STUDIES OF THE
CALIFORNIA CURRENT SYSTEM

by
JOSEPH L. REID, JR., GUNNAR I. RODEN,
and JOHN G. WYLLIE

Contributions from the Scripps Institution of Oceanography, New Series No. 998

CONTENTS

ILLUSTRATIONS

THE WINDS OVER THE NORTHEASTERN PACIFIC OCEAN AND THEIR EFFECT UPON THE WATER

The most important force moving the surface waters of the ocean is the wind. Upon comparing a current chart of the North Pacific Ocean with a chart of the winds, one is immediately struck by the similarities in direction of motion. The strong westerly winds in high latitudes move the water eastward and the strong and constant trade winds farther south push the water westward. Both the winds and the water go through an enormous clockwise circulation in the North Pacific Ocean. The California Current lies at the eastern, southward-flowing side of the circulation.

The circulation is of course not quite so simple as this. There are countercurrents and subsurface currents which are harder to understand and to measure, and there are seasonal changes in the circulation of the air which are reflected in the motion of the water. The California Current flows southeastward between a cell of high atmospheric pressure to the west and a cell of low pressure on the landward side. The winds over the California Current are mostly from the north and west and are strong when these two cells are close together and intense, weak when the cells are farther apart and moderate.

Both these cells are weakest in winter; that is, the high pressure cell is less high and the low is less low. The high to the west moves north in spring and summer as it grows slightly stronger and moves south again in the fall as it weakens. The low over the land is a semi-permanent feature with a wider range of seasonal variation. The pressure differences between these two cells afford the best data available for the

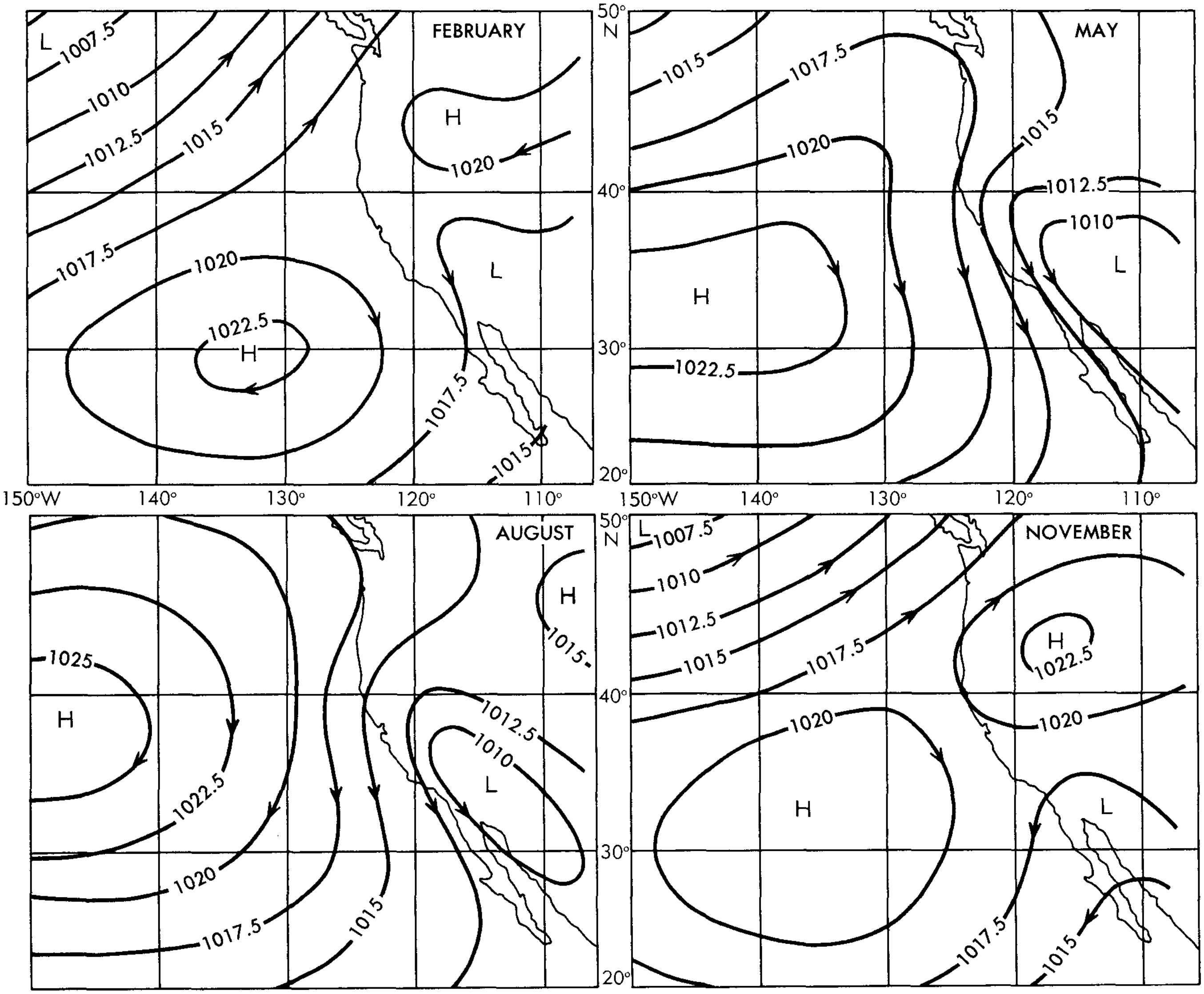


FIGURE 1. Average monthly atmospheric sea level pressure (in millibars) over the eastern North Pacific Ocean and the western coast of North America during four months of the year.

study of wind variations over the California Current region, since not enough direct measurements of wind are available to permit the study of year-to-year changes. Under certain assumptions winds can be calculated from the difference in atmospheric pressures at two places. Such calculated winds are called geostrophic. In some parts of this discussion the pressure gradients have been expressed as meters per second of (geostrophic) wind.

The changes in strength and location of the cells cause seasonal changes in the winds (Fig. 1). From spring through fall over most of the California Current the winds have a northerly component which tends to push the current along but in winter this northerly component either weakens or reverses. In winter when the north winds are less effective a countercurrent develops at the surface near the coast from Baja California to some distance beyond Point Conception.

Along the coast of California and Baja California winds from the north and northwest are of peculiar importance. Under the force of these winds and the earth's rotation the surface waters are turned from their movement along the coast to a direction offshore. Some part of the waters which move offshore are then replaced by water from below. This replacement is known as upwelling, and it is important because it brings to the surface waters which are richer in nutrient material than the waters they replace. Since upwelling is the result of the north and northwest winds it will be most marked when these winds are strongest. They are strongest off Baja California in April and May, off southern and central California in May and June, off northern California in June and July, and off Oregon in August. In winter the winds south of Point Conception are still northerly but north of Point Conception they are westerly and southwesterly. In the south upwelling will be strongest in spring and in the north it will be strongest in summer.

These two features, upwelling in spring and summer and countercurrent in fall and winter, will be referred to frequently in the sections on currents, water properties, and the relation of these to the plants and animals of the current system.

In any discussion of wind Point Conception stands out. Mariners have long known that strong winds are found to the west-southwest of the Point. Typical wind strengths, from measurements made by a CCOFI cruise in May, 1953, show the local intensification (Fig. 2). About one day was spent on each line shown. The strongest winds were found just beyond Point Conception where their strength was about twice the average along the line. This feature seems to be confined to the months from April to August. It may occur to the south also but the evidence is not conclusive.

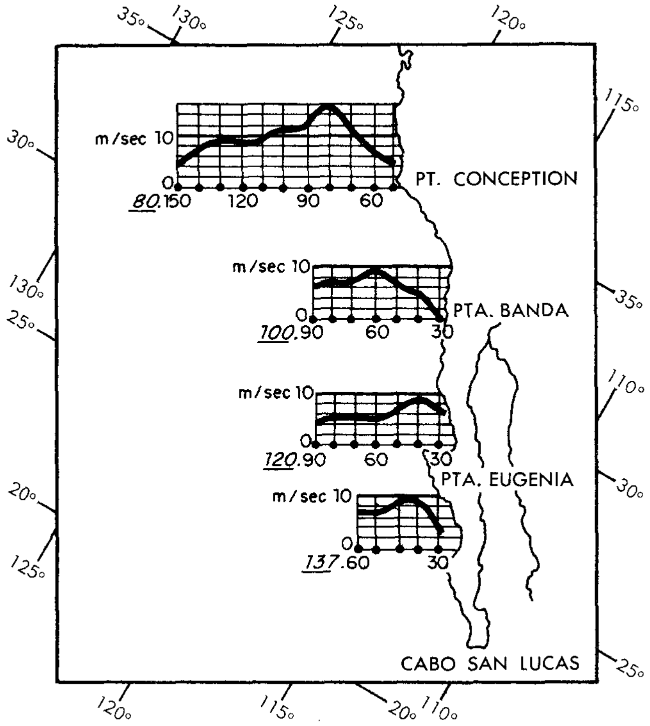


FIGURE 2. Variations of wind speed with distance from coast, May 1953. Measurements made along Station Lines 80, 100, 120, and 137, on CCOFI Cruises. Wind expressed as meters per second. Strongest winds occur off Point Conception.

THE CURRENTS

The California Current system is a part of the great clockwise circulation of the North Pacific Ocean. At high latitudes the waters move eastward under the influence of the strong westerly winds (the "roaring forties") and near the coast of North America divide into two branches. The smaller part turns northward into the Gulf of Alaska, and the larger part turns southeastward to become the California Current. In general the temperatures in the open ocean are lower toward the north so that the branch turning northward into the Gulf of Alaska is known as a warm current. The water which is brought south by the California Current system is cooler than the waters farther offshore. As it moves slowly south at speeds generally less than half a knot it becomes warmer under the influence of the sun and by mixing with the warmer waters to the west. As it nears the latitude of 25° N it begins to turn westward and its waters become part of the west-flowing North Equatorial Current. On the inshore side of the current some disturbances in the circulation are found.

A small eddy is usually found offshore from Cape Mendocino through most of the year (Fig. 3a). A similar eddy is found between Guadalupe Island and the mainland. A permanent eddy, the Southern California Countercurrent (Sverdrup and Fleming, 1941), is found inside the submerged peninsula that extends southeast from Point Conception and includes

Santa Rosa Island, San Nicolas Island, and Cortes Bank. The waters on the eastward side of this are protected from the northwest winds by the land and separated in part from the strong southeasterly-flowing offshore current. The currents are weaker and usually to the north. The waters remain off the coast of southern California for a considerable time and become much warmer than those offshore, which are constantly replaced by cooler water from the north.

The area off southern California was studied by Sverdrup and Fleming (1941) using the data taken by the California Division of Fish and Game vessel *Bluefin* in the late '30s and the University of California vessel *E. W. Scripps* in 1940 and 1941; and until the CCOFI program began it was the only area which had received any detailed attention. The small area covered by these cruises made speculations about the continuity of the northward flow around Point Conception extremely difficult. Only one extensive cruise was made from Punta Eugenia to Cape Mendocino. As this was conducted in the summer of 1939, it did not bear upon the problem of the continuity of the winter countercurrent. However, many of the results of the CCOFI program in the regions where Sverdrup and Fleming had little or no data had been anticipated to a remarkable degree by their speculations.

A deep countercurrent, below 200 meters, flows to the northwest along the coast from Baja California to some point beyond Cape Mendocino. It brings warmer, more saline water great distances northward along the coast. When the north winds are weak or absent in late fall and early winter the countercurrent forms at the surface well on the inshore side of the main stream and extends from the tip of Baja California to north of Point Conception, where it has been called the Davidson current. The causes of the deep countercurrent and its appearance at the surface in winter are not understood. Rossby (1936) derived a theory of oceanic circulation in which a large ocean current has associated with it on its lefthand side looking downstream a countercurrent; and Sverdrup *et al.* (1942) mentioned the possibility that the California Current system is an example of this sort of circulation. However, the assumptions are not all fulfilled and this theory cannot be applied with any confidence at present.

The process of upwelling, in which winds parallel to the coast move the waters offshore, has been mentioned. This effect seems to be intensified south of capes and points which extend out into the stream. Thus Cape Mendocino, Point Conception, and Punta Eugenia are regions of more intense upwelling than the rest of the coast.

Some of the current measurements made by the CCOFI program are shown in figure 3. They are computed from the density distribution of the water, measured at the points indicated. In order to express these density distributions as currents it is necessary to make certain assumptions. These are that the currents and density distribution are steady, there is no effect of friction either at the bottom or from wind at the surface, there is some depth (perhaps 1000 meters) at which there is no motion and to which the density measurement can be referred, and above this level all movement is horizontal and east-west. These assumptions are no doubt best fulfilled farther upstream where the west wind drift at 160° W longitude is very nearly east-west and where the ocean is deep. At any rate the currents computed from the density distribution in that area have been in agreement with the many measurements made by the set and drift of merchant vessels (University of California (in press) and U. S. Hydrographic Office, 1947).

Offshore in the California Current system these measurements are equally in agreement with the set and drift results and present a coherent picture of the clockwise circulation of the North Pacific. Near the coast, however, the assumptions are not so well fulfilled. The effect of the irregular coastline cannot be entirely ignored, nor the varying depth. These and the winds, which sometimes reinforce and sometimes oppose the current, and the significant vertical motion in the regions of upwelling and the oscillations of internal waves (Reid, 1956) all combine to make the measurement of currents by density distribution less accurate and less useful.

The currents computed from density are less clear near the coast (Fig. 3). Indeed it is not upon the density measurements alone that our knowledge of the countercurrent is based, but upon the observed effect of the countercurrent in moving large quantities of water of a distinct type far up the coast, and upon various direct measurements obtained by drogues, drift bottles, and an electronic current-measuring instrument, the Geomagnetic Electrokinetograph (von Arx, 1950).

Because of the doubtful validity of computing currents from density in the nearshore regions, especially around the Channel Islands, work was done as early as 1937 with drift bottles (Tibby, 1939) and in 1950 with drogues. The density distribution indicated a movement to the northwest inside the islands. Measurements of the currents made at the same time (in June 1950) by both the density method and drogues showed a northwesterly flow. Whether this flow reached as far as Point Conception and proceeded northward around the Point in summer has been more recently inquired into by using drift bottles. These have been put over on all the CCOFI cruises made in the last three years. The results have been very informative. They have indicated a flow northwestward from the Channel Islands region around Point Conception only in late fall and winter. In summer the

