

## CHARACTERISTICS OF SEA-SURFACE TEMPERATURE ANOMALIES

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## ABSTRACT

Sea-surface temperature anomalies in the North Pacific Ocean, constructed from a 14-year series (1949-62) of monthly mean charts, exhibit numerous instances of quasi-stationary behavior. Selected examples from this series reveal a recurring pattern in which the principal feature is a positive or negative cell in the anomaly field, located approximately between lat  $30^{\circ}$  N and  $50^{\circ}$  N. The cell in this pattern is partially encircled by anomalies of opposite sign to the north, east, and south in a zone contiguous with the North American coast. This anomaly configuration, viewed with consideration of the associated sea-temperature field, suggests the existence of a standing wave in the current structure. Such a wave could affect the partitioning of the West Wind Drift Current as it approaches the coast and splits into northward and southward flowing branches. Physical data for verification of a standing wave are not available, but dimensional attributes inferred from the sea-temperature anomaly structure conform loosely to theoretical constraints.

The temperatures in the upper mixed layer of the ocean undergo annual cycles, induced by seasonal heating and cooling, which vary from year to year. This variation can be expressed in terms of departures from the mean annual temperature cycle obtained by averaging over a number of years. The magnitudes, areal distributions, and time changes of such departures define anomalous conditions in the surface layer of the sea.

The 14-year series, 1949-62, of monthly sea-surface temperature charts, published by Eber, Saur, and Sette (1968), provides a base for studying temperature variations in the North Pacific Ocean. Monthly anomaly charts were constructed from this series by taking the difference between the sea-surface temperature fields for each month and year and the corresponding monthly normal fields. The latter were obtained by computing the 14-year averages, by month, at grid points. A number of selected examples are presented here to show the character of some of the prominent and long-lasting anomalies that occurred in the North Pacific Ocean between 1949 and 1962.

Many of the features to be discussed are in the vicinity of the transition zone between the subarctic and subtropic oceanographic regions as described by Tully (1964). Through this

zone, which is located approximately at lat  $35^{\circ}$  N to  $45^{\circ}$  N between long  $160^{\circ}$  E and  $140^{\circ}$  W, the surface current flows eastward as the West Wind Drift. The mean surface temperature distribution in this region is essentially zonal with isotherms oriented along the circles of latitude. The chart of the 14-year average for October (Figure 1) illustrates these characteristics. As the West Wind Drift approaches

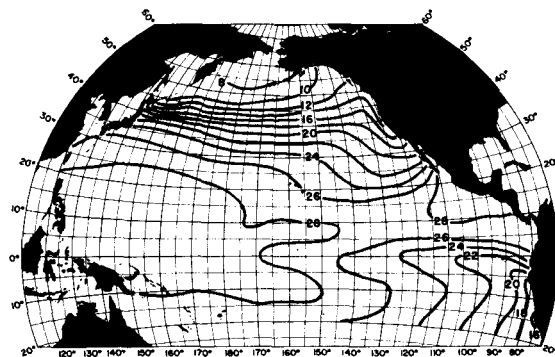


FIGURE 1.—Average sea-surface temperatures of the North Pacific Ocean in October, based on data from the 14-year period 1949-62.

the North American coast, it splits. One part turns north and moves in a counterclockwise trajectory around the Alaska Gyre and the other part turns south to become the California

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Current. The sea-surface isotherms, correspondingly, bend north and south, effecting a much-reduced temperature gradient parallel to the coast.

### BEHAVIOR OF SEA-SURFACE TEMPERATURE ANOMALIES

To facilitate description, I shall designate as "warm" or "cold" cells, areas where the magnitude of departure from normal was  $1^{\circ}\text{C}$  or greater. The evolution of an anomaly can be readily followed by noting the configuration of its principal cell, or cells, in successive months. This is evident in the figures used to illustrate selected examples (Figures 2-30). These show

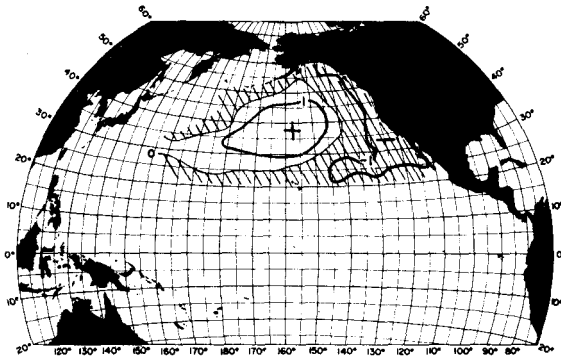


FIGURE 2.—Sea-surface temperature anomaly for January 1949. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}\text{C}$  anomaly contours which define warm (+) or cold (-) cells.

the sizes and locations of the principal cells, enclosed by heavy lines representing a magnitude of  $1^{\circ}\text{C}$ , in the regions relevant to the discussion. The cells are marked by plus or minus symbols according to the sign of the anomalies. The thin lines represent the zero anomaly contour separating areas of below normal temperature (hatched areas) from those where the temperature was above normal.

