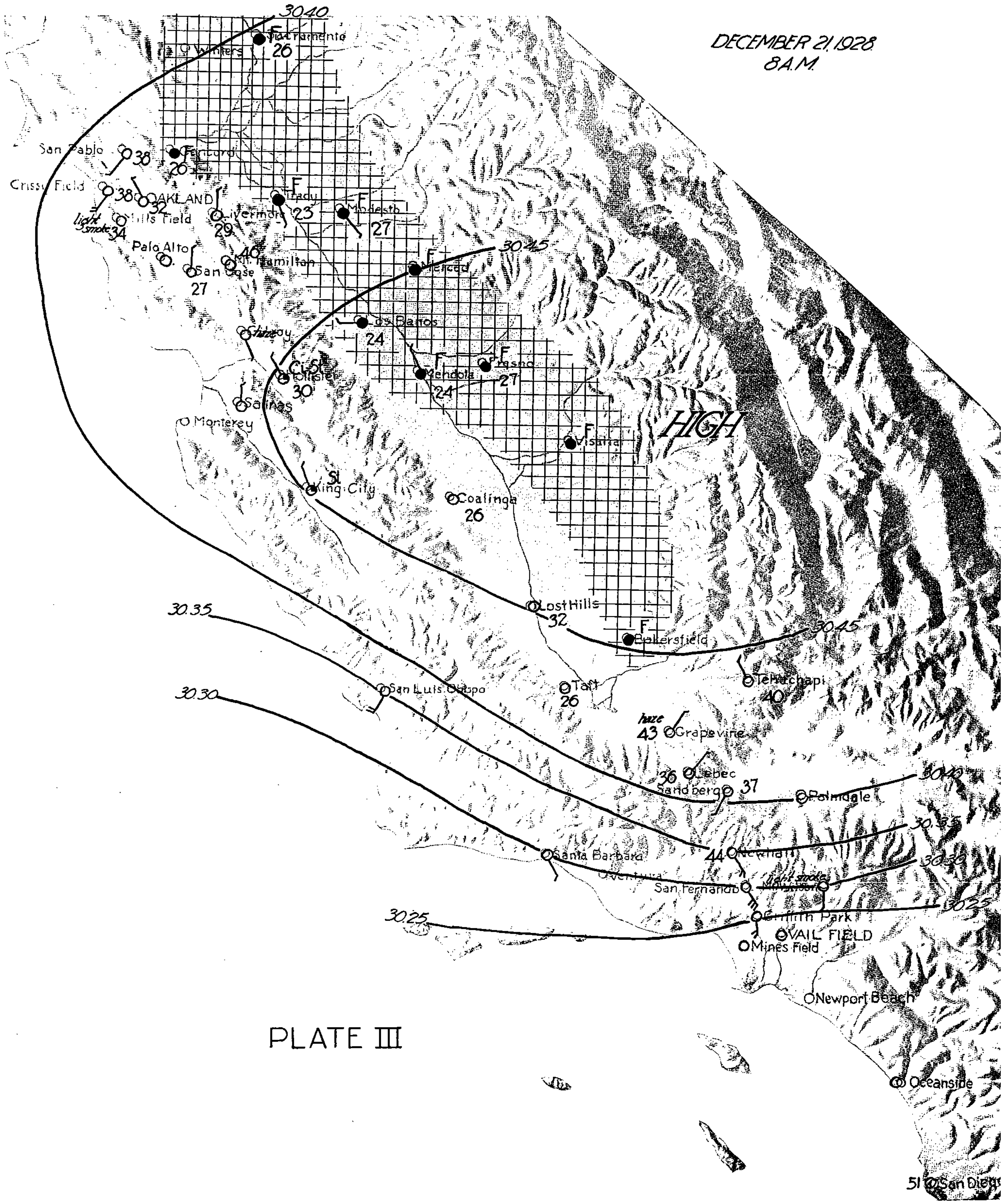
30.40
30.30
30.35
30.30
Sacramento
61
Winters
San Pablo
52
Concord
Crissy Field
54
OAKLAND
55
Tracy
54
Modesto
50
Livermore
Mills Field
53
Palo Alto
haze
Mt. Hamilton
San Jose
54
Merced
Los Banos
50
Gilroy
St Cu
Fresno
49
Mendota
40
Hollister
54
Salinas
Monterey
Visalia
light haze
King City
Coalinga
47
Lost Hills
48
haze
Bakersfield
Tehachapi
46
St
San Luis Obispo
59
Taft
54
Grapevine
52
Sandberg
42
Palmdale
Ci-St
Santa Barbara
Newhall
59
Ventura
San Fernando
Mt. Wilson
Ci-St
Griffith Park
VAIL FIELD
Mines Field
A-St
60
Newport Beach
Oceanside
San Diego

PLATE II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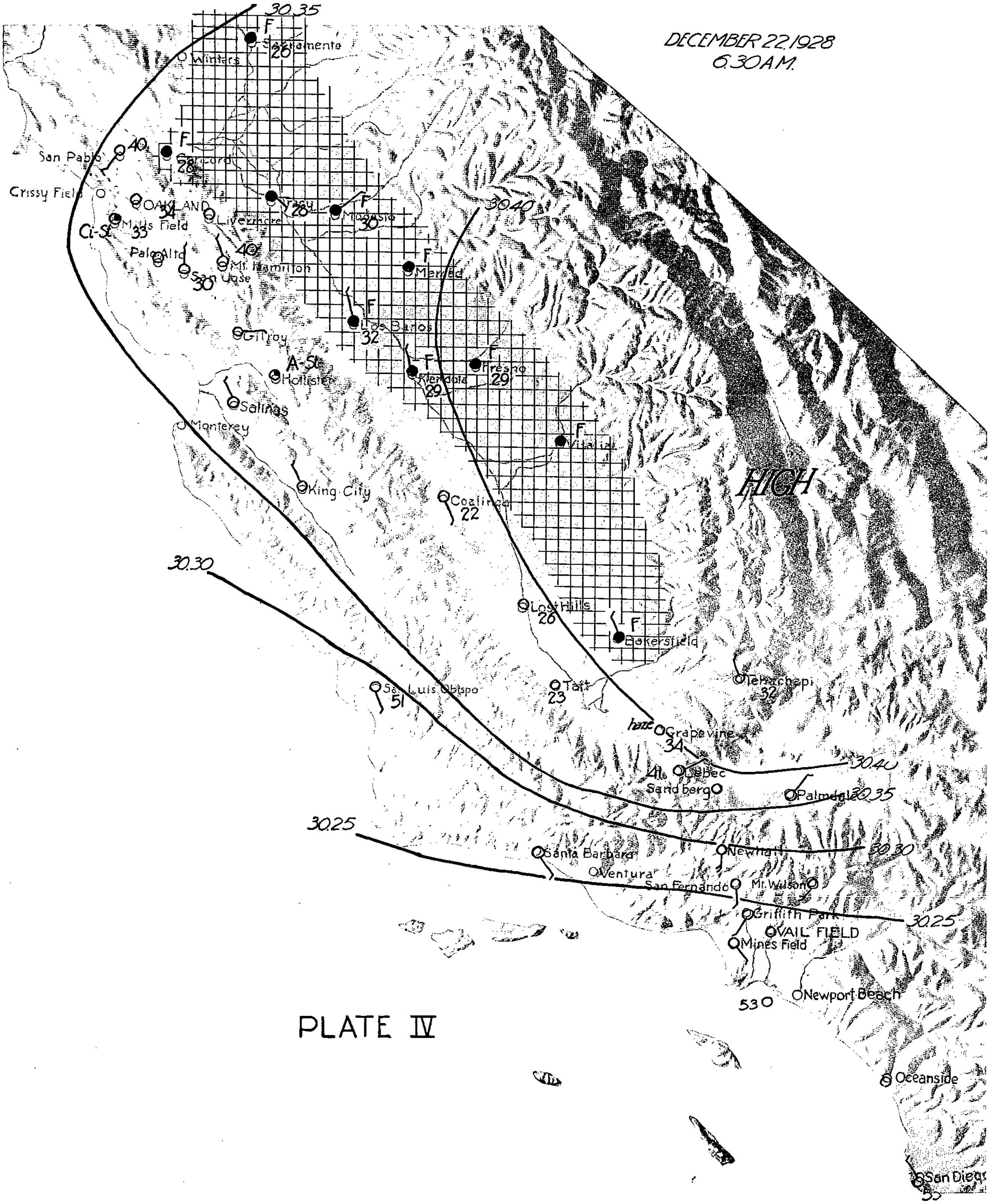
30.45
30.35
30.30
30.25
Sacramento
Winters
San Pablo
Concord
Crissy Field
OAKLAND
Mills Field
light smoke
Livermore
Tracy
Modesto
Palo Alto
San Jose
Mt. Hamilton
Merced
Los Banos
Gilroy
Hollister
Salinas
Monterey
Mendota
Fresno
Visalia
King City
Coalinga
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Taft
haze
Grapevine
Lebec
Sandberg
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
light smoke
Griffith Park
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego

