The Relation of Air Mass Structure to the Field of Motion over the Eastern North Pacific Ocean in Summer[1]

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Abstract

The normal structure of the inversion over the eastern North Pacific Ocean in summer is presented, and its relationship to the normal fields of horizontal and vertical motion is discussed. An example in which the field of motion deviated markedly from the normal is presented. The relatively large change in the motion had comparatively small influence on the temperature structure.

1. Introduction

The circulation and structure of air over the subtropical Atlantic Ocean was presented many years ago by SVERDRUP (1917) and VON FICKER (1936). For the Pacific Ocean similar data was much later in becoming available.

Beginning in the 1940's a series of investigations have been conducted at the University of California, Los Angeles, concerning the structure and circulation of the air over the subtropical Pacific Ocean. Many of the results of these studies have not yet been published. I shall in this paper present the essentials of a group of them, the details of which will subsequently be published separately. I should like to acknowledge the contributions of several of my students and associates to the work, particularly Messrs. A. H. Thompson, Lawrence E. Eber, David S. Johnson, and C. W. Chien. Their names will appear as co-authors on the separate detailed reports.

2. The inversion over the eastern North Pacific Ocean

As in the case of the Atlantic Ocean, the temperature structure over the eastern subtropical portions of the Pacific Ocean is characterized by a marked inversion during the warm season. Figure 1 shows the fre-

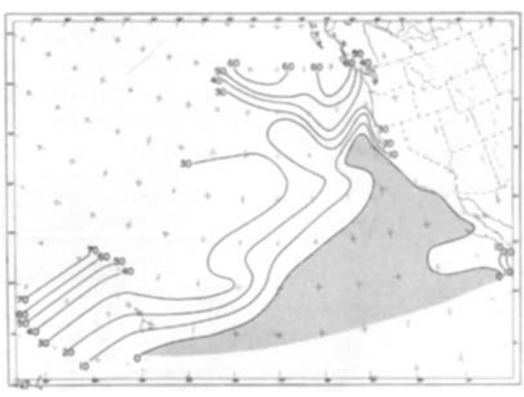

Fig. 1. Frequency (in per cent) of soundings with no subtropical inversion during warm season (June 1—September 30).

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quency with which inversions were absent during the period June—September over the eastern North Pacific Ocean. In the shaded area every observation taken during this period showed a characteristic trade-wind inversion. The lower frequency of inversion off the coast of Lower California is associated with the occasional occurrence of tropical cyclones moving from the southeast, while the lower frequency in the north is associated with moving cyclones in the westerlies.

Figure 2 shows the average height of the inversion base during summer. It slopes upward from about 400 meters along the California coast, rapidly at first, and then slowly to reach a height of more than 2,000 meters over the Hawaiian Islands. Figure 3, the average summer cross section from San Francisco to Honolulu, gives some impression of the vertical structure through the inversion. Near the coast, where the inversion is lowest, the temperature rises rapidly as one goes through it, with a temperature increase of more than 6° C. Farther westward, where the inversion is higher, the temperature increase through it is less, until Honolulu, where it amounts to about 2° C. Below the inversion the lapse rate is near the dry adiabatic, and above the inversion it is about normal.

Needless to say, the inversion acts as an effective lid on the upward transport of water vapor from the ocean, so that the air below is quite moist, but the air above extremely dry. Near the coast, where the inversion is low, stratus clouds are prevalent below the inversion, while farther seaward the cloud layer becomes broken up into cumulus clouds, with some showers where the layer gets sufficiently thick. In the Hawaiian Islands the showers are augmented by orographic effects.

3. Relation of the inversion to the field of motion

Von Ficker pointed out that the inversion over the Atlantic is due to the subsiding motion of the air circulating around the subtropical high pressure areas. Figure 4 shows the normal sea level pressure over the eastern

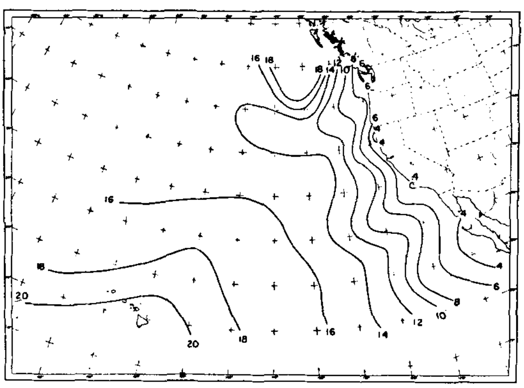

Fig. 2. Average height of subtropical inversion base during warm season (in hundreds of meters).

