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GENERAL CIRCULATION AND WATER CHARACTERISTICS IN THE SOUTHERN CALIFORNIA BIGHT

by JAMES H. JONES

SCCWRP

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FOREWORD

The Southern California Coastal Water Research Project (SCCWRP) is a part of today's evaluation of human activities as they affect the relationship between man and his environment. The Project aims at encouraging the conservation and enhancement of resources along the southern California coast by providing a better understanding of the ecological systems of the coastal waters in this area.

The Project was conceived by the five agencies of local government* that are responsible for most of the discharge of treated wastewater into the coastal waters of the region. Believing that their established applied research programs could benefit from the addition of a project with a region-wide geographical focus, they entered into a joint powers agreement to sponsor SCCWRP. The agreement established a commission, the SCCWRP Authority, to assume control of the Project and to be responsible to the public. This arrangement has provided the Project with complete freedom from control by any other agency, including the sponsors.

To ensure an adequate scientific basis for the Project, the joint powers agreement specified that a Consulting Board of internationally recognized experts be appointed to play a major role in the Project's supervision. The combination of experienced consultants and a relatively young but highly trained staff has created a unique interdisciplinary force directed at some of the most challenging technical problems of our time.

The general goals and objectives of SCCWRP are:

1. To attain a substantial understanding of the ecology of southern California coastal waters in present and recent times.
2. To gain insight into man's past, present, and predicted effects on the ecology, principally through wastewater discharge.
3. To outline methods for limiting or reversing the harmful effects of the various wastewater discharges in the future, and to recommend monitoring procedures.

In the initial review phase of the Project, an intensive information search has been conducted in 17 task areas of physical and chemical oceanography, marine biology, public health, and environmental engineering. Over 1,500 references and a large amount of the available raw data have been reviewed, and discussions with many individuals having relevant but unpublished information have been held. This document covers a few of the topics in the various task areas; the report therefore summarizes only a part of SCCWRP's initial assessment.

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*Ventura County, the Cities of San Diego and Los Angeles, and the County Sanitation Districts in Orange County and Los Angeles County.

The active research phase of the SCCWRP program is being developed from information collected and evaluated during the review. The last stage of the Project effort will be devoted to the analysis of all data and preparation of a final report. The report is expected to recommend criteria for wastewater discharge, to suggest alternate solutions for the problems of total environmental usage, and to outline further research needed to ensure protection and enhancement of the environment.

GEORGE E. HLAVKA
Project Manager

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INTRODUCTION

I

Oceanography is the science of the sea. It encompasses all of the analogous disciplines of science that are usually associated with the land: physics, chemistry, biology, and geology. We should not become too restrictive in considering each of these disciplines separately. It is especially important that their interrelationship be emphasized in studying practical problems, such as the effect of wastewater on the marine environment.

The physics of the ocean, more commonly referred to as physical oceanography, is concerned with (1) the characteristic or physical properties of seawater, such as temperature, salinity, density, optical and acoustical properties and chemical content and (2) the effects of advective and nonadvective processes on the distribution of these properties. Advection produces a concurrent flux of mass and of other properties by direct motion of seawater in the form of currents. Nonadvective processes produce a flux of properties but not of mass; these processes include the vertical and horizontal mixing caused by turbulent motion and the exchange between the atmosphere and the ocean and between the ocean and the sea floor.

There is need for more information on the ways in which the marine environment responds physically to pollutants. At SCCWRP, we are concerned with that part of the marine environment occupying the Southern California Bight, an open embayment of the Pacific Ocean bounded on the north by Point Conception, on the west by the California Current and extending southward to Cape Colnett, Baja California.

This technical report deals with some aspects of the physical oceanography in the Southern California Bight as they relate to the effects of pollutants introduced into that area. These pollutants may be introduced through atmospheric fallout, flood runoff, or wastewater outfalls, directly by ships, or through adjacent seawater flowing into the area. This last input source (and the natural inputs) may originate anywhere in the north Pacific; therefore, the Bight's relationship to the oceanography of the north Pacific is important.

The fate of the chemical pollutants is a prime consideration. We know that some of this material is altered chemically, some is consumed by organisms, and some settles to the sea floor. From the physical point of view, we are concerned with currents, advection, dilution, and other physical aspects of movement in the Bight—in particular, mixing and diffusion.