PLATE III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30.25
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Winters
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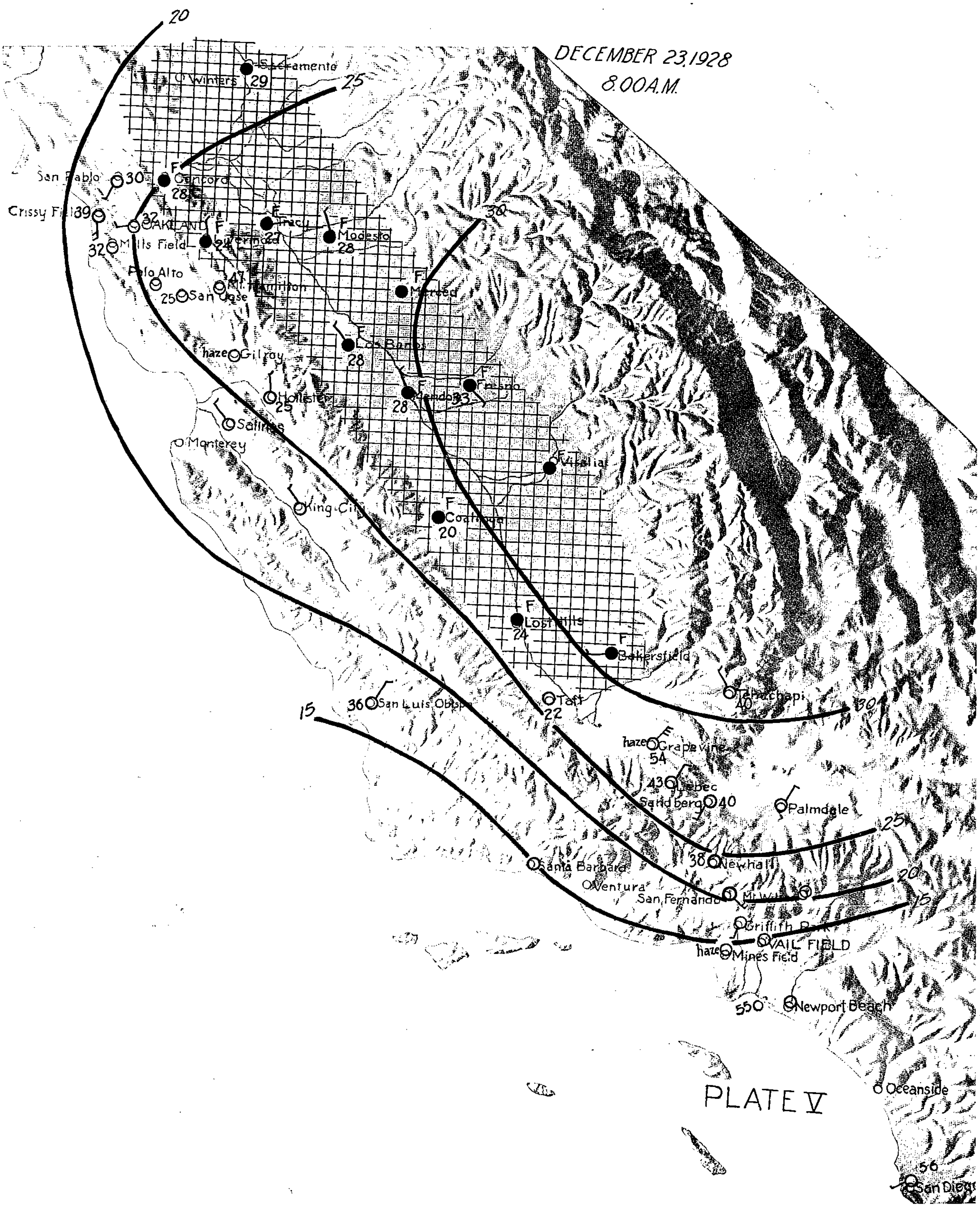
OAKLAND
Mills Field
Livermore
Palo Alto
San Jose
Mt. Hamilton
Tracy
Modesto
Merced
Los Banos
Gilroy
Hollister
Salinas
Monterey
Mendota
Fresno
Visalia
King City
Coalinga
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Taft
Grapevine
Lebec
Sandberg
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego

PLATE IV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8.00 A.M.
20
25
30
15
Sacramento
Winters
Concord
Oakland
Tracy
Modesto
Merced
Los Banos
Mendota
Fresno
Visalia
Coalinga
Lost Hills
Bakersfield
Tehachapi
Taft
San Luis Obispo
San Pablo
Crissy Field
Mills Field
Palo Alto
San Jose
Gilroy
Hollister
Salinas
Monterey
King City
Grapevine
Lebec
Sandberg
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
Griffith Park
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego
haze

PLATE V

DECEMBER 24 1928
9.30 A.M.

