OCEANOGRAPHY OF THE NORTHEASTERN PACIFIC OCEAN DURING THE LAST TEN YEARS[1]

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Since 1949 the California Cooperation Oceanic Fisheries Investigations have made hydrographic cruises over the California Current system nearly every month. From these measurements we have been able to construct averages from the first few years' data. We have compared some of the last year's measurements with these longer term averages and the differences are remarkable.

It will be necessary to review briefly the oceanography of the California Current system in order to discuss the recent deviations. I shall draw upon a recent paper (Reid, Roden, and Wyllie, 1958) published in the latest CCOFI Progress Report for this general discussion and for the first five figures, and then proceed to the more recent work.

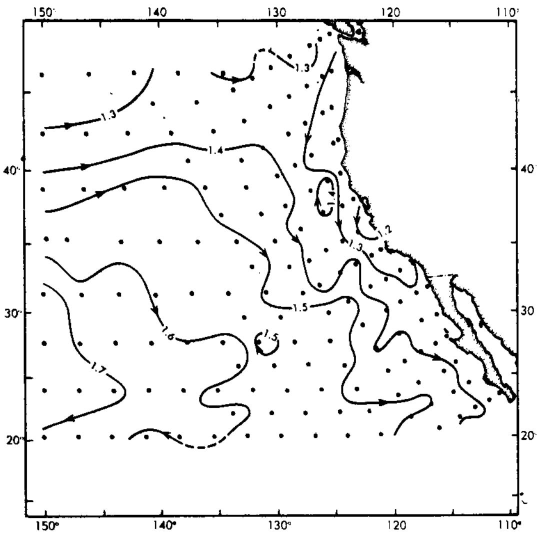


FIGURE 67. Surface current off the western coast of North America in August, 1955. Dynamic height anomalies, 0 over 1000 decibars, in dynamic meters.

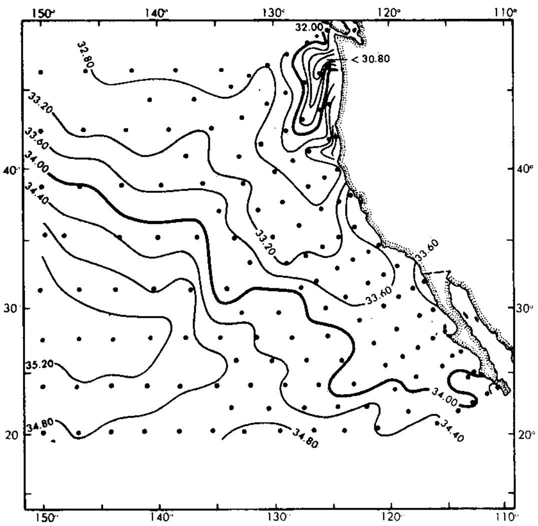


FIGURE 69. Salinity at 10 meters, in parts per mille. August 1955.

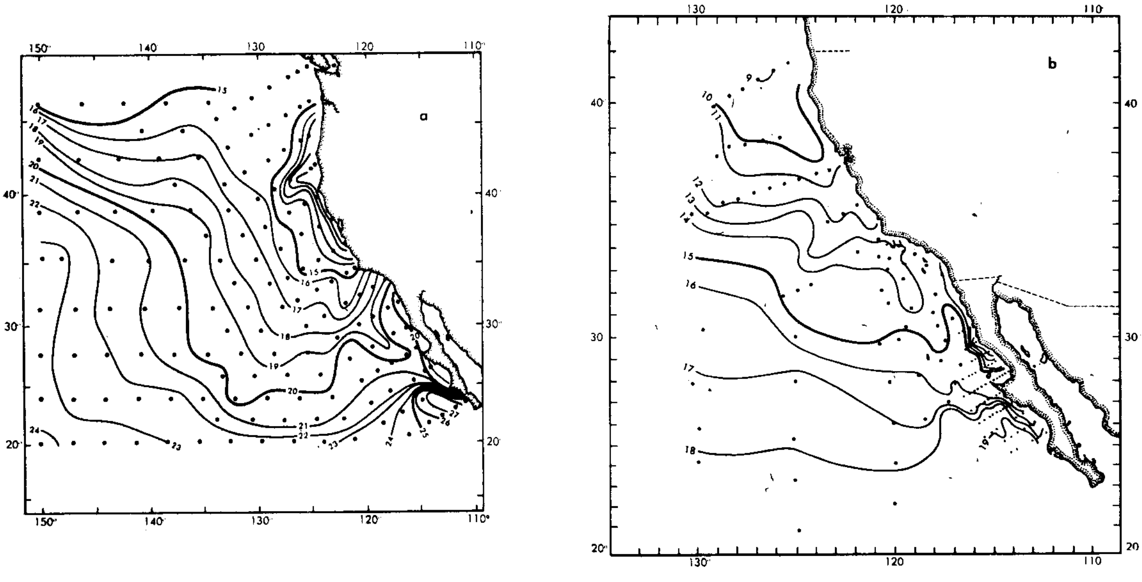


FIGURE 68. Ocean temperatures at 10 meters (degrees Centigrade). (a) August 1955. (b) March (composite).

[1] Contribution from the Scripps Institution of Oceanography.

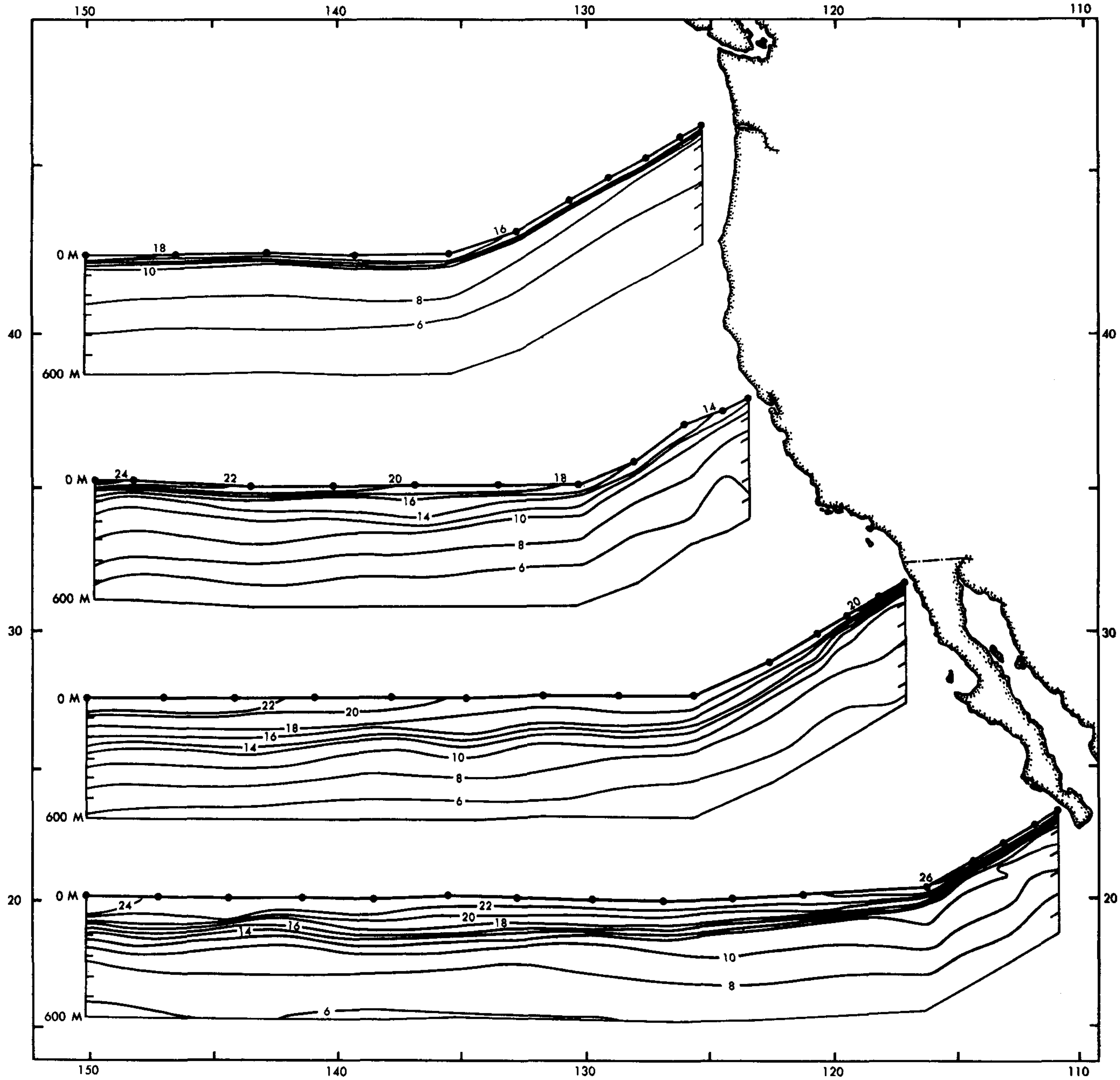


FIGURE 70. Vertical profiles of temperature from the surface to 600 meters, August 1955.

