MINIMUM TEMPERATURE FORECASTING IN THE CENTRAL CALIFORNIA CITRUS DISTRICT

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The citrus-growing region of central California consists of some 42,000 acres, mostly of oranges, in a narrow belt along the foothills of the Sierra Nevada in the southern San Joaquin Valley. Plantings are in the low foothills and on the floor of the valley immediately adjacent to a distance of not more than 5 miles. Elevations range from about 375 feet above sea level on the valley floor to about 1,500 feet in the foothills, with scattered groves at somewhat higher elevations. Over two-thirds of the total acreage is planted to navel oranges, which mature in November and are mostly picked before damaging temperatures ordinarily occur. Valencia oranges, however, and portions of the lemon and grapefruit crops are on the trees throughout the winter; of these about 5,000 acres are located where orchard heaters are needed to protect the fruit against damage by frost. As an aid to growers in protecting their crops the Fruit Frost Service of the Weather Bureau has maintained an organization in the district each winter since 1922–23, the season lasting from November 1 to February 15. Headquarters are centrally located at Lindsay. Forecasts of minimum temperatures at selected stations and other advisory warnings are broadcast nightly by radio.

While Polar Continental air masses make their way into the valley in rare instances, with low temperatures by day as well as by night, the predominant air masses of the San Joaquin Valley in winter are Polar Pacific, with temperatures of 32° or lower occurring only as the result of nocturnal radiation. Inasmuch as radiation from the ground is a function of the temperature and the absolute humidity, a simple mathematical formula was developed by Young [1] which expresses these factors quantitatively and shows the probable minimum temperature. As adapted empirically to the central California citrus district, this formula is as follows:

When relative humidity is below 52 percent:

$$T_m = D - \frac{D-28}{3} - \frac{H-30}{4}.$$

When relative humidity is 52 percent or more:

$$T_m = D - \frac{D-28}{3} - \frac{H-30}{4} + \frac{H-52}{6}$$

where T_m is the expected minimum,
D is the dewpoint at 5 p. m. (local time),
H is the relative humidity at 5 p. m. (local time).

This formula was devised from actual case histories of frost and therefore applies only to average conditions in a particular locality, i. e., the neighborhood of Lindsay, Calif. In 16 years of record the range of dewpoints at Lindsay preceding frost has been from 20° to 52°, frosts most often occurring within the range 30° to 48°, with maximum frequency at 40°. Dewpoints below 30° are infrequent in central California in winter and are significant of unusual conditions, limiting the applicability of the formula, It has not been found practicable to introduce constants into the formula for differing soils, ground moisture, maximum temperature, types of pressure distribution, etc., as these influences are too difficult of mathematical expression. At best the formula indicates the minimum temperature probable under average conditions on clear, quiet nights. Other factors must be weighed according to the judgment and experience of the forecaster, and the formula modified appropriately.

The use of this formula to show the probable minimum temperature resulting from nocturnal radiation under given conditions of air temperature and water-vapor content (note that dewpoint and relative humidity together associate these two factors) is dependent on the assumption that air in contact with the ground thus cooled will remain in place and not drain off down slope under the influence of gravity. Drainage of cooled air would cause replacement by warmer air, so that computations based on the formula would not apply. The place for which minimum temperature forecasts are made according to the formula, therefore, must be carefully selected. Generally speaking, this point will be on a flat plain or where the slope is very gradual. Locations near Lindsay, Calif., are suitable in this respect, so that the main key station for the entire citrus belt is located there. At the Lindsay key station the temperature shown by the formula will approximate the actual minimum within 2° on ideal radiation nights. Forecasts are therefore made for the Lindsay key station, and estimates for other stations are then made according to elevation. The theory is that minimum temperatures on slopes and hillsides are a function of the temperature inversion. Variations from the expected minimum at Lindsay are estimated on the basis of (1) topography; (2) maximum temperature of the preceding day; and (3) atmospheric water vapor (the temperature inversion is obviously a function of both the maximum temperature and absolute humidity of the surface air.)

Inasmuch as few nights in an average winter afford ideal radiation conditions, computing the minimum temperature by means of the hygrometric formula is but the first step in actual forecasting. It is necessary to foresee: (1) regional change of air mass, with resultant effect on local weather; and (2) changes *within* the air mass, such as local fog or cloud.

The topography of the San Joaquin Valley is fundamentally important in comprehending movement of air masses into and out of the region. Shaped like a gigantic U, the valley is bounded on the west by the Coast Range; on the south by the Tehachapi Mountains; and on the east by the Great Western Divide of the Sierra Nevada. This three-sided barrier, in effect one unbroken mountain chain, effectively interferes with change of air mass at low levels. Indeed, it is not uncommon for change in air mass to take place aloft with important effects on frost probability, while surface air remains unchanged. A spell of frost is sometimes brought to an abrupt close by intermediate or high clouds as warm air moves northward over the valley without disturbing the surface strata; or, conversely, frost may follow suddenly when fog is cleared by turbulent mixing due to the same cause. At times new air masses seem to cross the Coast Range laterally and move *over* the valley before change in the surface air has been accomplished. In occasional years Polar Continental air makes its way over the mountains into northern Cali-

[1] Forecasting Minimum Temperatures in Oregon and California. Floyd D. Young, Monthly Weather Review, Supplement 16. Also: A Critique on the Construction and Use of Minimum Temperature Formulas. Eckley S. Ellison. Monthly Weather Review. December 1928.

fornia, thence spreading southward into the San Joaquin Valley to cause abnormally low temperatures. As a rule, however, air masses in the valley are renewed by fresh Polar Pacific air moving into the region through the low passes of the Coast Range in the vicinity of San Francisco Bay. This provides an important element in forecasts for the southern portion of the valley, i. e., change of weather takes place progressively from north to south.

In actual practice, the procedure in forecasting minimum temperatures in the citrus belt is as follows:

1. Analysis of the prevalent surface air mass by means of the hygrometric formula, indicating whether or not frost is probable.
2. Reference to possible changes in the surface air taking place northward and progressing southward, as shown in hourly reports of airways weather stations.
3. Reference to the evening weather map to ascertain if regional change of air mass is likely to occur during the forecast period, either aloft or at the surface, or both.