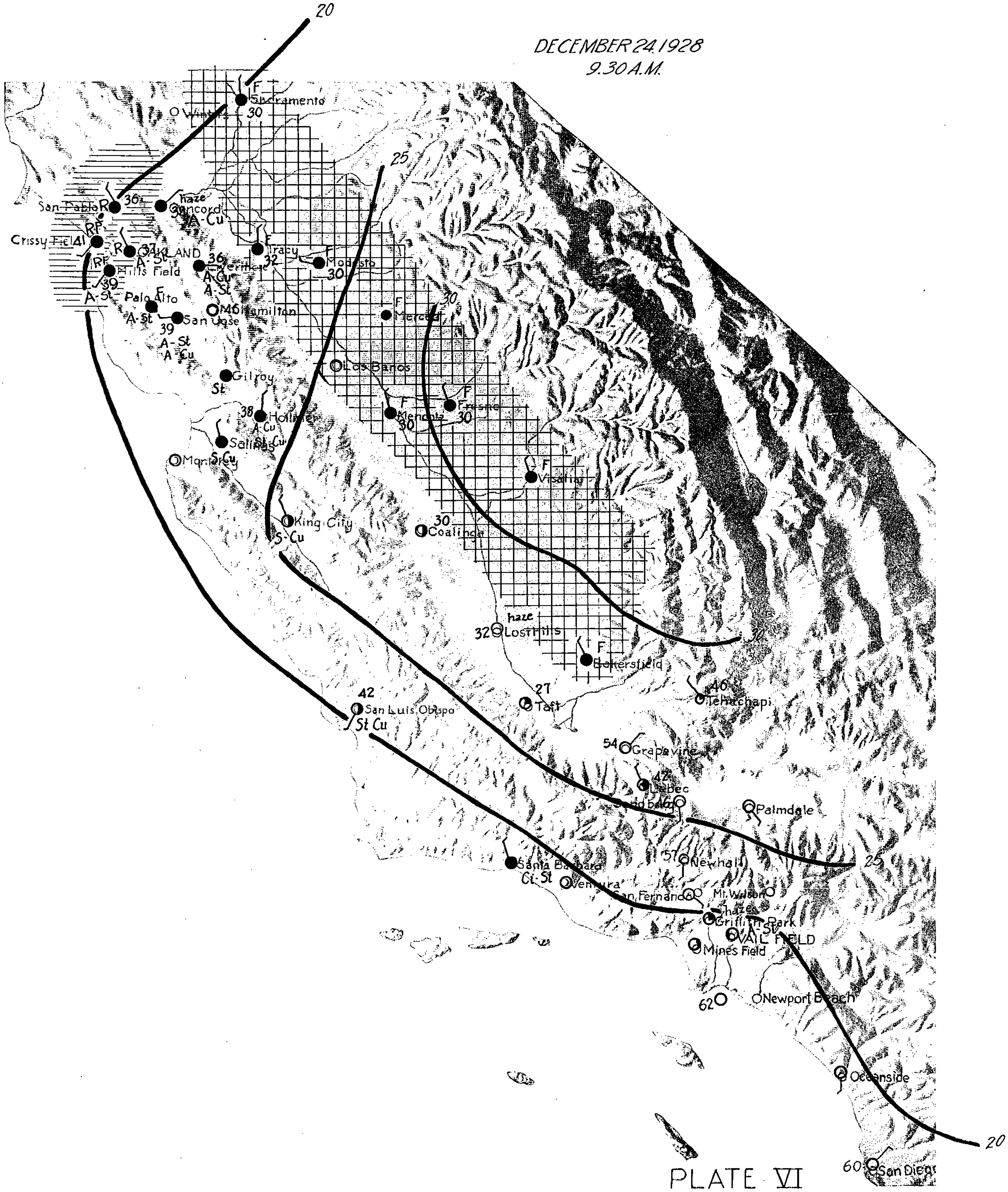


PLATE VI

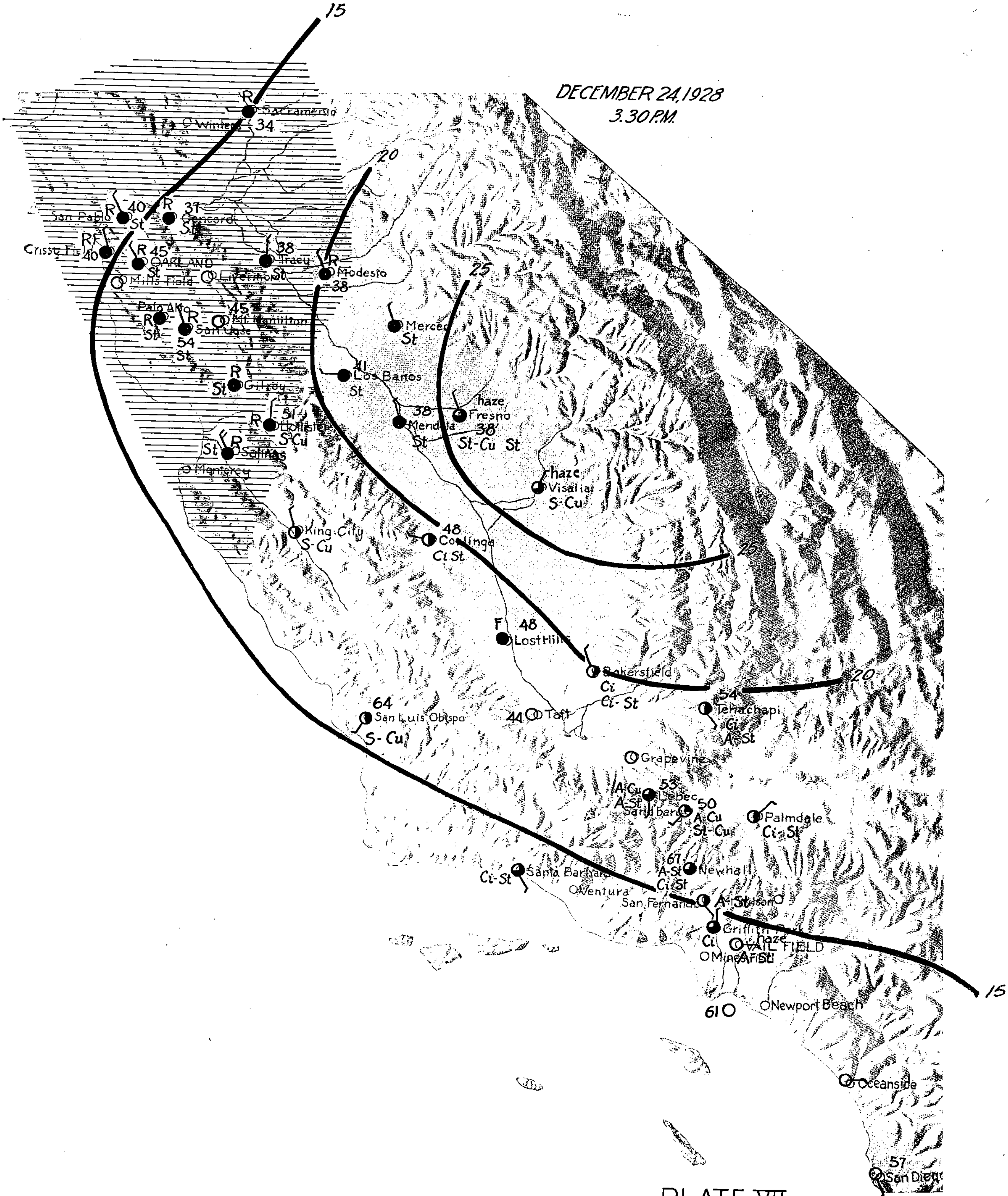
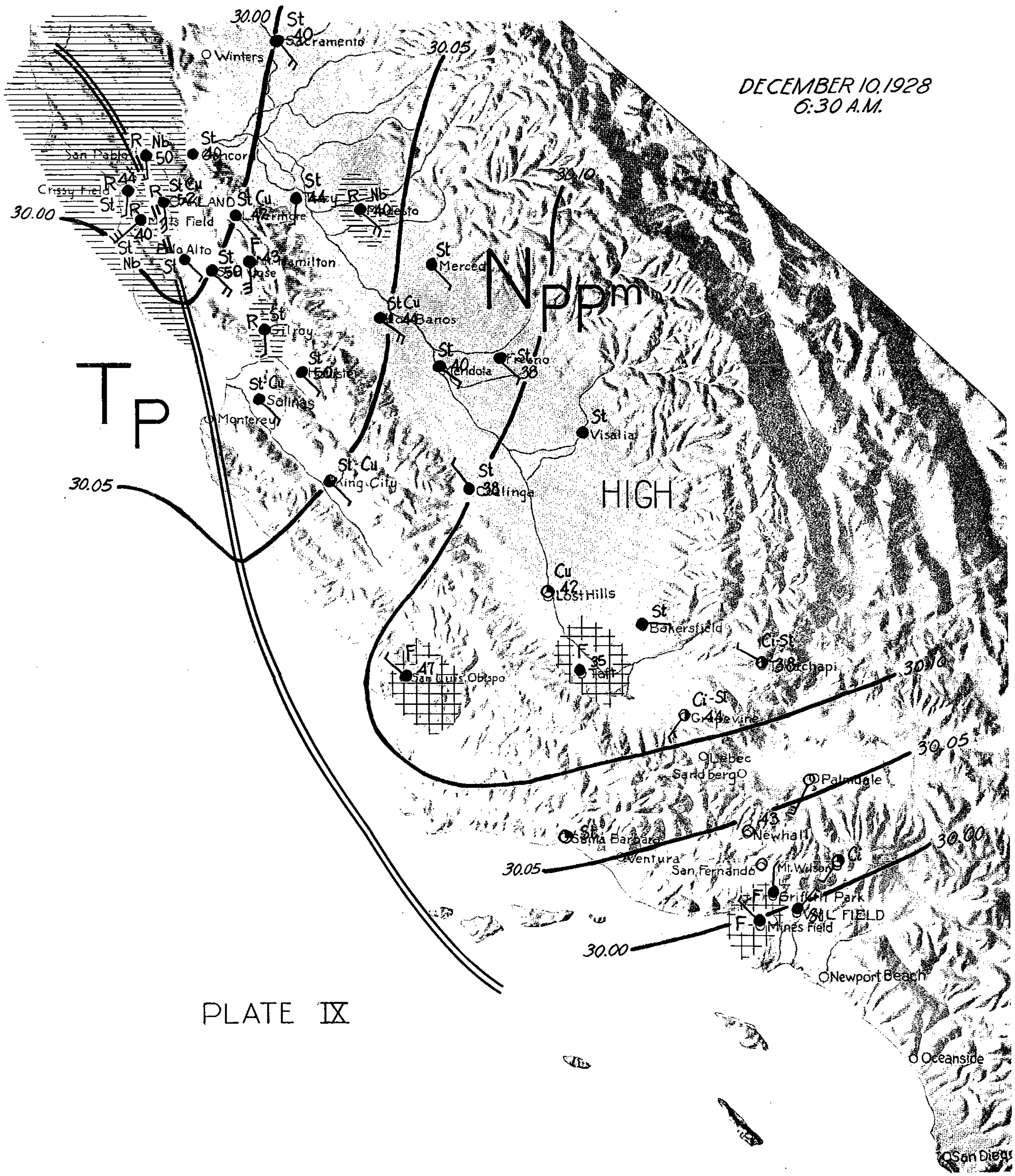

DECEMBER 24, 1928
3.30 P.M.
15
20
25
Sacramento
Winters
San Pablo
Concord
Crissy Field
OAKLAND
Mills Field
Livermore
Tracy
Modesto
Merced
Palo Alto
San Jose
Mt. Hamilton
Gilroy
Los Banos
Hollister
Salinas
Monterey
Mendota
Fresno
Visalia
King City
Coalinga
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Taft
Grapevine
Lebec
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
VAIL FIELD
Newport Beach
Oceanside
San Diego

PLATE VII

"HIGH FOG" DISTRIBUTION
AUGUST 24, 1928
8 A.M.
and
TYPICAL MID-DAY SUMMER
STREAM LINES

PLATE VIII


DECEMBER 10, 1928
6:30 A.M.
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Nppm
HIGH
30.00
30.05
30.10
Sacramento
Winters
Concord
San Pablo
Crissy Field
OAKLAND
Livermore
Tracy
Modesto
Palo Alto
San Jose
Mt. Hamilton
Merced
Los Banos
Gilroy
Hollister
Mendota
Fresno
Salinas
Monterey
Visalia
King City
Coalinga
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Taft
Grapevine
Quebec
Sandberg
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
OIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego

PLATE IX

DECEMBER 10, 1928
8 A.M.