The currents, temperature, salinity and oxygen as they have appeared during most years of the last decade, and the seasonal variation of temperature and salinity are illustrated by the first few figures. The geopotential anomaly in August of 1955 from North America to 150°W and between 20° and 46°N is shown in figure 67. This is the eastern edge of the great oceanic anticyclone which fills most of the temperate zone of the North Pacific. A small eddy is seen south of Point Conception. At 200 meters below the surface a narrow current next to the coast runs counter to the surface flow, and in the winter months the surface waters also run northward near the coast.

The south-flowing current brings water from high latitudes which is both colder and less salty than that farther offshore in the center of the anticyclone. The north-flowing current brings water which is saltier than that offshore. In addition, the deeper waters from the south are very low in dissolved oxygen content.

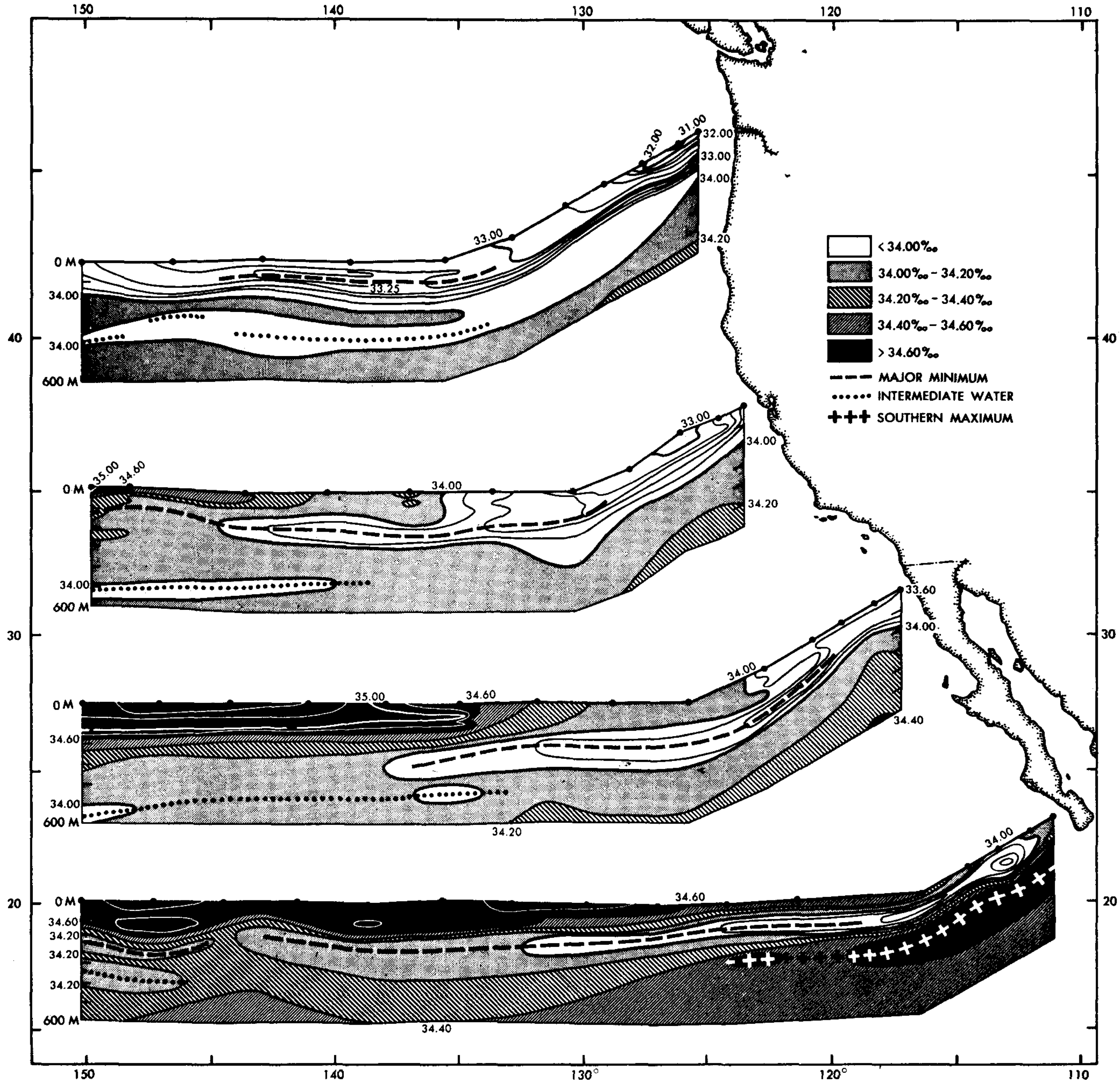


FIGURE 71. Vertical profiles of salinity, parts per mille, from the surface to 600 meters, August 1955.

A remarkable consequence of the strong northwesterly winds of spring and summer is the upwelling which occurs along most of the West Coast. The winds move the surface waters offshore, and they are replaced by the colder and more saline waters from below. Note the enclosed low in temperature from 35° to 46°N in August (Fig. 68a), with a minimum off Cape Mendocino less than 11°C. Note also the strong gradient in the extreme southeast. In March, when there is no upwelling but the seasonal cycle of temperature is at or near its minimum, the temperature off Cape Mendocino is still between 10° and 11°C (Fig. 68b). In the southeast, however, where there is no August upwelling, the seasonal difference in temperature may be as much as 8°C.

The 10 meter salinity in August (Fig. 69), shows the effect of a thin layer of fresh water from the Columbia River as well as the effect of the upwelling off Cape Mendocino. High values of salinity are seen to the west and south.