These steps are in the order of importance in making minimum temperature predictions in the central California citrus district. Inasmuch as air masses change with comparative slowness in the valley, the temperature and dewpoint at 5 p. m. afford the best indications of frost probability during the ensuing night. It is not too much to say that without knowledge of temperature and dewpoint *in the exact locality*, and that simple but useful device, the Young hygrometric formula, accurate quantitative forecasting would be impracticable. Once the local surface conditions have been accurately evaluated, the possibility of changes during the night must be investigated: If no material changes are taking place in the northern end of the valley by 7 p. m., when the forecasts are released, it is unlikely that there will be a change in the citrus belt before morning (exceptions are known, however). The role of the evening weather map of the northeast Pacific area is: (1) To show possible changes of air mass which might not be obvious from conditions in the north end of the valley at 7 p. m.; (2) to furnish clues to changes of or within the air aloft, as upper fronts, intermediate or high clouds, water vapor discontinuities resulting from subsidence, etc.; (3) for making forecasts for more than one night.

It is believed that in the central California citrus district, at least, weather maps cannot be classified as favorable or unfavorable to frost on the basis of barometric distribution alone. Frost has occurred under almost every conceivable type of pressure distribution, and differences in weather accompanying markedly similar pressure types can be extreme. Change in pressure distribution, however, may be associated with changes in air mass, or, in the San Joaquin Valley may act to prevent change. A simple classification of generalized pressure types may therefore be useful. With emphasis on the fact that they are but points of departure for analysis of individual situations, such a classification is herewith presented. All data except isobars are intentionally omitted, for classification being on the basis of barometric pressure, inclusion of air mass data would confuse the issue and make them examples of individual rather than type importance. For example, a weather map showing a Great Basin anticyclone might include anything from fine, warm weather to cool, foggy situations, or severe frosts.

Employing a nomenclature from the geographical center of pressure at the stage of development when frost is most probable in the citrus belt, these are called: Type I, Great Basin HIGH, Type II. California HIGH, Type III. Plateau LOW.

Type I, *Great Basin* HIGH.—See maps for December 25, 1929, to December 27, 1929, inclusive. Following a more or less rapid rise in pressure off the Washington-Oregon coast, there is also a rapid increase over the Great Basin area within 12 to 24 hours. The fully developed Great Basin anticyclone is connected with the semipermanent Pacific high pressure by a great, curved ridge. Pressure over California is decidedly lower. With this enormous mass of fresh Polar Pacific air to the west, north, and northeast, movement of new air masses into the San Joaquin Valley cannot take place, and the weather will remain more or less as at the beginning of the regime, or will be modified but slowly. The Great Basin anticyclone is also important because of its persistence, as, aided by nocturnal radiation, pressure at the center increases slowly and great stability is achieved. The weather of the San Joaquin Valley may show extreme variations under the dominance of this type, depending on the properties of the original air mass. If the valley has been filled previously with warm, dry air as often happens in November, the weather will continue fine. Quite warm days may be followed by frosty mornings, and a daily range of over 40° is not uncommon. If, on the other hand, cool, moist air is in the valley at the beginning of the cycle, persistent fogs are probable, typical of December weather. As subsidence within the anticyclone takes place, the cool, moist air resting on the ground is separated from the warmer and drier air aloft by an effective discontinuity. If the surface air is relatively dry and cool, however, no discontinuity becomes established to produce fogs, and a spell of frosty nights will follow, lasting sometimes 2 weeks or more without a break. Decadence of the Great Basin anticyclone is usually preceded by withdrawal of the Pacific center further offshore together with a pronounced 24-hour fall in pressure over the continent. Breakup is rapid in the final stages, and the map may change to a variant of Type III abruptly.

Type II. *California* HIGH.—See maps for January 19–21, 1934, inclusive. With the center of the Pacific HIGH off the California coast, weak low-pressure systems along coast and extending into California-Nevada are often followed by a rapid rise in pressure directly over California; the center of highest pressure may be in the San Joaquin Valley or in Nevada. This type is fairly frequent in winter, but is not persistent like Type I. Temperatures are not abnormally low as they may be with either Type I or Type III. Ground fogs may occur, but are not usual. Minimum temperature forecasting may be very difficult at the beginning of this type owing to the rapidity with which the new air mass moves into the valley. It is probable that air-mass change takes place aloft by lateral transport over the Coast Range before a surface change is effected by movement southward into the valley from the San Francisco Bay region.

Type III. *Plateau* LOW.—See maps for December 6–12, 1932, inclusive; and for January 4–8, 1937, inclusive. While this type is common in winter, it is associated with frost less frequently than Types I and II: nocturnal cloudiness or light winds so often persist after passage of the storm that the weather map has changed to Type I or II before the first night favorable to frost. Yet, in the final analysis it is in some ways the most important of the three types in that in may be attended by temperatures which are nothing less than catastrophic to citrus growers. Appearing as a small LOW over the Pacific Northwest, movement southeastward is very rapid, and maximum development of this type takes place when the center has reached the Colorado Plateau. Most of the annual rainfall, all of the rare and scant snowfalls on the valley floor, and the historic "freezes" or cold waves occur with this type, hence these storms demand careful scrutiny. Relatively low temperatures and evening dewpoints near or below 30° behind the cold front usually mean abnormally cold weather in the citrus belt within 24 hours, with little or no temperature inversion.

Even when the regional air mass is not expected to change, certain modifications may take place which will have important local effects on frost probability. Depending largely on the water-vapor content of the surface air in conjunction with anticyclonic subsidence, the most distinctive development within the air mass is radiation or "high inversion" fog (or stratus cloud). Varying in height above ground from one or two hundred to two or three thousand feet, this fog may last from one night to several weeks, and because of its obvious effect on ground cooling almost insuperable difficulties in minimum temperature forecasting are connected with its initial appearance, extent, and final clearing. The stages of a typical fog regime in the citrus belt are summarized briefly: Forming first in patches at elevations of 50 to 100 feet above ground, the fog soon reaches the ground and becomes dense over a wide area; it is not usually seen in the foothills until one or more nights after its first appearance on the valley floor. Following the first night of fog, clearing takes place in the forenoon over the citrus belt, although fog may remain all day far out in the main valley. When the foothill area is covered during the night, fog will persist most of the next day on the valley floor as "high fog," slowly thinning (evaporating) near the ground. During the ensuing night the process will be repeated, and thereafter the fog will cover the valley floor and more or less of the foothill area for days, even weeks, without a break. The "high fog" of the day lowers to the ground at night, and a familiar development is increasing wetness until trees are dripping and water stands on the ground as after a light rain. After a day or night of such wet fog the horizontal visibility abruptly and remarkably improves although the "high fog" (stratus cloud sheet) remains unbroken. This development is not necessarily a prelude to break-up of the fog.