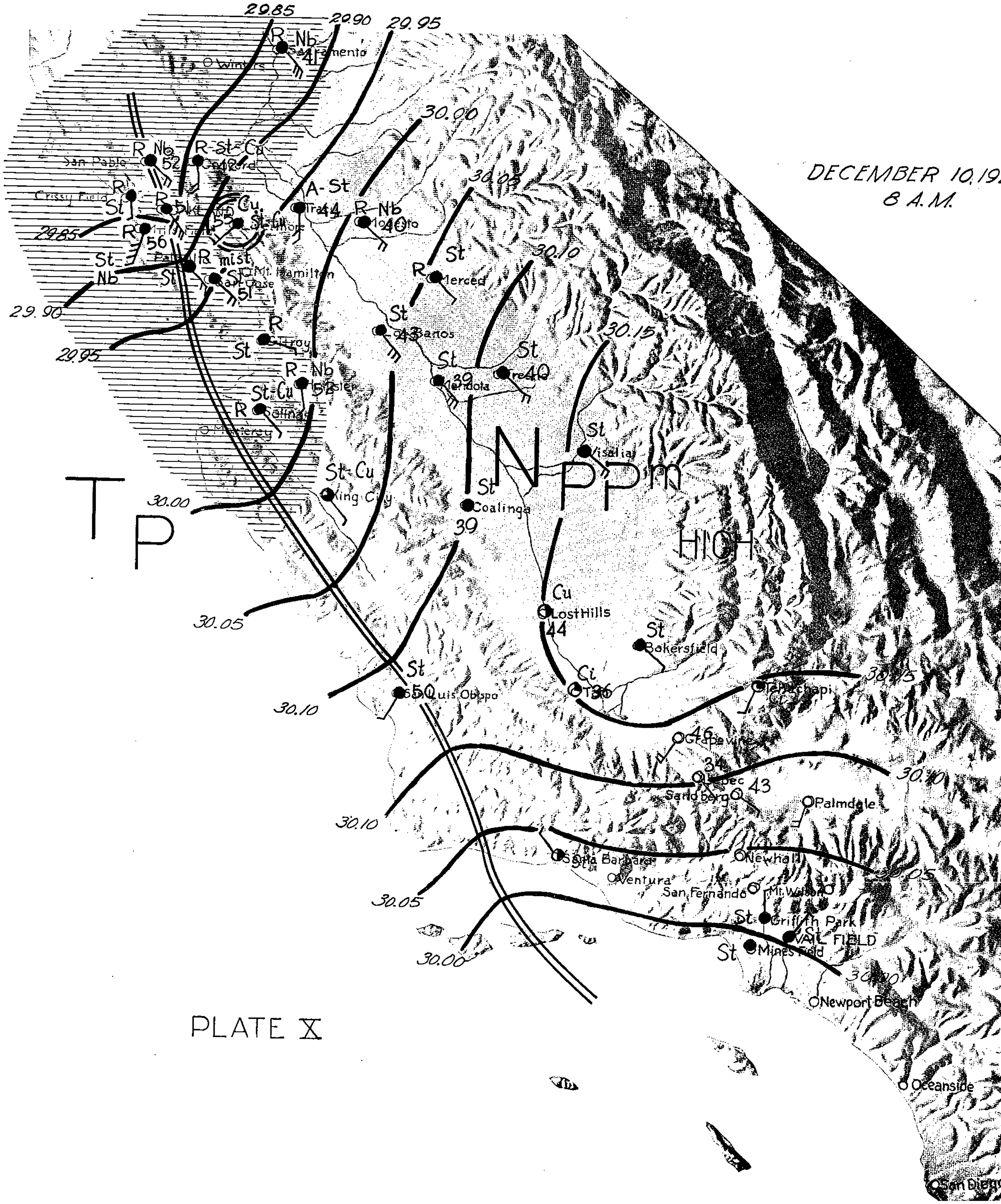


PLATE X

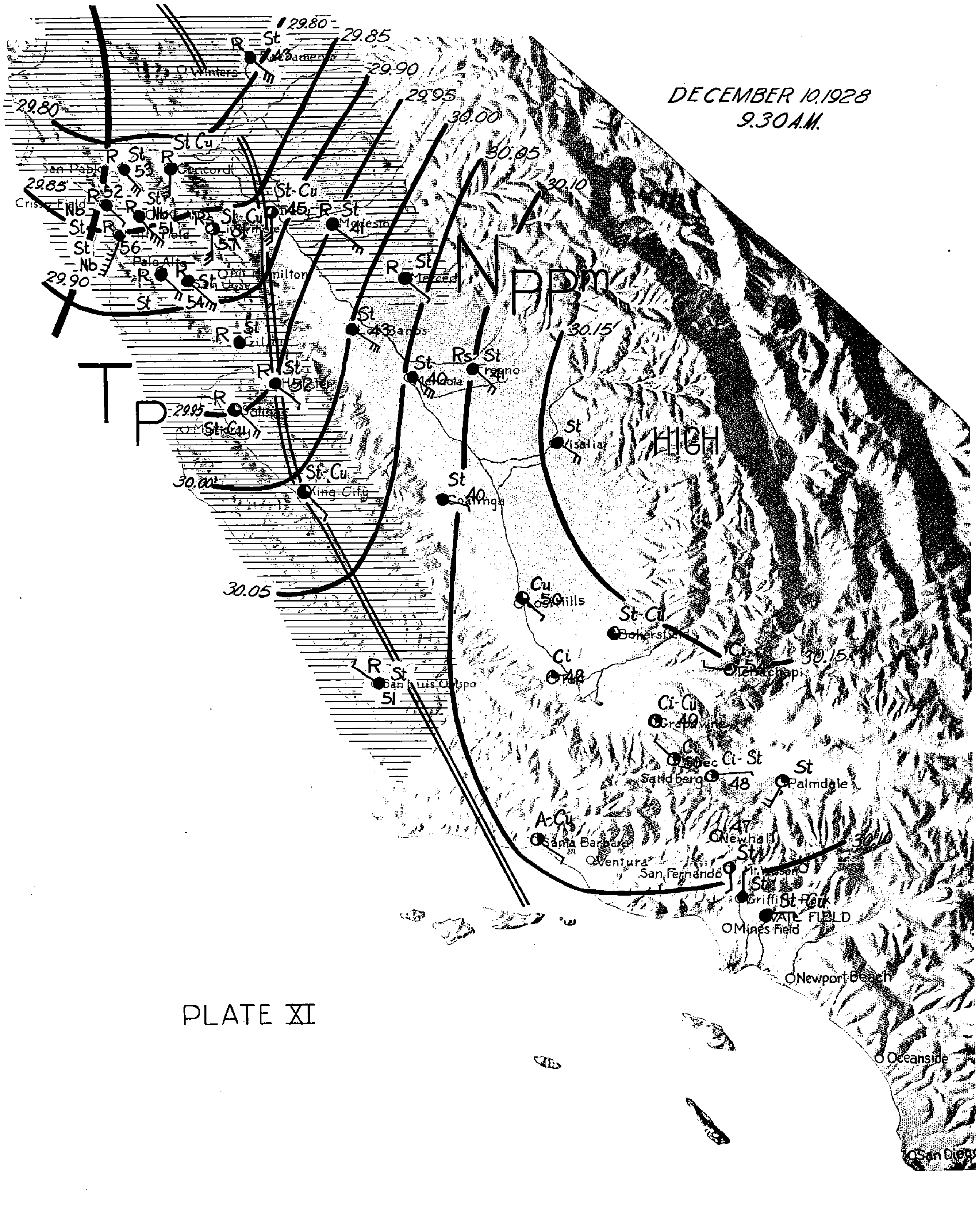

DECEMBER 10, 1928
9.30 A.M.
HIGH
T
P
N
Ppm
29.80
29.85
29.90
29.95
30.00
30.05
30.10
30.15
Winters
Sacramento
San Pablo
Concord
Modesto
Palo Alto
San Jose
Gilroy
Hollister
Salinas
Merced
Los Banos
Mendota
Fresno
Visalia
King City
Coalinga
Bakersfield
Tehachapi
San Luis Obispo
Grapevine
Sandberg
Palmdale
Santa Barbara
Ventura
Newhall
San Fernando
Mines Field
Newport Beach
Oceanside
Crissy Field

PLATE XI

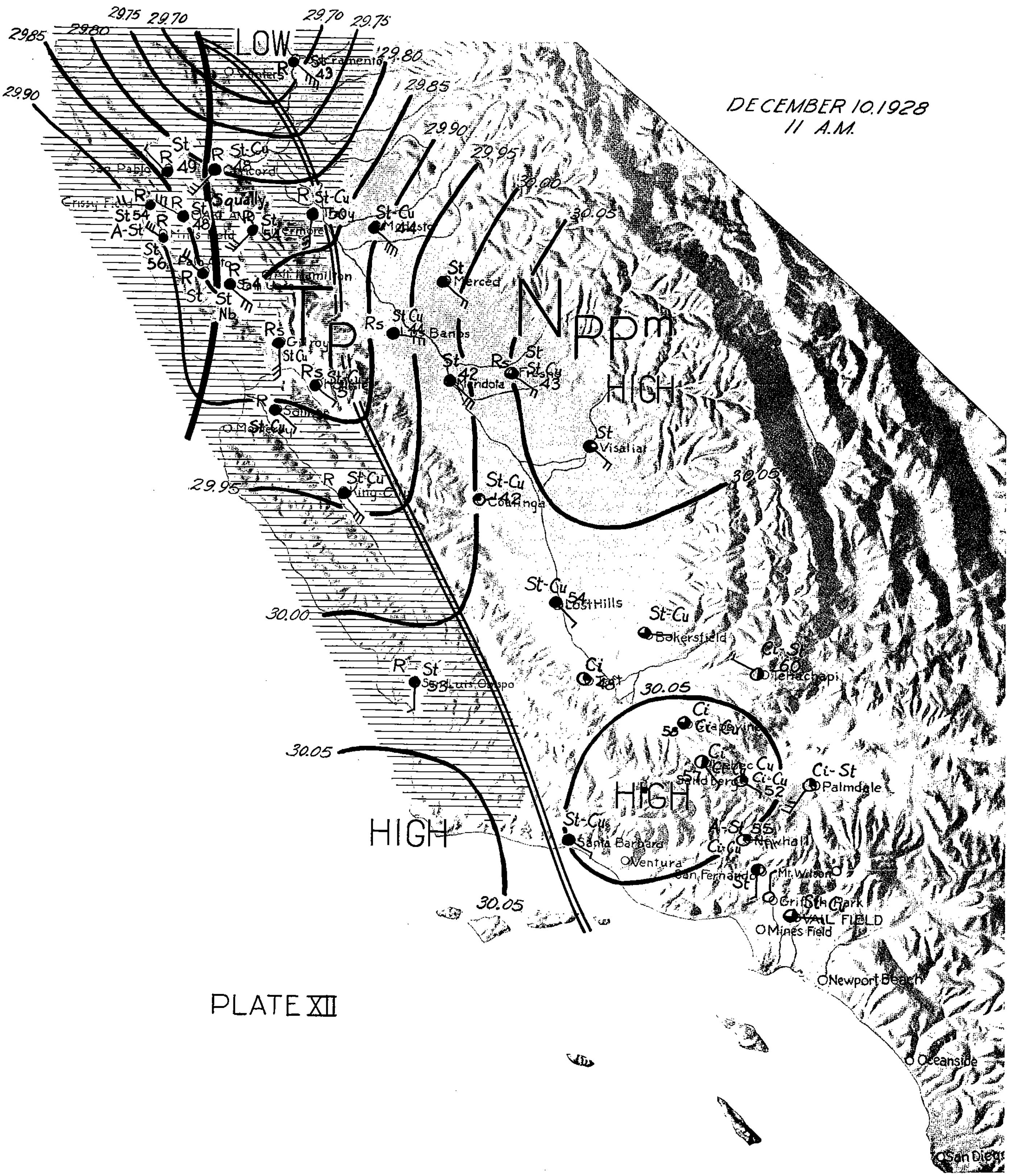
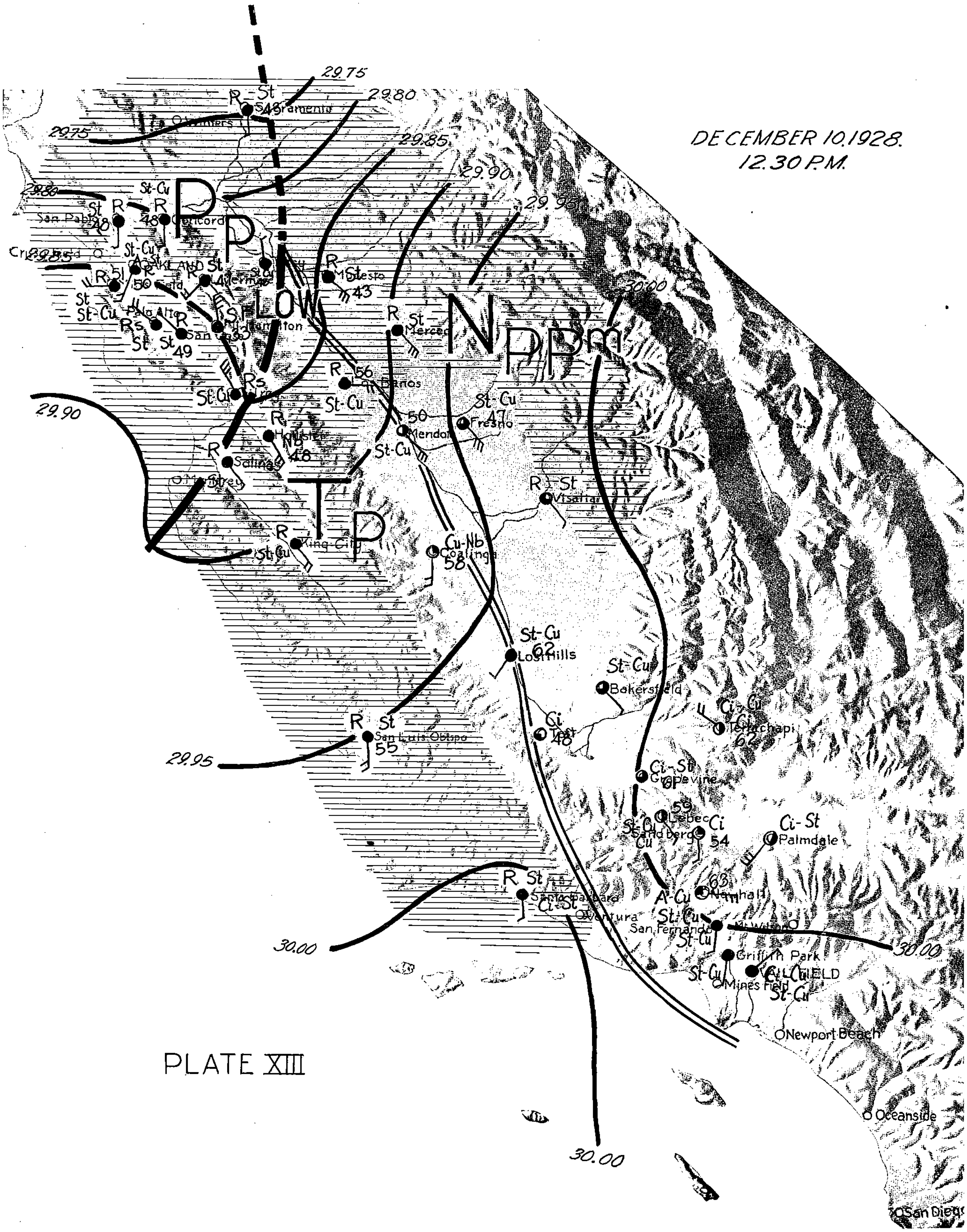