A good example of persistence was the warm anomaly present in the eastern North Pacific throughout most of 1949. In January the warm cell (defined by the  $1^{\circ}\text{C}$  anomaly contour) covered most of the area from lat  $30^{\circ}\text{N}$  to  $45^{\circ}\text{N}$  and long  $145^{\circ}\text{W}$  to  $180^{\circ}\text{W}$ . Maximum intensity

of the positive departures from normal within this cell exceeded  $3^{\circ}\text{C}$ . Off the North American coast, the temperature anomalies were negative, with magnitudes greater than  $1^{\circ}\text{C}$  in a broad zone from Alaska to the tip of Baja California.

Figures 3-5 show subsequent positions of the warm cell in March, July, and October, respectively. The maximum intensities waxed and waned over this time period, dropping in March, increasing again to more than  $3^{\circ}\text{C}$  in July and diminishing once more in October. Except for a slight northward shift, the warm cell remained essentially stationary. During most of the period, negative anomalies prevailed in the coastal

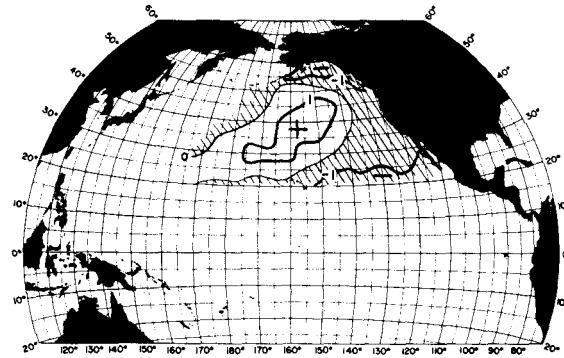


FIGURE 3.—Sea-surface temperature anomaly for March 1949. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}\text{C}$  anomaly contours which define warm (+) or cold (-) cells.

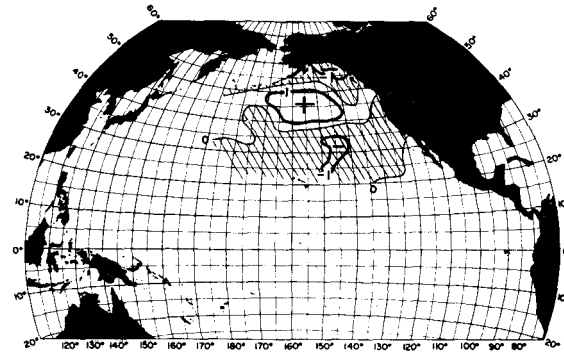


FIGURE 4.—Sea-surface temperature anomaly for July 1949. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}\text{C}$  anomaly contours which define warm (+) or cold (-) cells.

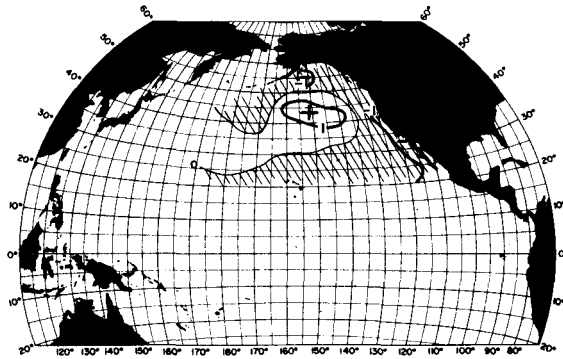


FIGURE 5.—Sea-surface temperature anomaly for October 1949. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

zone and in a southwestward tongue below 30° N but with fluctuating magnitudes.

The warm cell shrank in November and lost its specific identity in December. However, the general configuration of the colder than normal coastal zone and warmer than normal offshore region persisted through the winter and spring of 1950. In May 1950, the positive anomalies intensified and spread westward to Japan. The pattern stabilized in June and July marked by prominent warm cells in the east and far west portions of the positive area (Figure 6). At the same time, a cold cell in the Gulf of Alaska had begun to grow and push southward; this

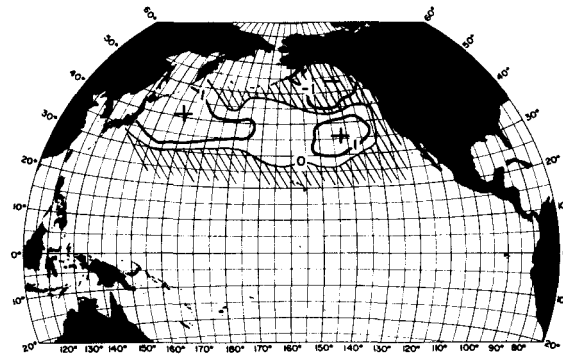


FIGURE 6.—Sea-surface temperature anomaly for July 1950. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

movement continued through September (Figure 7) accompanied by an eastward expansion of the warm belt. Ultimately, there was a deformation of the broad-scale pattern which had for many months dominated the central and eastern North Pacific, as negative anomalies spread through the Gulf of Alaska.