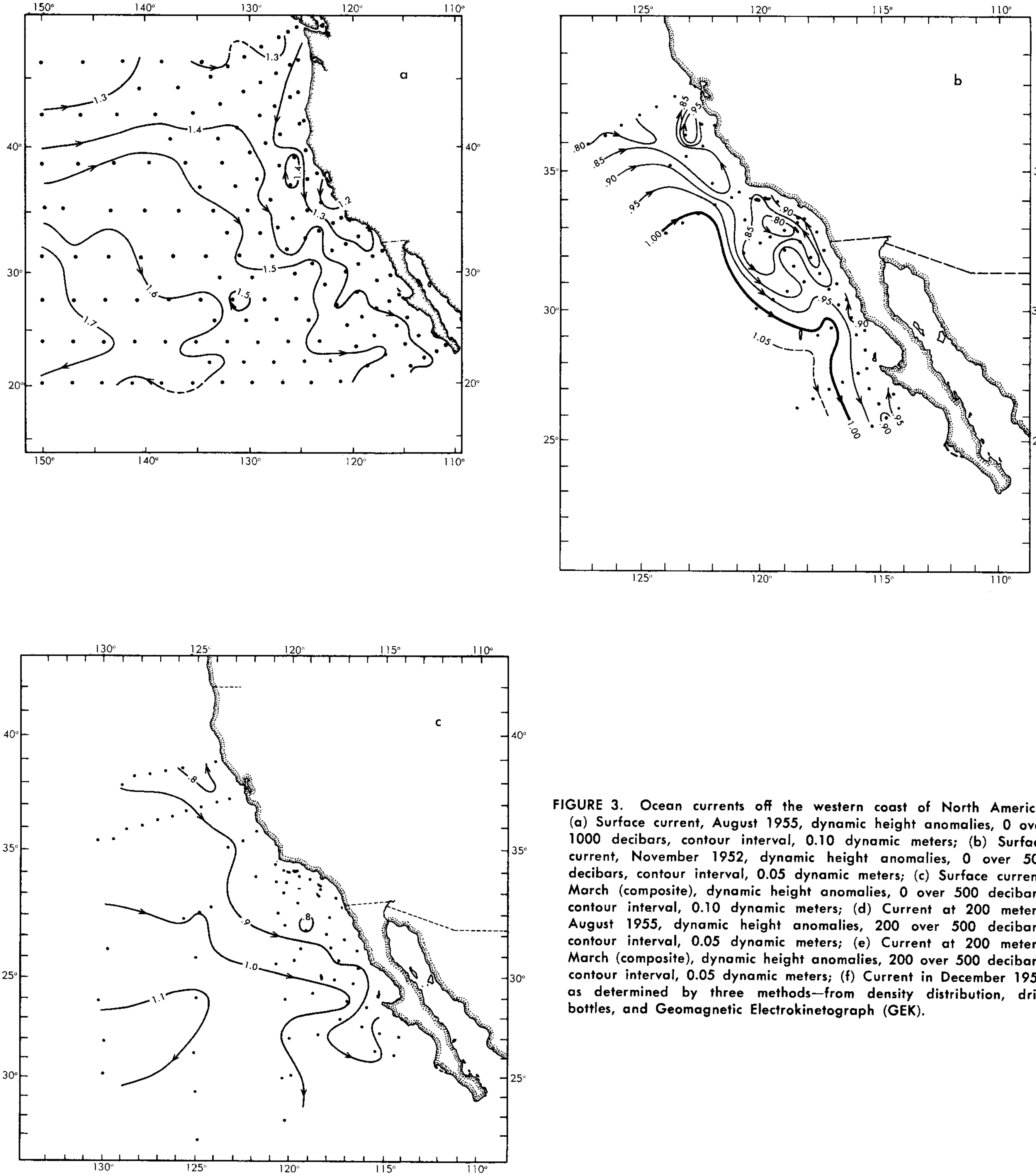
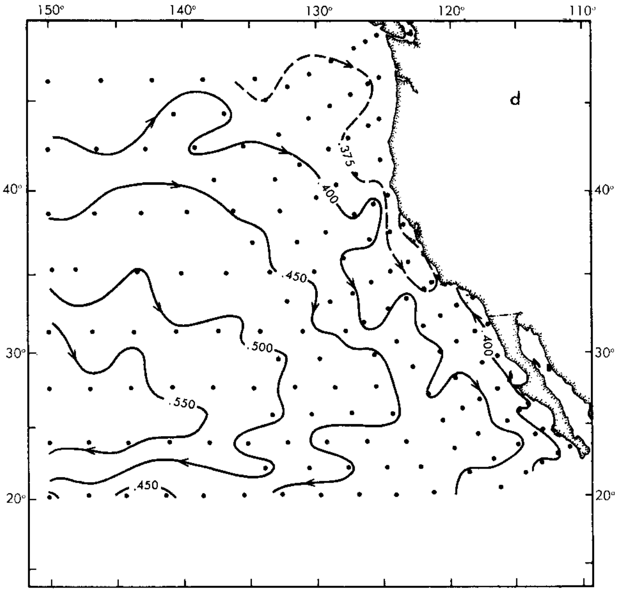
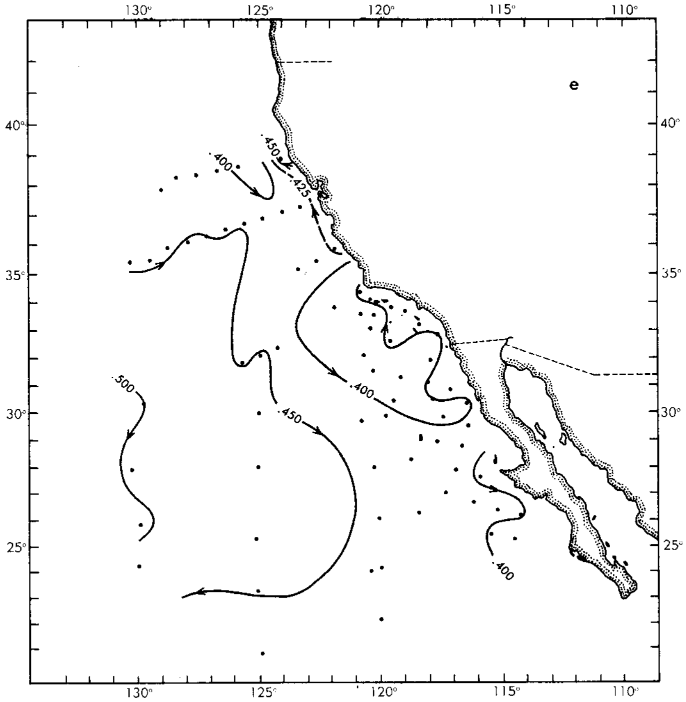
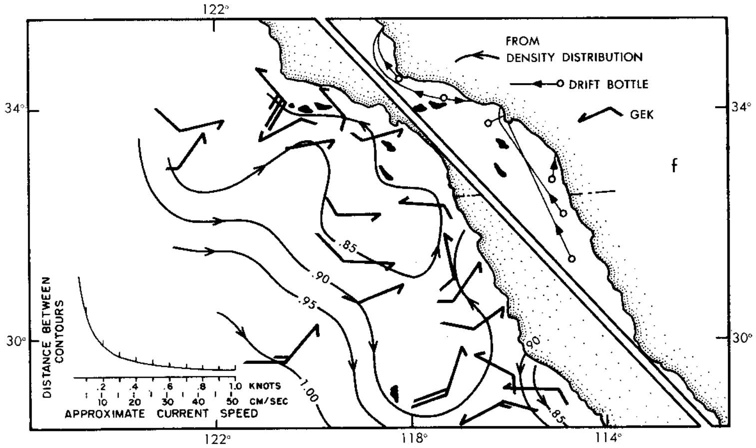


FIGURE 3. Ocean currents off the western coast of North America. (a) Surface current, August 1955, dynamic height anomalies, 0 over 1000 decibars, contour interval, 0.10 dynamic meters; (b) Surface current, November 1952, dynamic height anomalies, 0 over 500 decibars, contour interval, 0.05 dynamic meters; (c) Surface current, March (composite), dynamic height anomalies, 0 over 500 decibars, contour interval, 0.10 dynamic meters; (d) Current at 200 meters, August 1955, dynamic height anomalies, 200 over 500 decibars, contour interval, 0.05 dynamic meters; (e) Current at 200 meters, March (composite), dynamic height anomalies, 200 over 500 decibars, contour interval, 0.05 dynamic meters; (f) Current in December 1954 as determined by three methods—from density distribution, drift bottles, and Geomagnetic Electrokinetograph (GEK).


d
150°
140°
130°
120°
110°
40°
30°
20°
.375
.400
.450
.500
.550
.450
.400


e
130°
125°
120°
115°
110°
40°
35°
30°
25°
.400
.450
.425
.500
.400
.450
.400


f
FROM DENSITY DISTRIBUTION
DRIFT BOTTLE
GEK
122°
118°
114°
34°
30°
.85
.90
.95
1.00
.90
.85
DISTANCE BETWEEN CONTOURS
.2 .4 .6 .8 1.0 KNOTS
10 20 30 40 50 CM/SEC
APPROXIMATE CURRENT SPEED

drift bottles have moved short distances northwestward along the coast between San Diego and Port Hueneme but none has rounded the corner. There is reason to believe that they turn southward again in summer as they near the Point and are carried down with the main current. An interesting feature of the drift bottle results is that few of the bottles put over more than 40 miles offshore have returned to the coast. This result is consistent with the assumption that the surface waters are nearly always moved slightly offshore by the prevailing winds.

The currents were measured in December 1954 by the distribution of density, by drift bottles, and by means of an electronic current-measuring device (Fig. 3f). The three methods are in general agreement, all of them showing a northwestward flow past Point Conception. The electronic measuring instrument has revealed many short-period changes in the surface currents off California (Reid: in press). Some of these variations appear to be tidal. There is so much variation over a 12-hour period that a single measurement is difficult to interpret. A clearer picture is found when some averaging system is introduced either by area or by time (Knauss and Reid, 1957).

THE NATURE OF THE WATERS ENTERING THE MAIN STREAM

The waters of the California Current come from four water masses distinguishable by their content of heat, salt, oxygen, and phosphate. (The deeper circulation is excluded from this discussion.) Processes of mixing and surface effects cause these properties to change as the water moves. We shall identify them by their descriptions as they enter the area of interest.

From the North

A great part of the water mass which moves eastward across the North Pacific has been called Subarctic water. At 147° W longitude this eastward-moving mass is centered at about 48° N latitude in summer. It is this water mass which gives to the offshore waters of the California Current their characteristic surface properties of low temperature, low salinity, high oxygen and, in part, their high phosphate. These properties distinguish this water mass sharply from the waters to the southwest with which it mixes as it moves down the coast of North America. Mixing alters the properties of the Subarctic water considerably before the Current begins to turn southwest at about 25° N latitude. But it is still clearly recognizable, especially by the low salinity, as it turns westward and becomes part of the North Equatorial Current.

From the West

In the central part of the North Pacific lies water whose properties are in sharp contrast to those of the Subarctic water mass. This water has remained in the central part of the North Pacific gyral long enough for its temperature to be raised, its salt content to be raised by evaporation, and the nutrients in the surface layer nearly exhausted. These two bodies of water move eastward side by side until they approach the coast of North America. Some mixing takes place as they move to the eastward, though the boundary still remains relatively sharp. But as the Subarctic water turns southeastward to become the California Current much more horizontal mixing takes place near the surface. This continues down the coast so that the upper waters have attained quite different characteristic values by the time the Current begins to turn southwest. The mixing does not take place equally at all levels but is most intense near the surface, so that the upper waters come to be dominated more nearly by the Central Pacific characteristics than do the waters below 100 meters. This effect will be shown later on vertical profiles.

From the South

To the far south lies a great body of water called Equatorial Pacific, which has been defined by a certain easily recognizable temperature-salinity relation. In the upper levels these waters are very warm and salty. The major influx of these waters into the California Current system occurs along the coast well beneath the surface. At the tip of Baja California the temperature-salinity relation below 200 meters coincides with that of the definition of Equatorial Pacific water. This water also fills the lower levels of the Gulf of California. The water which moves up the western coast of Baja California at depth must have been beneath the surface for a long period because it is low in oxygen and high in phosphate. This implies a great deal of decomposition of organic matter fallen from the surface, and no extensive mixing with the surface waters.

From Below

The strong northwesterly winds near the coast of the Californias combine with the earth's rotation to effect an offshore transport of the surface waters. These are replaced by colder, more saline waters from below. Having been below the surface for a long time, the water thus upwelled contains nutrients which have been both produced in it by decay and by mixing with the still richer, untapped reservoirs below. Some part of these upwelling waters comes from the lower levels of Subarctic water and some parts are a transitional form of the Equatorial Pacific water which has flowed far up the coast beneath the surface and mixed with the lower levels of Subarctic water.

The wind charts (Fig. 1) have shown that winds are more likely to cause upwelling in spring and early summer but that there is some tendency for upwelling at other times of the year. The predominance of the wind from the northwest even when weak and the general southeastward movement of the current combine with the irregularities in the sea bottom and with such sharp breaks in the coastline as Cape Mendocino, Point Conception, and Punta Eugenia to cause spots of cold, salty water near the coast through a great part of the year though, as will be seen, spring and early summer are the periods of strongest upwelling.

RESULTANT DISTRIBUTION OF PROPERTIES AND THEIR VARIATION WITH SEASON

The properties of the water are shown by the horizontal charts and vertical profiles. Some have smooth patterns, some change abruptly, some are characterized by maxima and minima which appear as tongues or fingers penetrating other waters.

Temperature

In general ocean temperatures become higher toward the equator and lower toward the poles. Over most of the Pacific Ocean the lines of constant temperature run east-west. The clockwise circulation of the North Pacific Ocean, however, causes the isotherms to bend sharply toward the south as the currents approach North America. The southward flowing cooler Subarctic water collides with much warmer water toward the tip of Baja California (Fig. 4a) where a sharp front is nearly always found near the coast (Cromwell and Reid, 1956). In the southwest are found the high temperature values of the central part of the great North Pacific gyral. Even these high values, however, are surpassed by the warm water at the tip of Baja California.

The coldest water in the area shown on figure 4a, however, is not in the north, but off California. An isolated cold area extends from the Columbia River to Point Conception. In August the only possible origin of such waters is from below. This water then is upwelled and will later be seen to be high in salinity as well. Weaker upwelling takes place at numerous points from San Diego to Magdalena Bay. In August, the upwelling off Baja California is weak, as its maximum occurs earlier in the year, but off northern California upwelling is at its strongest and the temperatures are affected correspondingly.

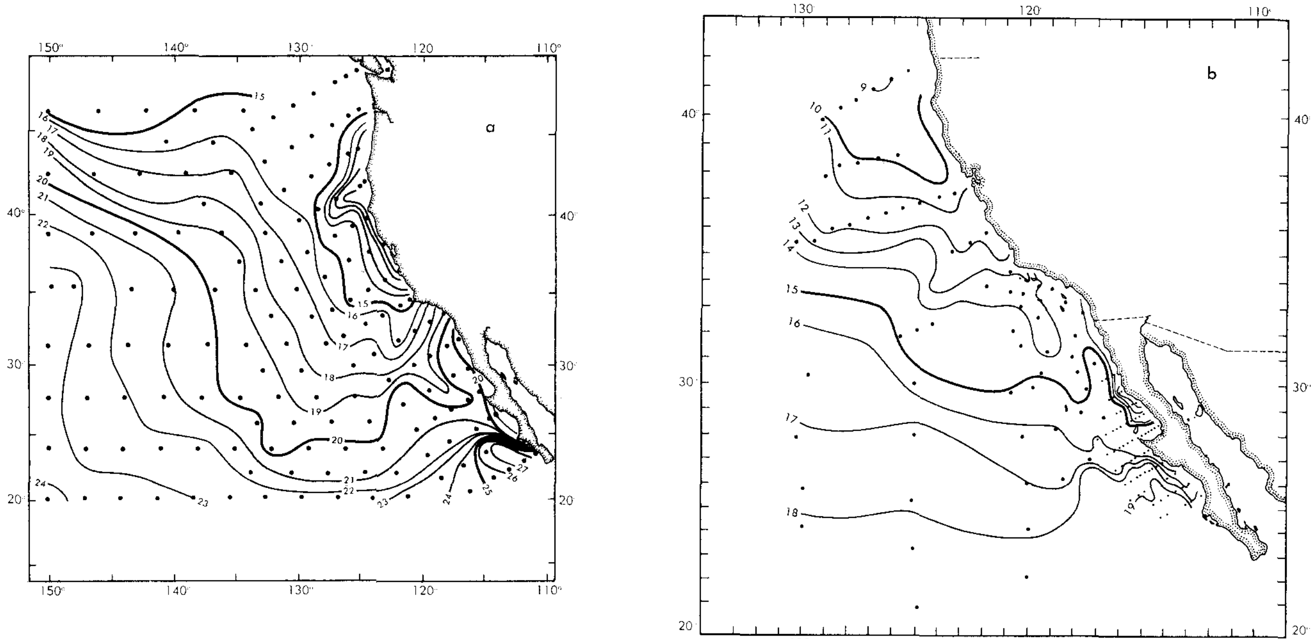


FIGURE 4. Ocean temperatures at 10 meters (degrees Centigrade). (a) August 1955. (b) March (composite).

The great eddy off southern California results at this time of year in a local high temperature between San Diego and San Clemente Island. This water is moving very slowly to the northwest and is warmed to these high temperatures as it moves.