DECEMBER 10.1928
11 A.M.
LOW
HIGH
HIGH
HIGH
T P
N Ppm
29.70
29.75
29.80
29.85
29.90
29.95
30.00
30.05
Sacramento
Winters
San Pablo
Concord
Crissy Field
Oakland
Livermore
Tracy
Modesto
Mills Field
Palo Alto
San Jose
Mt. Hamilton
Merced
Los Banos
Gilroy
Hollister
Salinas
Monterey
Mendota
Fresno
Visalia
King C.
Coalinga
Lost Hills
Bakersfield
Tehachapi
Taft
San Luis Obispo
Grapevine
Saugus
Sandberg
Palmdale
Santa Barbara
Ventura
Newhall
San Fernando
Mt. Wilson
Griffith Park
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego
Squally

PLATE XII



DECEMBER 10, 1928.
12.30 P.M.
29.75
29.80
29.85
29.90
29.95
30.00
LOW
Sacramento
Concord
San Pablo
Oakland
Palo Alto
Merced
Los Banos
Mendota
Fresno
Salinas
Monterey
King City
Coalinga
Visalia
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Grapevine
Lebec
Sandberg
Palmdale
Newhall
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
Mines Field
Newport Beach
Oceanside
San Diego

PLATE XIII

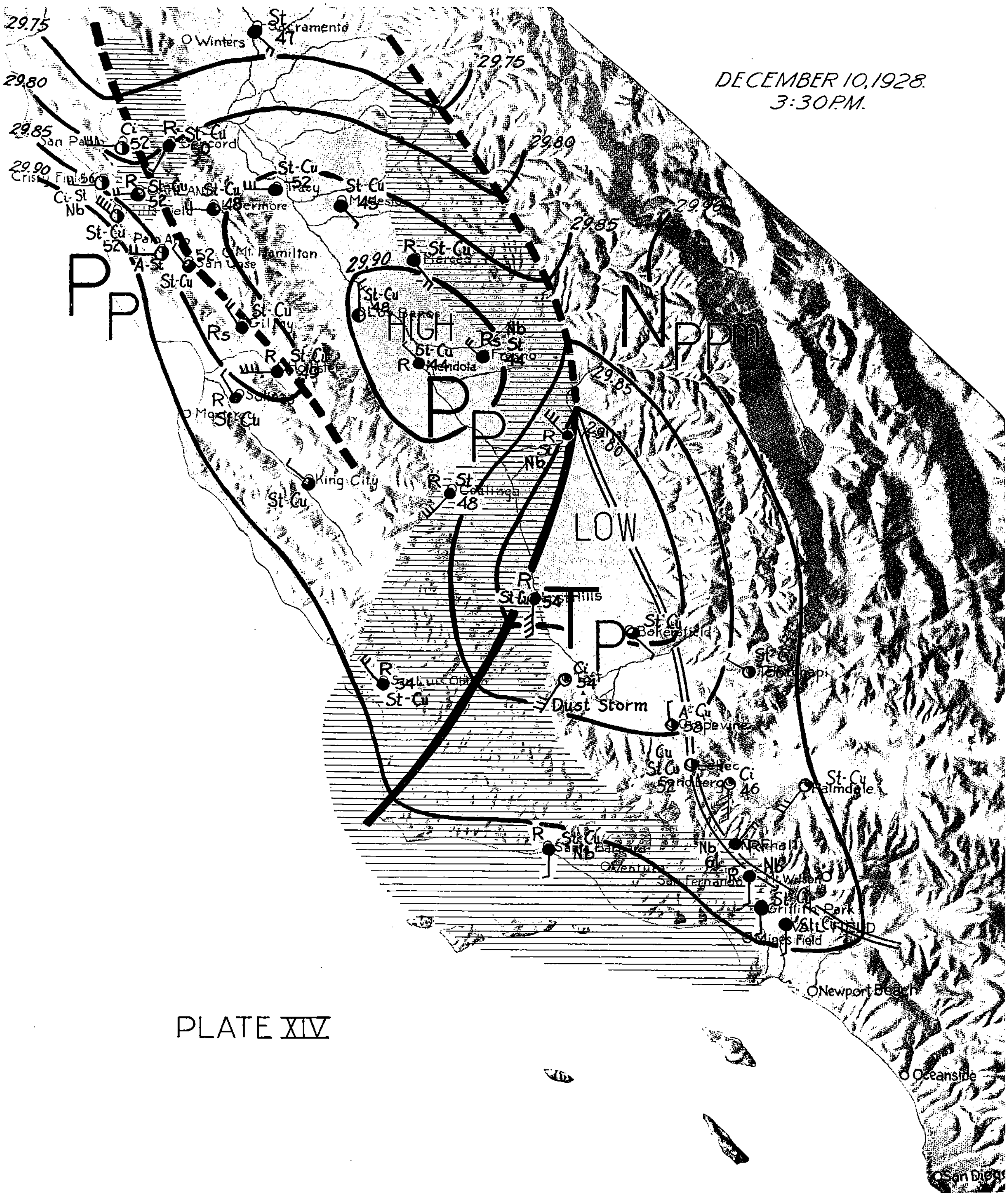

DECEMBER 10, 1928.
3:30 P.M.
HIGH
LOW
Dust Storm
Sacramento
Winters
King City
Bakersfield
Newport Beach
Oceanside
29.75
29.80
29.85
29.90

PLATE XIV

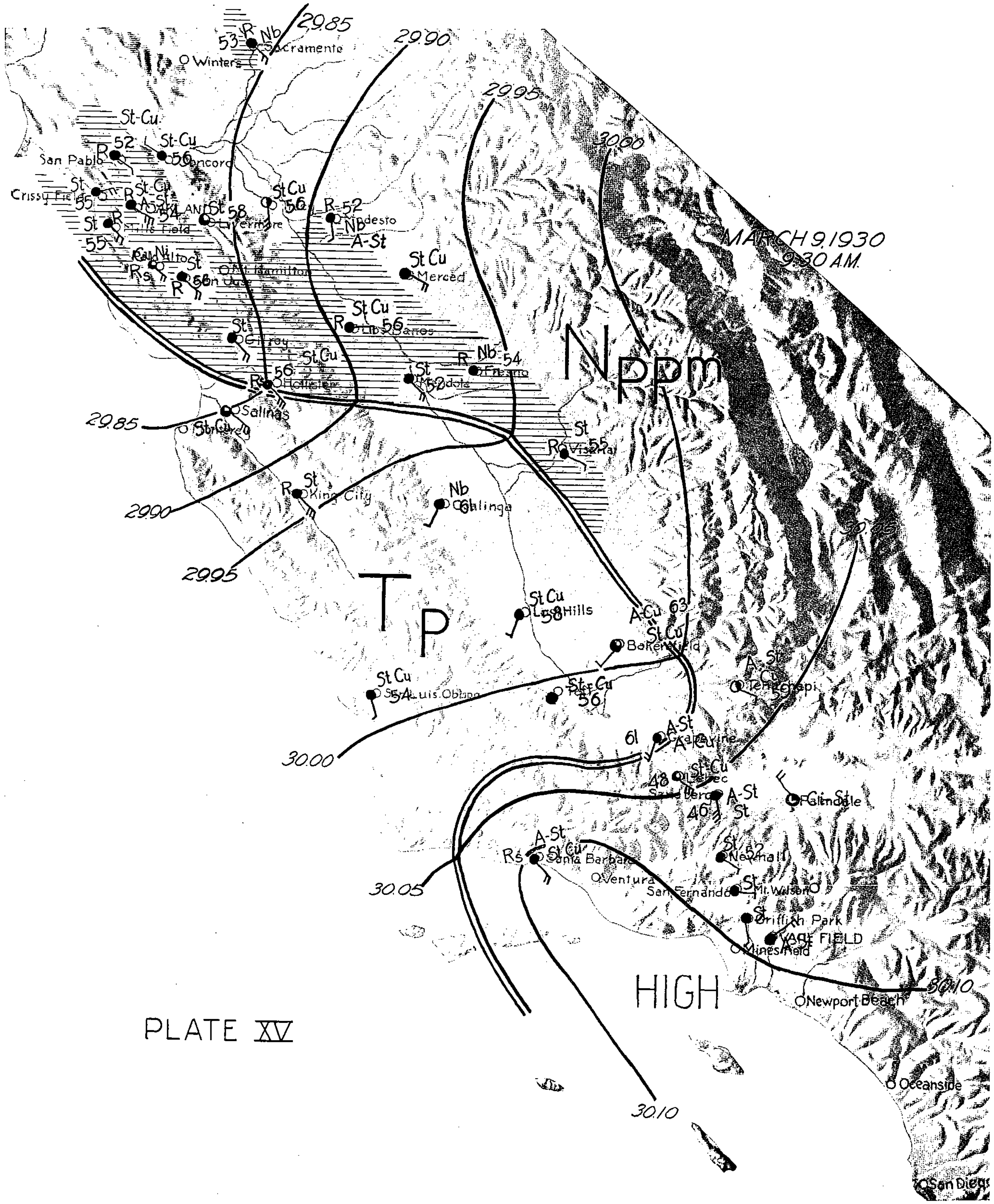

MARCH 9, 1930
9.30 A.M.
Nppm
Tp
HIGH
29.85
29.90
29.95
30.00
30.05
30.10
Sacramento
Winters
San Pablo
Crissy Field
Concord
Livermore
Modesto
Merced
Salinas
King City
Coalinga
Fresno
Visalia
Bakersfield
Lost Hills
San Luis Obispo
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
Newhall
Glendale
Newport Beach
Oceanside
San Diego
Tehachapi
St-Cu
St Cu
A-St
Nb
St
R