Clearing of the fog may come suddenly and over the entire region, either by day or by night. More often, however, general clearing is preceded by intermittent clearing *at night* at the limiting elevation of the fog in the foothills. Obviously, intermittent clearing during the day may be due to insolation without a significant change in the general meteorological situation. The end of the regime is also preceded at times by pronounced thinning of the stratus cloud at night, so that the moon's disk may be visible; if stars can be seen the break-up is assured. Falling dewpoints at valley stations, day temperatures remaining the same, are often noted as a prelude to clearing. Final clearing most often begins in the southern end of the valley, but can be so rapid as/to seem otherwise unless frequent reports are available from the whole region. An exception to this rule occurs when a fresh, relatively dry air mass moves into the valley from the northward, evaporating the fog by mechanical mixing.

Fog in the citrus belt is preceded by evening dewpoints of 38° or higher at Lindsay: out of 43 case histories of fog regimes, extending over 6 winters, only once did fog follow a 5 p. m. dewpoint of less than 39°. In 28 of the 43 cases the initial appearance of fog was preceded by dewpoints of 45° to 51°, from which it may be deduced that fog becomes increasingly probable as dewpoints are above 38°. Day temperatures are not a good indication of fog probability: maximum temperatures immediately preceding are usually well below 60°, but fog has been known to follow a maximum temperature at Lindsay of 71° (dewpoint 40°).

While the fog regime is becoming established barometric pressure is rising after a period of cyclonic activity. Center of highest pressure may be in the valley itself, but in the greater number of times by far the center is over the Great Basin. Thereafter the fog regime continues as the Great Basin anticyclone is persistent. This dependence of fog on the Great Basin anticyclone has been observed so many times as to be axiomatic. During early stages of the regime temperatures at mountain stations begin to rise and dewpoints to fall; fine weather continues throughout the cycle. Decadence of the anticyclone signals the end of the fog regime; the process is hastened in proportion to the rapidity of the pressure decline along the north Pacific coast. As temperatures at mountain stations begin to fall and dewpoints to rise, while at the same time winds shift from northeast and east to southerly, fog clears rapidly in the valley.

Although little is known of the vertical structure of valley air masses aside from inferences drawn from mountain station reports, it seems reasonable and logical to attribute the persistent winter fogs of the region to radiational cooling from a humidity discontinuity at varying levels above the ground.[1] In agreement with this assumption, fog is not forecast in the citrus belt until it appears that a discontinuity exists or will be established during the forecast period; and final clearing is expected only when it is believed that the discontinuity will be destroyed.

Since fog is so common in the San Joaquin Valley in winter it is not strange that minimum temperature forecasting in that region resolves itself much of the time into a problem of forecasting fog—the extent, vertical as well as horizontal, and time of beginning and ending *to the very hour*. The horizontal is dependent on the vertical distribution: With little or no air movement in the valley at night, fog does not move or extend from the valley floor to the foothills in a literal sense. Since the upper limit of fog will be nearly the same as the top of the cool, moist surface stratum, the depth of this stratum must first be estimated, and the extent of the fog in the foothills can then be allowed for. Unfortunately, there is no way at present of measuring the depth of the surface stratum with accuracy, since no observations are made of temperatures and humidity aloft over the valley. Observations of the vertical structure of the air are made in the San Francisco Bay region and in southern California, but their applicability to air masses in the valley is questionable, especially at moderate elevations. Nor are observations from foothill stations (temperature-humidity) of much value, since they are affected by ground exposure and are not representative of free-air conditions. In practice, therefore, the height of the discontinuity level is estimated by the distribution of minimum temperatures over the valley floor and adjacent foothills on the general theory that maximum cooling will take place near the discontinuity. Ordinarily, this level seems to be 1,000 feet or more above the valley floor, so that fog forming at this elevation will cover most of the citrus belt. Cases are on record, however, when severely damaging temperatures have occurred in the foothill citrus areas while the valley floor was blanketed under dense fog. It is supposed

[1] For discussion of the physical basis of this assumption, see the following literature: On the Causes and Forecasting of California Fog, Sverre Petterssen, Journal Aero. Sciences, July 1926. Characteristic Weather Phenomena of California, H. R. Byers, ch. II, A Winter Fog in the Interior, by W. M. Lockhart. Fog and Haze: Their Causes, Distribution, and Forecasting, H. C. Willett, Monthly Weather Review, November 1928.

that in such cases the discontinuity level is very low, within a few hundred feet of the valley floor. Inasmuch as temperatures have been observed to fall steadily throughout the night when the sky was clear at moderate elevations in the foothills, it is considered that falling temperatures under dense fog indicate a low discontinuity level.

The question might well be asked why fog is first seen at lowest elevations in the valley, to appear hours or nights later in the foothills. Actually, fog would first form at the condensation level, which under certain conditions might be below the elevation of the foothill stations. Also, it is possible that stratification of the air may be exceedingly complex at times, with more than one discontinuity. Furthermore, in the early stages of a fog regime, the difference in water-vapor content between the surface stratum and warmer air above may not allow of sufficient cooling to produce fog throughout the entire mass. As evaporation from the soil increases the moisture content of the surface air, while anticyclonic subsidence sharpens the discontinuity, cooling would later be sufficient to cause fog throughout the entire layer.