Except in very high latitudes, the temperature structure of the ocean is characterized by warm water near the surface and colder water below. The transition between these two regions, called the thermocline, is usually sharp and distinct. The mixed layer at the surface ranges from 0 to 300 m in thickness; in southern California coastal water, it rarely extends to depths of more than 50 m.

Salinity is a measure of the content of solids dissolved in sea water. It is expressed in parts per thousand or per mille (⁰/oo) rather than percent (%); that is, grams per kilogram of seawater. The range in the open ocean is from 33 to 37⁰/oo. In some areas such as the Red Sea, where high evaporation occurs, it may exceed 40⁰/oo. In regions of high rainfall, excessive runoff, where rivers enter the sea, or where sea ice-melting is extensive, it approaches 0⁰/oo, the salinity of fresh water. In the waters of the Southern California Bight, it ranges from about 33⁰/oo to somewhat less than 35⁰/oo. In its structure above the thermocline, salinity is often more complicated than temperature, probably as a result of the difference in the mixing rates of heat and salt.

The density of sea water increases with increasing salinity, decreasing temperature, and increasing pressure or depth. Thus, any change in these three physical properties will produce a variation in the density.

There are three principal types of currents present: (1) those related to the distribution of mass, (2) those caused directly by the stress of the wind on the sea surface, and (3) tidal currents.

The first type, called geostrophic currents, results from the lack of coincidence of isobaric surfaces (along which the pressure is constant) and level surfaces (along which no component of gravity acts). In the sea, isobaric surfaces slope relative to level surfaces in a direction opposite to surfaces of equal density. Water moves slowly down the sloping surface, and the resulting current is deflected by the earth's rotation (called the Coriolis force). The small deviations from a state of perfect static equilibrium (in which level and isobaric surfaces coincide) can be determined from the density at different depths. Density is computed at many depths from observed temperature, salinity, and pressure observations. These data are taken during hydrographic cruises or surveys in which many temperature and salinity observations are made at many locations at multiple depths.

The second type of current is due to wind stress on the sea surface. The wind moves the surface water, which is then subject to both friction and the Coriolis force. In very deep water, the surface water moves at an angle of 45 degrees to the wind direction. This motion is transferred to the underlying layer, causing it to move at a lower speed. At the greatest depth in the layer affected by the process, the water is moving very slowly in a direction opposite to the surface current. This current profile is called the Ekman Spiral. The angle between the surface current and wind direction depends on latitude and interference from water piled up by the wind. The integrated effect over the entire layer under the influence of the wind is an average transport at right angles to the wind. A second effect is the redistribution of mass, which produces a geostrophic flow, the first type of current described.

Off southern California, the onset of strong, steady winds blowing in the late winter moves the surface water to the west and permits water to well up. This water brings up nutrients, which support heavy plankton blooms and cause the area to be one of high organic production. The resulting distribution of mass maintains a geostrophic current.

Tidal currents are produced when the tide rises and falls in the ocean as the result of the gravitational attraction between earth, moon and sun and the centrifugal force which balances the attractions. Although lunar and solar tides produce a rhythmic wave motion, irregular sea-bottom and shoreline topography causes many secondary effects. The observed tide is the resultant.

Short-term erratic currents are also produced in exposed shallow areas. These include rip currents, which return the water piled up on the coastline by breaking waves and create longshore currents. Surface waves progressing forward cause a flow of surface and subsurface water to depths as great as a few tens of meters in the case of high-amplitude, long-period swells.

Of particular importance in problems such as the disposal of wastewater in the ocean are the regions in which currents mingle. Convergences exist in areas where currents merge, and divergences occur where surface currents arise and diverge. In coastal waters, which have a complex system of currents of a wide spectrum of dimensions and velocities, many such features, large and small, occur. Their importance in the distribution of pollutants is obvious, but detailed knowledge of such phenomena is unfortunately limited.

When sewage effluent is discharged below the ocean surface, it tends to rise because of its relatively low density. As it rises, it mixes with sea water and spreads over an increasingly large area. The depth at which it ceases to rise and the amount of dilution depend on the depth of discharge, density differences between effluent and ocean water, density stratification of the ocean, and current velocity.