Four profiles of the upper 600 meters of water drawn roughly perpendicular to the direction of flow are shown in figure 5a. The high temperatures at the surface diminish very rapidly with depth and at 600 meters the difference between the northern and southern temperatures is of the order of a degree. At the surface this difference may be as high as 10° C. Near the tip of Baja California, where the deep waters reach their maximum temperature, a small inversion in the temperature is nearly always found. The cool and less saline waters of the California Current here have overridden the warmer and more saline waters of the deep countercurrent to such an extent that over

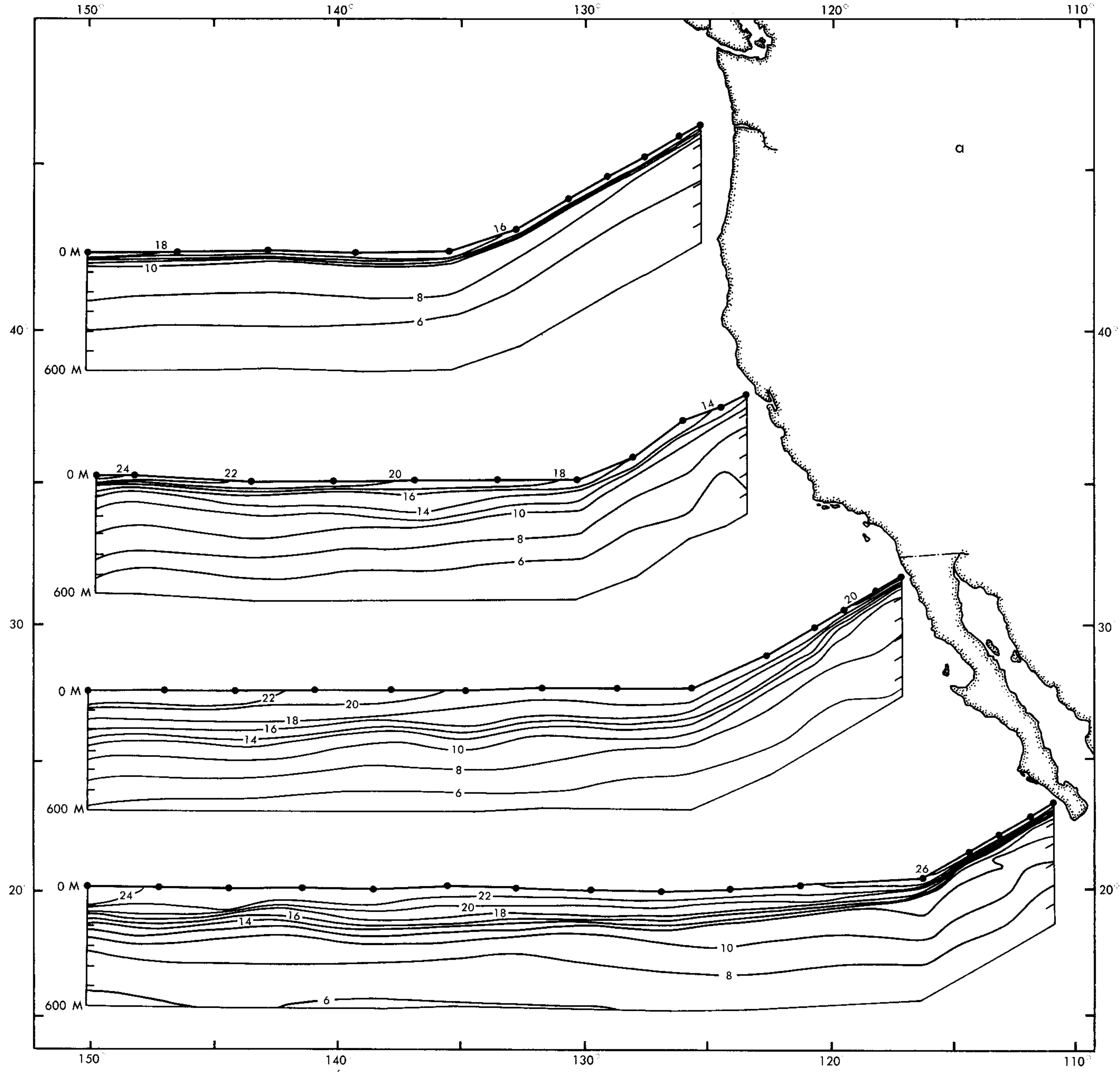


FIGURE 5. Vertical profiles of temperature, salinity, oxygen and phosphate from the surface to 600 meters, August 1955.

(a) Temperature, degrees Centigrade.

a small area and through a narrow range of depth the temperatures may actually increase with depth at about 100 to 150 meters.

Offshore the upper waters vary seasonally in a rather smooth and regular pattern (Fig. 6.). In January and February a well-mixed surface layer is found with the water becoming colder quite suddenly beneath it. The region of sharp change is called the thermocline. In spring the water receives more heat from the sun and a thin layer of warmer water appears at the surface. A new thermocline is formed near the surface and this strengthens and becomes deeper as the summer passes, and the original winter thermocline loses its identity. The surface is warmest from August to October but the new thermocline continues to deepen until finally it reaches the depth of

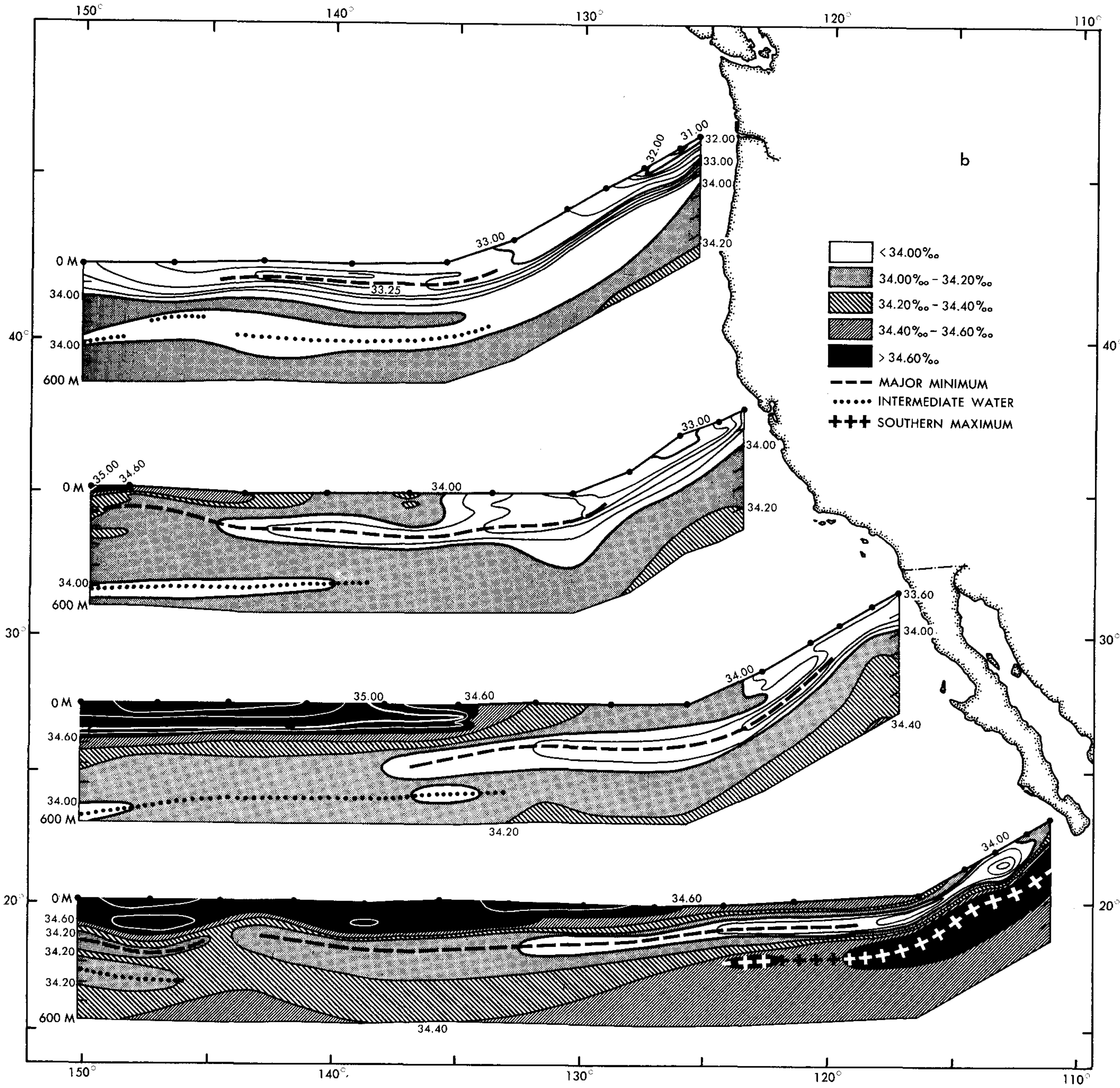


FIGURE 5—Continued

(b) Salinity, parts per mille.

the original thermocline. A curious result of this sequence is that the high temperatures are found later in the year at deeper levels than at the surface. Heat is still conducted downward by the process of mixing long after the highest surface temperatures are past. This circumstance may be of some importance in the distribution of dissolved oxygen and will be mentioned again. (The upper left-hand section of figure 6 is taken from Robinson, 1957, and Mrs. Robinson also prepared the rest of the data for the figure.)

Near the coast two entirely different causes of seasonal change are found, and these alter the simple offshore sequence. The first is upwelling, which occurs earlier south of Point Conception than northward. To the south it occurs at about the time of the offshore seasonal low in temperature. Upwelling and seasonal

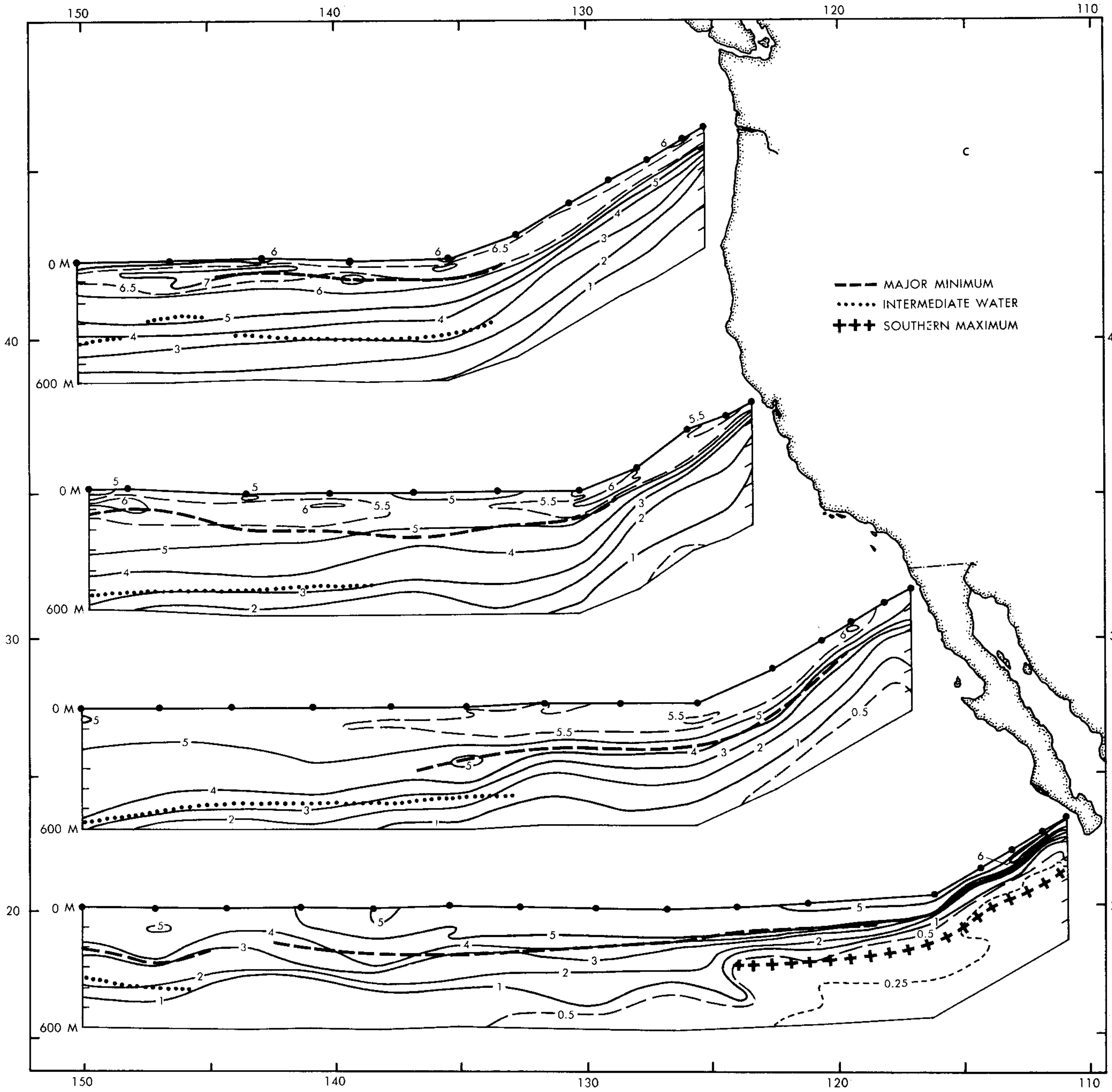


FIGURE 5—Continued

(c) Oxygen, milliliters per liter.

cooling combined result in a wider range in temperature than is found offshore. North of Point Conception upwelling occurs later and lengthens the cold period, and diminishes the seasonal range well below that of the offshore waters. Thus the March and August temperatures off Cape Colnett (30° N) are 12° C and 19° C while off Cape Mendocino they are both between 10° C and 11° C (Figs. 4a and 4b).

The second principally coastal cause is the seasonal ebb and flow of the countercurrent. This current, which is found off Baja California in the fall, brings warmer water from the south northwestward along the coast. It increases the fall high in temperature and extends it long enough to delay the spring low. It will be seen to be even more effective in altering the salinity.

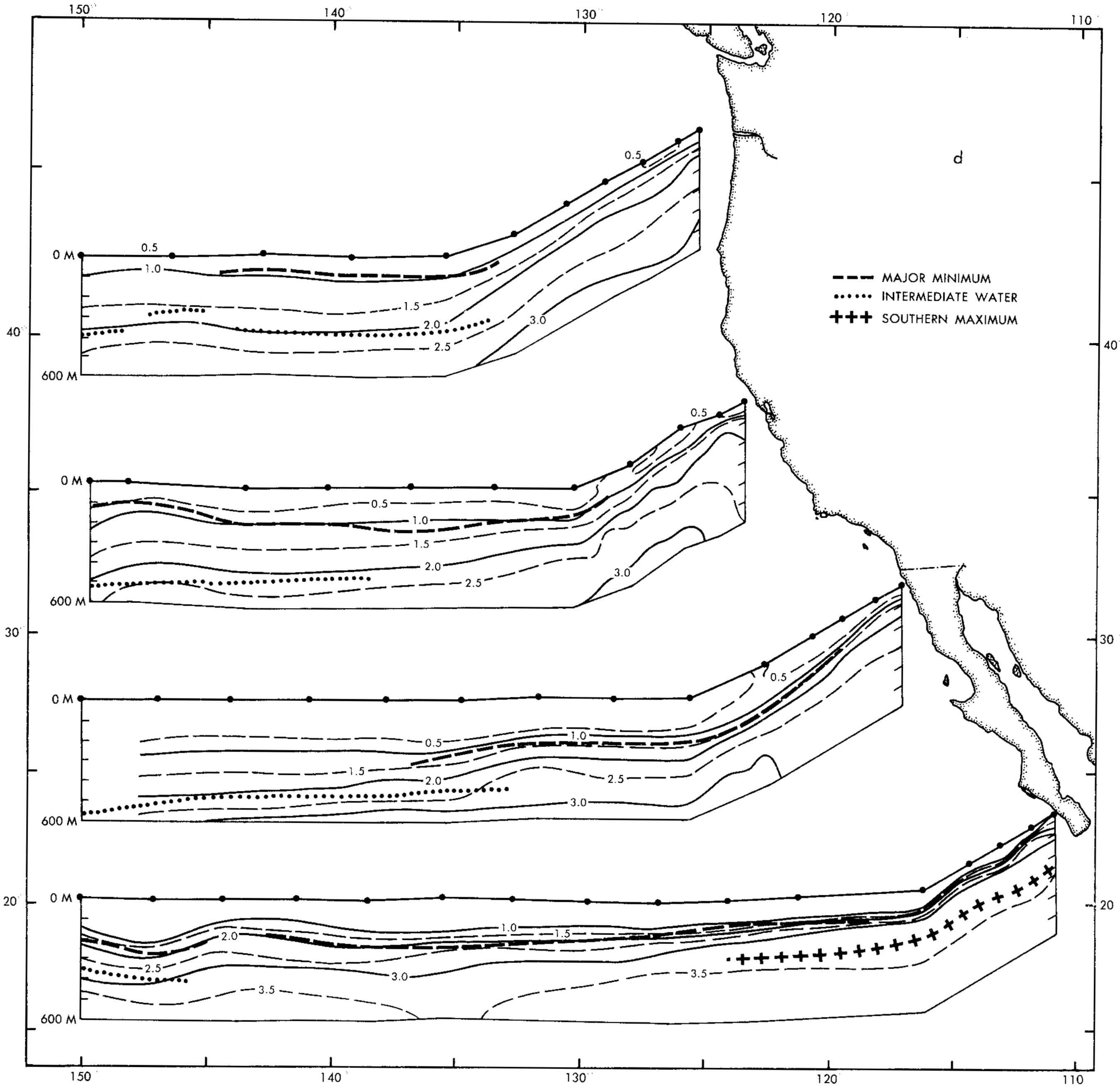
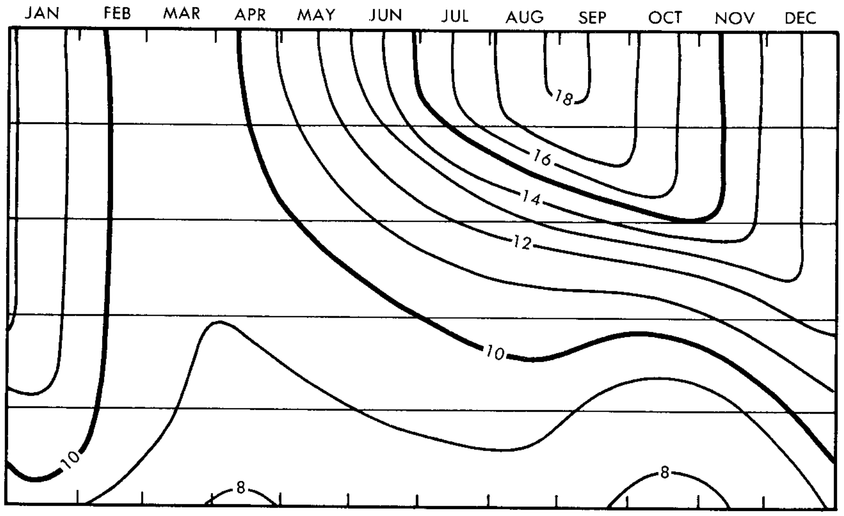


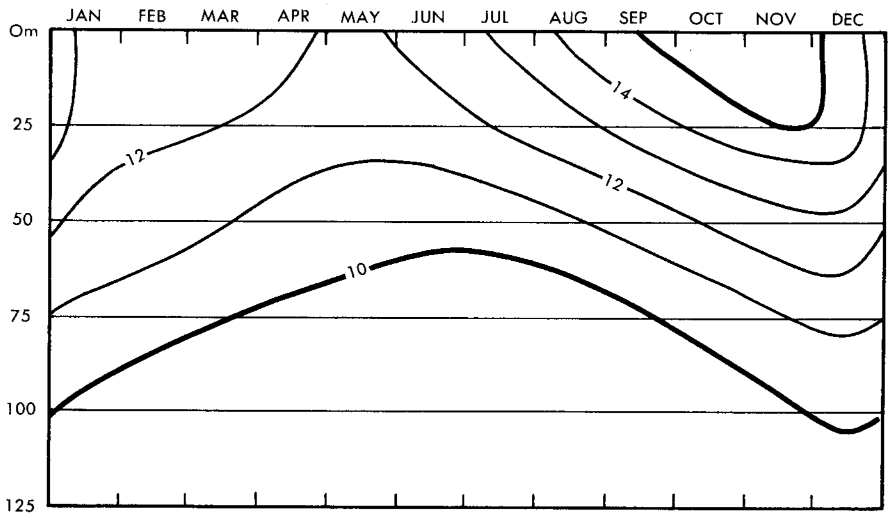
FIGURE 5—Continued

(d) Phosphate-phosphorus, microgram atoms per liter.