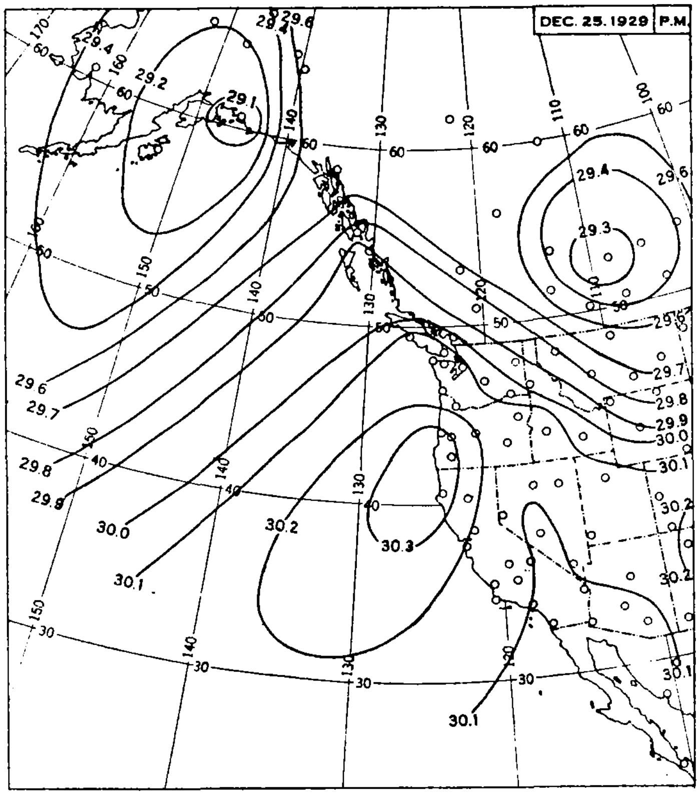
Timing of fog is also essential to minimum temperature forecasting, as the difference of even one hour in appearance or clearing of fog may mean a difference of several degrees in the minimum temperature. In fact, timing of fog is probably the greatest single difficulty in forecasting minimum temperatures in the San Joaquin Valley in winter. For example: From the hygrometric formula a temperature of 26° may be expected if the sky remains clear all night, while at the same time there are indications of fog. If the fog forms early in the night the temperature may not go below 32°; on the other hand delay in appearance of fog until late in the night may allow the temperature to fall to a degree dangerous to crops. Conversely, a few hours difference in the time of clearing of fog may mean the difference between safe and damaging temperatures. In practice, first appearance of fog (almost invariably at night) is timed by general considerations of water vapor content, horizontal visibility at 7 p. m. at valley stations, and previous history of fog in the prevalent air mass. Timing of clearing at night—daytime clearing obviously is not important to the problem in hand—is based on general considerations as to the rapidity of change of air mass, rate of increase in turbulence aloft, and frequent observations at the highest foothill stations, where clearing will usually begin hours before final clearing over the entire district. In this respect it is important to distinguish between the intermittent clearing in the foothills which precedes the break-up of the fog, and the irregular clearing which may be only a function of the height of the fog, i. e., clearing at the top level of the fog due to local turbulence in the foothill region.

Owing to the topography of the valley, wind is not an important consideration in winter, for when frost is probable the weather has become settled and quiet nights are the rule. When the dewpoint is relatively low for the valley, i. e., below 35°, ground cooling is so rapid that the resultant air drainage down the slopes of the foothills is felt as a light breeze several miles out on the valley floor.

Rarely, a cold front moving into the valley with a Type III weather map is attended by northwest winds at night and a clear sky; if properties of the fresh air mass are suitable, temperatures of 32° or lower will occur before sunrise, with wind continuing. On one such occasion, following rain during the early part of the night the sky cleared rapidly, and even with fresh to strong northwest winds all night the temperature fell steadily to a minimum of 26° at sunrise. Indications of wind continuing during the night, therefore, as the sky clears after a storm, do not necessarily signify that the temperature will not fall: Properties of the incoming air mass must be properly evaluated in order to make an accurate forecast. If the fresh air mass is relatively dry it conserves but little of the heat given off by the ground during the night; and since the regional air mass previously heated by insulation has been removed, there is no opportunity for the usual temperature inversion to develop. Consequently there is no warmer air to be mixed by the wind with the air cooled by contact with the ground, and surface temperatures will be the same as on a windless night, other conditions being equal.

Conclusion.—It is a matter of experience that within a given area such as a single citrus grove minimum temperatures will show local variations of one degree or more on even ideal radiation nights. Erratic air drift, unequal amounts of radiation from various kinds of ground covering, and other vague, complex, and perhaps contradictory influences may operate to bring about differing minima within such short distances that it is a practical impossibility to estimate the net effect within the rather small limits of one degree on the Fahrenheit scale. It seems a wholly reasonable consideration, then, that maximum possible accuracy is achieved if predictions for definite locations are within 2° of the actual minima.

By use of a technique more or less as outlined in the foregoing pages, minimum temperature predictions for the Lindsay district key station have been over 90 percent as an average, and occasionally 95 percent within the 2° limit. It is no doubt true that errors of more than 2° are sometimes the result of causes so confused and individually unimportant that they can be described only as meteorological accidents and as such they may occur at any time. It is probable, however, that these errors in general can be ascribed to lack of precise and timely data on air aloft over the San Joaquin Valley. The water vapor content and temperature of the air up to one or possibly two thousand feet must control to an important extent the net loss of heat at the ground: it is believed that further improvement in minimum temperature forecasting must come from quantitative investigation of these lower strata.



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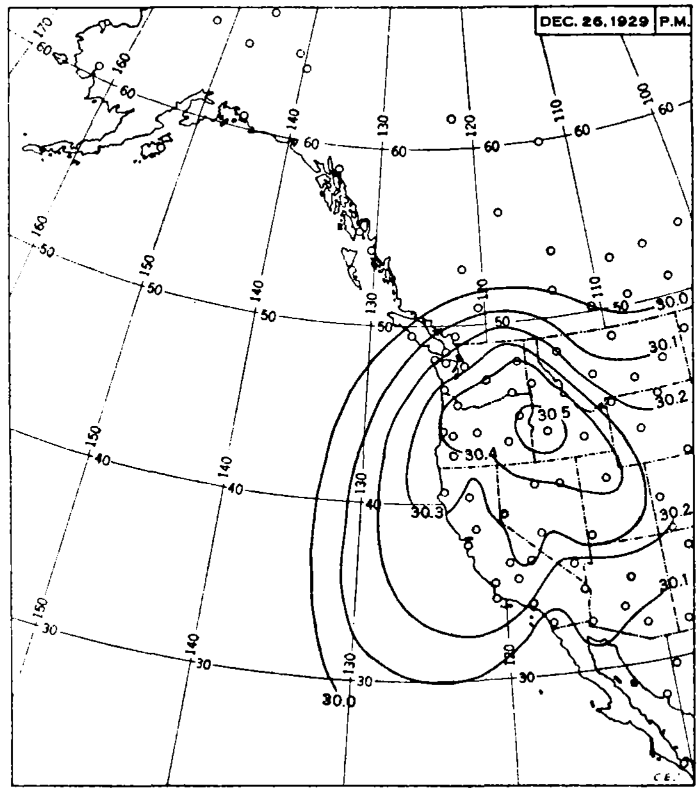