This report contains a description of the general circulation and water characteristics in the Southern California Bight. Additional information concerning seasonal fluctuations, upwelling, aperiodic fluctuations and long-term temperature variations is included. Aspects of the physical oceanography of this region are not discussed in detail in the report, however. Air-sea exchanges, small-scale turbulent mixing, the details of near-shore circulation, as well as many other related topics, are also important to the primary problem.

MEAN CURRENT PATTERN

II

The large-scale surface currents in the Southern California Bight are principally the result of winds, the earth's rotation, and solar heating. However, a myriad of complex, smaller scale motions produced by local conditions are superimposed on this overall pattern.

Water in the north Pacific is driven eastward by the prevailing westerly winds until it impinges on the western coast of North America. This blockage results in flows to the north and south. The southern component of this flow comprises the California Current.

The southerly progress of this flow is strongly affected by the earth's rotation. The peripheral velocity of the North American continental coast near the U.S.-Canadian border (about 48° N. Lat.) about the earth's axis of rotation is approximately 1,080 km/hour. Near San Diego (about 33° N. Lat.), which is further from this axis, the velocity is about 1,350 km/hour. As a result, if the California Current is to flow approximately parallel to the coastline, there must be an easterly directed force that is capable of accelerating the water to the same peripheral speed as the adjacent coast. This acceleration is produced by westerly components of the prevailing winds and interrelated pressure forces caused by the slope of the cold deep water upward toward the coast.

Absorption of solar radiation and the resultant heating in the upper layer of the ocean reduce the density of this layer. This effectively stabilizes newly upwelled or newly mixed water, and, where these processes are not present, it tends to isolate the motions of the surface waters from those of the colder, deeper waters. These deeper waters flow in a northerly direction off the coast of California. The earth's rotation requires a deceleration in the peripheral speed of this current as it moves north, thus producing a tendency to build up against the coast.

The basic features of the seasonal dependence of the California current can be qualitatively explained by considering the effects of the seasonal wind patterns on a simplified two-layer ocean. In spring and early summer, the prevailing coastal winds are from the northwest and tend to speed up the surface current and maintain the flow parallel to the coast. In some areas immediately adjacent to the coast, the northern component of the winds may be increased. Here, the influence of the westerly component of the wind on the surface layer may be insufficient to prevent surfacing of the deeper layer that has built up against the coast. This produces the phenomenon known as upwelling. The source of this upwelling is usually restricted to waters that are within 200 to 300 meters below the ocean surface.

In other seasons, the strength of the northwest winds diminishes. They may become insufficient to maintain the surface current against the coast, particularly where it rounds Point Conception at the northern extremity of the Bight. As the current breaks off from the coast, a large gyre is usually produced. This gyre occasionally breaks down into a number of smaller eddies. The eastern portion of the gyre is comprised of a northward flow and, because of its nearly permanent nature, has been called the Southern California Countercurrent (abbreviated here as S-C Countercurrent).

From November through February, the coastal winds tend to be from the southeast, causing the southerly current to move offshore and the inshore surface waters to be accelerated to the north. This commonly produces an inshore surface countercurrent (the Davidson Current), which remains until the northwesterly winds resume in the spring.

Although this simple description qualitatively explains the large-scale flow pattern off of the Californias, the quantitative description of the current patterns and intensities is not complete at present. For example, the strong, poleward currents, located at the western side of the subtropical gyres, have been noted in the literature for nearly 200 years. However, only recently has a satisfactory explanation, in terms of a vorticity balance, been offered for the intensification of flow on the western side of the gyre and the broad, variable flows observed on the eastern boundary (Stommel, 1965). Since 1945, both descriptive and theoretical studies have been conducted on the process of coastal upwelling, a basic feature of eastern boundary currents. Work has also been done on the descriptive processes of the seasonal flow patterns. (See "References.") Although the descriptive data are fragmentary and theoretical studies far from complete, this report is intended to synthesize the existing knowledge of the water mass distribution in the California Current and off the coast of southern California.

CIRCULATION AND WATER CHARACTERISTICS FROM 0-100 M DEPTH

III

There are many variations in the surface characteristics of the water off southern California. These variations occur with a frequency ranging from weeks to years and add substantially to the problem of presenting a succinct picture of the flow. Difficulties are further compounded by the nearshore limitations of the most generally useful oceanographic approach to delineating current systems—the determination of geostrophic currents.