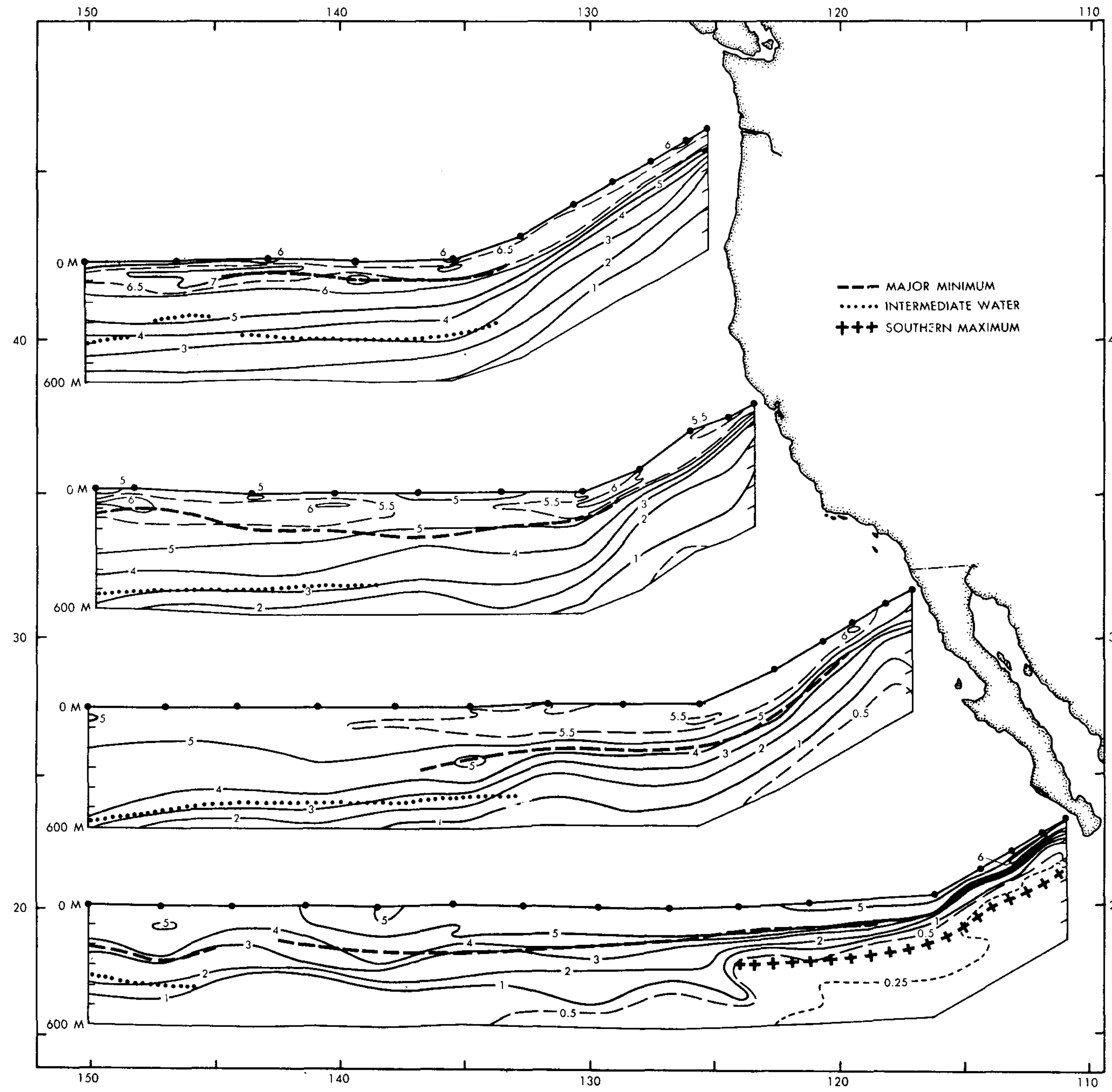
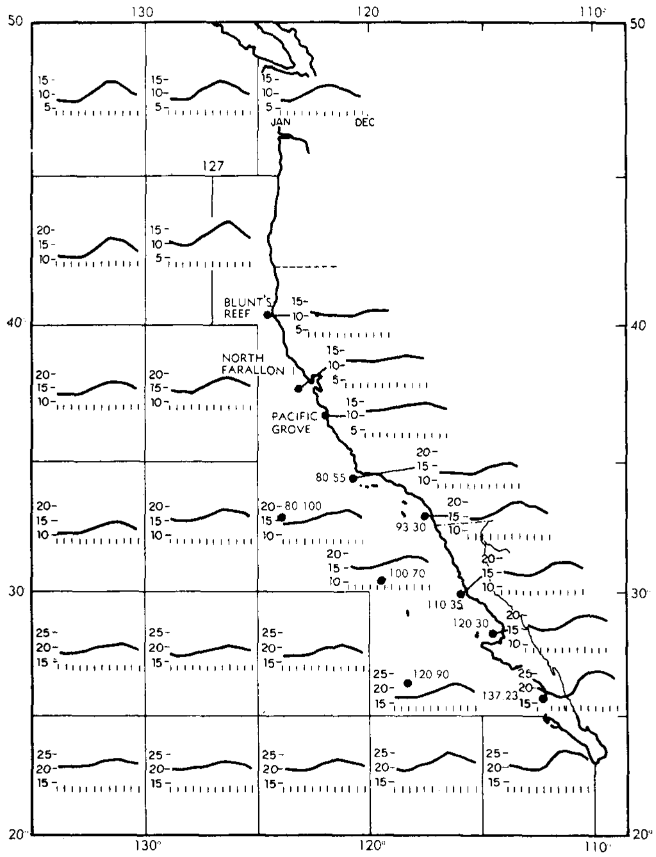


FIGURE 72. Vertical profiles of dissolved oxygen content, milliliters per liter, from the surface to 600 meters, August 1955.

Vertical sections of temperature, salinity, and oxygen in the upper 600 meters in a direction normal to the current are shown in figures 70, 71, 72. Note that at the surface the higher temperatures occur offshore in the north, and in the south they occur at the extreme offshore ends of the section. The vertical sections of salinity show the water of low salinity coming in at the surface in the north. As the water moves south the upper layers are strongly mixed with the more saline water from the west with the result that a subsurface minimum (the dashed line) lies beneath the pycnocline over most of the area. The deeper minimum (the dotted line) is North Pacific Intermediate Water, which is too deep to be of influence in the present problem. In the southeast beneath this subsurface salinity minimum in water from the north lies a salinity maximum in water from the Equatorial regions. The effect of this intrusion of very saline water can be seen to the northward on all of the profiles.



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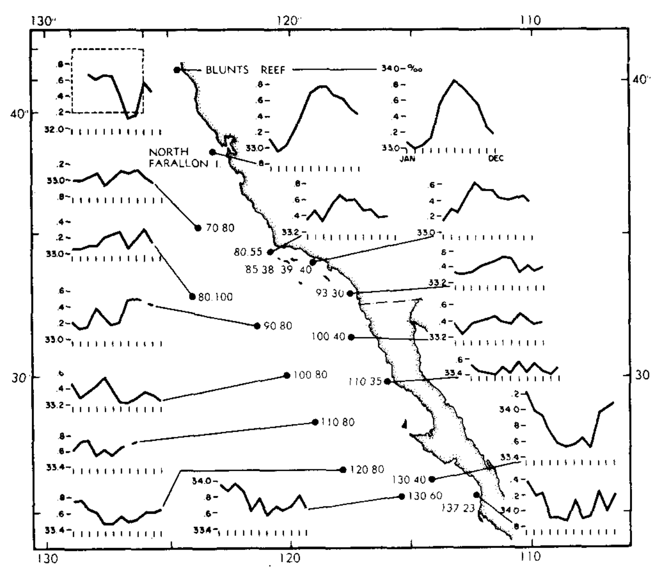

73b

FIGURE 73. Seasonal variation of temperature and salinity at the surface off the western coast of North America.

(a) Temperature in degrees Centigrade. Values over five-degree squares are from Robinson (1957); values at Blunt's Reef, North Farallon Island and Pacific Grove are from U. S. Coast and Geodetic Survey (1956); values at numbered stations are from CCOFI data, 1949-55.

(b) Salinity in parts per mille. Values at Blunt's Reef and North Farallon Island are from U. S. Coast and Geodetic Survey (1954); all other values are from CCOFI data, 1949-55.

The upper waters are saturated with dissolved oxygen or nearly so. The most remarkable feature at depth is the extremely low value found near the coast —especially in the southeast where the water of higher salinity is seen to be of low oxygen content as well.

The extent of seasonal variation of surface temperature over the region is shown in figure 73a. Far offshore the variation, which is principally the result of variation in radiation and exchange with the atmosphere, has a simple pattern with the greatest range in the highest latitude. Near the coast in the region of strong upwelling north of 34°N the seasonal range is reduced and the cool period lengthened by upwelling. Between 28°N and 34°N the upwelling occurs earlier in the year, more nearly at the period of the offshore seasonal minimum, and increases the seasonal range. South of 28°N it is the fall and winter countercurrent which accounts for the high range and delays the low until late spring.

The seasonal variation in surface salinity (Fig. 73b) indicates that the direct effect of evaporation and precipitation is small and, indeed, there is little coherence in the variation of the northern offshore stations. Inshore it is again the processes of upwelling in the north and the countercurrent in the south which dominate the seasonal variation. The effect of the spring and summer upwelling of deeper water to the surface in the north causes a wide range with the maximum value of salinity in summer. In the south the winter countercurrent brings highly saline water northward along the coast giving a maximum in winter. The two effects tend to cancel each other in the middle region between 28°N and 34°N latitude.

The seasonal variation of oxygen is generally in response to the seasonal change in temperature, which causes a change in saturation value.

It has been necessary to give this material as a brief background in order that the variation within the last ten years can be discussed; and again it is necessary to have some idea of the last decade in terms of previous temperatures if we are to think in terms of disturbances of a steady state.