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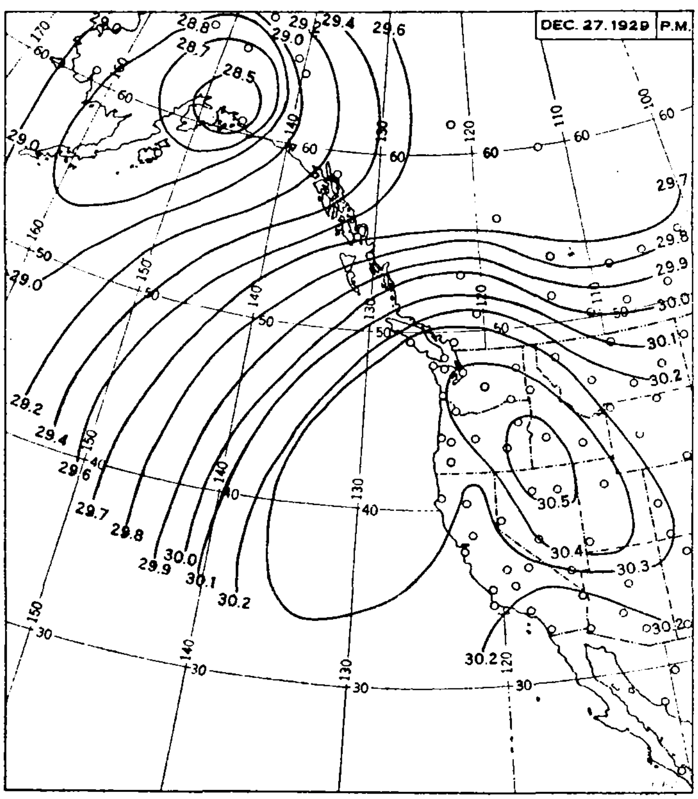

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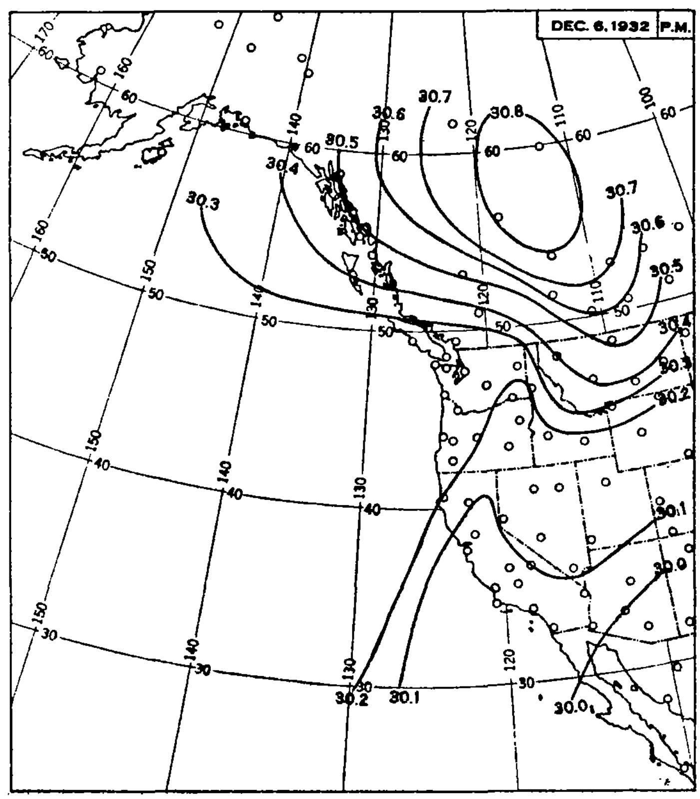

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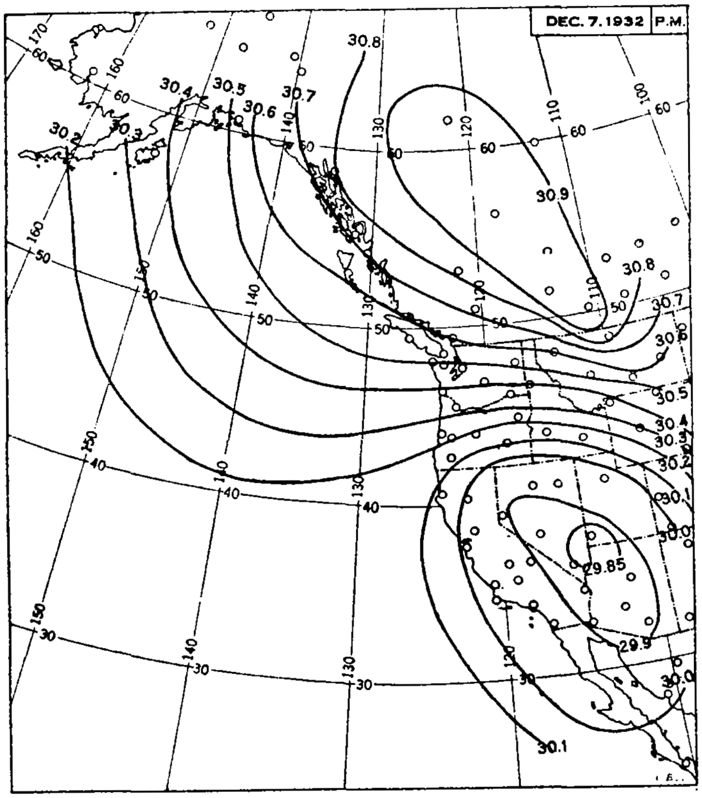

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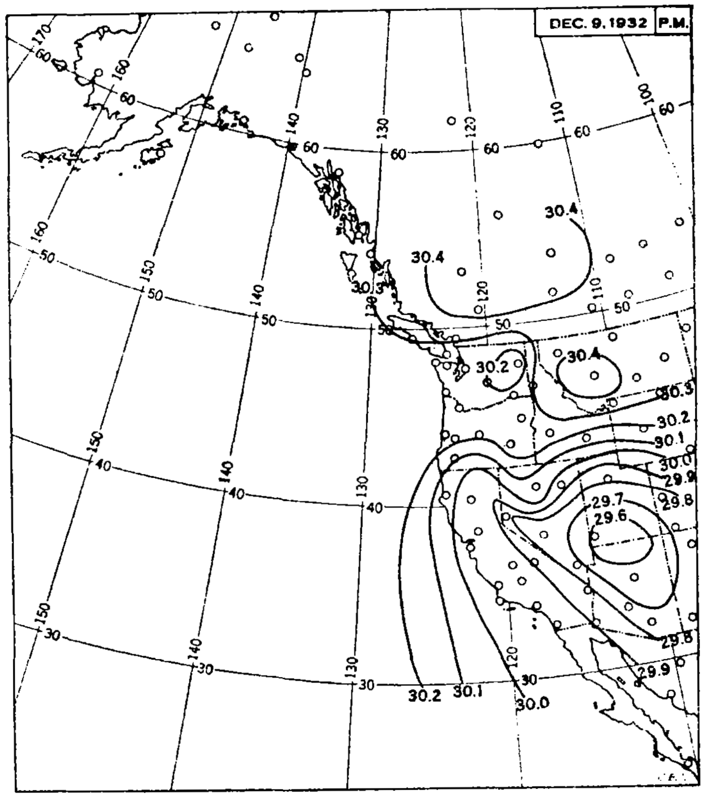