Geostrophic currents are calculated from observations of the horizontal distribution of pressure and latitude. In geostrophic flow, the assumption is made that there are no accelerations other than the pressure gradient acceleration and the Coriolis acceleration, and that these are in balance. This implies that a steady state exists, that there is no curvature of the flow path, and that the frictional effects of current shear are negligible. The currents computed by this method are necessarily referenced to some lower layer in the water column assumed to be motionless. Geostrophic speeds are not usually considered useful for locations where the depth is less than 500 m, nor where bottom friction, strong curvature and transient flows are common. Thus, direct but cruder methods (e.g., drift bottles) must be used in delineating some features of nearshore circulation, although average conditions shown by geostrophic calculations are qualitatively meaningful.

The following general description of the large-scale oceanic flow off southern California will provide a basis for a later, detailed discussion of the nature, effects, and frequency of the variations.

In the southern California region, the characteristics of the offshore ocean waters above 100 m appear to be relatively independent of the characteristics of the deeper water. Water from the north creates the surface characteristics of low temperature and salinity and high oxygen. As this water mass moves southeastward towards Point Conception, it takes on some of the characteristics of the central Pacific water. This central Pacific water mass is identified by high temperature and salinity and a relatively low oxygen-nutrient content.

For example, in August, off the coast of Washington, surface temperatures are about 10 to 11°C and salinity about 32.0‰. Near the Mexican border, these values are 20°C and 33.7‰. Oxygen values are near saturation at the surface, and variations generally indicate only the inverse effect of temperature on the saturation value of oxygen.

Figure 1 gives a composite picture of the surface circulation to 100 m in the area of the Southern California Bight. North of Point Conception, the California Current flows southeastward with a mean speed of approximately 15 cm/sec and a volume transport of 12 x $10^6 m^3$/sec (Pavlova, 1966). There is no true western edge to this current. More than 90 percent of the southeastward transport is within 800 km of the coast of central California and is located above 300 m depth (Sverdrup and Fleming, 1941). Within 150 km of the coast, north of Point Conception, the surface currents often flow northwestward along the coast from about November through February and southeastward during the rest of the year (Reid, 1965b).

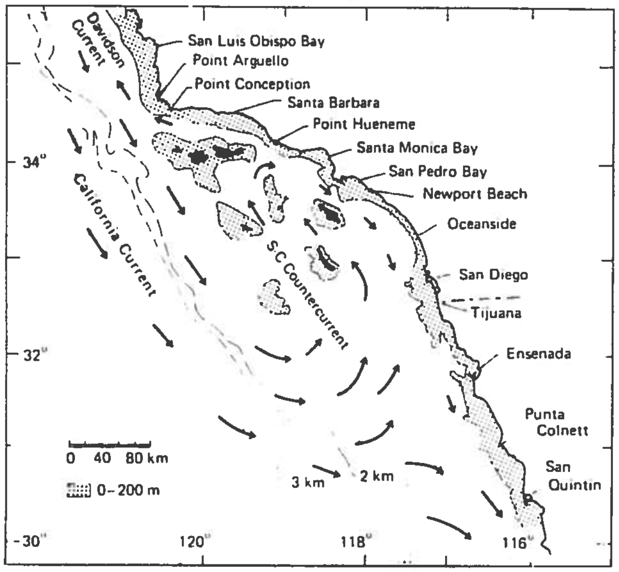

Figure 1. Surface circulation to 100 m in the Southern California Bight. Arrows indicate approximate direction of flow.

South of Point Conception, and in the Channel Islands off southern California, the flow is to the northwest throughout most of the year. This flow forms the inshore edge of the Southern California Eddy and is referred to as the S-C Countercurrent. The Eddy is a nearly permanent feature of the flow pattern in this region and has been found to be well developed in winter and weak in the spring (Schwartzlose, 1963, and the CalCOFI reports). Its location may be influenced by the shape of the coast and the bottom topography, as implied by Sverdrup and Fleming (1941). Estimates of surface speed in the S-C Countercurrent are comparable to that observed in the California Current itself: 12 to 18 cm/sec (Sverdrup and Fleming, 1941). Transport estimates in this branch of the eddy are only slightly less than that calculated for the California Current (Pavlova, 1966) and appear to vary seasonally with the California Current (Pavlova, 1966; Sverdrup and Fleming, 1941).