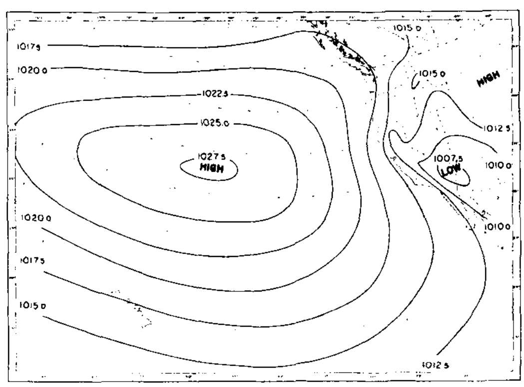

Fig. 4. Normal sea level pressure (mb) in July.

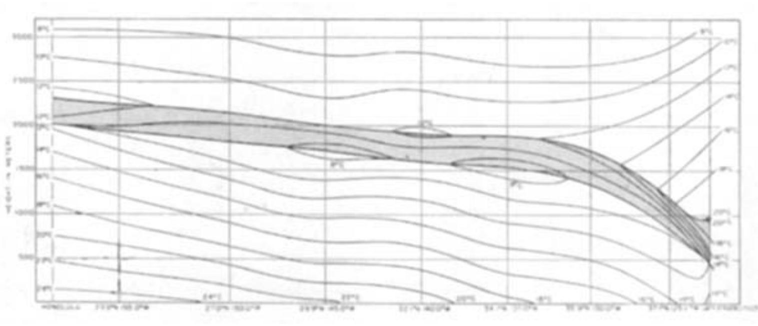

Fig. 3. Cross section showing average temperature in warm season, San Francisco to Honolulu. Subtropical inversion layer is shown by stippled shading.

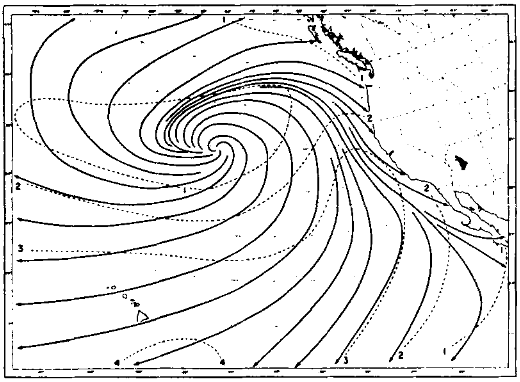

Fig. 5. Normal resultant surface wind stream lines (continuous lines) and isotachs (dashed lines) for July.

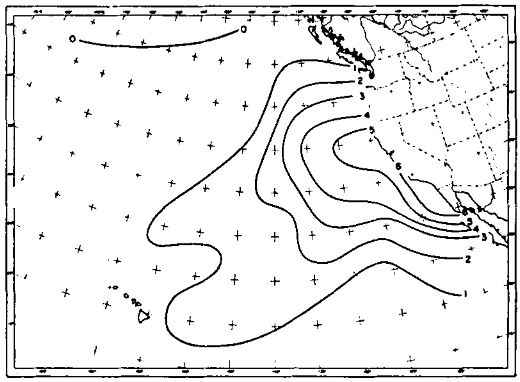

Fig. 6. Divergence of the normal resultant surface winds for July (in 10^{-6} sec^{-1}).

part of the North Pacific Ocean. The center of the anticyclone lies at about 38° N and 150° W, with its axis oriented west-southwest to east-northeast, but with bulges extending northeast and southeast. One frequently sees discussions of the flow pattern over the surface of the ocean based upon deductions concerning the geostrophic winds or gradient winds corresponding to this pattern. However, as is seen in Figure 5, the winds deviate far from the isobars over this area. The normal resultant winds spiral outward from the anticyclonic center, with an asymptote of divergence extending southeastward parallel to the California coast. Together with the streamline divergence there is a general longitudinal divergence due to the increase of wind outward from the center of the anticyclone. The resulting divergence, in units of 10^{-6} sec^{-1} is shown in Figure 6. Note that while the divergence has a maximum along the California coast it is positive over practically all of the eastern part of the North Pacific Ocean.