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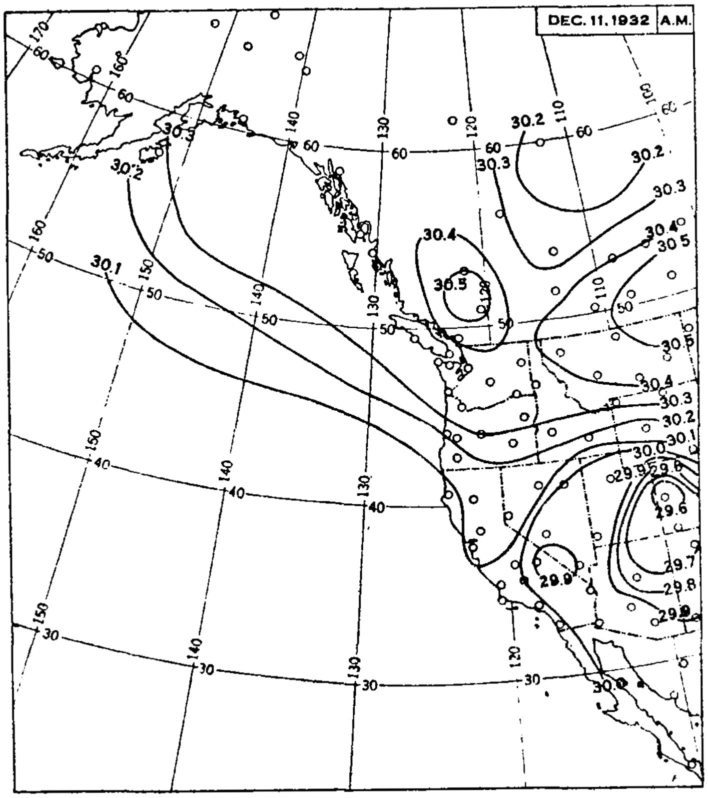

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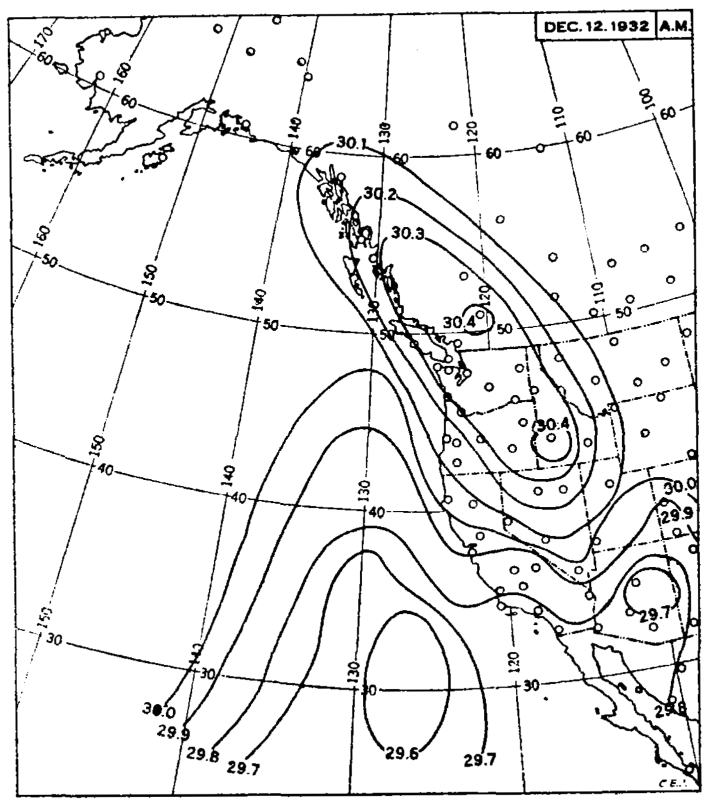

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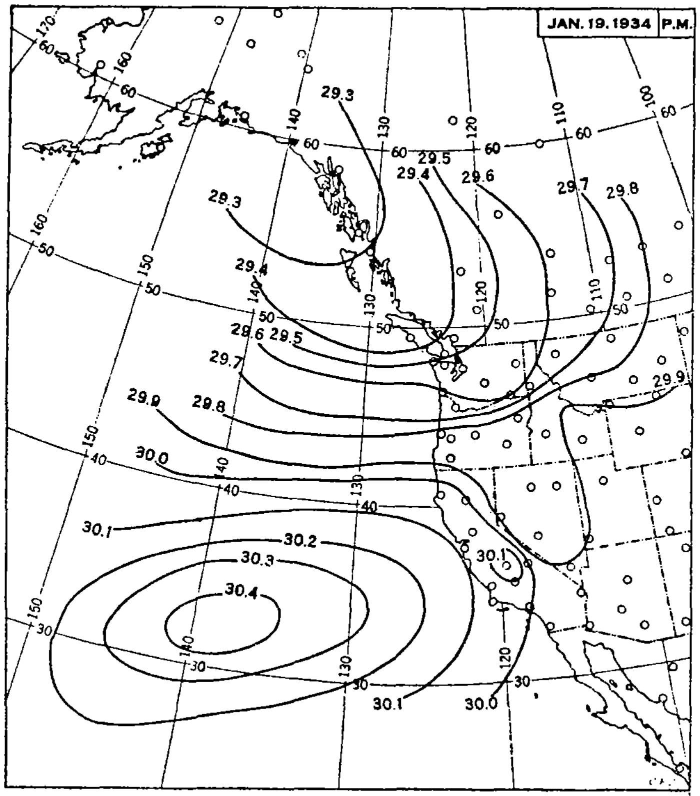