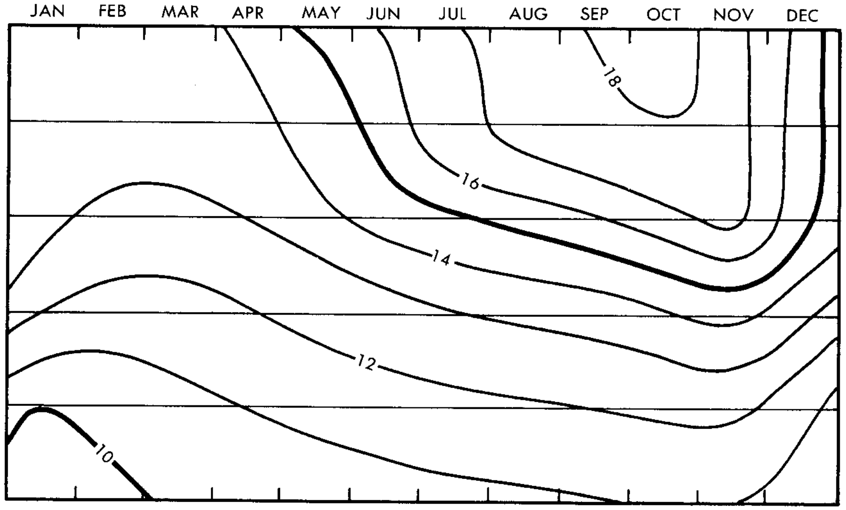
The results of the various seasonal forces are shown in figure 7 for the surface temperatures. Offshore the seasonal variation is largely the result of radiation and exchange with the atmosphere. A simple pattern is found with the ranges greatest in the north, where the variation of sunlight is greatest. Near the continent north of Point Conception the seasonal range is decreased and the cool period lengthened by upwelling. Between Point Conception and Punta Eugenia upwelling increases the seasonal range. South of Punta Eugenia the fall countercurrent raises the range above that offshore and delays the low until late spring. (Data for the areas 40-45° N 127-130° W, and 45-50° N 124-127° W, are from Robinson, 1957.)



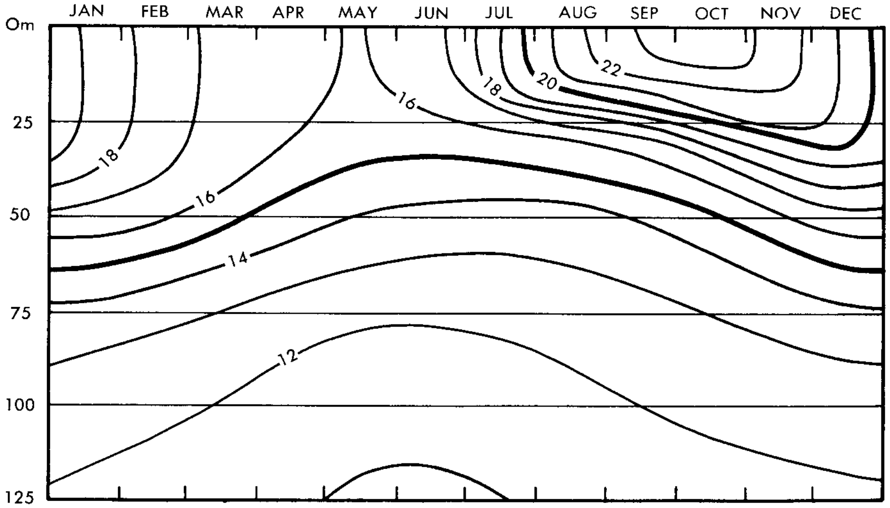
40°-45°N 130°-135°W



25 MILES OFF POINT CONCEPTION



185 MILES OFF POINT CONCEPTION



70 MILES OFF PUNTA ABREOJOS 26°N-114°W

FIGURE 6. Seasonal variation of temperature in the upper 125 meters at four locations. Temperature in degrees Centigrade, depth in meters. The upper left-hand section is from Robinson (1957); the other sections are from CCOFI data, 1949-55.

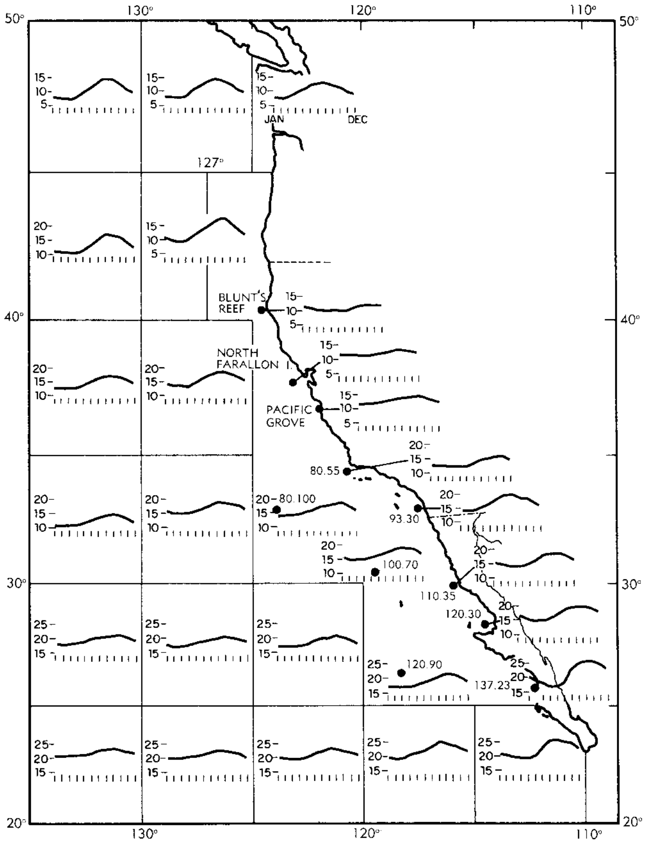


FIGURE 7. Seasonal variation of temperature at the surface off the western coast of North America. Temperature in degrees Centigrade. Values over five-degree squares are from Robinson (1957); values at Blunt's Reef, North Farallon Island and Pacific Grove are from U. S. Coast and Geodetic Survey (1956); values at numbered stations are from CCOFI data, 1949-55.

There are marked year-to-year differences in monthly average temperature. Such differences are indicated in the long and continuous (40 years) data for the Scripps Pier (Fig. 8). (Temperatures at this position will later be shown to represent to a high degree the general fluctuations in conditions off southern California and northern Baja California.) The maximum observed range of average monthly temperature is about 7° C and the average range is nearer 5° C. The frequency distributions are not symmetrical, especially during the months of minimum temperature (February through April). In this period the mean temperature is closer to the minimum than to the maximum of the range. This can be interpreted to mean that large temperature departures in the cold months are caused by an intrusion of warm rather than cold water. In late summer an opposite asymmetry is less clearly suggested.

In regions of small seasonal range the highest temperatures in one year may be lower than the lowest in another. Thus the monthly temperature averages at North Farallon Island (where the seasonal range is reduced by upwelling) in 1940 were higher throughout the year than in any month in 1955 (Fig. 9).

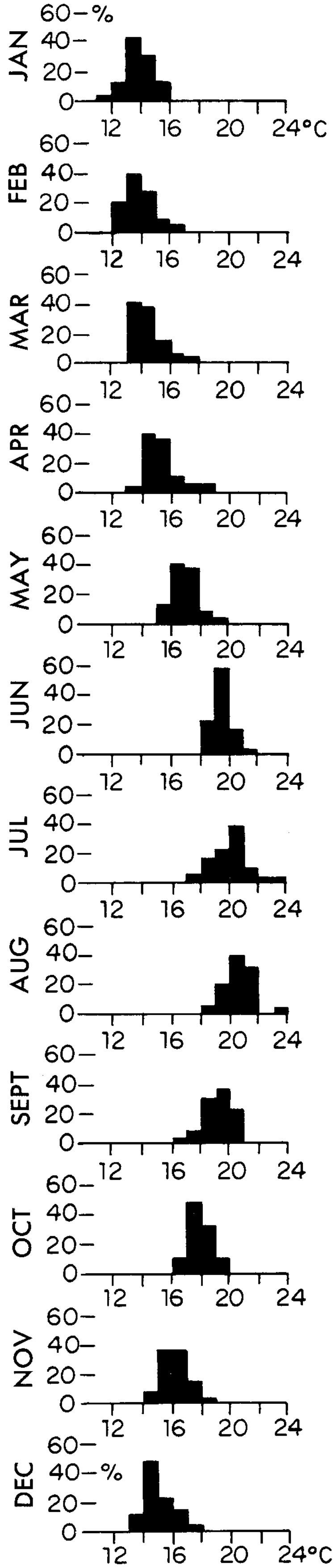


FIGURE 8. Frequency distribution of monthly average temperature at Scripps Pier, La Jolla, from 1917 to 1956. Temperature in degrees Centigrade.

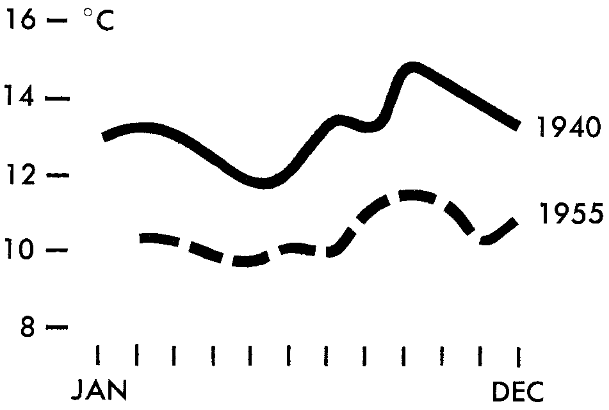


FIGURE 9. Monthly average temperature at North Farallon Island in 1940 and 1955. Temperature in degrees Centigrade.

Salinity

The California Current brings water of low salt content (about 32.5 parts per mille is the minimum value farther upstream) from higher latitudes down the coast where it mixes with water of higher salinity from below, from the west, from the inshore upwelling areas and the south (Figs. 10a and 10b). At times (Fig. 10a) the Columbia River makes an appreciable contribution of fresh water and at other times the countercurrent in the south contributes very salty water (Fig. 10c).

This history of the low-salinity Subarctic water as it moves down the coast is shown by the vertical profiles of figure 5b. On the upper line the water of low salinity is shown coming in above 200 meters. Already the horizontal mixing (which takes place faster in the upper layer) has caused the surface layer to be increased more than that below the permanent thermocline, and a slight but clearly detectable and continuous minimum can be seen (it is indicated by the long dashes). Values greater than 34.00 parts per mille (the shaded areas) are found over most of the deeper waters of the North Pacific (Sverdrup *et al.*, 1942) except where they are interrupted by Intermediate Water (dotted line). This water is generally supposed to form (*ibid.*) in the western Pacific at the intersection of the warm salty Kuroshio and cold, low-salinity Oyashio Currents in the winter, and it sinks to a depth corresponding to its density after mixing and spreads over nearly all the North Pacific. In the upper profile it loses its identity in the low-salinity Subarctic water of the California Current, and in the other profiles its low value is gradually increased by mixing with the higher salinities of the Equatorial Pacific and transition water to the east.

Before the water reaches the latitude of San Francisco much more east-west mixing has taken place, and the influx of salty water from the west has greatly intensified the difference between the surface values and the minimum. The effect of the Columbia River, shown to be small by the first profile, has now almost entirely disappeared.

Still farther south the amount of water of low salinity has diminished and the minimum has been gradually eroded by vertical mixing. The California Current does not terminate here, however, but can be traced to the west by its low salinity into the westward-flowing North Equatorial Current.

The effect of the subsurface countercurrent is most strongly seen in the last profile. The water, as it enters, has the temperature-salinity relation characteristic of the Equatorial Pacific water. The salinity is sufficiently greater than that of the California Current water above it and the deeper Pacific water below it to produce a maximum which continues as far north as Guadalupe Island. After the local maximum has been mixed away the Equatorial Pacific water can still be identified in a state of transition along the coast possibly as far north as the Gulf of Alaska, and in offshore waters as far as 40° N latitude.

The direct effect of the seasons upon salt content at the surface is limited to processes of precipitation and evaporation. Jacobs (1951) has estimated the difference between these terms in each season. Over the northern part of the current, rainfall predominates throughout the year, and evaporation in the south, with the boundary at San Francisco in summer and at Point Conception in winter. The seasonal changes are not large compared to other areas of the ocean. The largest difference is found off Washington and Oregon where rainfall exceeds evaporation in the winter by 14 centimeters per month and in the summer by only 3 centimeters per month. If this difference of 11 centimeters of rainfall were mixed into the upper 30 meters of water of about 32.5 parts per mille the salinity would drop by 0.12 part per mille, and this might be the order of the seasonal variation expected from exchange with the atmosphere.

Such a small range is difficult to detect against a background of strong vertical and horizontal variation (Figs. 5b and 10a-d). The minimum value would fall at about the time of year when the winds off Washington are from the southwest, and these may bring in enough salty, offshore water to cancel or reverse the trend. In any case, no such consistent minimum has been found in the offshore waters of the California Current. Although several large changes are indicated in the data taken by the CCOFI program in this region, they occur in such a scattered fashion as to present no coherent pattern at this writing. This may mean that offshore the seasonal variations are small compared to changes of other periods, and this will be taken up in the section on long-term variations.