At 700 mb (Figure 7) the normal position of the anticyclonic center is southwest of its surface position, and a trough is present off the coast of North America, so that the winds along the coast at this level have weak southerly components. At 500 mb the normal position of the high pressure center is displaced farther southward, to 25 degrees north, the trough is farther west (130° west) and the southerly winds along the coast are somewhat stronger.

Resultant winds at upper levels over the Pacific Ocean are not available for the computation of divergence and vertical motion, and so the attempt was made to estimate these quantities from the distribution of pressure and temperature, on the assumption that the mean state represents a stationary one. In this case, the tendency for temperature changes due to advection and radiation must be offset by the vertical motion. Since the flow pattern is not truly stationary the contribution to the mean temperature change due to fluctuations should properly be taken into account. However, because the fluctuations in this region and season are always slow it seems reasonable to assume that their neglect will not affect the accuracy of the estimate. Figure 8 shows the temperature changes which would be produced at 700 mb due to advection of the normal isotherms by the gradient winds corresponding

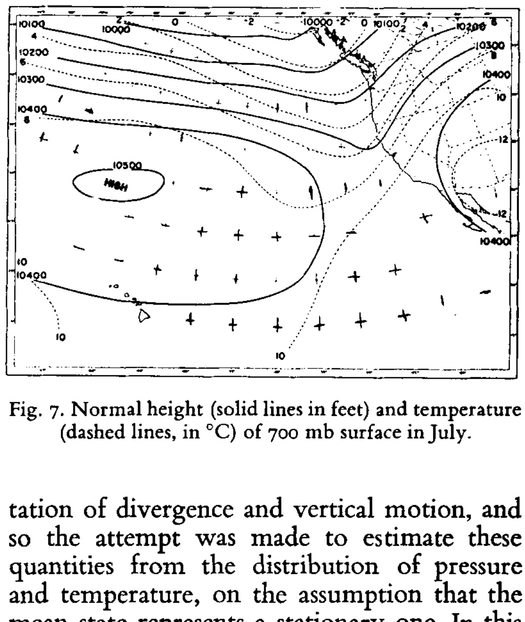

Fig. 7. Normal height (solid lines in feet) and temperature (dashed lines, in °C) of 700 mb surface in July.

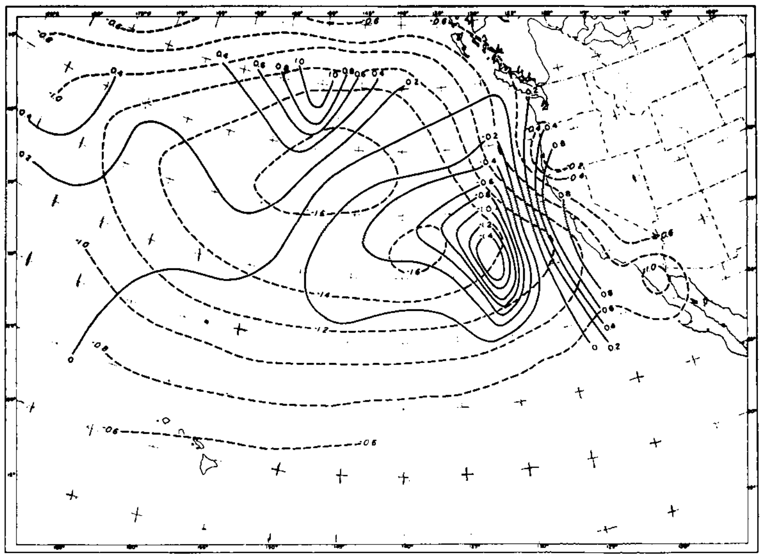

Fig. 8. Mean advective (solid lines) and radiative (dashed lines) temperature changes (°C/24 hrs) at 700 mb in July.

to the normal contours, and an estimate of the temperature change which would be due to the average radiational loss of energy at this level. The latter estimate is based on computations of the radiative cooling for six individual days during July 1949 (THOMPSON and NEIBURGER, 1953). As a crude estimate it is assumed that the average of the six individual cases approximates the normal.