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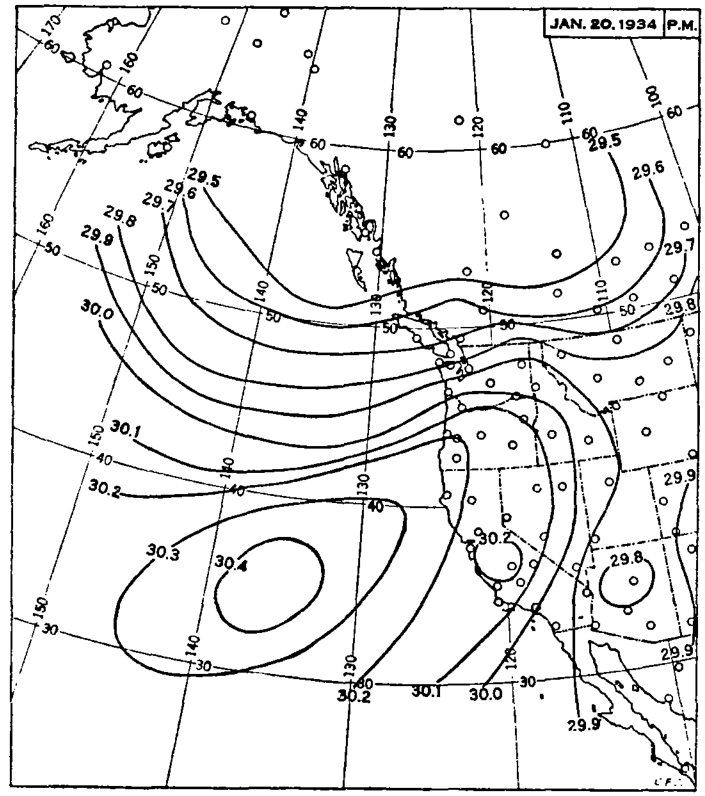

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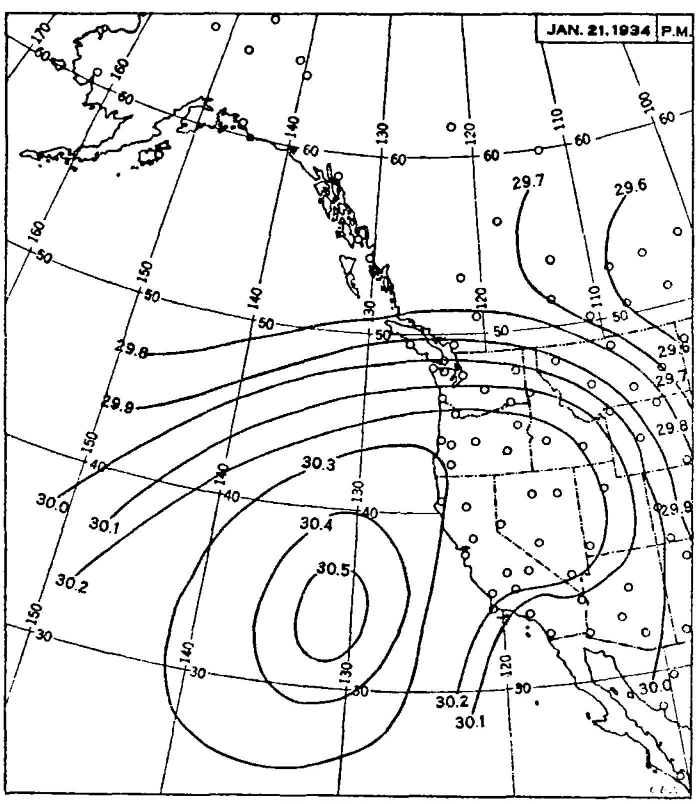

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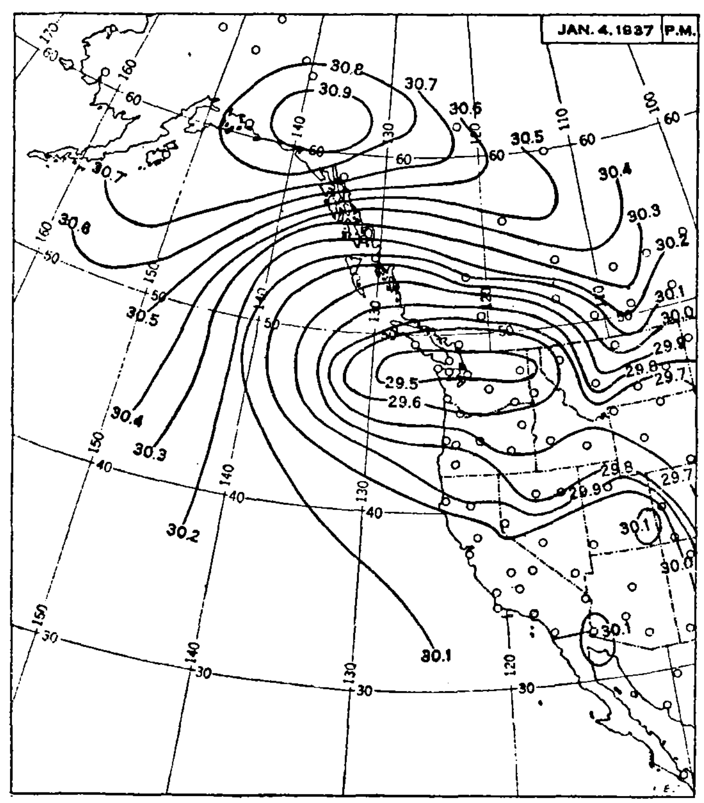