A time-series of temperature anomaly from 1921 to the present and the anomaly of the northerly wind components determined from the pressure difference along 30°N between 110° and 130°W (Fig. 74) indicates that the anomalies of surface temperature along the coast and over the California Current have been remarkably coherent over this period. Certain periods stand out as quite cold and certain other periods as quite warm. The warm periods are seen in 1926, 1931, 1939-40, and 1941. The cold periods are seen in 1924 and 1933. A period of not excessive cold but well below normal values is found from somewhere in the late 1940's through 1956.

The difference is seen more clearly when the mean monthly temperature averaged from 1949-1956 is compared with the 1920-1938 data (Fig. 75). The major differences are seen to occur from March through August. (The gap between 1938 and 1949 is not deliberate. No offshore temperature data were available during this period.)

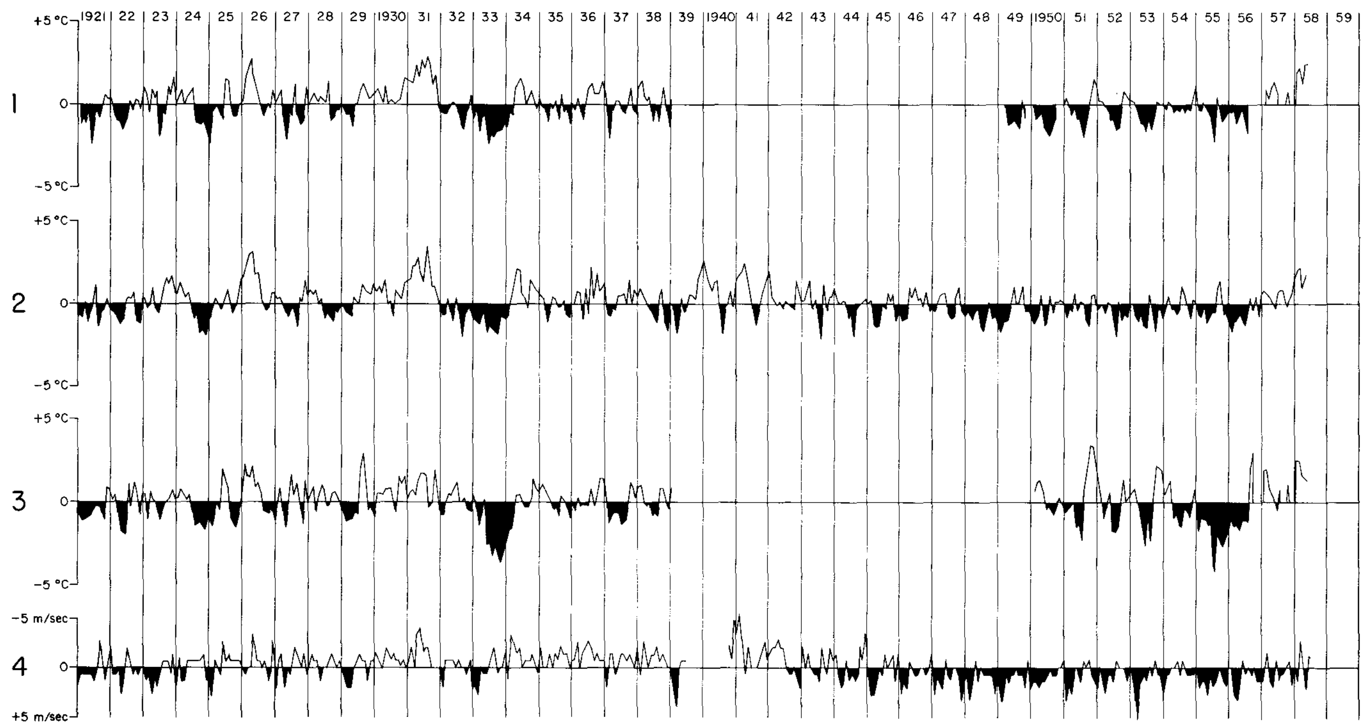

FIGURE 74. Monthly differences from average sea surface temperatures (degrees Centigrade) at (1) 30°-35°N, 115°-120°W, (2) Scripps Pier, and (3) 25°-30°N, 110°-115°W; and (4) monthly differences from average northerly wind component (in meters per second) at 30°N, 110°-130°W. The period 1921-1938 was taken as the average.

However, by early 1957 a substantial difference from the previous eight years had been noted in that the surface waters had become substantially warmer. The recent history of this warming is traced by comparing the weekly averages of temperature for 1957 and 1958 to the present with the longest term means available at each of six positions (Fig. 76). I believe that in the invitations to the Symposium certain anomalies of sea surface temperature over the California Current were presented. I shall refer to those, and more recent ones through May of 1958 (Fig. 77). Let me emphasize that these anomalies are from the mean measured by the CCOFI program period for 1949 through 1954 or 1955, depending upon the stage of data processing. Previous figures (74 and 75) have indicated that this is a period which is different from the long term mean in that February through August temperatures are low and the remainder normal or somewhat high. However, in this series of surface temperature anomalies all of the months since early 1957 have high temperatures relative to the CCOFI mean. It has also been possible to prepare charts of the anomaly of salinity. Here we have selected 10 meters rather than the surface because in the northern regions the outflow from the Columbia River and various other rivers brings into the upper few meters water of low salinity whose values, however, vary from station to station so severely that both an average chart and an anomaly chart are difficult to interpret. By taking the values at 10 meters, rather than at the surface, this incoherence is largely eliminated. These anomaly charts of salinity have also since early 1957 shown consistently high values (Fig. 78).

Another approach is to examine the hydrography of the region with the aim of identifying the source of the anomalous water. Unfortunately when temperature and salinity are both high, suitable sources are found both to the west and to the south. Our ordinary hydrographic casts reach to 600 meters beneath the surface and we can examine the depth of penetration of the anomaly. We find that it reaches to a depth somewhat below the bottom of the mixed layer and is generally not significantly present at depths much below 150 meters. This, however, at first gave some hope of using a third indicator of the source of the anomaly—the dissolved oxygen content. We have prepared vertical sections along three lines extending out from the coast at intervals of 320 miles. These sections show temperature, salinity and oxygen anomalies in the upper 500 meters for July and October of 1957 and for January of 1958.

I shall not present all of the data we have examined but shall discuss briefly the nature of the anomalies in January 1958 (Fig. 79). We find temperature

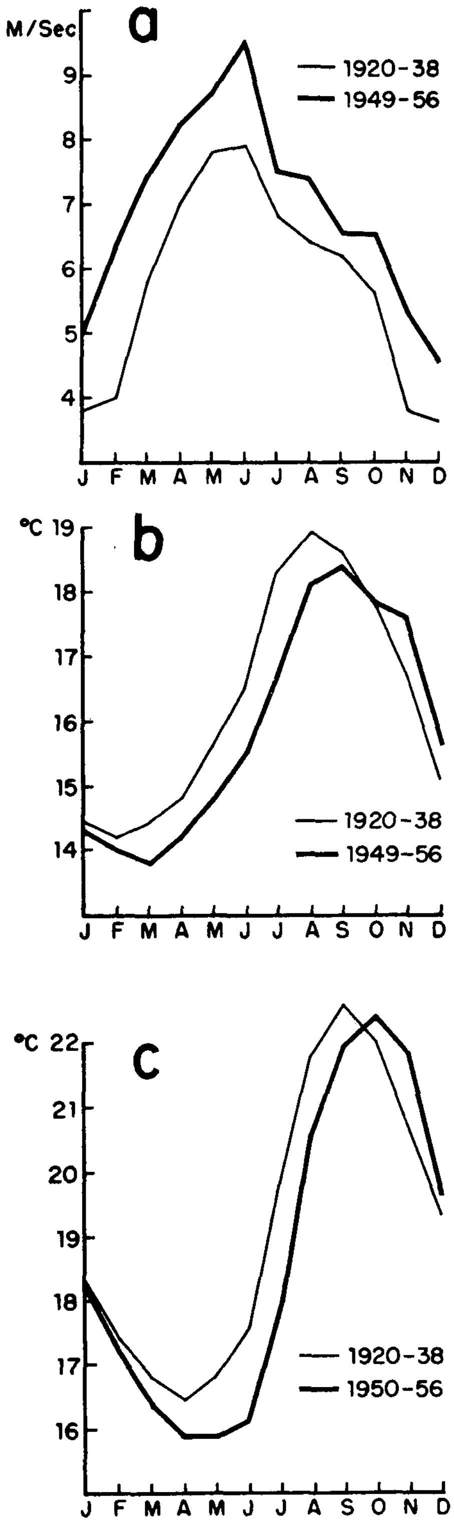

FIGURE 75. Average northerly wind component and temperature in the recent period compared to averages for 1920-38. No data available 1939-48.
(a) Northerly wind component in meters per second at 30°N, 110°-130°W.
(b) Temperature in degrees Centigrade at 30°-35°N, 115°-120°W.
(c) Temperature in degrees Centigrade at 25°-30°N, 110°-115°W.