The vertical velocity at 700 mb computed on the assumption that the temperature changes in Figure 8 are offset by adiabatic cooling due to vertical motion is shown by the dashed lines in Figure 9. It will be noted that sinking motion is prevalent except along the coast of the United States, with maximum values along the axis of the anticyclone and the asymptote of divergence in the sea level resultant winds. The values of the vertical velocity are small, but it must be remembered that the horizontal velocities are likewise quite small so that there is plenty of time for the air to sink during its movement around the high. On the assumption that the divergence varies linearly from sea level to 700 mb, the average divergence of the layer 1,000 mb to 700 mb as represented by the vertical velocity at 700 mb and the sea level divergence were used to determine the divergence and vertical velocities at other levels. The solid lines in this figure show the divergence pattern at 700 mb computed on this basis. It will be noted that the divergence is positive at 700 mb over most of the region, but that relatively large values of convergence occur in the southerlies east of the trough.

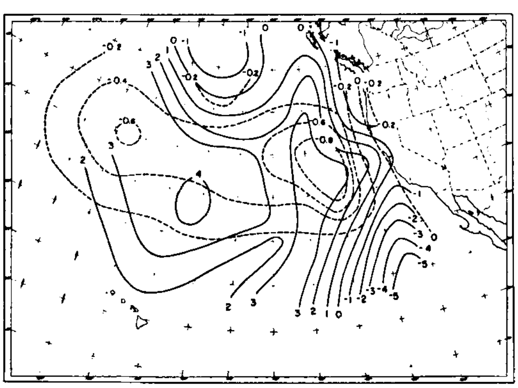

Fig. 9. Mean vertical velocity (dashed lines, in cm/sec) and divergence (solid lines, in 10^{-6} sec^{-1}) at 700 mb in July.

From the vertical velocities computed in this fashion for all levels it is possible to compute three-dimensional trajectories of the air leaving or reaching any particular location. Thus, in Figure 10 there are shown the trajectories reaching San Francisco and Los Angeles at 2,000 feet, traced backward to the 700 mb level, and trajectories leaving particular positions to the north and east of the high center

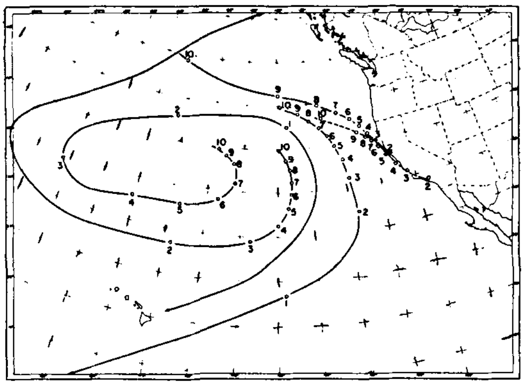

Fig. 10. Three-dimensional trajectories of air parcels starting at 700 mb. (Numbers along trajectories, height in thousands of feet.)

at 700 mb. The numbers beside the trajectories are the heights in thousands of feet. In the trajectories reaching San Francisco and Los Angeles, the air descends most rapidly in the vicinity of the coast, while in the cases of the trajectories starting northeast of the anticyclonic center at 700 mb, the most rapid descent occurs at the beginning of the trajectories. Since the vertical motion must be zero at the sea surface, it is natural that the sinking motion decreases as the air approaches the sea surface.

It will be noted that the computations indicate air sinking through the inversion to the east and south of the anticyclone. In this region the heating of the air crossing from colder to warmer sea surface offsets the sinking motion so that the inversion rises westward from the coast all the way to Honolulu in spite of the divergence and sinking motion in this area. This phenomenon was pointed out by RIEHL and his associates (1951).

4. Effects of deviations from the normal pressure field

While the anticyclone is usually not far from its normal position and intensity, variations do occur, and occasionally they are fairly large even in summer. A case of a wide deviation from the normal occurred in the first half of July, 1949. During this period the anticyclone was considerably more developed than normal at the beginning of the period, broke down into two weak centers at the middle, and reformed to approximate the normal situation by the end of the period. It is interesting to inquire to what extent this wide fluctuation from the norm affected the structure of the air masses and in particular the inversion.