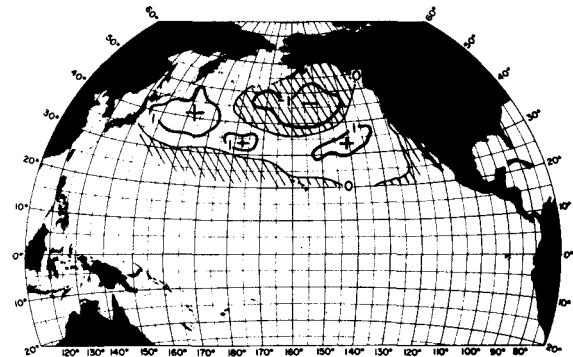


FIGURE 7.—Sea-surface temperature anomaly for September 1950. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

The years 1951-54 presented no striking examples of persistent sea temperature anomalies. Some relatively large-scale anomalies did develop in this period but they were short-lived. Much of the time the anomaly field was flat and featureless. Midway through 1955, however, a long-term progression of events began to evolve with the development of an anomaly pattern which was characterized by a positive belt that stretched eastward from Japan and a negative zone along most of the North American coast. The anomaly field intensified in August (Figure 8) when maxima exceeded 2° C in the warm cell and an extensive cold area was present in the coastal zone with negative departures exceeding 1° C in magnitude. The negative area stretched southwestward below lat 30° N. This pattern prevailed through November 1955 (Figure 9) but became weaker in December. In January 1956, the positive area contracted to the west while the region of negative anomalies to the east became flat and disorganized. Figure 10 shows the situation in February 1956. The

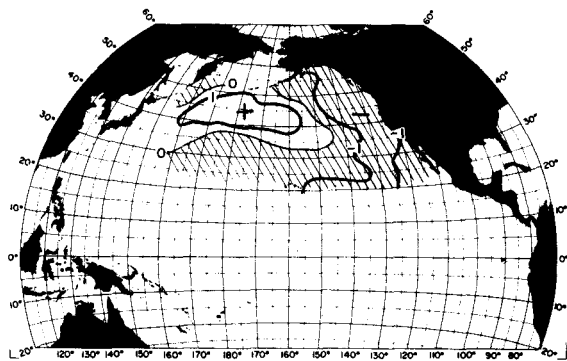


FIGURE 8.—Sea-surface temperature anomaly for August 1955. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

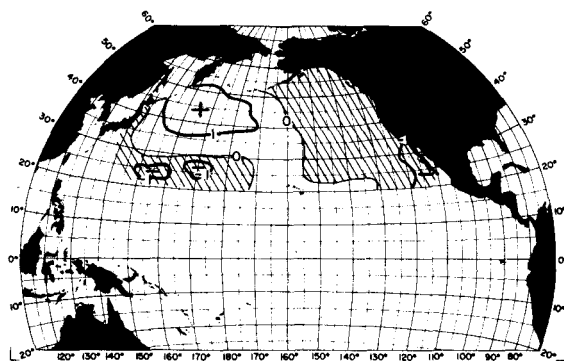


FIGURE 10.—Sea-surface temperature anomaly for February 1956. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

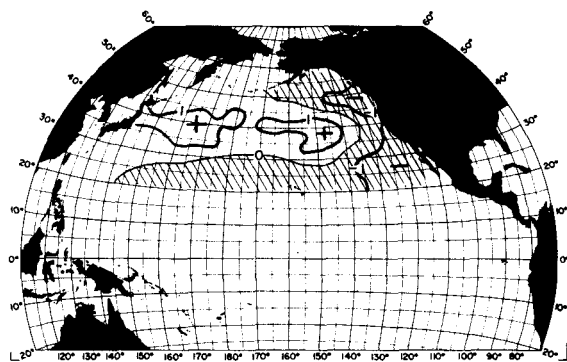


FIGURE 9.—Sea-surface temperature anomaly for November 1955. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

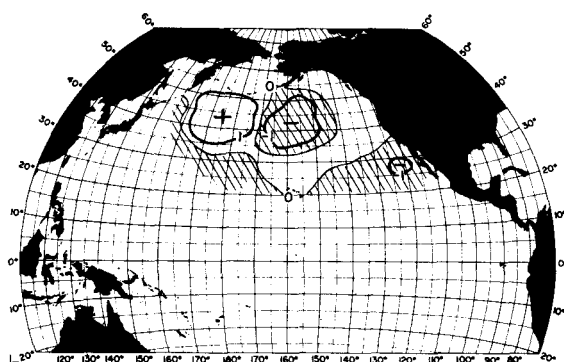


FIGURE 11.—Sea-surface temperature anomaly for August 1956. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

warm cell at lat  $36^{\circ}$  N to  $50^{\circ}$  N, long  $175^{\circ}$  W to  $150^{\circ}$  E was the only prominent feature in evidence and remained so until August 1956, when a large cold cell developed just east of it (Figure 11). This latter feature was short-lived, however, and during the next few months the positive area once again expanded eastward while the tendency of anomalies along the North American coast changed from variable to predominantly negative. The chart for November 1956 (Figure 12) depicts the result of this process.