Near the coast, however, several sorts of seasonal change are found. In the far north the runoff from the Columbia River has a seasonal variation, with the

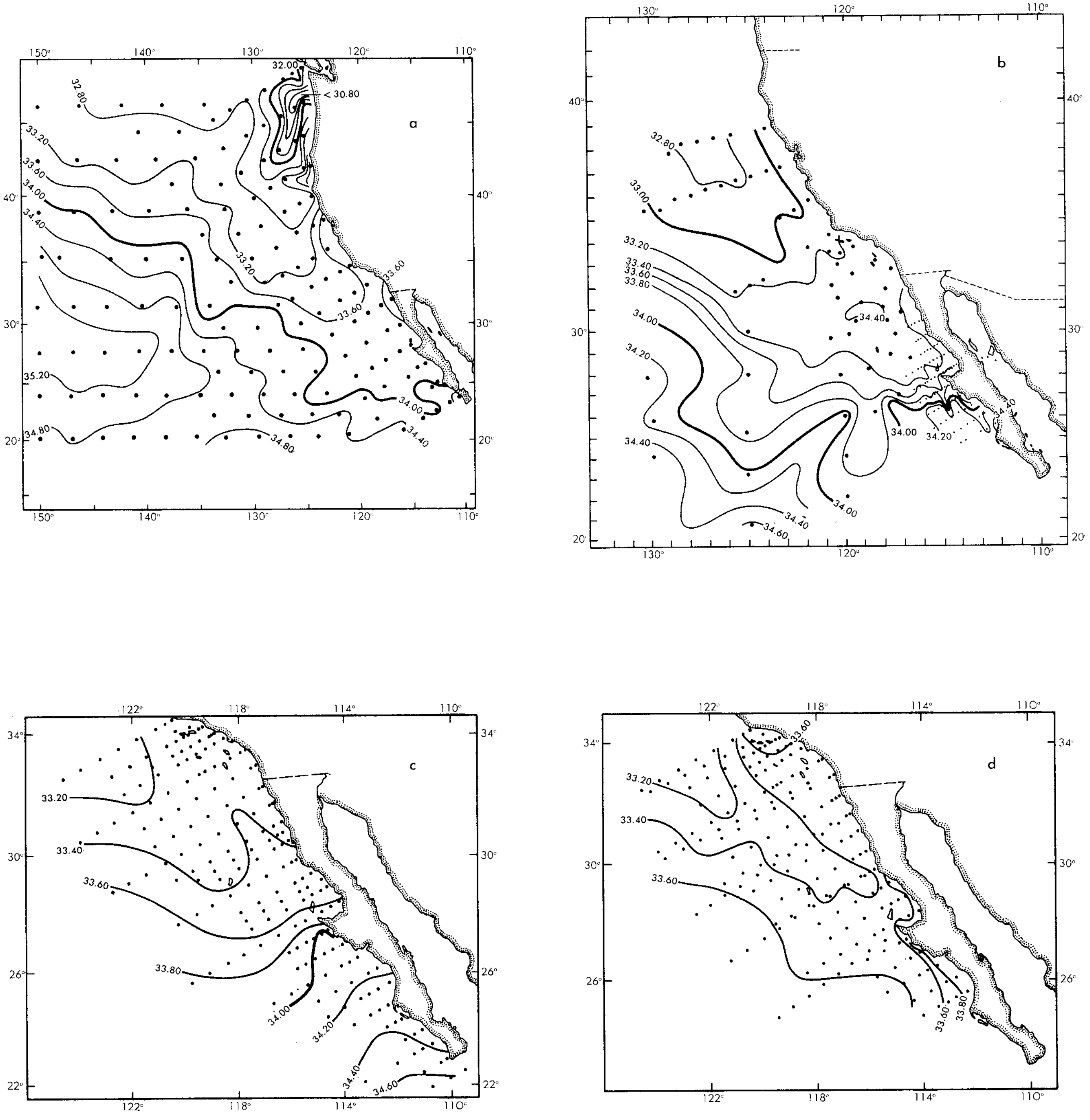


FIGURE 10. Salinity at 10 meters, in parts per mille. (a) August 1955. (b) March (composite). (c) January (average of three years). (d) June (average of three years).

highest outflow in May and June and the lowest from November through February. The U. S. Geological Survey (1952) reported that in 1951 and 1952 the rate of outflow ranged from 1800 to 7000 cubic meters per second. Although the greatest outflow is about a thousandth part of the California Current (Sverdrup, *et al.*, 1942), the fresh water is lighter and lies upon the top of the ocean water until it loses its identity by mixing.

It is in the salinity that the effect of the river water is most obvious. It spreads over the surface of the southward-moving current in a thin layer affecting noticeably only the upper 10 meters. In this thin surface layer the salinities may be reduced from the offshore value of 32.5 parts per mille to as low as 30 parts per mille. This is at once noticeable as a local minimum in salinity (Fig. 10a).

In temperature and oxygen measurements the effects of the river water are much less obvious, since the values in the river water are not so vastly different from those of the ocean water. The amount of dilution which has taken place by the time the waters have moved 100 miles offshore (in the above case 8 percent of river water to 92 percent of ocean water), obscures any difference. The same situation apparently holds true for the phosphate. Although the effect of the river water stands out on the charts of salinity, the charts of temperature, oxygen, and phosphate do not show any corresponding offshore peculiarities.

The CCOFI program has not measured the salinity north of Cape Blanco in the period December through February. The salinity in the area well south of the river shows a drop in July, which would be consonant with a maximum outflow in May and June, and the values are below oceanic from July through September.

Southward the two great causes of seasonal variation in salinity are upwelling and current. The values change as the upper waters are moved offshore by the wind at Point Conception and the countercurrent ebbs and flows south of Punta Eugenia (Fig. 11). The salty southern water advances in the fall and retreats in the spring.

North of Point Conception where the range of temperature from March to August is reduced by upwelling the range of salinity is increased (Figs. 10a and 10b). South of Point Conception the range is less. March and August are not the extreme months in the south. It is in January and June that the 10-meter salinities show the greatest effects of the countercurrent (Figs. 10c and 10d).

There are striking differences in seasonal variation at the surface over the whole area (Fig. 12). The extreme effect of upwelling is seen north of Point Conception and of the countercurrent south of Punta Eugenia, with their high and low values at different periods. In the intermediate area these effects combine and reduce the seasonal range. In the south the seasonal effects extend well offshore, but in the north the range is small and the nature of the variation is not clear.

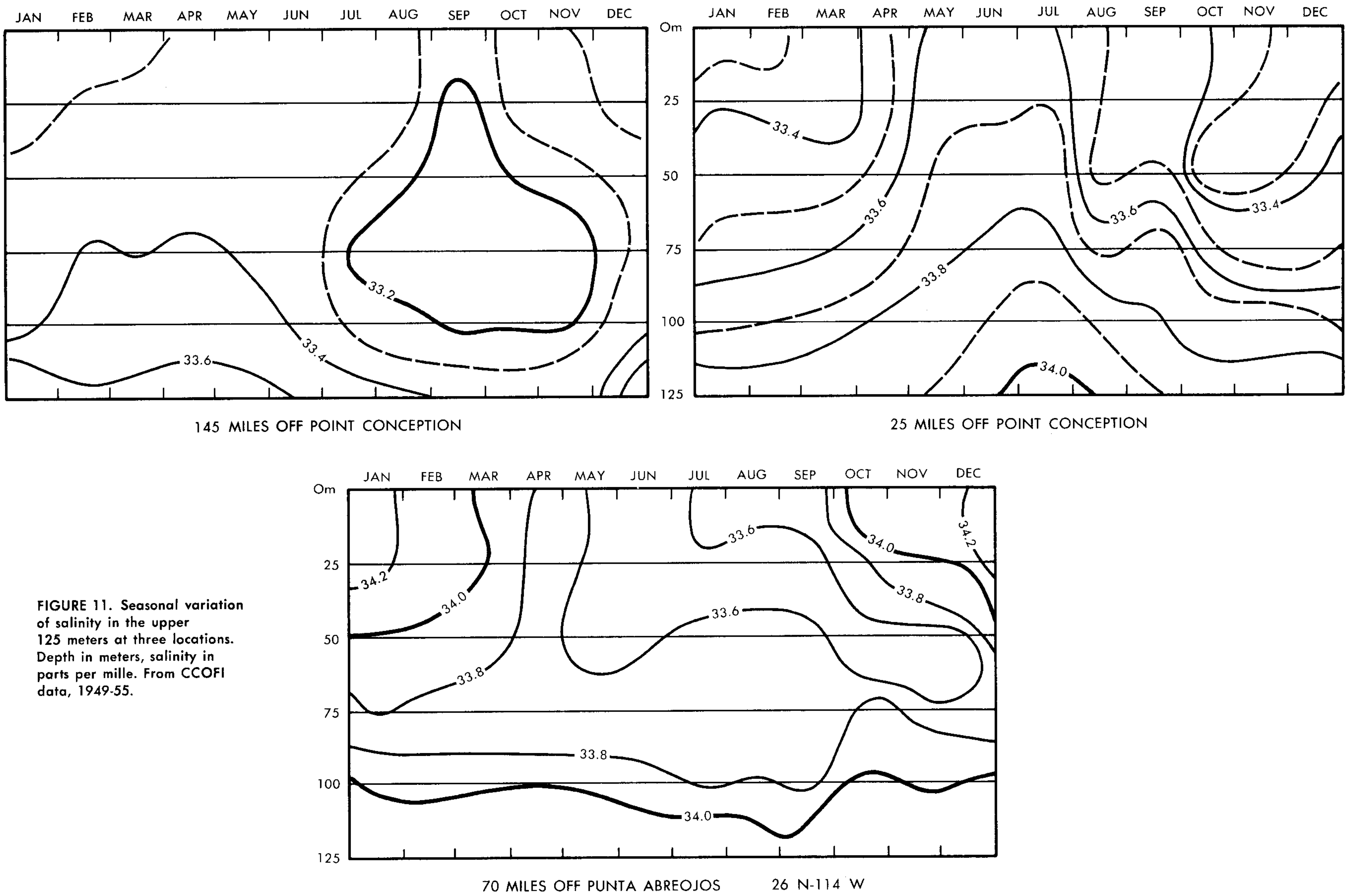
Oxygen

Oxygen will dissolve in sea water up to a limit (saturation value) which depends upon the temperature and salinity. Over most of the California Current the oxygen above the thermocline is concentrated to about 100 percent saturation. Oxygen is produced by the photosynthetic activities of plants in the upper levels of the ocean to which light can penetrate, and it is consumed by processes of respiration and decay. Since there are no new sources of oxygen at depth, the deeper waters become depleted in oxygen. The concentration of oxygen has been used as an indicator of the ''age'' of the water, that is, the length of time it has been away from any contact with the surface; and it is partly because of its low oxygen values that the deep Pacific water is thought to be older than the deep Atlantic water and to have originated in the Atlantic (Sverdrup *et al.*, 1942).

Most of the time the content of oxygen at the surface is at or slightly above 100 percent of the saturation value. Less often it is slightly below saturation. The saturation value of oxygen depends upon both temperature and salinity, but over the range of variation of these two quantities in the upper layers of the California Current, the temperature effect is several times larger than the effect of salinity. The saturation value of oxygen is higher at low temperatures; thus the deep waters, which are colder than the surface waters, could hold more oxygen, but they rarely do since the supply at depth is limited to mixing from above or vertical movement.

In summer the upper waters entering from the northwest are high in oxygen, containing greater than 7 milliliters per liter (Fig. 5c). In the southwest they hold generally less than 5.5. A striking feature of the upper-layer oxygen distribution is the shallow subsurface maximum found over most of the area in summer and fall. Below this maximum, and at a level corresponding to the salinity minimum, the oxygen shows a sharp drop. The percentage of saturation value, which has been at or above 100, drops as markedly. This may mean that the water above the permanent thermocline has relatively free access to the atmospheric oxygen, but that the stability of the water at the level of the salinity minimum (which allows a thin layer to preserve its low salinity over so many miles of motion) severely limits the transfer of oxygen downward from the rich layers.

In the deeper layers very low values are found off southern Baja California and extending northward along the coast. Values at 200 meters off the tip of the peninsula are less than one-tenth as high as those in the northwest (Fig. 13). This water of low oxygen



145 MILES OFF POINT CONCEPTION

25 MILES OFF POINT CONCEPTION

70 MILES OFF PUNTA ABREOJOS 26 N-114 W

FIGURE 11. Seasonal variation of salinity in the upper 125 meters at three locations. Depth in meters, salinity in parts per mille. From CCOFI data, 1949-55.

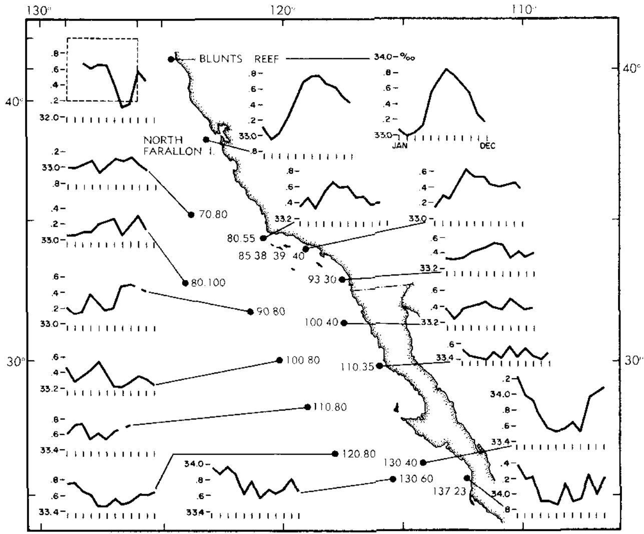


FIGURE 12. Seasonal variation of salinity at the surface off the western coast of North America. Salinity in parts per mille. Values at Blunt's Reef and North Farallon Island are from U. S. Coast and Geodetic Survey (1954); all other values are from CCOFI data, 1949-55.

has been discussed with the salinity and seen to be water from far south gradually weakening in distinction as it moves northwest. It is of high salinity and high phosphate as well (Fig. 5d). It must have been below the surface for a long period, for its oxygen has nearly been consumed in the decay of organic matter from the upper layer.

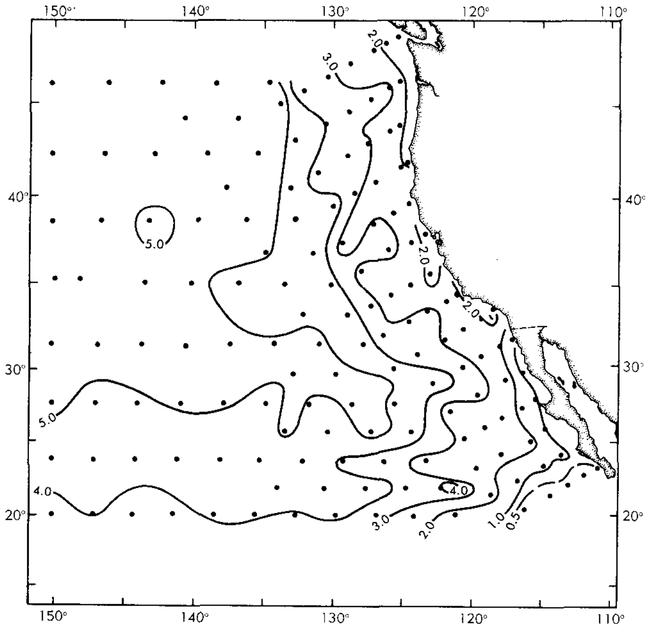


FIGURE 13. Dissolved oxygen, in milliliters per liter, at 200 meters, August 1955.

The seasonal variations of oxygen at the surface occur generally in response to the seasonal change in temperature (and thus saturation value); that is, in the cold months the water has more oxygen than in the warm months. The average range of this variation is about one milliliter per liter, though it may sometimes be higher. Thus the surface oxygen values offshore from Point Conception are usually slightly over 6 milliliters per liter from March to May and slightly under 5.5 from August through November. The occurrence of the high values is delayed over a month off Punta Eugenia, corresponding to the delayed minimum of temperature. The high and low values are about 6 and 5 milliliters per liter.

The surface values are sometimes less than 100 percent saturation. In periods of intense upwelling the water of low oxygen content from below may arrive at the surface and remain below saturation (as its temperature increases) for several days before saturation is attained.

The slight subsurface maximum (Fig. 5c) has been referred to as a summer and fall occurrence. Such a maximum is rarely found in the winter or spring. The sequence of formation of the maximum is generally as follows: In winter the oxygen values in the mixed layer are fairly constant with depth at about 100 percent saturation or very slightly above. In spring the surface values begin to fall. The oxygen content at 30 to 70 meters depth does not begin to fall until July or August; thus a maximum value is found around 50 meters from late spring until winter, nearly always slightly supersaturated.

A possible cause of the subsurface oxygen maximum is the subsurface production by phytoplankton. A more likely one might be the "entrapment" of oxygen by the water during the cold periods. If the values near the surface, which is in contact with the air, decrease more rapidly from their common winter maximum, then the subsurface water will for some period contain more oxygen. The lag of the deeper values behind the surface in the period of minimum and maximum temperature has been mentioned. This would cause the saturation limits of oxygen to decrease later at depth than at the surface. Redfield (1948), after examining the seasonal changes in the Gulf of Maine, concluded that over the whole year photosynthesis there has considerably less effect than changes of saturation value, but that at the period of minimum temperature (and small change) photosynthesis may dominate.

Phosphate

Phosphate is important to life in the sea as one of the principal nutrients. The North Pacific contains higher phosphate concentrations than the Atlantic or Indian Oceans. Its maximum values are well below the surface, usually just below the oxygen minimum, which places them at a depth of 1000 to 1200 meters (Wooster, 1953). Values greater than 1 microgram atom per liter are found in the Subarctic water at the surface north of 45° N latitude, increasing to values as great as 3 at a depth of 200 meters. At corresponding latitudes in the Central Atlantic Ocean the surface values are less than 0.1 microgram atom per liter (Sverdrup *et al.,* 1942). It has been shown, in fact, that for certain organisms the phosphate is present in sufficient quantity for growth everywhere in the North Pacific (Goldberg *et al.,* 1951). This has not been shown, however, for all organisms and for other nutrients. The phosphate continues to be investigated in the Pacific, not only because of its own possibly critical value, but because it may be an indicator of other nutrients.