The surface situation near the beginning of the period is shown in Figure 11, in which

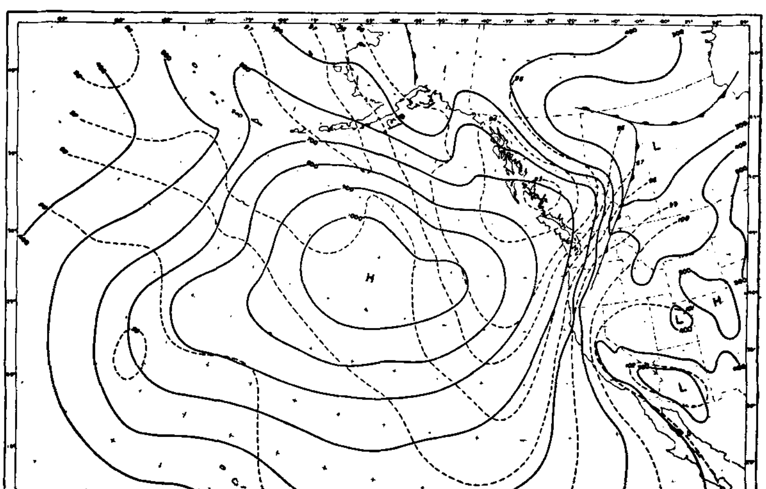

Fig. 11. Topography of 1,000 mb surface and relative topography, 1,000 mb—700 mb, 0300 GCT July 2, 1949.

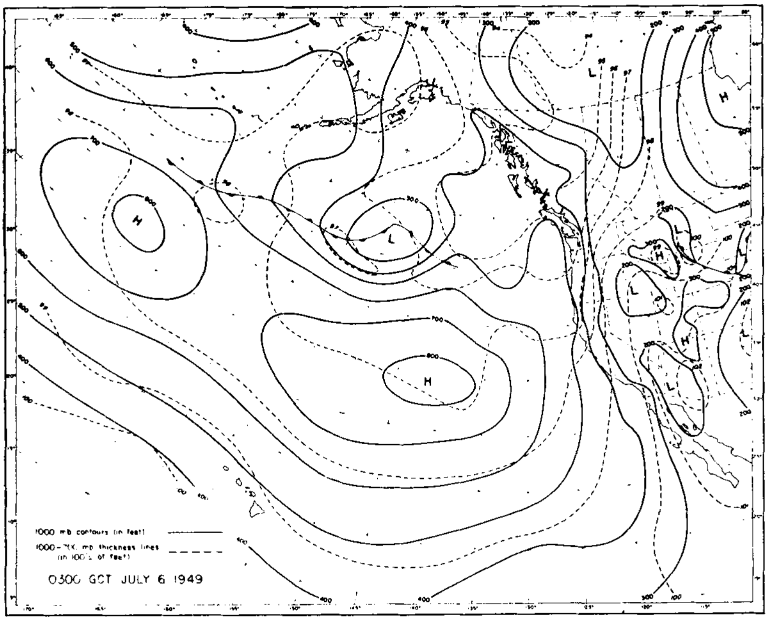

Fig. 12. Topography of 1,000 mb surface and relative topography, 1,000 mb—700 mb, 0300 GCT July 6, 1949.

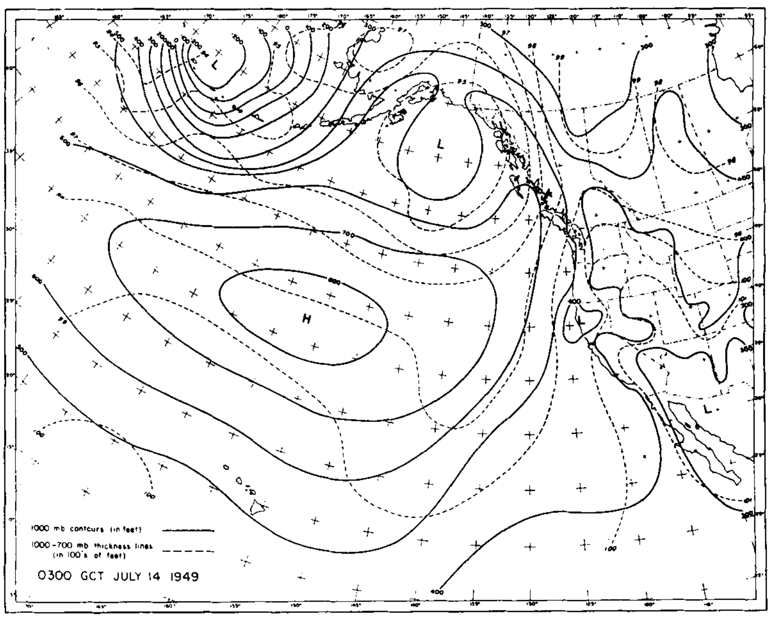

Fig. 13. Topography of 1,000 mb surface and relative topography, 1,000 mb—700 mb, 0300 GCT July 14, 1949.