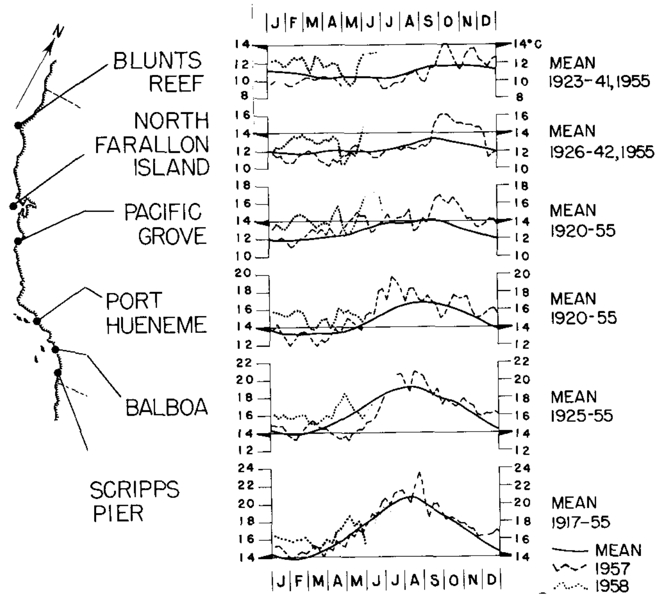

FIGURE 76. Temperature in 1957 and 1958 at six locations along the coast compared to long term means.

anomalies of from 1°C to 3°C at the surface. They generally increase to a high of from 2°C to 4°C in a narrow layer perhaps 10 to 30 meters thick and below the ordinary depth of the thermocline. This depth is from 50 to 100 meters depending upon the distance from the coast, 50 meters being a typical depth inshore and 100 meters more typical at the outer end of the lines. Below this maximum the anomaly dies away to less than 0.5°C nearly everywhere. This would be consonant with a slight warming of the mixed layer and an increase in its depth of 10 to 30 meters.

The salinity anomalies show a somewhat similar picture. The minimum beneath the pycnocline, which we measure at only a few discrete points along the vertical, causes some small confusion, but the general anomaly picture includes a maximum in the pycnocline. The salinity minimum is still present but is somewhat deeper and is higher in salinity.

In the upper layers the change of oxygen should correspond to that of temperature. As the mixed layer temperature has risen, the oxygen should decrease slightly. But if the mixed layer has deepened also, the upper oxygen value should remain constant with depth for another few meters, and the result should be a positive oxygen anomaly in the pycnocline. This situation is indeed found in a great many of the stations.

The deeper oxygen values—those at 200 meters—show something more complex. Both high and low values are found at various stations and at this time no interpretation can be offered.

The data indicate that by January 1958 enough warmer water (or heat) and more saline water have been added to the mixed layer to raise its temperature by about one and one-half degrees and its salinity by about 0.2 parts per mille. The depth of the mixed layer has increased by from 10 to 30 meters. This

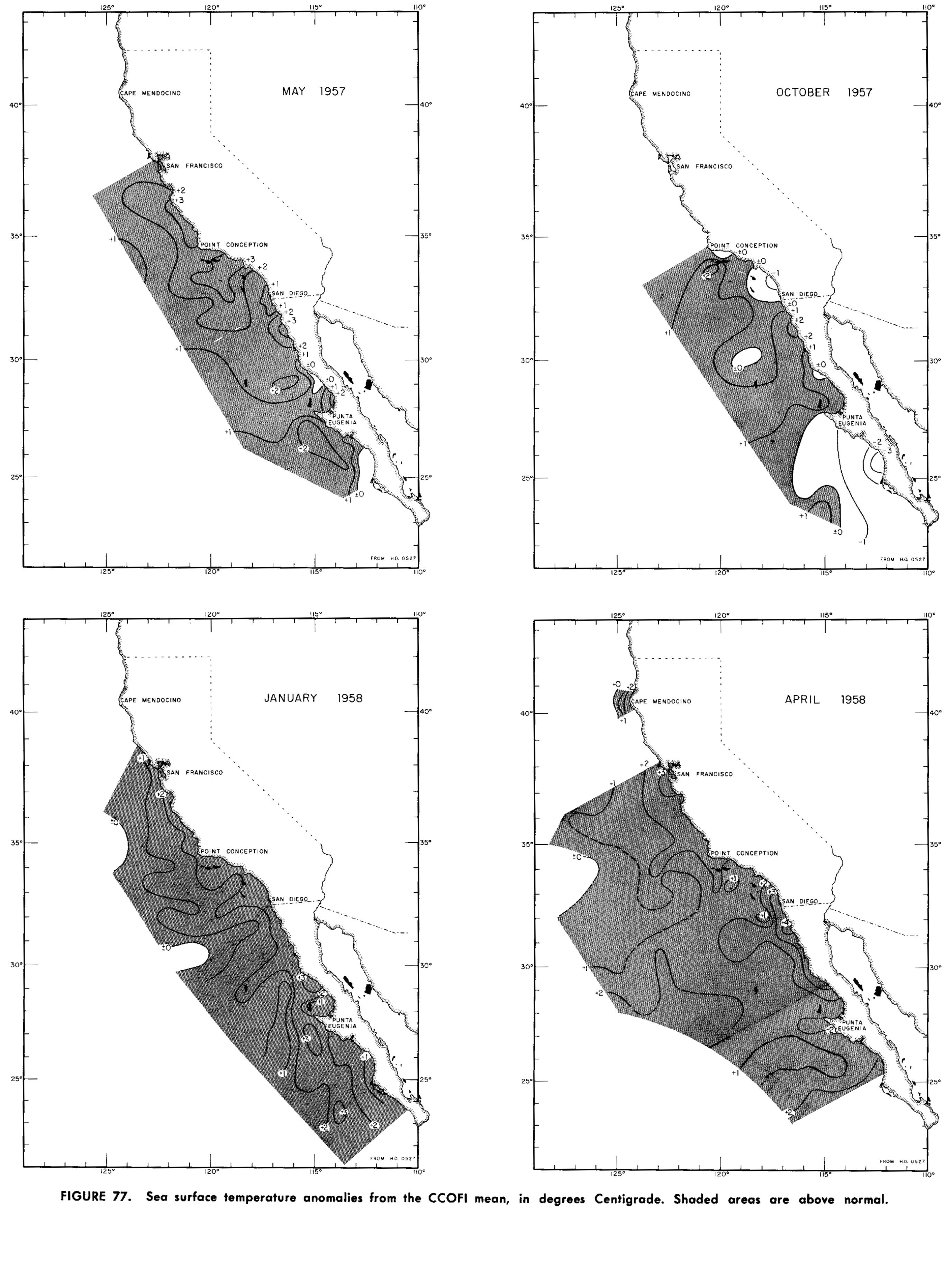

FIGURE 77. Sea surface temperature anomalies from the CCOFI mean, in degrees Centigrade. Shaded areas are above normal.