The high phosphate values of the Subarctic water at 147° W longitude drop off sharply to the south (Fig. 5d). Below 35° N in that longitude they are less than 0.5 microgram atom per liter in the mixed layer. The average value over the southwest part of the region is about 0.3 microgram atom per liter. Phosphate is concentrated at depth (Fig. 5d) and its upward diffusion is found to be limited, as was the downward diffusion of the oxygen, by the stable layer below the seasonable thermocline. In regions where there is a salinity minimum below the mixed layer, the first marked increase of phosphate is almost invariably found at the minimum value of salinity. In the California Current system the mixed layer is shallower near the land. Some photosynthesis may take place beneath the mixed layer in the nearshore regions, and the nutrients used in the process can be more easily replaced than those in the mixed layer by diffusion from below.

Over the Northeastern Pacific the horizontal distribution of phosphate at 100 meters depth and the horizontal distribution of zooplankton are very much alike (Figs. 14 to 16). The higher zooplankton volumes are found in the Subarctic waters where they lie near the surface in the California Current region, and especially in the regions of upwelling. Farther offshore the high values of phosphate are found at greater depths, where no photosynthesis can take place, and where replenishment of the surface waters is very slow.

The close relation of phosphate to zooplankton is somewhat baffling if, as has been suggested, the phosphate values in the Pacific are high enough everywhere to promote normal growth. The relation holds however not only in a rough fashion over large areas (Figs. 14a and 14b) but in a remarkable station-to-station coherence (Figs. 15a-b and 16a-b). This indicates that the zooplankton growth takes place in the areas of high phosphate near the coast, and that parcels of this water moving outward into the main stream contain both high phosphate and high zooplankton volumes.

The seasonal variations of phosphate are more difficult to understand in the California Current system than they have been in the Atlantic. Redfield (1948) and Redfield, Smith, and Ketchum (1937) have discussed the seasonal variation of phosphate in the Gulf of Maine; and Atkins (1923-30) and Cooper (1933 and 1938) have discussed the variation in phosphate in the English Channel. In both regions a marked change occurred in the upper levels in summer owing to the consumption of the phosphate by the phytoplankton. However, the lowest values near the California coast at any time of year are generally higher than the highest values ever attained in the two Atlantic areas mentioned. The same consumption of phosphate in the California Current would cause a proportionately smaller drop in phosphate. Furthermore, the periods of minimum phosphate found by the authors mentioned above occur in summer as the result of heavy plant growth. This same period in the California Current is one of great replenishment of phosphate by upwelling. In a discussion of the seasonal variation of oxygen in the Gulf of Maine, which has already been mentioned, Redfield (1948) made use of a relation between the oxygen and phosphate transformation in the biological processes of photosynthesis and respiration. He accounted in part for the seasonal change in oxygen by the change in phosphate. Using this relation, and taking into account the maximum effect of photosynthesis allowed by the observed values of chlorophyll "a" in the region south of Point Conception (Holmes, personal communication), an absolute maximum consumption of phosphate of the order of 0.4 microgram atom per liter per month might be attained. The actual value is likely to be much less than this, and the amount of upwelling necessary to produce the observed temperature and salinity effects near the coast could easily counterbalance this consumption.

On the other hand, the phosphate values have not shown the effects of upwelling as clearly as have temperature and salinity. The measurement of phosphate has not been carried on as successfully by the program as have the measurement of temperature, salinity, and oxygen; and the measurement has not been so continuous nor covered so wide an area. Higher values near the surface are found at the appropriate times as the result of upwelling, but the appearances are not so regular or simple as those of temperature and salinity.

RELATION OF THE ENVIRONMENT TO THE PLANTS AND ANIMALS

The previous discussion has shown that the California Current system contains a band of cool water reaching from high latitudes far down the coast of North America. It brings in waters of relatively high phosphate content (Fig. 14a), in sharp contrast to the waters farther offshore. Along the coast this

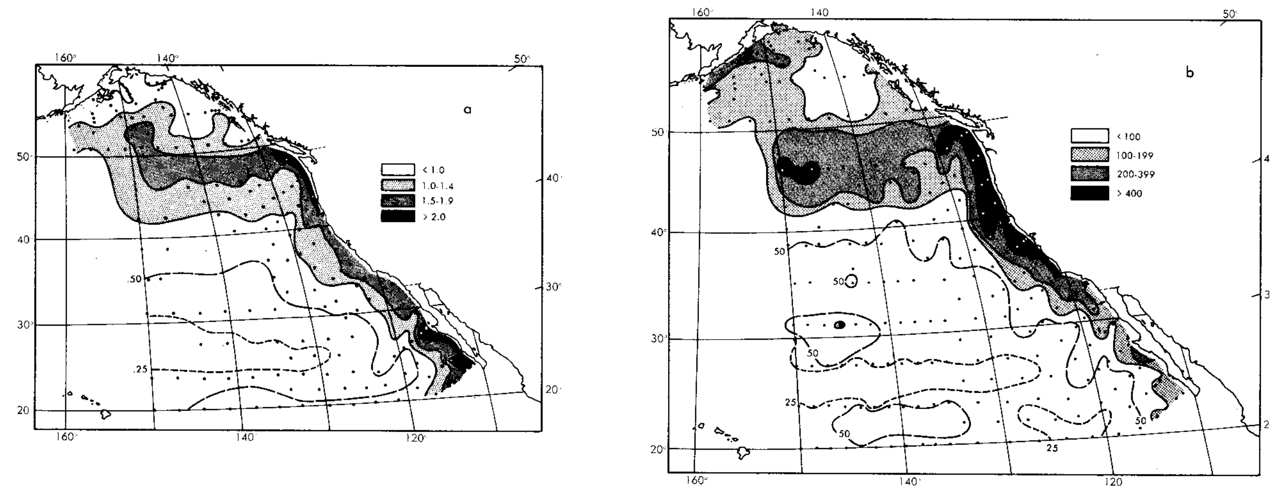


FIGURE 14. Distribution of phosphate-phosphorus and zooplankton volumes, August 1955. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

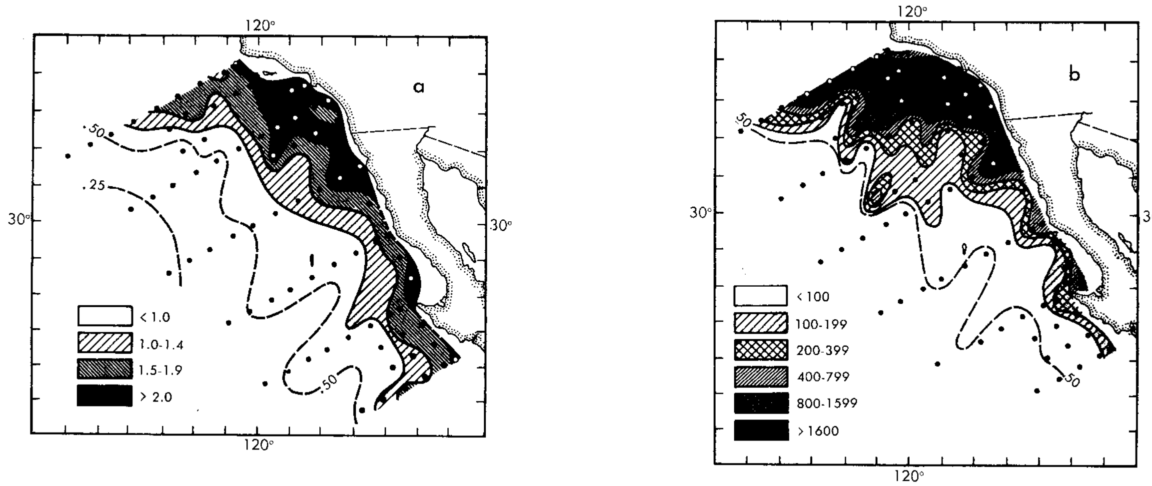


FIGURE 15. Distribution of phosphate-phosphorus and zooplankton volumes, April 1950. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

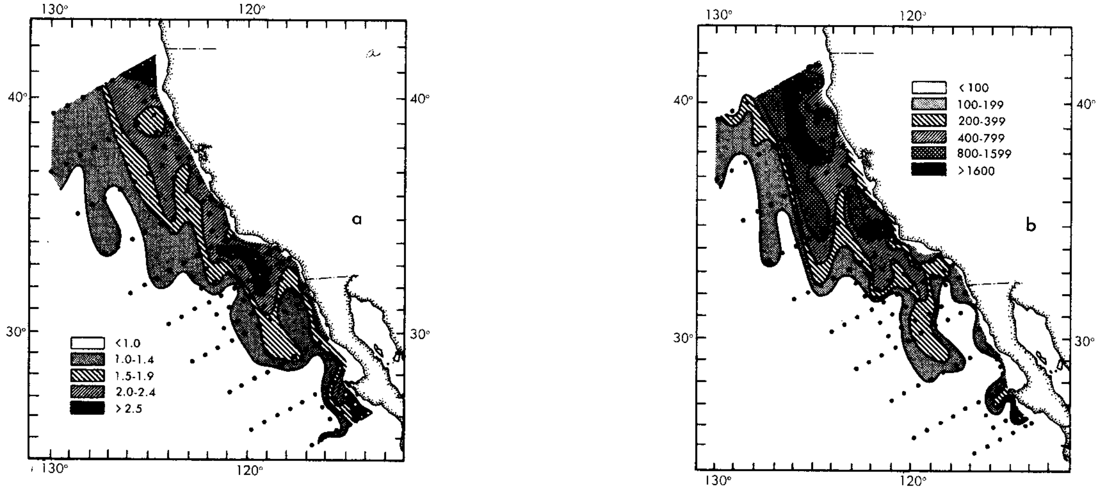


FIGURE 16. Distribution of phosphate-phosphorus and zooplankton volumes, July 1950. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

higher value of phosphate is reinforced by the upwelling of deeper waters whose nutrient properties have not been exhausted. From the south at a depth of about 200 meters another current, also high in phosphate content, moves northward. This water has but little dissolved oxygen left (Figs. 5c and 13). This indicates that the oxygen has been depleted by respiration and the decay, over a long period, of organic material. The product of this decay is nutrient material, which is transported up the coast immediately below the surface layer and becomes available to the plants by mixing and upwelling.

The result, then, is a narrow band of waters all along the coast which are high in phosphate and presumably other nutrients. One effect of the richness of these waters is seen in the high volumes of zooplankton along the coast (Figs. 14 to 16), which are highest in regions where the upwelling and mixing are strongest. These high volumes contrast sharply with those of the less abundant waters of the west and southwest, and it is this great mass of living matter which accounts for the coastal fisheries.

This living matter, however, is of vastly different kinds, each with its own particular needs, so that within the region the species have quite different sorts of distributions. Most of the planktonic animals prefer the nearshore waters, but some have particular needs which cause them to live in greatest quantity offshore.

Relations have been found between the character of water masses and currents off southern California and the marine plants, diatoms (Sverdrup and Allen, 1939). Of particular interest is the finding that the offshore waters contain few diatoms, whereas the eddies of inshore water may contain large numbers. They found that the "age" of the surface water was an important factor. Newly upwelled water is high in nutrients, but after it has been at the surface for a long time, as is the case with the offshore waters, its nutrients have been consumed.

The planktonic animals have little power to move through the water and are transported largely by the currents. Different species and different stages of one species may live at different depths and have different limitations. Some must live near the surface and some avoid light and some move up and down. Some thrive at high temperature, some at low and some over a wide range of temperature. The charts showing the distribution of properties have shown that the properties vary in different manners. It does not seem impossible that an organism may be limited on one side of its distribution by temperature and on another side by some other properties, such as nutrients. Certain interesting examples of the regions inhabited by particular species are shown in figures 17a to e, on which are drawn certain other properties, which seem to coincide with their boundaries. The examples cover the larger part of the California Current system. Some species are distributed in the very cold, rich, waters of the northeast; others limited perhaps by a need for higher temperatures, are found to the southwest and may have an upper temperature limitation farther west.

The requirements of the organisms shown are not well enough understood for us to conclude that the properties illustrated at the boundaries are the effective ones. The euphausiids, in particular, are difficult to understand since they undergo a diurnal migration, and are deep in the daytime and near the surface at night. As they must move back and forth across a wide range of temperature in their migration, it is difficult to think that some temperature at a particular depth should be the major limiting factor. Work has been done upon this (Boden, *et al.*, 1955) and is being continued. The euphausiid distributions (Figs. 17a to d) are from work made available by Dr. Edward Brinton and the salp distribution (Fig. 17e) is from Dr. Leo D. Berner.

NON-SEASONAL VARIATIONS IN THE CALIFORNIA CURRENT SYSTEM SINCE 1916

The dependence of specific organisms on certain properties of the water masses has been assumed and to some extent measured. If conditions in the water are different in one year from another, certain organisms which thrive in the one year might not do well in the other. If long series of data were available for both the organisms and the current, the dependence might be explored statistically. The length of time this series would have to cover would depend upon the simplicity of the relation and upon the nature of the variations in condition and distribution. If the period since 1949 contained several highly unusual years, which were different from each other, the dependence could be much more easily established than if the years were more nearly alike.

In order to have some background against which the period of the CCOFI program can be examined, certain previous data have been used. In the late '30s and early '40s the cruises of the California Fish and Game vessel *Bluefin* and the Scripps Institution vessel *E. W. Scripps* made many measurements near the Channel Islands area of southern California. The *E. W. Scripps* also made one long cruise in 1939 from Cape Mendocino to Punta Eugenia and two cruises into the Gulf of California, in 1939 and 1940.

In addition to these data, surface temperatures had been measured by merchant vessels for many years, and various agencies have collected these and arranged them by monthly averages for 5-degree squares of latitude and longitude for each year. Principal among these agencies is the Kobe Imperial Marine Observatory in Japan to which we are indebted for

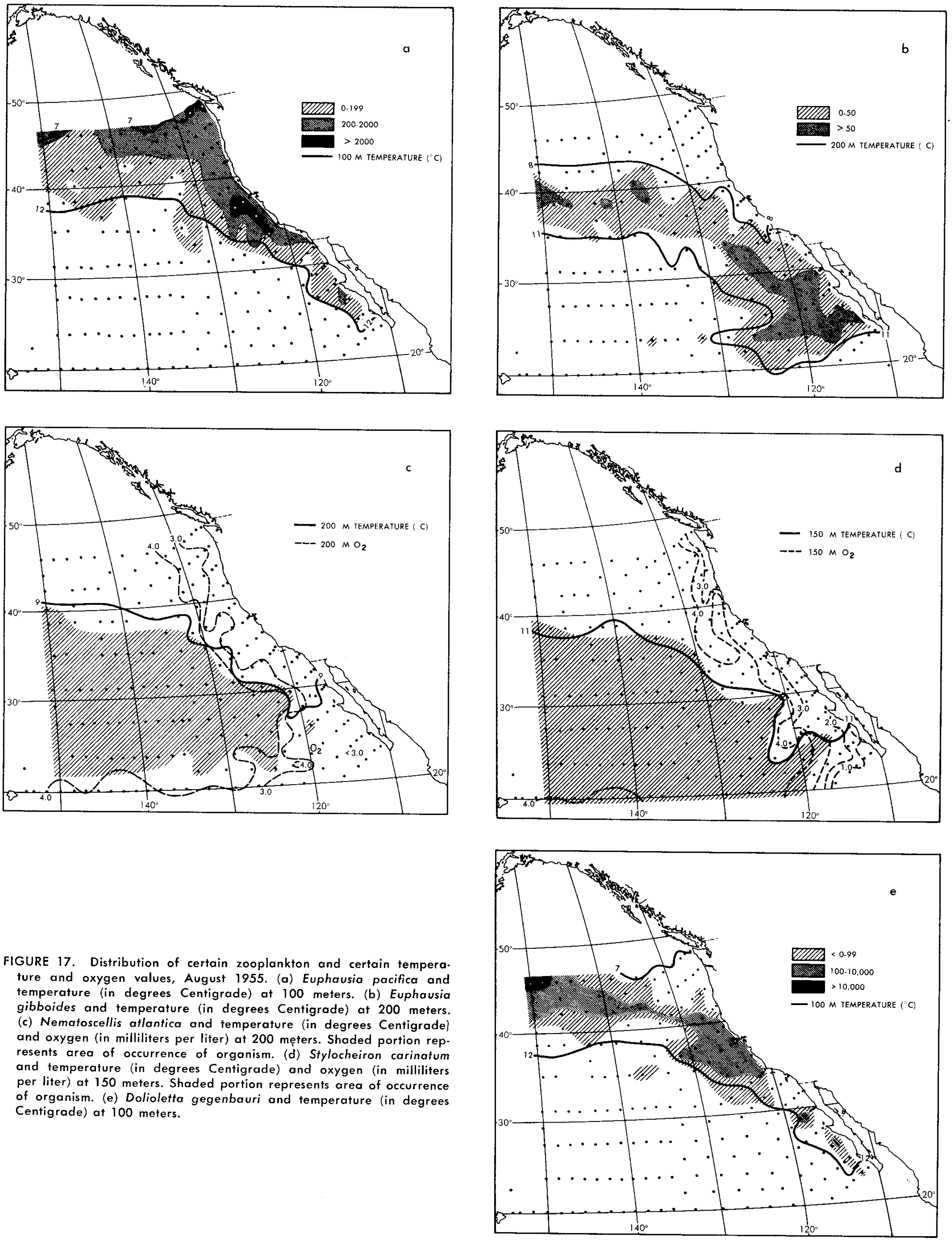


FIGURE 17. Distribution of certain zooplankton and certain temperature and oxygen values, August 1955. (a) *Euphausia pacifica* and temperature (in degrees Centigrade) at 100 meters. (b) *Euphausia gibboides* and temperature (in degrees Centigrade) at 200 meters. (c) *Nematoscellis atlantica* and temperature (in degrees Centigrade) and oxygen (in milliliters per liter) at 200 meters. Shaded portion represents area of occurrence of organism. (d) *Stylocheiron carinatum* and temperature (in degrees Centigrade) and oxygen (in milliliters per liter) at 150 meters. Shaded portion represents area of occurrence of organism. (e) *Doliolettta gegenbauri* and temperature (in degrees Centigrade) at 100 meters.

the publication of such data over the North Pacific Ocean from 1911 through 1938. In addition, for many years, the U. S. Coast and Geodetic Survey has taken sea level temperature and salinity measurements at various of its tide gauge installations along the west coast of North America and Alaska. Observations of surface temperature and salinity from 1923 through 1940 are available for the Blunt's Reef light vessel and from North Farallon Island. Surface temperature and salinity measurements have been made daily at Pacific Grove and at Scripps Pier for many years.