the pressure field is given by the topography of the 1,000 mb surface instead of the pressure at sea level, and the temperature field is indicated by the 1,000 to 700 mb thickness lines. Figure 12 shows the 1,000 mb distribution at the middle of the period, July 6, when the high was broken in two centers. During this period a series of weak low centers moved into the Gulf of Alaska, intensified somewhat, and then moved eastward with decreasing intensity. Figure 13 shows the situation after the anticyclone had resumed its normal shape. In Figure 14 the 700 mb contours at the beginning of the period are shown by the

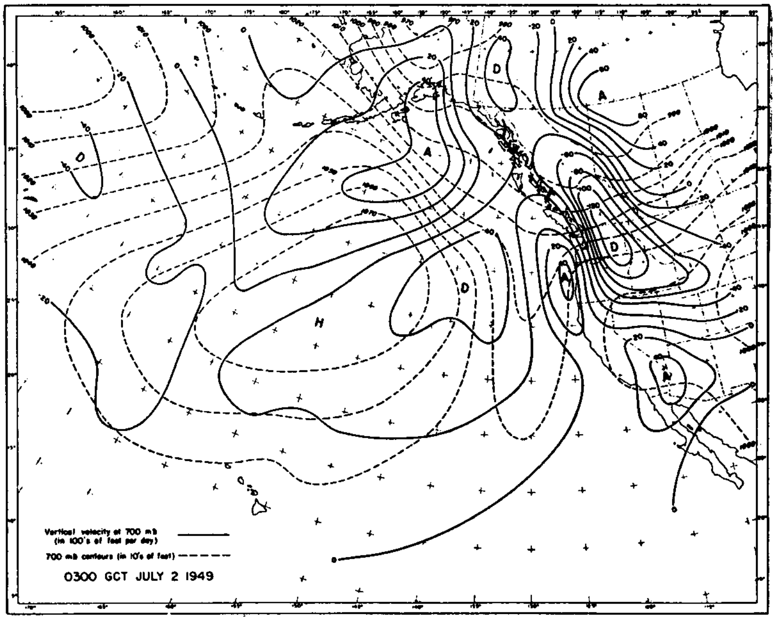

Fig. 14. Topography and vertical velocities at 700 mb, 0300 GCT July 2, 1949.

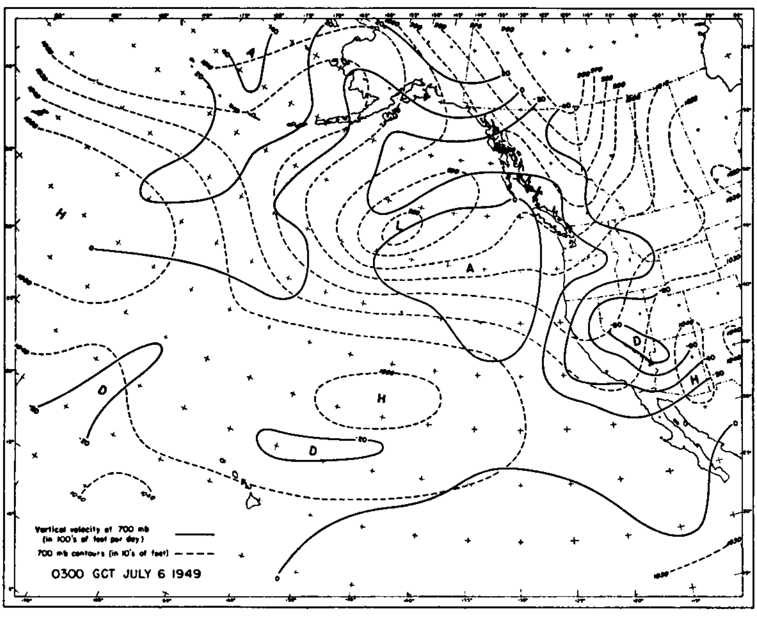

Fig. 15. Topography and vertical velocities at 700 mb, 0300 GCT July 6, 1949.