Transition to a second phase in the long-term evolution of the anomaly field was foreshadowed by a small cold cell at lat  $25^{\circ}$  N to  $30^{\circ}$  N, long

$160^{\circ}$  E to  $170^{\circ}$  E (Figure 12). This cold cell grew in size but remained in about the same location through March 1957 (Figure 13) while the area of positive anomalies edged toward the North American coast. The transition was complete by June, when the cold cell shifted north and stretched eastward in a belt of negative anomalies between lat  $30^{\circ}$  N and  $40^{\circ}$  N (Figure 14). Positive values prevailed in the Gulf of Alaska and along the North American coast, effecting an almost complete reversal from the late 1955 pattern.

The negative anomalies in the west central sector, long  $175^{\circ}$  W to  $160^{\circ}$  E, contracted to form

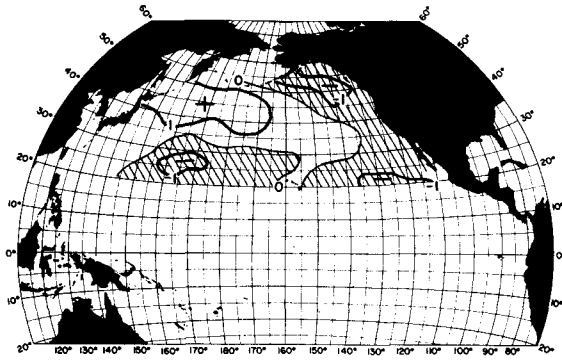


FIGURE 12.—Sea-surface temperature anomaly for November 1956. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

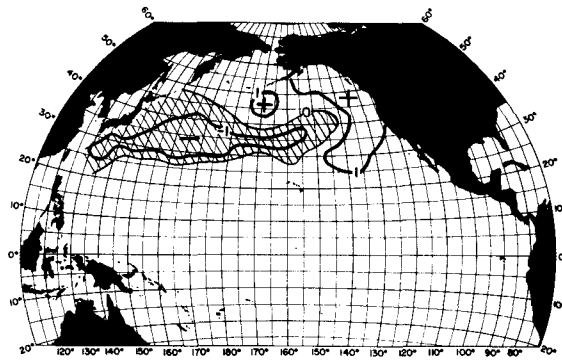


FIGURE 14.—Sea-surface temperature anomaly for June 1957. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

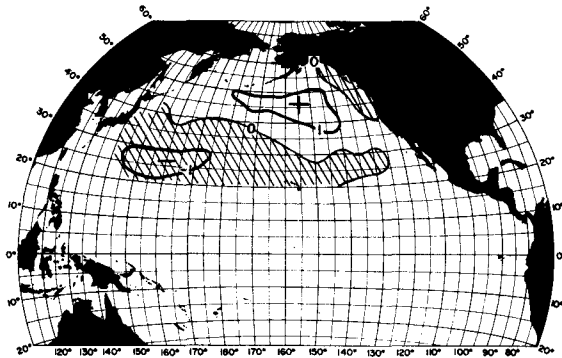


FIGURE 13.—Sea-surface temperature anomaly for March 1957. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

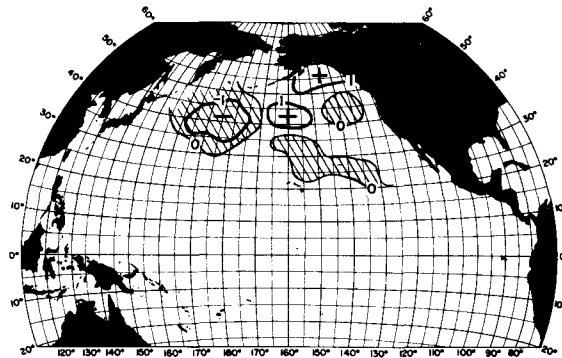


FIGURE 15.—Sea-surface temperature anomaly for August 1957. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

a single prominent cell which, in August 1957, was centered at about lat 40° N, long 175° E (Figure 15). This feature remained fairly steady through November 1957 (Figure 16), but all remnants of the cold anomalies in the east sector vanished.

The cell structure in the negative anomaly deteriorated at the beginning of 1958, but reformed in March with the cold cell east of its earlier position, at lat 30° N to 40° N, long 145° W to 170° W (Figure 17). Further fluctuations took place in the negative region until August 1958, when a dominant cold cell appeared at lat 35° N to 50° N, long 150° W to 175° W

(Figure 18). The zone of positive anomalies along the North American coast was strongly developed during most of 1958 and 1959. However, the emphasis in the distribution shifted to the south after mid-1958, and the warm tongue reaching southwestward, south of lat 30° N, was most intense in the early months of 1959 (Figures 19 and 20).