Meteorological data are available from the U. S. Weather Bureau in the form of sea level atmospheric pressure averaged by months from 1899 to the present.

With these data in hand, it has been possible to compare the variations from year to year of temperature, salinity, and wind at various places. With the exception of the surface temperatures from merchant vessels, however, the hydrographic data are almost entirely from the *Bluefin* and *E. W. Scripps* cruises 20 years ago and the CCOFI cruises which began in 1949.

These data would seem rather scanty for an analysis of variations in a major current over a long period, but certain of the initial results have been encouraging. The variations in temperature at points along the coast of North America show considerable coherence over great distances. The major anomalies in temperature, high or low, seem to last several months, implying that monthly averages are not an unlikely method of approach. Certain of these data are shown by monthly anomalies (Fig. 18); that is, the value plotted in June of a given year represents the amount by which the average temperature in June of that year was higher or lower than the average of all the Junes from 1920 to the present. (Some of the data are from the Japanese sources and are available only through 1938.)

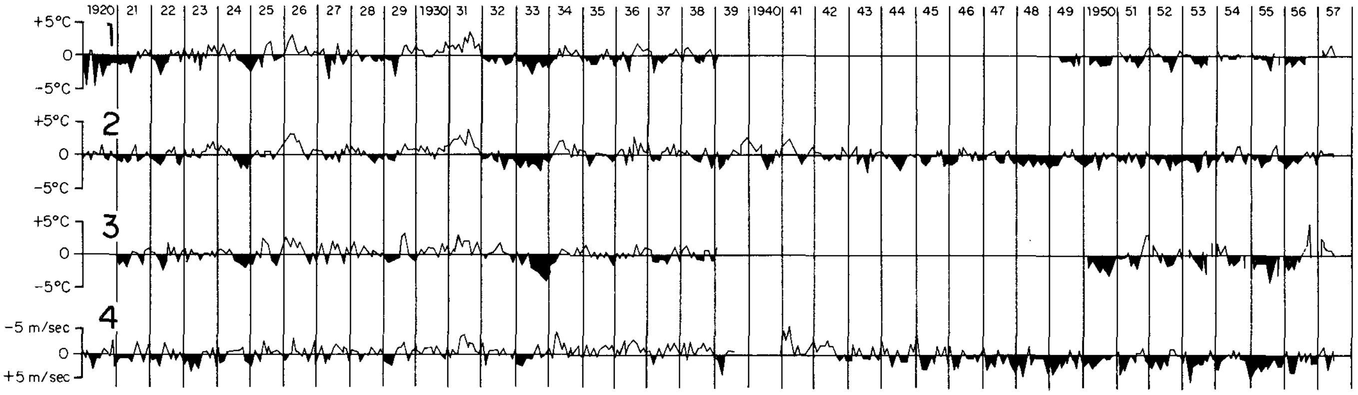


FIGURE 18. Monthly differences from average sea surface temperatures (degrees Centigrade) at (1) 30°-35° N, 115°-120° W, (2) Scripps Pier, and (3) 25°-30° N, 110°-115° W; and (4) monthly differences from average northerly wind component (in meters per second) at 30° N, 110°-130° W.

The principal cold periods were from 1920 to 1924, in 1932 and 1933, and from 1948 through 1956. The warmest groups of years were from 1926 through 1931, and from 1934 through 1944. The variation in the strength of the north wind from its monthly mean over the same period is also shown (Fig. 18, part 4) and a certain similarity in long-term variation is seen between wind and temperature anomalies.

The last few years stand out from the long-term mean both in temperature and salinity (Figs. 19 and 20). The winter and spring temperatures are low and the summer values more normal or high. The salinity values are high in winter and spring and more nearly normal the rest of the year. Although there is some variation from year to year since 1949, the deviations have not been extreme (Fig. 18) except possibly south of Punta Eugenia. From 1949 through 1956 there were no years as extreme as 1926, 1931, 1933, or 1941.

A cause for this behavior has been sought in the variations of the strength of the wind. The northerly component of wind (computed from atmospheric pressure difference at 30° N latitude between 110° W and 130° W longitude) was generally stronger in the last decade (Fig. 20). A significant correlation has been found between the wind anomalies and the temperature and salinity anomalies in the spring and early summer months where as many as 18 years of data are available (Roden and Reid, Ms. in preparation). It is in these months that the greatest variations from the mean are found in the wind data. In August, although the winds are strong, the variation of monthly averages about the long-term mean is much smaller. The mechanism of this relation may be an increased amount of upwelling, and possibly an increased amount of Subarctic water being brought south by the northerly winds. The correlation holds in all the data from Blunt's Reef to Magdalena Bay during these months. In the latter part of the year the winds have varied less, and no significant correlation has been found.

The fact that temperature has been lowered and salinity raised during this period implies that at least

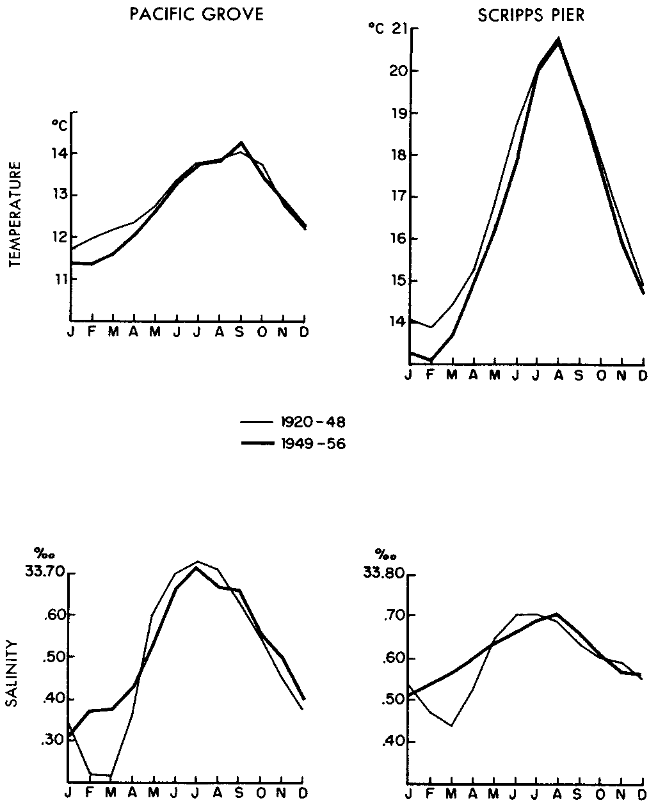


FIGURE 19. Average surface temperature (degrees Centigrade) and salinity (parts per mille) at Pacific Grove and Scripps Pier for the periods 1949-56 and 1920-48.

part of this process is upwelling, since the evaporation minus precipitation values here (Jacobs, 1951) are quite small. There are no earlier phosphate data with which the CCOFI data can be compared.

It may then be concluded that the period from 1949 to 1956 is distinguished from the previous 15 or 20 years by substantially colder waters in the first few months of the year. There are differences in the years from 1949 to the present (which will be taken up later), but they have nearly all exhibited this colder feature in the early months.

The sea surface temperature in the period from 1945 to 1956 showed no values extreme enough to compare with those of the intensity and endurance of 1926, 1931, 1933, 1940, or 1941 (Fig. 18). A certain coherence of the system is at once obvious from the data from 1949 to the present (Fig. 21). These data allow one to generalize somewhat about the difference in the various years. South of Punta Eugenia the data in the 5-degree square show some greater irregularities and indicate some difference in behavior from those to the north. They generally show the same phenomenon of cold springs which have a significant correlation with the northerly winds. The most remarkable variations in this period have been south of

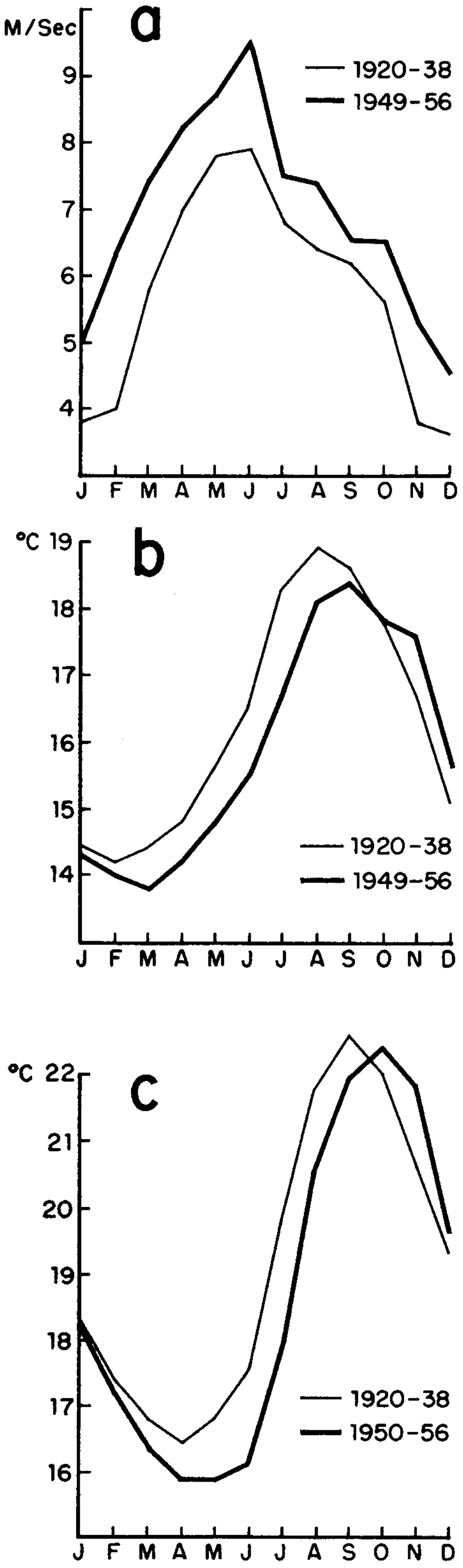


FIGURE 20. Average northerly wind component and temperature in recent period compared to averages for 1920-38. (a) Northerly wind component in meters per second at 30° N in years 1949-56. (b) Temperature in degrees Centigrade at 30°-35° N, 115°-120° W, 1949-56. (c) Temperature in degrees Centigrade at 25°-30° N, 110°-115° W, 1950-56. No data 1939-48.

Punta Eugenia where the late fall of 1951 was unusually warm and the summer of 1955 was unusually cold. It is unfortunate that in 1940 and 1941, when the temperatures over all the west coast north of San Diego are known to have been at their highest in the last 25 years, no data are available from the vicinity of Punta Eugenia. A comparison of 1951 with 1940 and 1941 might be of interest.

Over most of the area, 1954 was the warmest year, though there was at least one cold month toward the end of the year. The year 1949 began well below normal in winter and spring and was somewhat above normal in the early fall. Likewise, 1950 was below normal in winter and spring but did not show the same summer and fall warming as had 1949. The year 1951 was more normal during the first few months but at different places showed both warming and cooling toward the end of the year. In most places, 1952 began somewhat above normal but dropped below normal in the fall. The year 1953 began slightly above normal and in the north was above normal again in the fall but in the south was cooler in the fall. The year 1954, in most of the data, was well above normal most of the year dropping below only in November and December in most places. The year 1955, in much of the data, was well below the normal and 1956 was likewise generally cool. In 1957, the southern California waters seem to be at or above normal through June (Fig. 22). North Farallon Island shows temperatures slightly below normal averaged through June, and data from Blunt's Reef through April show values generally below normal.

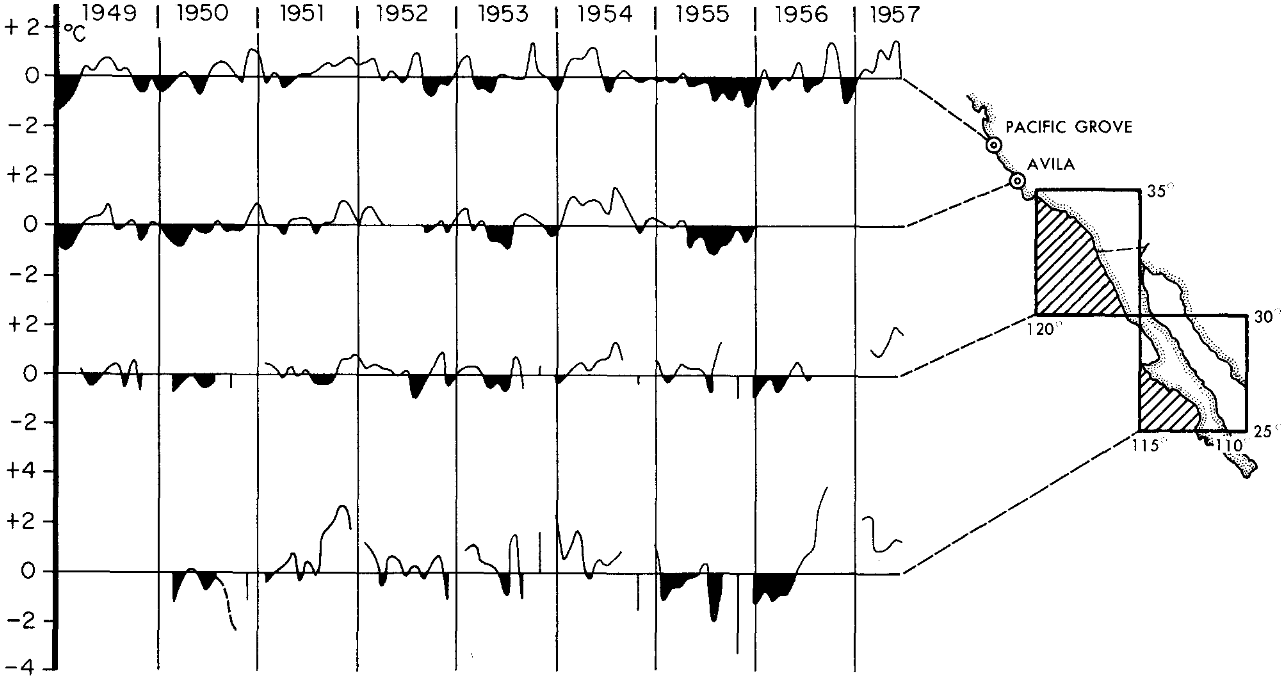


FIGURE 21. Temperature anomalies, 1949 to 1957, at four locations as referred to 1949-56 mean. Temperature in degrees Centigrade.

POSSIBLE EFFECTS OF VARIATION IN THE CURRENT SYSTEM UPON THE ORGANISMS

Before 1949 only a few measurements of the plant and animal populations of the California Current system had been made. Since 1949 the volume of zooplankton has been measured over a great part of the current nearly every month, and much has been learned about the distribution in space and time. Because different methods of measuring zooplankton were used before 1940, it is not easy to compare present populations with those in the past, yet some significant indications have been obtained. The nature of the waters of the California Current has been discussed, and the distribution of the properties, especially phosphate as an index to the nutrients, has been described. A simple relation between zooplankton and phosphate has been shown (Figs. 14-16). Phosphate has not been measured regularly, and very few measurements in this region were made before 1949; therefore in using the available data any significant relation of zooplankton to the environment which can account for changes in time of the population must involve some other parameter than phosphate or nutrients—some parameter for which data exist over a longer period.