dashed lines. The vertical velocity, computed in the fashion discussed in the normal case but with the non-adiabatic cooling computed for the particular situation, is shown by the solid lines. It will be noted that descending motion was general to the east and south of the anticyclonic center, but a strong center of ascending motion was present to the north, in the region where the trough developed. Figure 15 shows the 700 mb contours and vertical velocities for July 6. At this time descending motion was very slight, although still widespread. The 700 mb contours and vertical velocity on July 14 are shown in

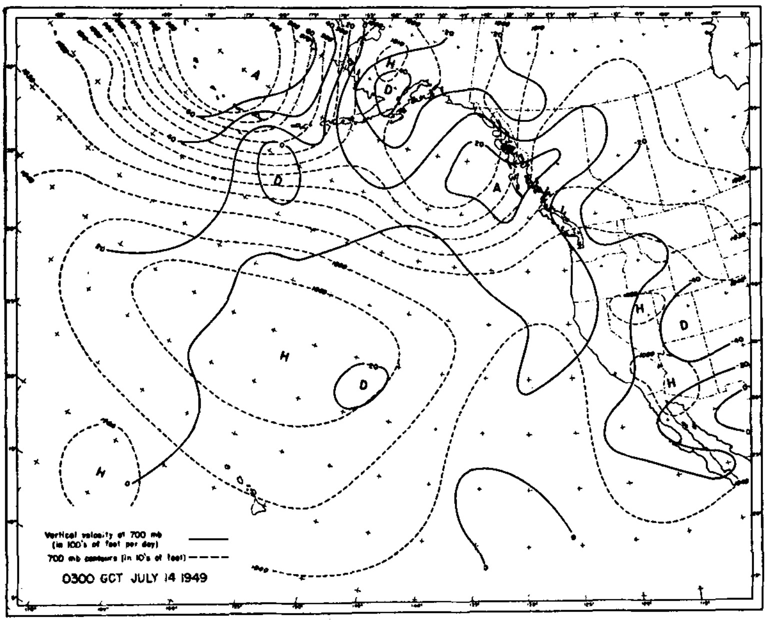

Fig. 16. Topography and vertica velocities at 700 mb 0300 GCT July 14, 1949.

Figure 16. While the pressure system had become nearly normal, the vertical velocity still had not resumed its normal intensity or extent.

As illustrations of the effect of this splitting of the anticyclone on the trajectories and the air mass structure, trajectories for the air reaching various levels at the weather ship at 30° N and 140° W on July 6 and July 12 will be shown. On July 6 (Figure 17) the air reaching the various levels above the ship followed more or less normal trajectories.

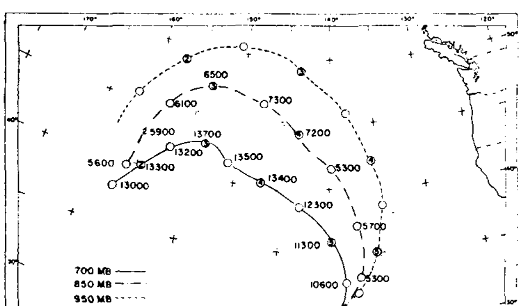

Fig. 17. Three dimensional trajectories of air reaching various pressures over weather ship at 30° N, 140° W at 0300 GCT July 6, 1949. Numbers in position circles show dates (0300 GCT). The air at 950 mb was assumed to move isobarically.

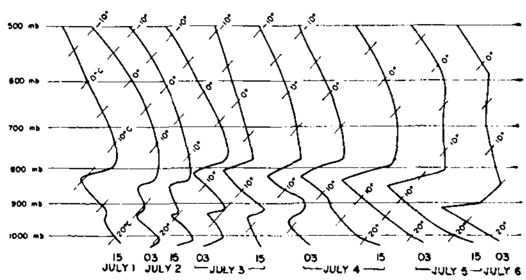

Fig. 18. Synthetic soundings along trajectory of parcel reaching weather ship at 30° N, 140° W, at 700 mb, 0300 GCT July 6, 1949. Soundings are plotted on "Skew-T-log p" diagrams; segments of isotherms are shown sloping upward to right, labelled in °C; dry adiabatic process lines would slope upward to left at 45° from isobars.