Elsewhere the pattern tended to be somewhat weak and disorganized, and remained so until November 1959, when prominent cells, in which departures from normal exceeded 2° C, were evident in the central oceanic region of negative anomalies and in the positive coastal zone

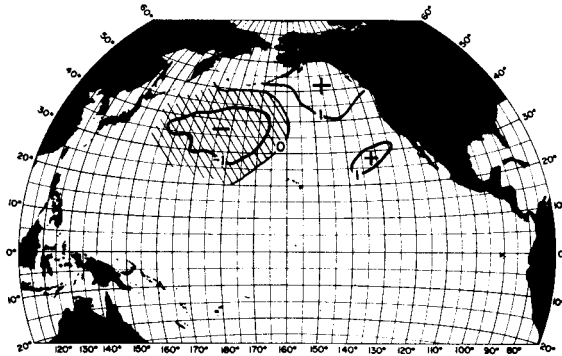


FIGURE 16.—Sea-surface temperature anomaly for November 1957. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

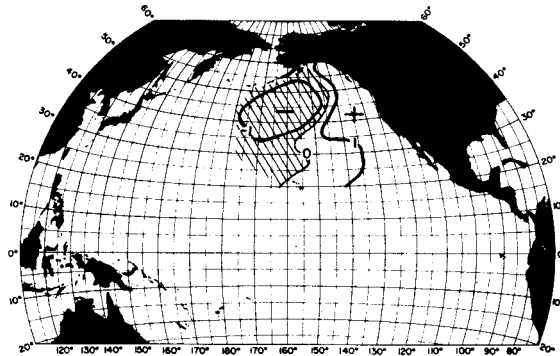


FIGURE 18.—Sea-surface temperature anomaly for August 1958. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

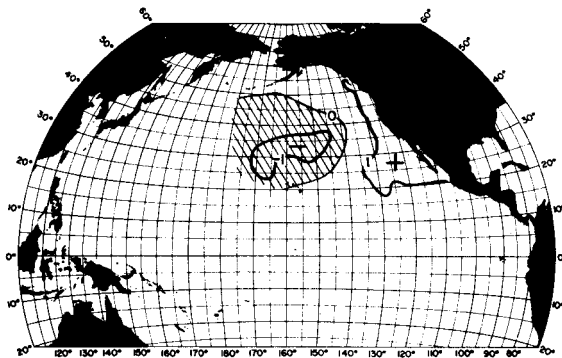


FIGURE 17.—Sea-surface temperature anomaly for March 1958. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

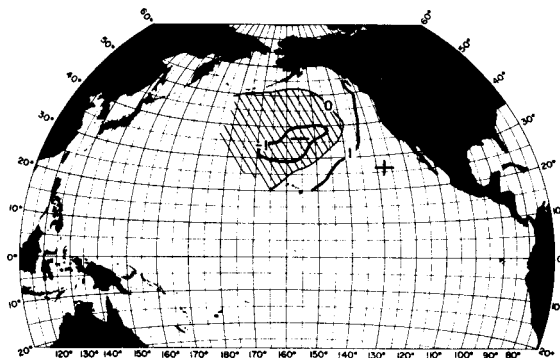


FIGURE 19.—Sea-surface temperature anomaly for January 1959. Hatched areas colder than normal. Heavy lines represent the  $1^{\circ}$  C anomaly contours which define warm (+) or cold (-) cells.

(Figure 21). The intensity and size of the warm cells diminished by February 1960 (Figure 22) and anomalies along the North American coast were generally weak, although mostly positive, through mid-1961.

The cold cell present in the west central Pacific in November 1959 had, by February 1960, pushed eastward to a new location, at lat  $32^{\circ}$  N to  $48^{\circ}$  N, long  $155^{\circ}$  E to  $155^{\circ}$  W (Figure 22). Thereafter it remained essentially within this region until the spring of 1961. However, the size and shape of the cold cell fluctuated considerably during this extended interval, as indicated in the charts for June 1960, November

1960, and February 1961 (Figures 23-25). This cold cell began to shift eastward in May 1961 and, by June, had reached a position at lat  $32^{\circ}$  N to  $45^{\circ}$  N, long  $137^{\circ}$  W to  $160^{\circ}$  W (Figure 26) where it remained through August. A new warm cell had appeared in the west sector at lat  $30^{\circ}$  N to  $40^{\circ}$  N, long  $170^{\circ}$  W to  $165^{\circ}$  E in June, but cannot easily be related to an impending transition in the anomaly field. It appeared to shift westward in July and August then vanished in September 1961, when the overall pattern collapsed.