In previous discussion of the current system and its variation it was mentioned that the only property for which any long series of data exist is temperature. The general relation of temperature to phosphate has not yet been mentioned, but an examination of the

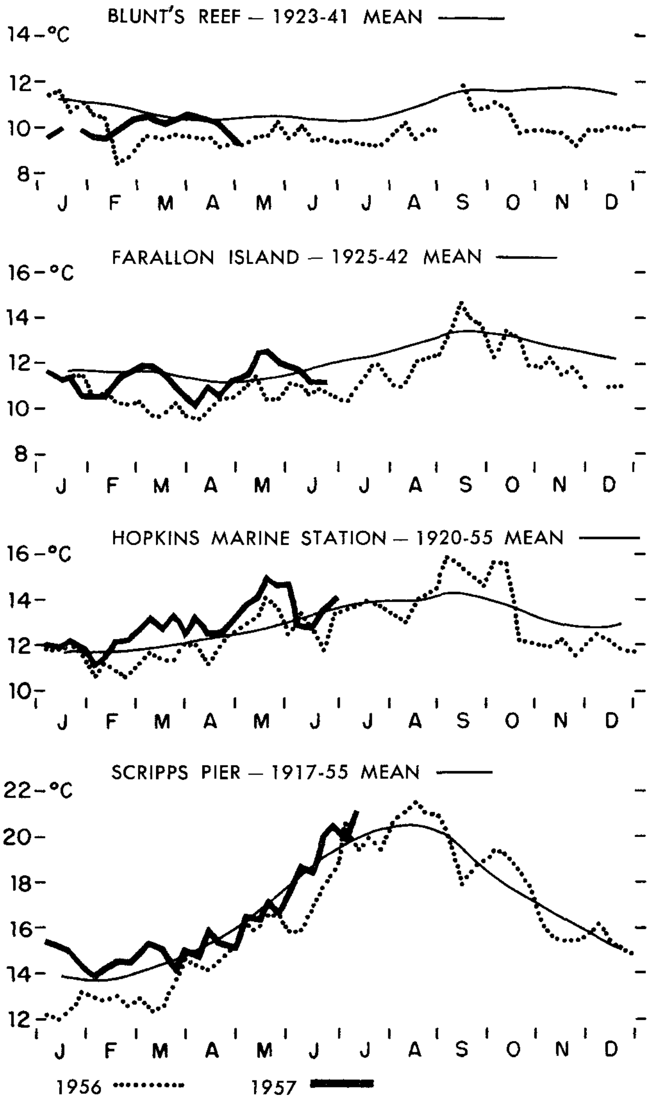


FIGURE 22. Temperatures in 1956 and 1957 at four locations as compared to long-term means. Temperature in degrees Centigrade.

charts of temperature and phosphate shows that over a vast area, including the nearshore waters of Baja California and the west coast of the United States, high phosphate values are generally accompanied by low temperatures. This holds not only vertically, where the deeper waters contain the products of decayed organic matter, but horizontally as well. The Subarctic waters of the north, which form a great part of the surface waters of the California Current system, are both cool and high in phosphate. Therefore, in the regions of the California Current one may with some confidence use the low temperature in the mixed layer as an indicator of higher nutrient properties.

The succession of relatively cool years from 1946 has been mentioned. Where data have been available salinities have been found to be higher near the coast in the same period. If one assumes that the cooling of the surface waters of the California Current and the increase in their inshore salinities are due to an internal redistribution of the heat and salt, as would result from upwelling, rather than a loss of heat and water to the atmosphere, then the accompanying redistribution of phosphate and other nutrients would have considerably enriched the surface waters.

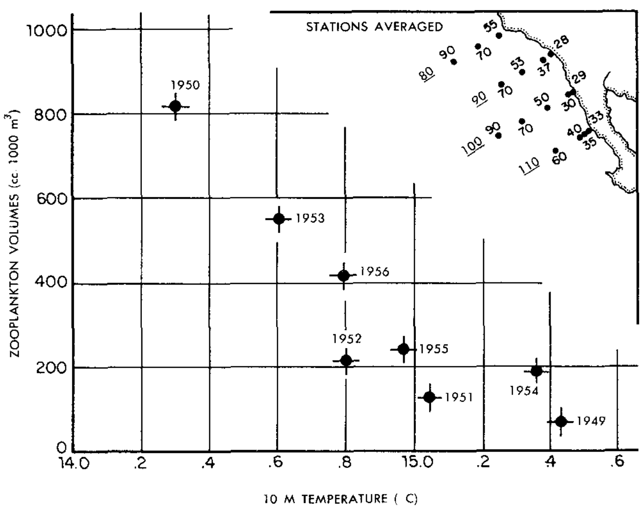


FIGURE 23. Temperature at 10 meters (in degrees Centigrade) and zooplankton volumes (in cubic centimeters per 1000 cubic meters) averaged from February through August for each year from 1949 through 1956.

The dependence of zooplankton upon the nutrients is, of course, an indirect one via the phytoplankton. If it had been consistently measured, the phytoplankton might be expected to yield a better correlation than zooplankton with the nutrients. In the region between Point Conception and Punta Eugenia, however, a satisfactory relation has been found during the seven years for which data are available (Fig. 23). (Zooplankton data were prepared for figure 23 by Mr. James Thrailkill of the U. S. Fish and Wildlife Service.) Indeed, if there is no direct relation between zooplankton growth and temperature, the relation shown between the temperature as an indirect measure of nutrients and zooplankton as an indirect measure of phytoplankton is better than would be expected, and greater irregularities will almost certainly be found in subsequent data.

Within certain limits of temperature, the zooplankton volumes were lowest when the temperatures were high and highest when the temperatures were low (Fig. 23). Data from 1940 and 1941 cannot be plotted on this chart, since the cruises made in those years covered only a small part of the area. However, there is qualitative agreement in that the plankton volumes measured in the region of southern California in 1941 (E. H. Ahlstrom, personal communication) averaged only 103 cubic centimeters per 1000 cubic meters, and 1941, as has been shown (Fig. 21), had also the highest temperatures observed in any year from 1931 to the present.

South of Punta Eugenia, where the zooplankton volumes have generally been smaller and the temperatures higher, a similar plot of zooplankton volumes against temperature is not nearly so regular. Although a similar trend can be seen, these data are hardly convincing.

Correlations of this type are difficult to make not only because the temperatures and zooplankton are not sampled as completely as we should desire, but because the zooplankton varies from year to year in a fashion more complex than gross amount. There are data to suggest, at least, that the response of the zooplankton to changing hydrographic conditions is not only in mass but in change of species as well. Salps, for example, may predominate one year and other groups in other years, with the volumes not changing significantly. All of the area is inhabited (Figs. 17a-e), and it can well be imagined that a change in conditions could cause the boundaries to move so that the species would inhabit slightly different regions, without a great change occurring in gross amount.

CONCLUSION

The waters of the California Current and their manner of flow in the fishery region of California, both horizontal and vertical, have been briefly described. The seasonal variations and long-term variations have been mentioned, and some attempt at relating the environment to the organisms has been made. The bearing of these matters upon the central problem of the CCOFI program, that is, the fluctuations in the catch of the sardine and other oceanic fishes, has not yet been mentioned. One difference between the last decade and the previous period when the sardine fishery was at its height has been pointed out. The temperatures during the early months of the year—the sardine spawning months—have been consistently lower in the last ten years and with certain assumptions inferences bearing upon the sardine problem can be drawn. These cooler months seem to be cooler because the winds were stronger and caused more upwelling. Assuming this relation to hold, and that the low temperatures are indicative of high nutrients, then the result of the enrichment has been higher zooplankton volumes. If this relation between temperature and zooplankton is a real one and has held over the last 20 years, as it did in 1941 and from 1949 through 1956, then we must assume that plankton volumes were smaller in the great period of the sardine fishery than they are now when the sardine catch is much reduced. How the zooplankton and sardines could be so inversely related is beyond the purpose of this report to speculate. It is unfortunate that we do not have a coverage of the area in years when the catch was high or when at least there was a high survival rate. Until such a year occurs any correlations of this sort will be severely limited.

REFERENCES

Atkins, W. R. G.

1923. The silica content of some natural waters and of culture media. *J. Mar. Biol. Assn. U. K.*, vol. 13, pp. 151-159.

1926. Seasonal changes in the silica content of natural waters in relation to the phytoplankton. *J. Mar. Biol. Assn. U. K.*, vol. 14, pp. 89-99.

1928. Seasonal variations in the phosphate and silicate content of sea-water during 1926 and 1927 in relation to the phytoplankton crop. *J. Mar. Biol. Assn. U. K.*, vol. 15, pp. 191-205.

1930. Seasonal variation in the phosphate and silicate content of sea-water in relation to the phytoplankton crop. Part V. November 1927 to April 1929, compared with earlier years from 1923. *J. Mar. Biol. Assn. U. K.*, vol. 14, pp. 821-852.

Berner, Leo D., Jr.

1957. Studies on the Thaliacea of the temperate northeast Pacific Ocean. Unpublished doctoral dissertation on file in the Library, University of California, Scripps Institution of Oceanography. 144 pp., 26 figs.

Boden, Brian P., Martin W. Johnson, and Edward Brinton

1955. The Euphausiacea (Crustacea) of the north Pacific. *Univ. Calif., Scripps Inst. Oce., Bull.*, vol. 6, pp. 287-400, 55 figs.

Canadian Joint Committee on Oceanography

1956. Physical, chemical and plankton data record. Project NORPAC, July 26 to September 1, 1955. Prepared by Pacific Oceanographic Group, Nanaimo, B. C., Duplicated report. File N 6-17-4(2). 202 pp., 4 figs.

Cooper, L. H. N.

1933. Chemical constituents of biological importance in the English Channel. Part I. Phospate, silicate, nitrate, ammonia. Part II. Hydrogen ion concentration, excess base, carbon dioxide, and oxygen. *J. Mar. Biol. Assn. U. K.*, vol. 18, pp. 677-753.

1938. Phosphate in the English Channel, 1933-8, with a comparison with earlier years, 1916 and 1923-32. *J. Mar. Biol. Assn. U. K.*, vol. 23, pp. 181-195.

Cromwell, Townsend, and Joseph L. Reid, Jr.

1956. A study of oceanic fronts. *Tellus*, vol. 8, no. 1, pp. 94-101.

Goldberg, Edward D., Theodore J. Walker, and Alice Whisenand

1951. Phosphate utilization by diatoms. *Biol. Bull.*, vol. 101, no. 3, pp. 274-284.

Imperial Marine Observatory, Kobe, Japan

1925. The mean atmospheric pressure, cloudiness and sea surface temperature of the north Pacific Ocean and the neighboring seas for the lustrum, 1916 to 1920. Kobe, Imp. Mar. Obs., 581 pp.

1927. The mean atmospheric pressure, cloudiness and sea surface temperature of the north Pacific Ocean and the neighboring seas for the year, 1926. Kobe, Imp. Mar. Obs., 171 pp., 20 figs.

1929a. The mean atmospheric pressure, cloudiness and sea surface temperature of the north Pacific Ocean and the neighboring seas for the lustrum, 1921 to 1925. Kobe, Imp. Mar. Obs. 623 pp.

1929b. The mean atmospheric pressure, cloudiness, air temperature and sea surface temperature of the north Pacific Ocean and the neighboring seas for the year, 1928. Kobe, Imp. Mar. Obs., 176 pp., 20 figs.

1930. *Ibid.* 1929. 173 pp., 20 figs.

1931. *Ibid.* 1930. 176 pp., 22 figs.

1932. *Ibid.* 1931. 167 pp., 16 figs.

1933. *Ibid.* 1932. 167 pp., 16 figs.

1934. *Ibid.* 1933, 168 pp., 16 figs.

1935. *Ibid.* 1934. 160 pp., 16 figs.

1936. *Ibid.* 1935. 168 pp., 16 figs.

1937. *Ibid.* 1911 to 1935. 197 pp.

1938. The mean air temperature, cloudiness and sea surface temperature of the north Pacific Ocean and the neighboring seas for the year, 1936. Kobe, Imp. Mar. Obs., 195 pp., 12 figs.

1939a. *Ibid.* 1937. 195 pp., 9 figs.

1939b. *Ibid.* 1938. 195 pp., 12 figs.

Jacobs, Woodrow C.
1951. The energy exchange between sea and atmosphere and some of its consequences. *Univ. Calif., Scripps Inst. Oce., Bull.*, vol. 6, no. 2, pp. 27-122, 67 figs.

Knauss, John A., and Joseph L. Reid, Jr.
1957. The effects of cable design on the accuracy of the GEK. *Am. Geophys. Un., Trans.*, vol. 38, no. 3, pp. 320-325.

Redfield, A. C.
1948. The exchange of oxygen across the sea surface. *J. Mar. Res.*, vol. 7, pp. 347-361.

Redfield, Alfred C., Homer P. Smith, and Bostwick Ketchum
1937. The cycle of organic phosphorus in the Gulf of Maine. *Biol. Bull.*, vol. 73, pp. 421-443.

Reid, Joseph L., Jr.
1956. Observations of internal tides in October 1950. *Am. Geophys. Un., Trans.*, vol. 37, no. 3, pp. 278-286.

(In press.) A comparison of drogue and GEK measurements in deep water. *Limnol. and Oceanogr.*

Robinson, Margaret K.
1957. Sea temperature in the Gulf of Alaska and the northeast Pacific Ocean, 1941-1952. *Univ. Calif., Scripps Inst. Oce., Bull.*, vol. 7, no. 1, pp. 1-98, 61 figs., 1 chart.

Roden, Gunnar I.
(In press.) Oceanographic and meteorological aspects of the Gulf of California. *Pac. Sci.*

Roden, Gunnar I., and Joseph L. Reid, Jr.
(ms.) On a relation between atmospheric pressure and sea surface temperatures in the north Pacific Ocean.

Rossby, C. G.
1936. Dynamics of steady ocean currents in the light of experimental fluid mechanics. *Papers in Phys. Oceanogr. and Meteorol.*, vol. 5, no. 1, 44 pp.

Staff, South Pacific Fishery Investigations
1952. Zooplankton volumes off the Pacific Coast, 1941. *U. S. Fish and Wildl. Serv., Spec. Sci. Rept.: Fish.*, no. 73, 37 pp.

1953. *Ibid.* 1952; no. 100, 41 pp.

1954a. *Ibid.* 1949-50; no. 125, 54 pp.

1954b. *Ibid.* 1953; no. 132, 38 pp.

1955. *Ibid.* 1954; no. 161, 35 pp.

(ms.) Biological results of the portion of NORPAC occupied by agencies participating in the California Cooperative Oceanic Fisheries Investigations.

Sverdrup, H. U., and E. W. Allen
1939. Distribution of diatoms in relation to the character of water masses and currents off southern California. *J. Mar. Res.*, vol. 2, no. 2, pp. 131-144.

Sverdrup, H. U., and R. H. Fleming
1941. The waters off the coast of southern California, March to July, 1937. *Univ. Calif., Scripps Inst. Oce., Bull.*, vol. 4, no. 10, pp. 261-378, 66 figs.

Sverdrup, H. U., Martin W. Johnson, and Richard H. Fleming
1942. *The oceans, their physics, chemistry and general biology.* New York: Prentice-Hall, Inc., 1087 pp., 265 figs., 7 charts.

Tibby, Richard B.
1939. Report on returns of drift bottles released off southern California, 1937. *Calif. Div. of Fish and Game. Fish Bull.*, no. 55, 36 pp., 22 figs.

U. S. Coast and Geodetic Survey
1954. Density of sea water at tide stations. Pacific Coast. North and South America and Pacific Ocean islands. Spec. Pub. No. 281, 64 pp.

1956. Surface water temperatures at tide stations. Pacific Coast. North and South America and Pacific Ocean islands. Spec. Pub. No. 280, 74 pp.

U. S. Geological Survey
1952. Quality of surface waters of the United States. Colorado River basin to Pacific slope basins in Oregon and lower Columbia River basin. Geol. Surv. Water-Supply Paper 1253. Part 9-14, 344 pp., 1 fig.

U. S. Hydrographic Office
1947. *Atlas of surface currents. Northeastern Pacific Ocean.* H. O. Pub. No. 570.

University of California, Scripps Institution of Oceanography
1957. *Oceanic observations of the Pacific, 1949.* Berkeley: Univ. Calif. Press, 363 pp., 6 figs.

(In press.) *Oceanic observations of the Pacific, 1955. NORPAC Vols. I, and II.* Berkeley: Univ. Calif. Press.

(In preparation.) *Oceanic Observations of the Pacific, 1950-57.* Berkeley: Univ. Calif. Press.

University of Washington, Dept. of Oceanography
1956. Special Report No. 22. Preliminary Data Report. NORPAC 1955. Duplicated report. Ref. 56-4, 104 pp., 1 fig.

von Arx, William S.
1950. An electromagnetic method for measuring the velocities of ocean currents from a ship under way. *Papers in Phys. Oceanogr. and Meteor.*, vol. 11, no. 3, 62 pp., 17 figs.

Wooster, Warren Scriver
1953. Phosphate in the eastern north Pacific Ocean. Unpublished doctoral dissertation on file in the Library, Univ. Calif., Scripps Inst. Oce., 83 pp., 16 figs.