PLATE XV

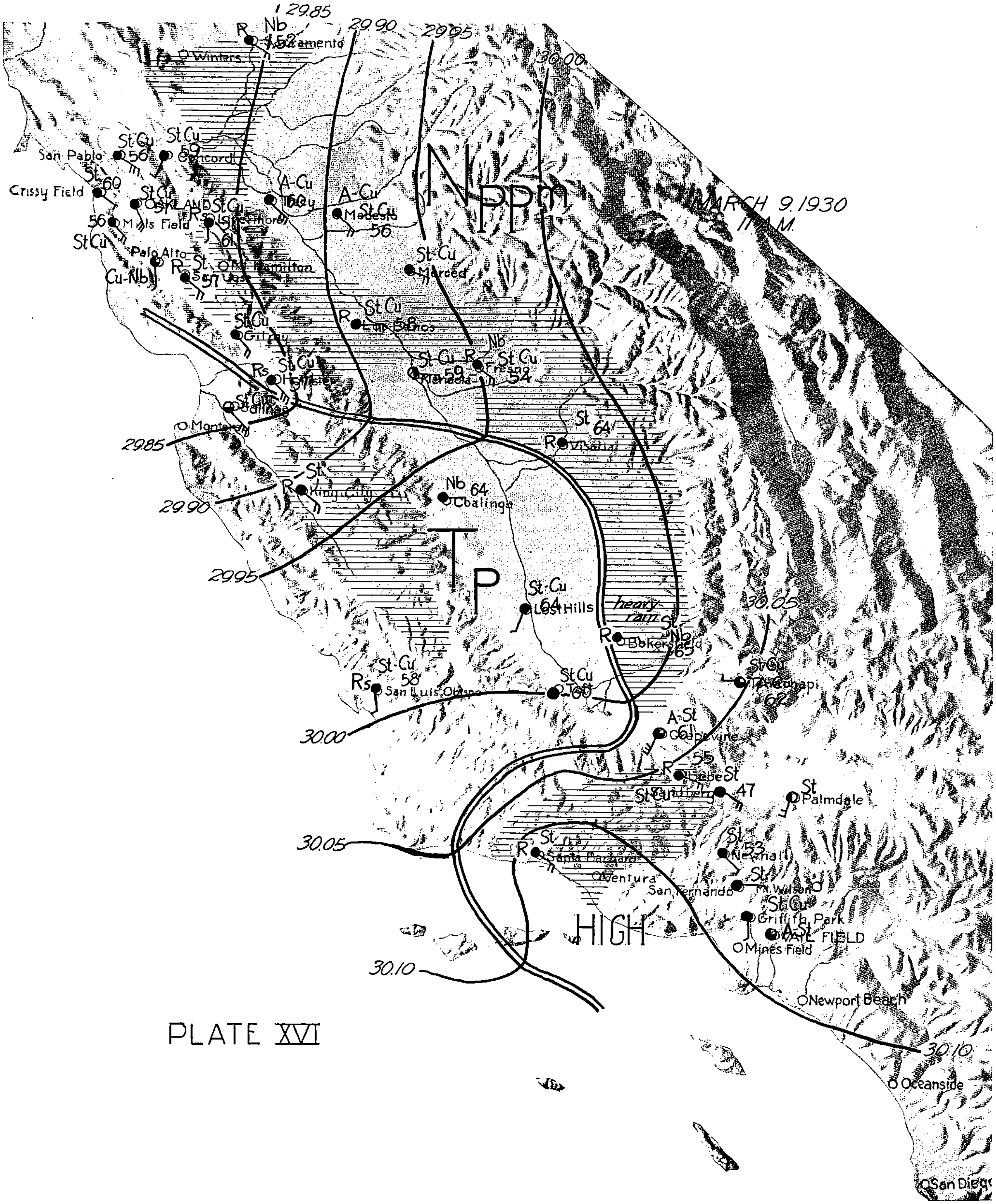

MARCH 9, 1930
11 A.M.
29.85
29.90
29.95
30.00
30.05
30.10
Npp
Tp
HIGH
heavy rain
Sacramento
Winters
San Pablo
Concord
Crissy Field
OAKLAND
Mills Field
Palo Alto
Mt. Hamilton
Modesto
Merced
Gilroy
Hollister
Salinas
Monterey
Los Banos
Fresno
Mendota
Visalia
King City
Coalinga
Lost Hills
Bakersfield
San Luis Obispo
Tehachapi
Grapevine
Lebec
Palmdale
Santa Barbara
Ventura
Newhall
San Fernando
Mt. Wilson
Griffith Park
Mines Field
Newport Beach
Oceanside

PLATE XVI

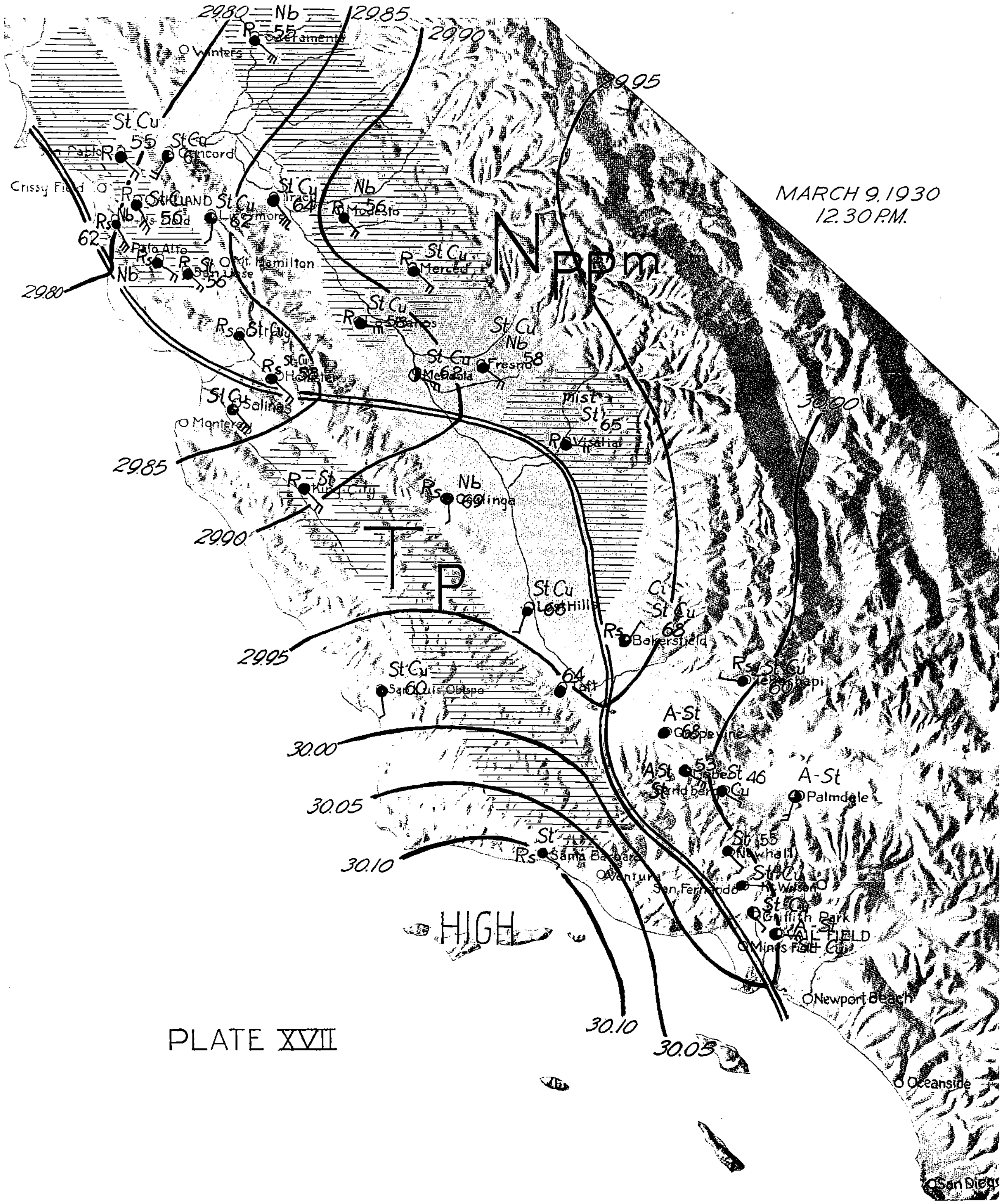

MARCH 9, 1930
12.30 P.M.
HIGH
Sacramento
Winters
Concord
Crissy Field
Modesto
Merced
Palo Alto
Mt. Hamilton
San Jose
Salinas
Monterey
Fresno
Mendota
Visalia
King City
Coalinga
Lost Hills
Bakersfield
San Luis Obispo
Taft
Grapevine
Palmdale
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
Mines Field
Newport Beach
Oceanside
San Diego
29.80
29.85
29.90
29.95
30.00
30.05
30.10