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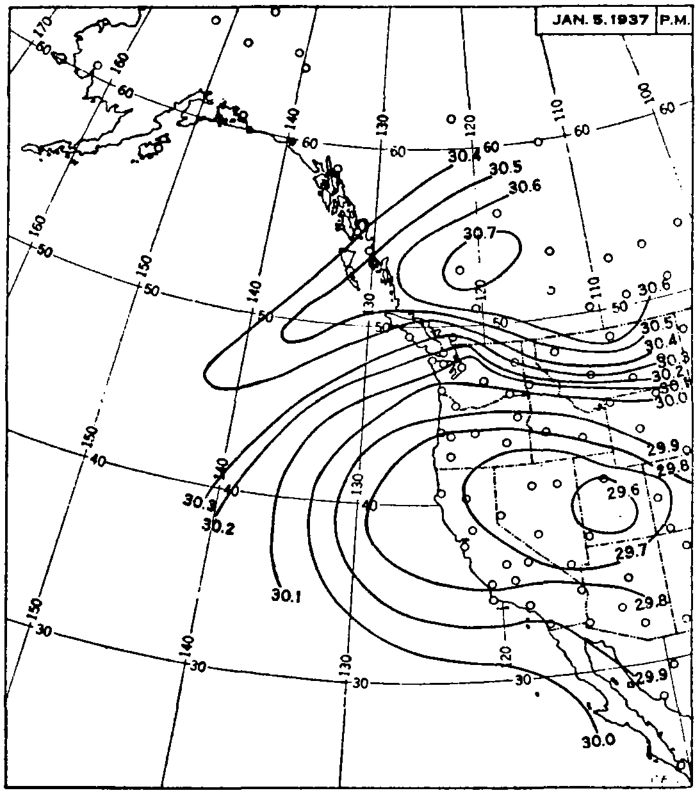

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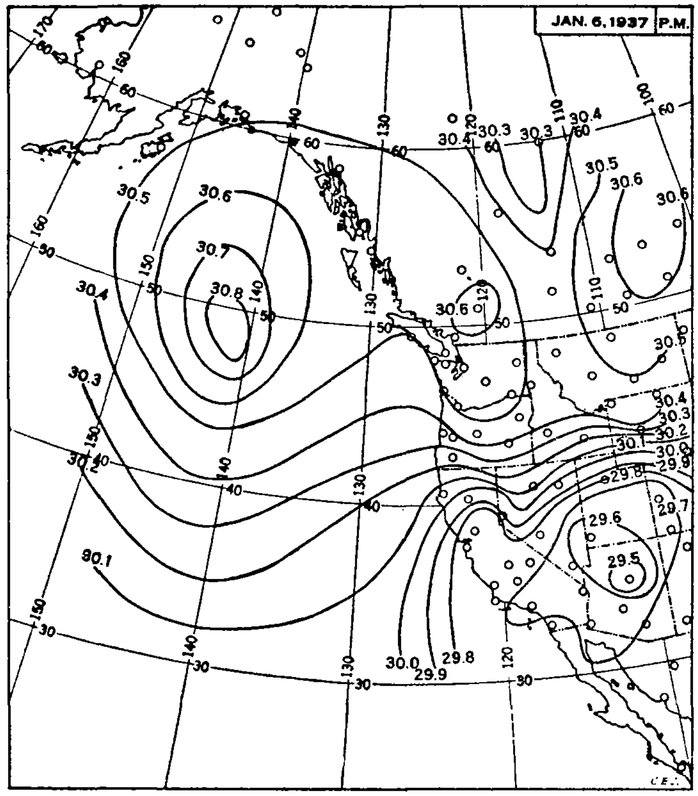

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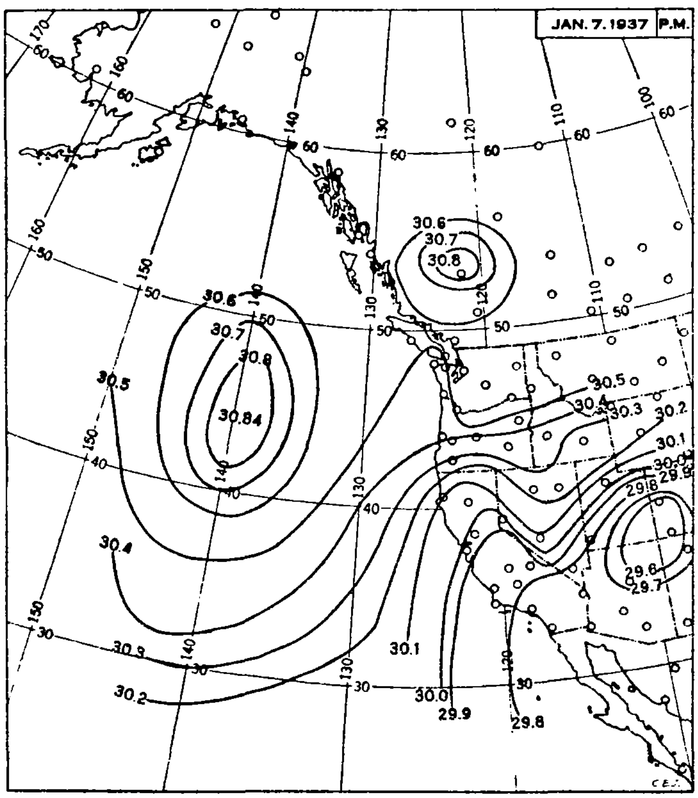

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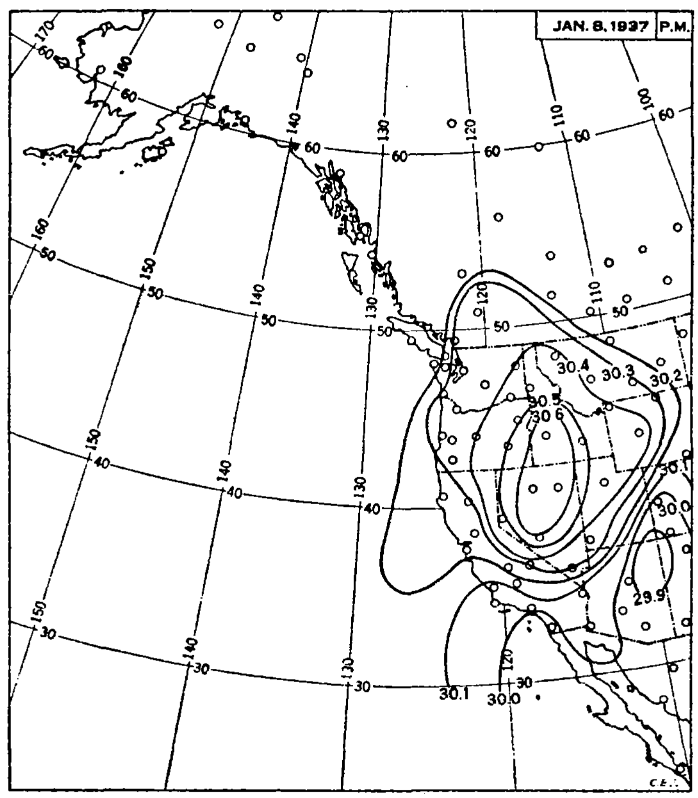

Figure 16.