The third and final phase in the progression of events began rather abruptly in October 1961

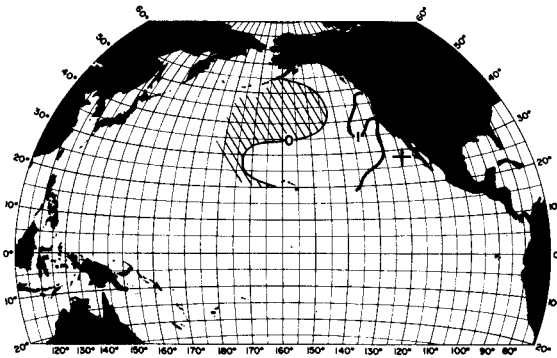


FIGURE 20.—Sea-surface temperature anomaly for March 1959. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

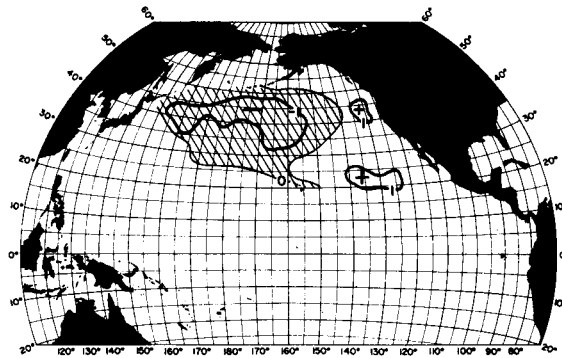


FIGURE 22.—Sea-surface temperature anomaly for February 1960. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

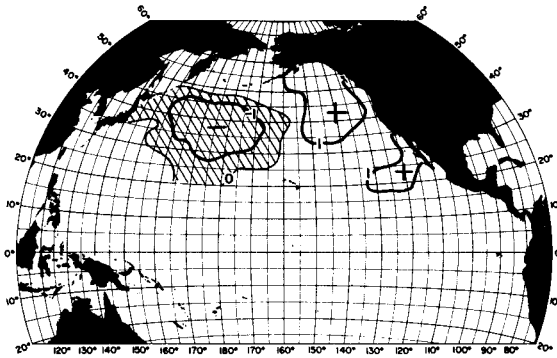


FIGURE 21.—Sea-surface temperature anomaly for November 1959. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

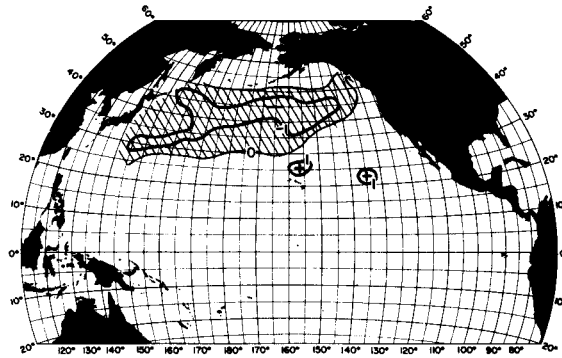


FIGURE 23.—Sea-surface temperature anomaly for June 1960. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

with a second reversal of the anomaly field in the central and eastern North Pacific Ocean (Figure 27). The principal feature of the new pattern was a warm cell which developed at lat 35° N to 45° N, long 145° W to 175° W. Departures from normal temperatures along the coastal zone and in the region to the south-east of the warm cell were weak but predominantly negative. In a broad sense, this distribution remained essentially undisturbed for nearly a year. The warm cell shifted eastward in January 1962 (Figure 28), diminished in size and intensity in March and April, but revived in June 1962 (Figure 29). A second warm

cell was present at that time, but did not retain a separate identity for long. The original warm cell began a westward movement which, by September (Figure 30), returned it to the same location it occupied 11 months earlier in October 1961 (Figure 27).

#### MAINTENANCE OF PERSISTENT ANOMALIES

The examples described in the preceding section depict a recurring pattern in the distribution of sea-surface temperature anomalies. Schematically, the principal features consist of

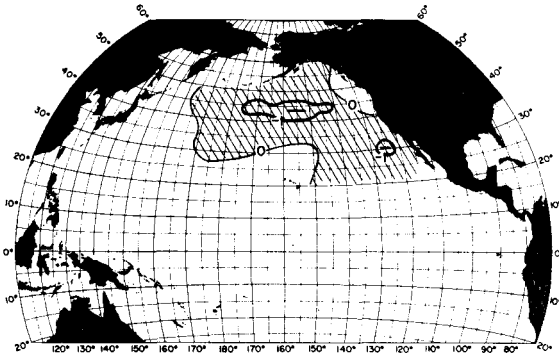


FIGURE 24.—Sea-surface temperature anomaly for November 1960. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

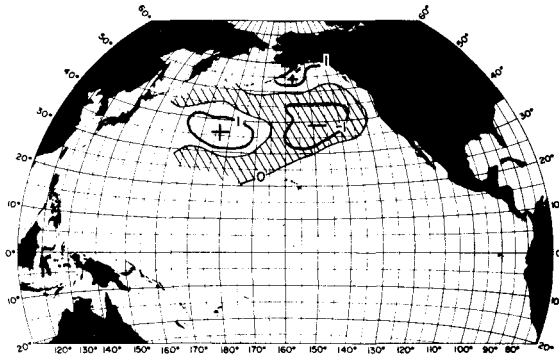


FIGURE 26.—Sea-surface temperature anomaly for June 1961. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