There had not been time for the splitting of the high to have much influence on them. For the portions of the trajectories moving from the south there was ascending motion, and for the portions moving from the north the air descended fairly rapidly. While the trajectories were not identical at all levels, they were sufficiently close together so that one can think of an air column moving with an "average" of these trajectories. Figure 18 shows soundings estimated for the various positions of the parcel reaching the ship at the 700 mb surface. During the period when the air column

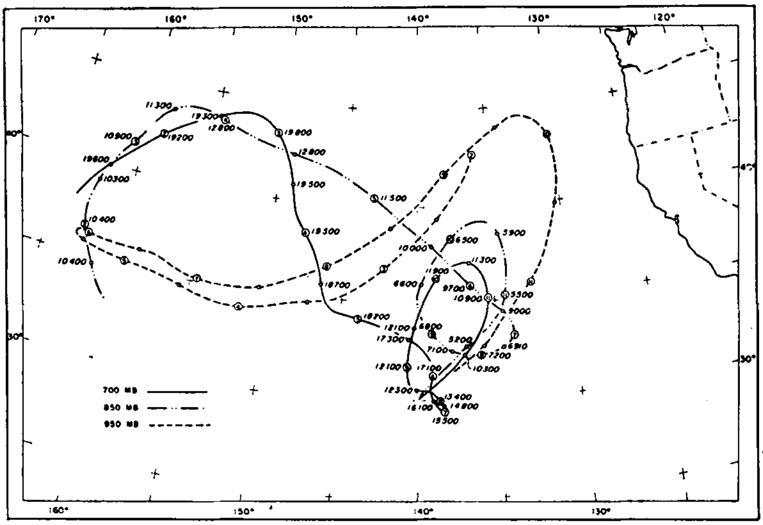

Fig. 19. Three-dimensional trajectories of air reaching weather ship at 30° N, 140° W at various pressures, 0300 GCT July 12, 1949.

was moving northward, the inversion rose and became somewhat less intense; during the period of descent the inversion descended and became more intense. In the lower layers the air was characterized by some additional inversions during the northward movement, but these were eliminated by heating as the air moved southward again across sea surface isotherms towards higher temperatures. The trajectories reaching the ship at the various levels on the 12th, on the other hand, were greatly influenced by the weakening and splitting of the anticyclone. In Figure 19 it will be noted that the trajectories were much less regular, and in fact executed loops as they proceeded toward the ship. In the trajectory reaching the ship at 700 mb, for instance, there was little change in height until the air came fairly close to the position of the ship (July 5) and after that the air descended fairly rapidly. The trajectory reaching the ship at 850 mb likewise was characterized by ascent during the first part, followed by fairly rapid descent from the 5th to the 7th and continued descent from then on.

With such irregular trajectories of the air at various heights one cannot consider air columns moving essentially as units, but instead must regard a vertical column at any instant as made up of air which has come from various directions at various levels. Nevertheless it is interesting to examine the synthetic soundings along the trajectory reaching the ship at 700

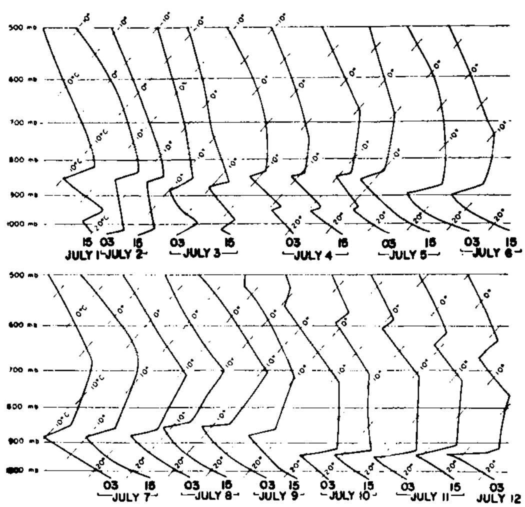

Fig. 20. Synthetic soundings along trajectory of parcel reaching weather ship at 30° N, 140° W, at 700 mb, 0300 GCT July 12, 1949. See legend of Fig. 18 for explanation.

mb on July 12. It will be noted in Figure 20 that the behavior of the inversion was much the same as the vertical motion at 700 mb, and the characteristics were not much different than those represented by the trajectory ending on July 6, in spite of the greatly different trajectory. In spite of the wide differences in the trajectories, the final soundings on July 6 and July 12 are remarkably close to being the same.

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