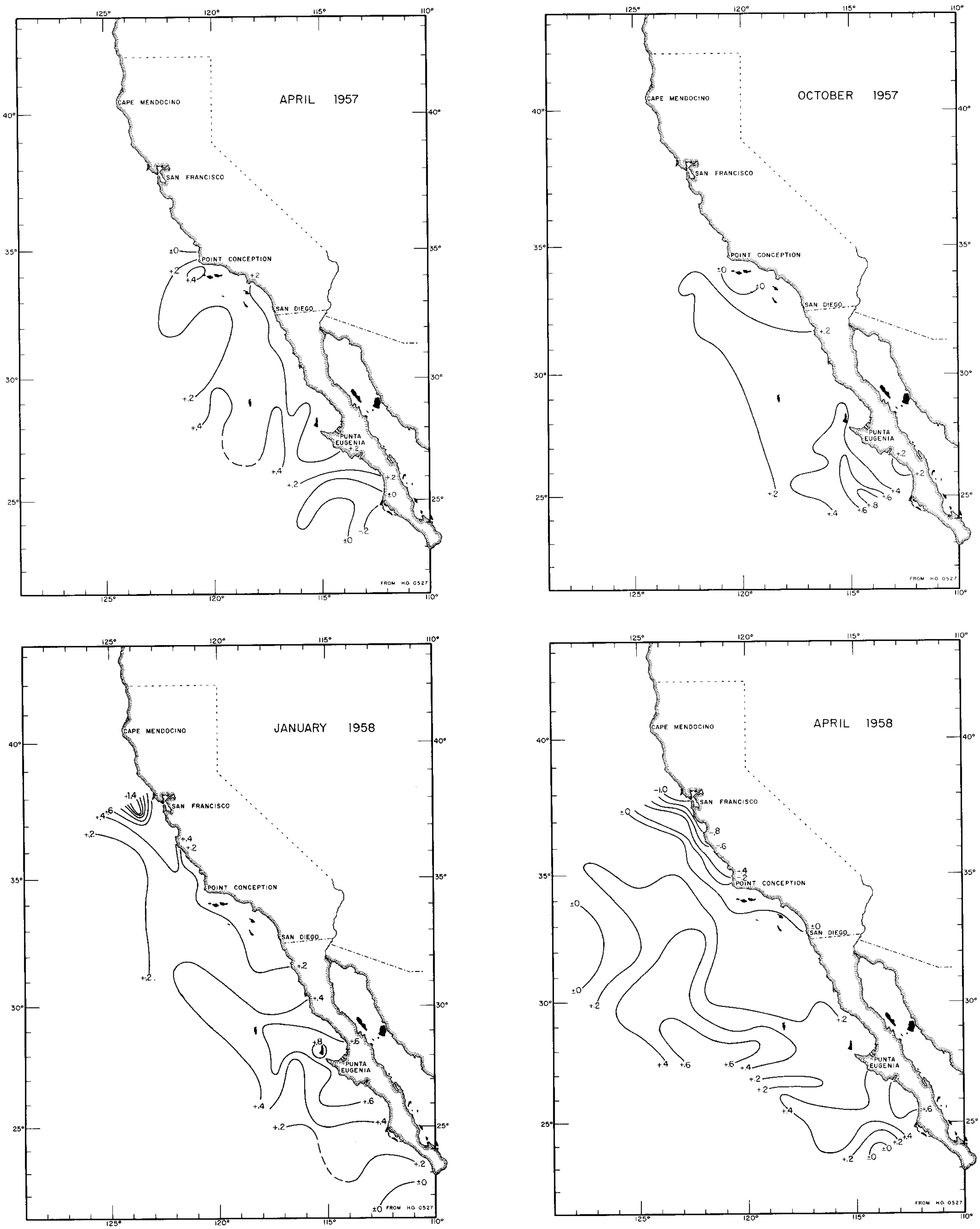

FIGURE 78. Ten-meter salinity anomalies from the CCOFI mean, in parts per mille.

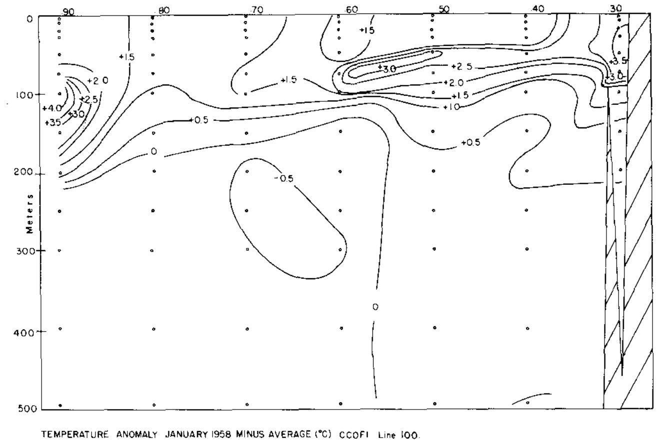

FIGURE 79. Temperature anomaly on a vertical section extending 250 miles offshore. The values are those measured in January 1958 less the CCOFI mean.

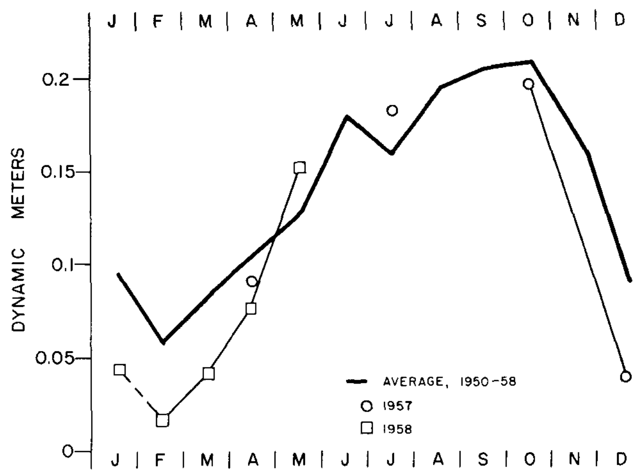

FIGURE 80. Difference in dynamic height (0 over 500 decibars) between a station 140 miles offshore and one 20 miles offshore.

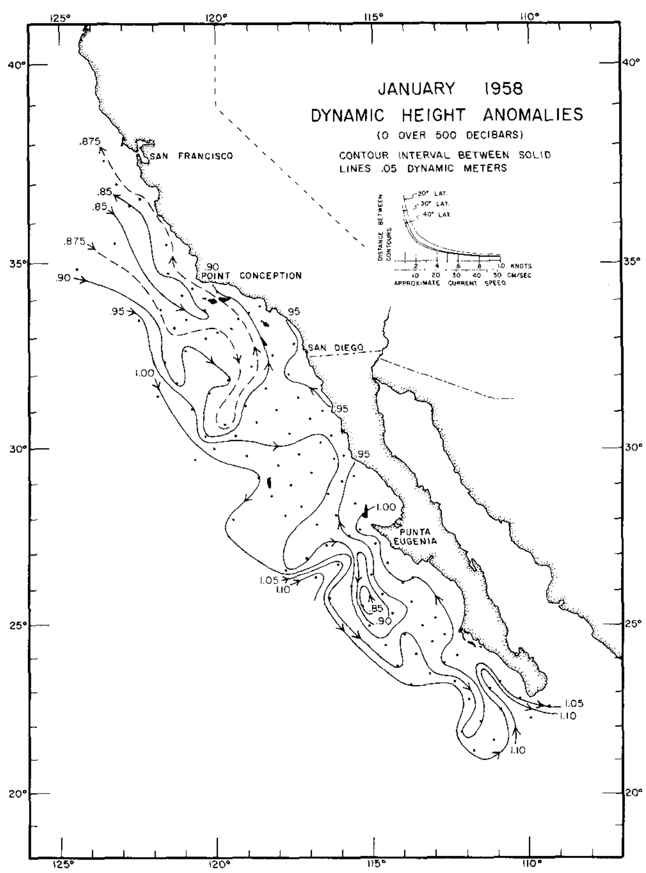

FIGURE 81. Surface currents in January 1958. Dynamic height anomalies 0 over 500 decibars.

means a net gain of about 10,000 calories per square centimeter and about 1.4 grams of salt. The result of the extra heat is a steric rise of sea level of an average of about 5 cm.

It is not possible at this time to show steric anomalies over the whole area, but a pair of stations, one near the coast and one 140 miles offshore have been compared with each other and with the long-term mean (Fig. 80). Their dynamic heights at the surface relative to 500 decibars are above normal by several centimeters. The difference corresponds to a strong surface flow to the south. The two stations span the region of the countercurrent, with the offshore one so far out as to be always higher than the inshore one. In winter the countercurrent flows north and the difference is reduced. The 1957-58 winter values are about 5 centimeters below the 1950-56 mean. That this really corresponds to a countercurrent is shown by the dynamic topography in January 1958 (Fig. 81) and by the movement of drift bottles to the northward (Fig. 82).