PLATE XVII

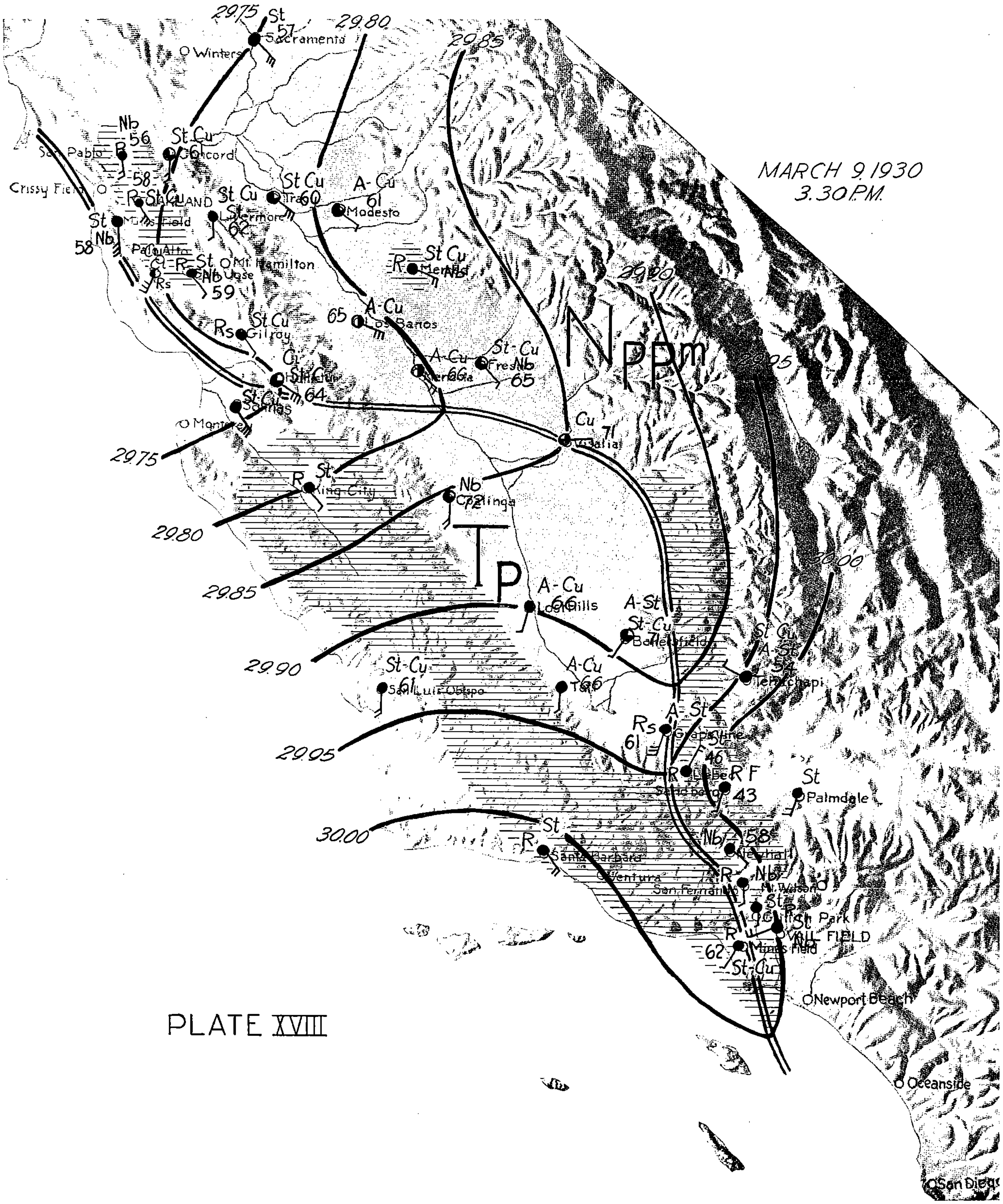

MARCH 9 1930
3.30 P.M.
29.75
29.80
29.85
29.90
29.95
30.00
NPP^m
TP
Sacramento
Winters
Concord
San Pablo
Crissy Field
Mills Field
Livermore
Modesto
Tracy
Palo Alto
Mt. Hamilton
San Jose
Merced
Los Banos
Gilroy
Salinas
Monterey
Fresno
Visalia
King City
Coalinga
Lost Hills
Bakersfield
Tehachapi
San Luis Obispo
Taft
Grapevine
Lebec
Sandberg
Palmdale
Santa Barbara
Ventura
Newhall
San Fernando
Mt. Wilson
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego

PLATE XVIII

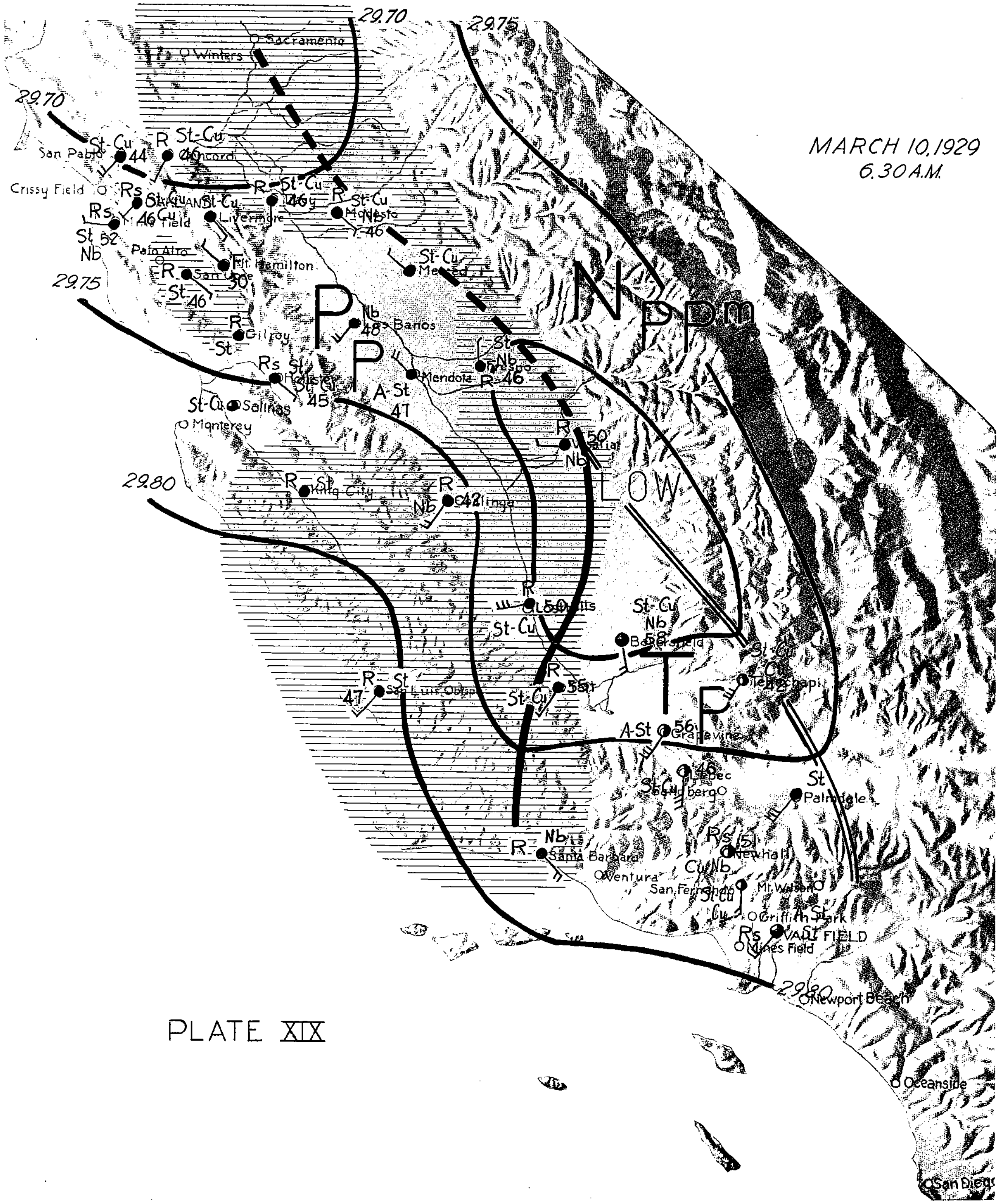

MARCH 10, 1929
6.30 A.M.
29.70
29.75
29.80
Sacramento
Winters
San Pablo
Concord
Crissy Field
Livermore
Modesto
Merced
Palo Alto
Ft. Hamilton
San Jose
Gilroy
Hollister
Salinas
Monterey
Los Banos
Mendota
Fresno
Visalia
LOW
King City
Coalinga
Bakersfield
Tehachapi
San Luis Obispo
Grapevine
Palmdale
Santa Barbara
Ventura
Newhall
San Fernando
Mt. Wilson
Griffith Park
Mines Field
Newport Beach
Oceanside
N
P
T
St-Cu
Nb
A-St
R
Rs

PLATE XIX

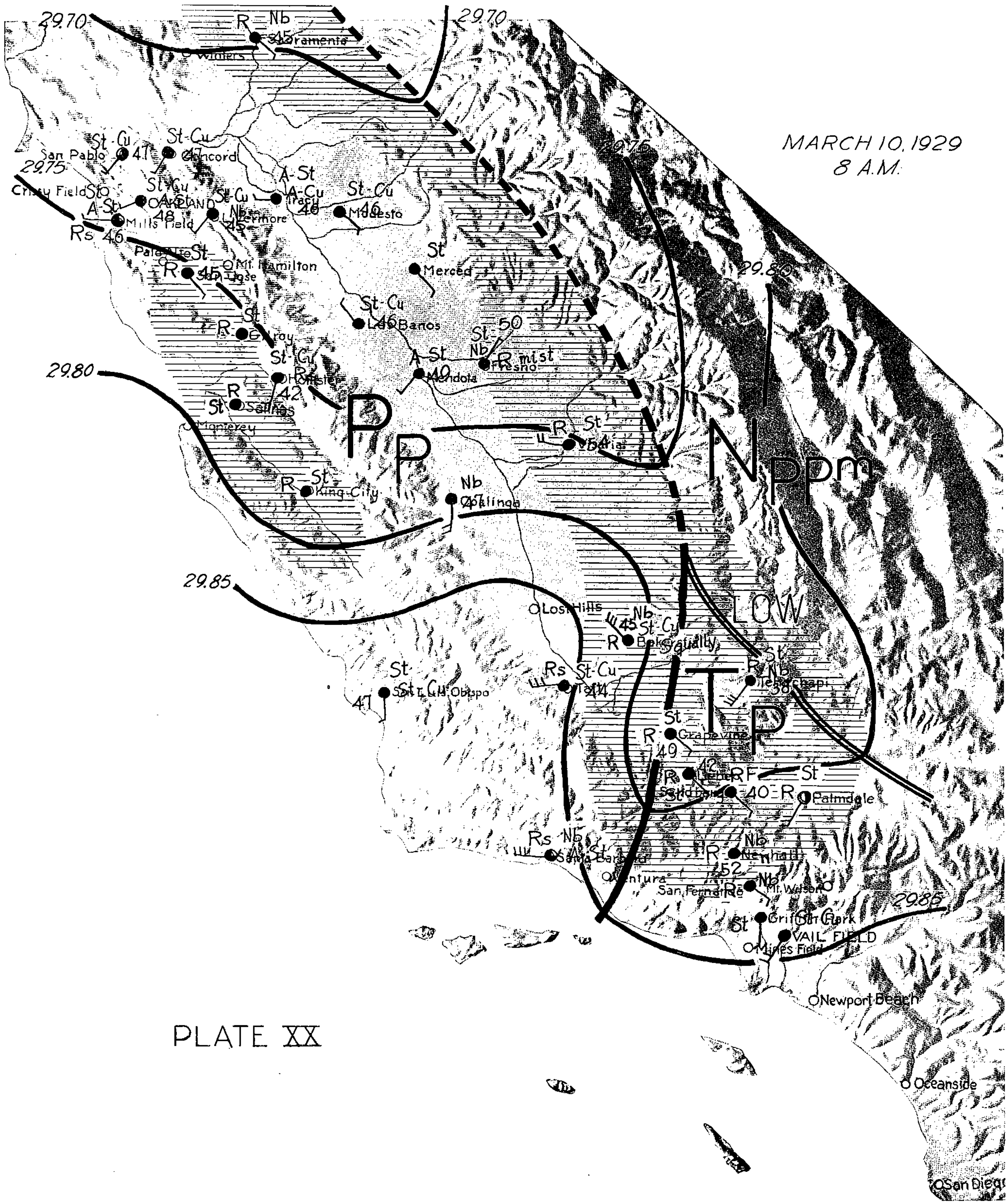

MARCH 10, 1929
8 A.M.
29.70
29.75
29.80
29.85
Sacramento
Winters
San Pablo
Concord
Crissy Field
Mills Field
Livermore
Tracy
Modesto
Mt. Hamilton
San Jose
Merced
Los Banos
Gilroy
Hollister
Fresno
Mendota
Salinas
Monterey
King City
Coalinga
Lost Hills
Bakersfield
San Luis Obispo
Santa Barbara
Grapevine
Palmdale
Newhall
Ventura
San Fernando
Mt. Wilson
VAIL FIELD
Mines Field
Newport Beach
Oceanside
San Diego
LOW
Nppm