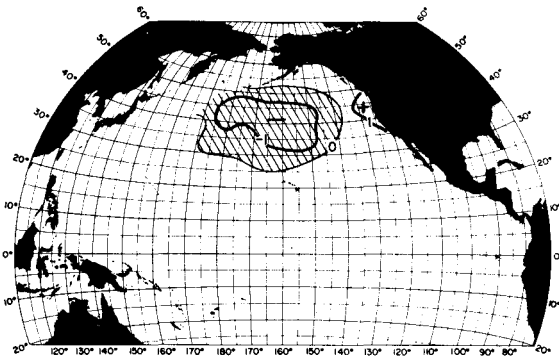


FIGURE 25.—Sea-surface temperature anomaly for February 1961. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

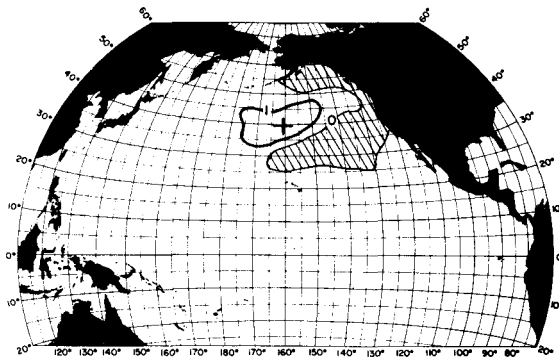


FIGURE 27.—Sea-surface temperature anomaly for October 1961. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

a dominant, quasi-stationary cell in a latitudinal belt of either positive or negative anomalies, located approximately between lat 30° N and 50° N, partially encircled by anomalies of opposite sign to the north, east, and south, in a zone contiguous with the North American coast. The dominant cell in this model is embedded in the North Pacific West Wind Drift Current. It reflects a wavelike displacement of the isotherms, which normally are very nearly zonal from about long 150° E to 140° W in the vicinity of lat 40° N.

The fact that this cell, which defines an area of maximum departure from normal in the tem-

perature field, is not propagated eastward with the ocean current suggests the existence of a standing wave, or perturbation, in the current structure. Assuming this to be so, water entering the wave would turn north (or south) of its normal course, cutting across the normal isotherms and thereby causing anomalous local advection of high (or low) temperature. Downstream from the point of maximum excursion the water cuts back toward its original course and temperature conditions revert toward normal. Because the temperature gradient across the West Wind Drift Current is moderately strong, a small displacement of the isotherms



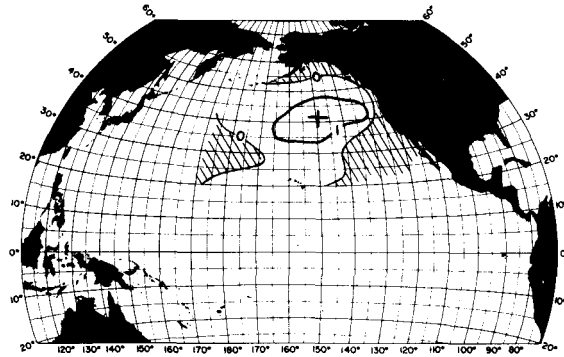


FIGURE 28.—Sea-surface temperature anomaly for January 1962. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

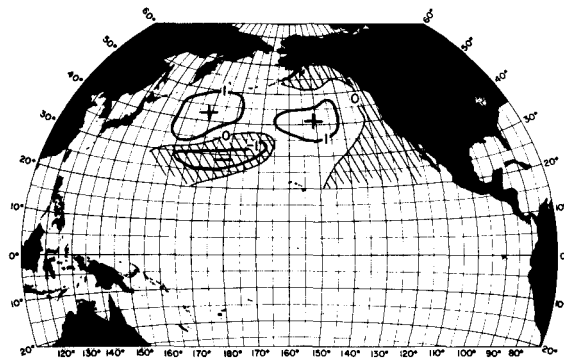


FIGURE 29.—Sea-surface temperature anomaly for June 1962. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

relative to the width of the current can create an anomaly of 1° C to 2° C. The amplitude of the perturbation in the current must, of course, be greater than that in the temperature field, since the water must adjust toward new equilibrium temperature appropriate to the local heat exchange processes as it changes latitude. Thus, a parcel of water following a northward deflection of the streamlines would arrive at the northern bend, or crest, of a standing wave with a temperature lower than it would have had if no deviation from zonal flow had occurred. Owing to the advective effect, it would nonetheless be warmer than an equivalent parcel of water