Mr. Roden and I are trying to establish the cause of the anomalous conditions I have described. Our first thought was that in the California Current, coastal upwelling might vary as a result of varying winds. Stronger winds might cause more upwelling, and lower temperatures would result. Under weaker winds upwelling might be weaker and higher temperatures would result. The component of wind from the north along this coast has been higher in the period 1949 through 1956 than the long term mean, and we have seen the sudden change to below-average values from early 1957 to the present. We have also seen the large positive anomalies of temperature and salinity which have occurred at the same time as this change in the wind. Without placing too much confidence at this stage in the hypothesis we have prepared a plot of the north component of wind at 30°N and 110°W-130°W and the surface temperature in the 5° square north of 30°N, east of 120°W and bounded on the north and east by the coast (Fig. 83). We have included all of the available data for the month of May, using CCOFI data for the temperature values from 1949 to the present and values measured by Japanese merchant vessels and averaged and published by the Kobe Imperial Marine Observatory for the years 1916 through 1938. Temperature data are not available in the intervening years and for some of the years pressure data are not available. It would be interesting to have comparable values for 1941 during which period we have good reason from coastal measurements to believe temperatures were high.

Mr. Namias has already described the anomalous wind field of the last year and has presented charts considerably more detailed and accurate than those which Mr. Roden and I have been able to prepare from the data available to us. However, the pressure differences have been so severe that even our limited data have not caused our charts to be substantially different from his.

By looking back into previous years we have found other large anomalies (Fig. 84). January of 1931 was characterized by a severe negative pressure anomaly in the central North Pacific and a temperature anomaly which was negative in the center and positive around the edges. The converse obtained in January of 1933 when the pressure anomaly was positive and large in the center. The temperature anomaly was positive in the center and negative around the edges.

Our own data do not extend far enough offshore to test the effect of the large negative pressure anomalies of the Central Pacific which have obtained during the last year, but by combining them with the ten-day anomaly charts recently prepared by the Pacific Oceanic Fishery Investigations, of which the most recent is for May of 1958, we learn that the anomaly is very similar to that observed in 1931, with low temperatures in the central North Pacific and high temperatures around the edge.

It is thus obvious that even if our first hypothesis of coastal upwelling could account for the temperature variations over the California Current region, there are other and larger area anomalies well offshore for which it could not account. The concurrent large area pressure anomalies suggest that a relation may exist between pressure and temperature anomalies over vast areas of the North Pacific.

The mechanism of the relation could be the intensification or shift of the wind-driven circulation. Over the greater part of the ocean the surface currents are approximately parallel to the winds, yet the isotherms are not everywhere parallel to the currents. They deviate especially on the eastern and western edges of the circulation, along the coasts. Any change in the speed of the current will thus displace the isotherms and result in temperature anomalies. Such an explanation might fit the California Current system as well as that of coastal upwelling, but in itself cannot account for the changes in the central North Pacific temperatures.

Another aspect of the same relation might be a lateral movement of surface waters under increased wind stress, which might account for changes independent of coastal effects. This might be more apt to account for the central North Pacific temperature anomalies.

A third aspect of the relation is the gradual adjustment to a new state of geostrophic equilibrium. If the recent weakened wind circulation over the eastern

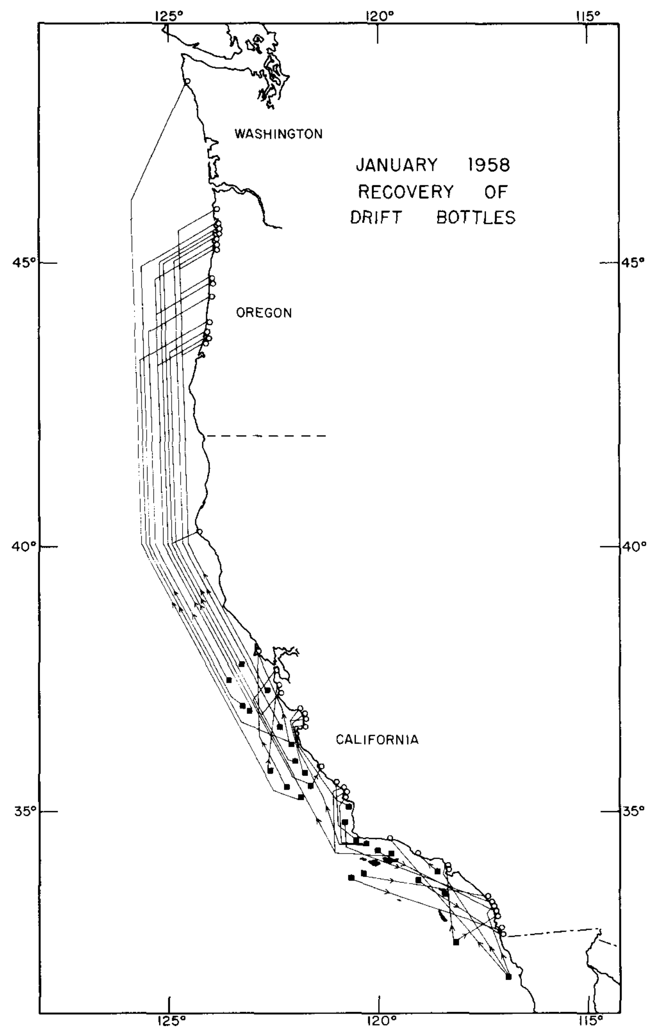

FIGURE 82. Recoveries of some drift bottles released in January 1958. Black squares show the release points, circles show the recovery points.

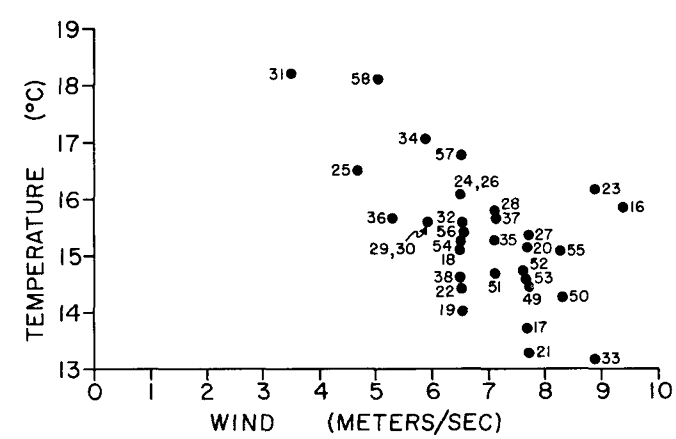

FIGURE 83. May sea surface temperature plotted against May wind for the years 1916-38 and 1949-58. Temperature is measured in the five-degree square 30°-35°N, 115°-120°W. Wind is computed from the pressure difference between 110° and 130°W along 30°N, and represents the component of wind from the north.