PLATE XX

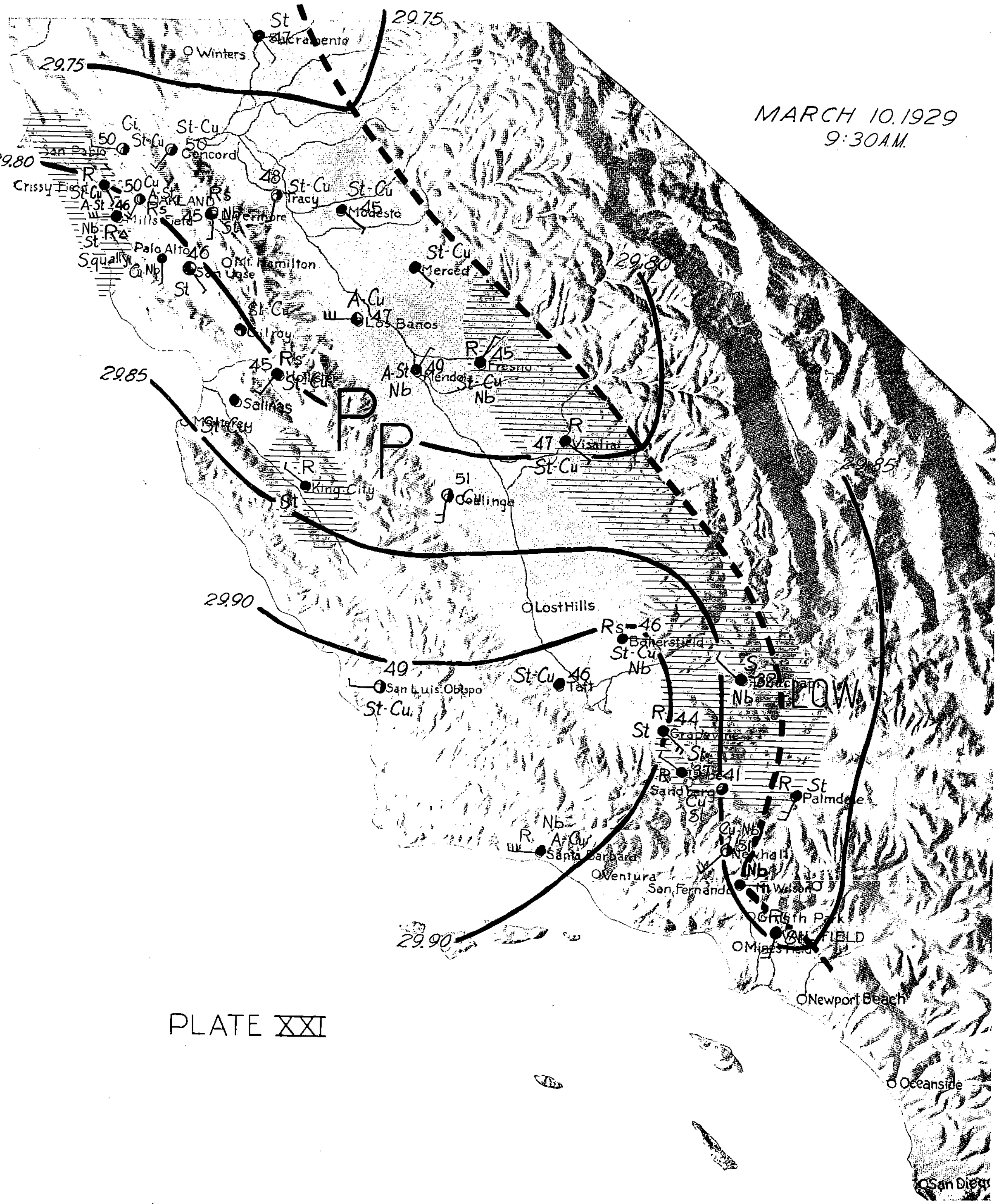

MARCH 10.1929
9:30 A.M.
29.75
29.80
29.85
29.90
LOW
Winters
San Pablo
Concord
Crissy Field
Tracy
Modesto
Merced
Mills Field
Palo Alto
Mt. Hamilton
San Jose
Gilroy
Los Banos
Fresno
Salinas
King City
Visalia
Coalinga
Lost Hills
Bakersfield
Taft
San Luis Obispo
Grapevine
Palmdale
Santa Barbara
Ventura
San Fernando
Newhall
Griffith Park
Mines Field
Newport Beach
Oceanside
St-Cu
A-Cu
A-St
Nb
Squally
Cu-Nb

PLATE XXI

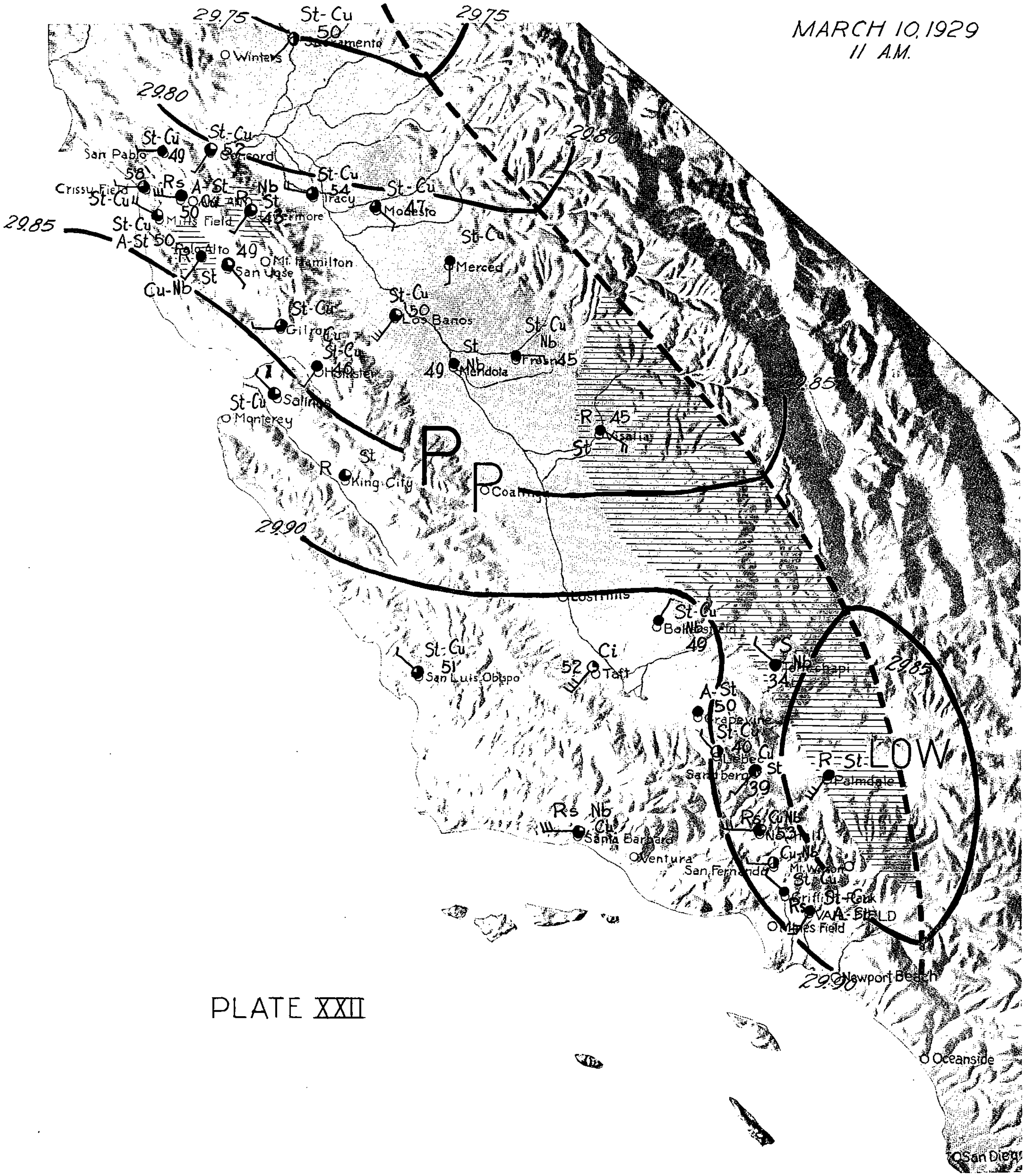

MARCH 10, 1929
11 A.M.
29.75
29.80
29.85
29.90
LOW
Sacramento
Winters
San Pablo
Concord
Crissy Field
Oakland
Livermore
Mills Field
Tracy
Modesto
Palo Alto
Mt. Hamilton
San Jose
Merced
Los Banos
Gilroy
Hollister
Mendota
Fresno
Salinas
Monterey
Visalia
King City
Coalinga
Lost Hills
Bakersfield
San Luis Obispo
Taft
Tehachapi
Grapevine
Lebec
Saugus
Palmdale
Santa Barbara
Ventura
San Fernando
Mt. Wilson
Griffith Park
Mines Field
Newport Beach
Oceanside
San Diego

PLATE XXII