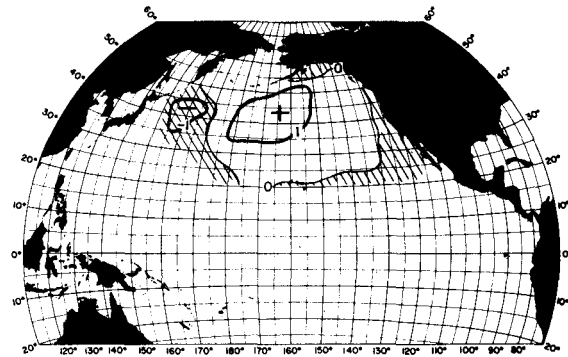


FIGURE 30.—Sea-surface temperature anomaly for September 1962. Hatched areas colder than normal. Heavy lines represent the 1° C anomaly contours which define warm (+) or cold (-) cells.

reaching the same location by a normal, zonal trajectory.

The existence of a perturbation upstream from the location where the West Wind Drift splits may have a significant effect on the proportional flow into the Alaska Gyre and the California Current. For example, in a wave formed by a northward deflection of the zonal current, water moving downstream from the crest would have a southward component which might favor more transport into the California Current. A strengthening of this current would cause the isotherms to adjust to the effects of increased cold advection and local heat exchange processes southward of their normal positions, creating a negative anomaly. Correspondingly, the reduced northward transport would decrease warm advection into the Gulf of Alaska and the isotherms would adjust to equilibrium positions farther south than normal, also creating a cold anomaly.

If the northward deflection in the foregoing example is replaced by a southward deflection, then, after passing the southern bend or trough of the wave, the water would approach the coast with a northward component, favoring more transport into the Gulf of Alaska. The balance between advection and local heat exchange would be established with the isotherms north of their normal positions, creating a warm anomaly.

In a comprehensive treatment of oceanographic survey data taken in 1955-58, Tully, Dodimead, and Tabata (1960) found the warm coastal anomaly of 1957-58 to be associated with increasing transport into the Alaska Gyre. They describe this condition in terms of a southward shift of the point of separation of flow from the West Wind Drift. From their study of the dynamic topography, they inferred that prior to the shift, in 1955 and 1956, most of the water approaching the coast south of lat 45° N entered the California Current. The fact that negative anomalies prevailed along the coastal zone in the latter half of 1955 and, to a lesser extent, in 1956 suggests that the point of separation in this period was farther north than usual.

Whether the partition of the West Wind Drift is influenced by upstream perturbations in the zonal flow structure cannot be established with certainty from the available survey data. The geopotential topography as presented by Dodimead, Favorite, and Hirano (1963) for the years 1955-59 does not reveal conclusive evidence of upstream wave structure. The physical evidence is limited to the anomalous characteristics of the surface temperature field which have already been discussed.

Some added perspective might be gained by looking briefly at the dynamic constraints applicable to a standing wave in the West Wind Drift. The average eastward current speed,  $U$ , for a wave of length  $L$  and lateral (north-south) extent  $D$  is given by Panofsky (1956) as follows:

$$U - C = \frac{2\Omega \cos\phi L^2}{4\pi^2 E} \left( \frac{1}{1 + L^2/D^2} \right)$$

where  $C$  is the wave speed (zero for a standing wave)

$\phi$  is the mean latitude

$\Omega$  is the angular velocity of the earth  
( $7.292 \times 10^{-5} \text{ sec}^{-1}$ )

$E$  is the radius of the earth  
( $6.37 \times 10^6 \text{ m}$ ).

This expression reduces to the Rossby wave equation for a uniform zonal stream on a rotating planet when the value of  $D$  approaches infinity.

In order to evaluate the right side of the above equation, we will assume dimensional similarity between the inferred wave and areas enclosed by the plus or minus 1° C anomaly contours for those cases where we presume a causal relation with the current structure. Estimates of the wave length  $L$  and of the ratio  $L/D$  were determined from rough measurements of the longitudinal and lateral extent of the warm cell present from October 1961 to September 1962. Excluding two extreme cases (April and July 1962) the longitudinal dimensions of the warm cell ranged between about 800 (March 1962) and 1600 (January 1962) nautical miles. The corresponding ratios of longitudinal to lateral extent for these particular cases were 1.3 and 2.0 respectively. Substitution of these values for  $L$  and  $L/D$  in the wave equation yields 35 and 85 cm/sec (approximately) for average current speed through a stationary wave. Of course, the areas enclosed by the 1° C anomaly contours presumably define only a portion of the hypothetical wave, and to substitute the dimensions of these areas for  $L$  and  $D$  would understate the theoretical current speed.

Current speeds in the West Wind Drift, computed from dynamic height anomalies, are generally less than 10 cm/sec (Dodimead et al, 1963). Data from drift bottles (Dodimead and Hollister, 1962) indicate current speeds up to 20 cm/sec in the same region. Thus, the theoretically computed results are too high, but considering the approximations used they are not altogether unreasonable.

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