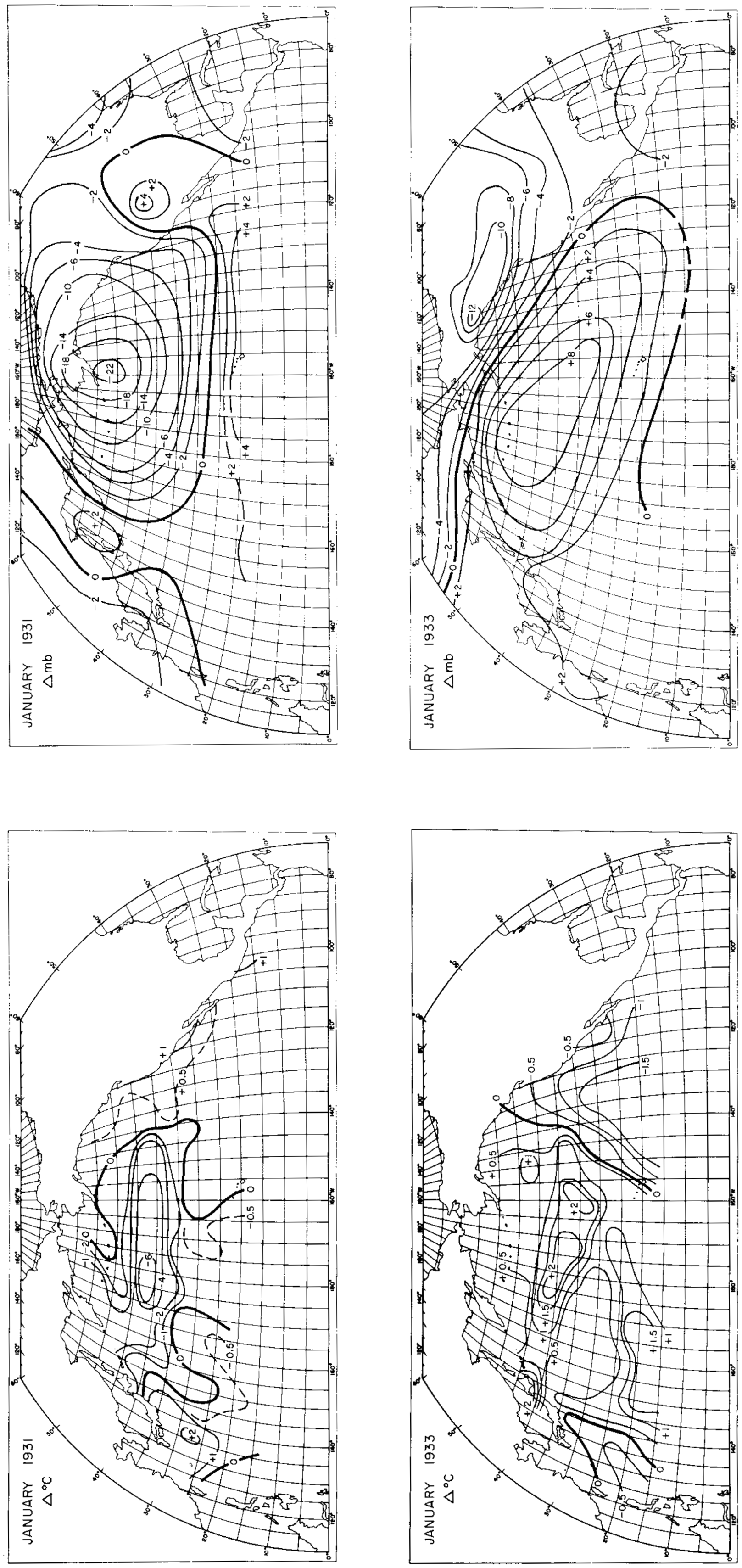

FIGURE 84. Sea surface temperature anomalies and sea level atmosphere pressure anomalies from the long term January means in January of 1931 and January of 1933.

North Pacific has caused a weakened ocean circulation, and a year has passed since the wind pattern changed, some alterations in the height and slope of the sea surface might be expected. We know of at least one location where the slope has decreased (Fig. 80), and the temperature and salinity anomalies have accounted for a steric rise of about five centimeters averaged roughly over the California Current system. The sea level rise at the coast has been about twice the steric rise. Both of these features are consistent with all three of the possible mechanisms I mentioned, that is, with reduced coastal upwelling, reduced lateral flow from the effect of wind stress, and geostrophic readjustment by moving new surface water from the west and south into the region. The latter two, however, might also account for the central North Pacific anomalies.

DISCUSSION

Fleming: Tell us more about your drift bottle program and the countercurrent.

Reid: The drift bottle program began in the fall of 1954. Before January 1958 we released drift bottles from south of Point Conception on the winter cruises. Each time several of the bottles moved northward past Point Conception. In 1958 bottles were dropped north of Point Conception in January for the first time (Fig. 82). Many went northward with velocities as high as 0.5 knot. Some of these bottles traveled over 600 miles northward along the coast.

Isaacs: When you say 0.5 knot, this is only a minimum?

Reid: Yes. This is computed from the time we put them out until the time they are found on the beach. The number of bottles that went past Point Conception was not larger than in the past years. It was principally those we put north of Point Conception that had this tremendous movement to the north.

Wooster: Are you implying that this countercurrent is a double one? And the ones that you put out south of Point Conception did not commonly go north of the Point?

Reid: A few of them did. I have not said that this was a different countercurrent.

Stommel: The deep countercurrent you have mentioned is hard to define.

Reid: You do it essentially by the distribution of the properties. Equatorial Pacific water is identified by certain temperatures, salinities, and a certain temperature-salinity relationship. It extends up from the Equator all along the coast.

Stommel: How deep is it?

Reid: It is found at 200 meters below the surface. The thickness is uncertain since we use as a reference level the 1000 decibar surface, but it is at least 200 or 300 meters thick. Near the coast the deep salinities are higher than those offshore, and at lower latitudes we have a maximum in salinity that shows the northward intrusion of the high salinity water from the Equatorial Pacific.

Question: Low oxygen is a pretty good identifier?

Reid: Yes, it is. The lowest oxygens are along the coast. Offshore the minimum oxygen value is higher and there is a tongue of high salinity and low oxygen water all the way to the Aleutian Islands. Whether it is a movement along the coast or movement upward from deep water, I do not know.

Saur: This is year around?

Reid: Probably, since it is below 200 meters in depth. I have examined it only for July and August.

Fleming: The Davidson Current was well known about ninety years ago, so it is not an original discovery of the Marine Life Research Program. And presumably the knowledge was based in part upon the experience of sailing vessels operating along the coast and from surface temperatures that were available at the time. In other words, it shows up on the surface in the winter when we do not have much northerly wind. We might say that when we have a northerly component of wind it disappears at surface but persists at depth.

Reid: One of the reasons we have had so much trouble obtaining historical data about the Davidson Current is that when Davidson discussed it, he based a good part of his argument on the location of drifting redwood logs. Such information would of course not be available for Southern California since no redwood logs drift into the ocean here, and we cannot draw any information about continuity of northward flow past Point Concepcion from his work.

Schaefer: I think we are talking about three different things: first the Davidson Countercurrent, that is somewhere up the northern coast. The second is this movement of water near the surface from somewhere down off the Mexican-Baja California coast, shown very well by MLR studies. This is near the surface. And the third thing, is the general movement of deeper water off the southern Mexican and Baja California areas. I think they are not quite the same.

Charney: This water has to come from some place —presumably from beneath the thermocline. This would produce vertical motion. And if this is going to be balanced, from considerations of continuity, you have to have northerly flow. This, in a sense, is what you are arguing about.

Reid: This may be perfectly right. I have nothing against your explanation, except that it would have upwelling off California moving water northward from a position 2,000 miles to the south of the upwelling. This may be perfectly right, however.

Fleming: What is your southern boundary on the chart (figure 67)?

Reid: These data were from the NORPAC Expeditions, which extended from 45°N to 20°N.

Wooster: You show the thermocline is getting shallower as it approaches the coast. Some of the profiles also show something I feel is very common on approaching an upwelling coast—a weakening of the thermocline and the presence of a trough in the isopleths. You have shown one profile, and I have seen others across the Peru Current that show this sort of thing, the isopleths separating near the coast. Do you think this trough has anything to do with the countercurrent?

Reid: Certainly. The trough in temperature and salinity means a trough in the density distribution. The integral of the density shows a cyclonic circulation.

Wooster: There are two classical explanations of the trough. One is that you have horizontal advection of water coming in from the south giving these properties, which apparently cause troughs.

Fleming: I do not think you even have to have upwelling. Obviously at the ocean boundaries you have a source of energy for mixing. Temperature structures not unlike what you have drawn on the board might appear in the absence of any permanent flow along the coast, purely by mixing at the ocean boundaries. If you did get this kind of mixing, then you would have some kind of circulation set up. It is a little difficult to understand the characteristics of this circulation that might result from this vertical mixing.

Wooster: Is it not characteristic of upwelling that the deeper isopleths slope downward toward the coast?

Schaefer: You show the countercurrent there. How deep do you put it at its deepest point? What is the greatest depth for this countercurrent off Baja California? Do you put the center of it at 600 meters?

Reid: The basis of computation for these currents is the geopotential above 1,000 meters. The bottom limit of this flow is probably uncertain with the present methods.

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