In their detailed discussion of the water masses off the coast of southern California, Sverdrup and Fleming (1941) have indicated that the water in the S-C Countercurrent is a mixture of offshore California Current surface water and upwelled surface water. The increase in surface temperature is accounted for by heating. An indication of the extent of the flow of water from the west and south into the southern California circulation system is evident from Figure 2. These direct indications emerge from drift bottle results (the arrows in Figure 2 should not be interpreted as lines of flow but only as an indication of the release and pick-up points of the various drift bottles).

Observations show that the counterclockwise gyre is centered over the shallow ridge (Santa Rosa-Cortez Ridge) that extends southward from the northern three Channel Islands and rises to a depth of less than 200 m over most of its length. This region is usually an area of high productivity and of low transparency from the resultant growth of phytoplankton. Inshore of the S-C Countercurrent, the surface flow is poorly defined and data are scarce.

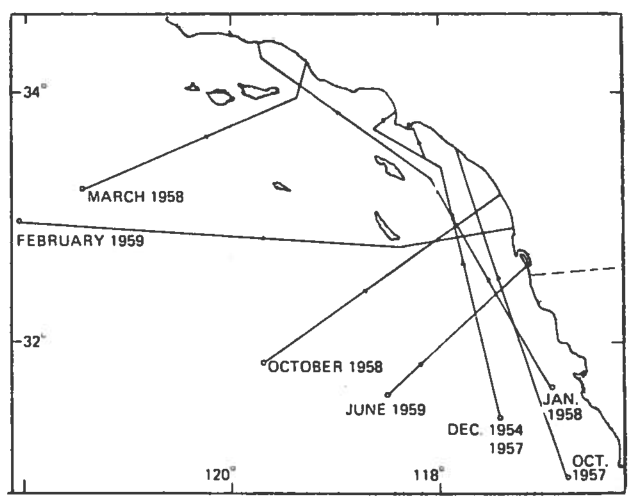

Figure 2. Indications from drift bottles of the flow of water from the west and south into the Southern California Bight. From Schwartzlose, 1963, fig. 9, p. 20.

Drogue and drift bottle studies (Schwartzlose, 1963; SIO Report 62-27, 1962; Reid, 1965b) have indicated the truly complex nature of the flow in the Southern California Bight as contrasted to the average flow presented above. Schwartzlose (1963) summarized the results of the CalCOFI drift bottle returns from January 1955 through June 1960 and provided examples of the different patterns of return. It is significant that only in the region off southern California were bottles returned from release points greater than 200 km offshore. The total percent of returned bottles was also higher from this area (9.2 percent). Schwartzlose states that "the most variable drift was observed in the Channel Island area off southern California where the data are most numerous" and the "Southern California Counterclockwise Eddy was present most of the year. The months it commonly was not present were March, April and May." Drift bottles are a direct but inadequate technique for studying the Eddy, since only the beginning and end points (the beach) are known. A large number of travel paths is probable, the least likely of which is a straight line between two points. However, data on geostrophic flow also give an incomplete picture of the Eddy movement as they indicate only the more persistent offshore features.

Figure 3 gives an example of an unusually strong development of the S-C Countercurrent as indicated by drift bottles. Generally the Countercurrent is at its usual maximum strength (0.5 to 0.9 knots) during October, November and early December. It is always in evidence as the Davidson Current during these months north of Point Conception. South of the Point, the S-C Countercurrent is usually undetectable. However, some northwestward drift off southern California is indicated. At present, there are no reliable estimates of the amount of surface water passing to the north of Point Conception during this Countercurrent regime. The amount of flow, however, is sometimes sufficient to displace large numbers of southern planktonic organisms far to the north.

Local studies with shallow drogues have indicated that the short-term flow pattern is complicated by the presence of small eddies within the region of the large counterclockwise eddy (SIO Report 62-27, 1962). Portions of this study were conducted in the California Channel Island area. Figure 4 illustrates the paths of these drogues located at a depth of 10 m determined from a ship survey from 23 to 27 October 1958. The paths of the various drogues were determined from radar locations from the ship when it was positioned within a few tens of meters from the attached surface float. The northwestward S-C Countercurrent is evident between San Nicholas and San Clemente Islands. The

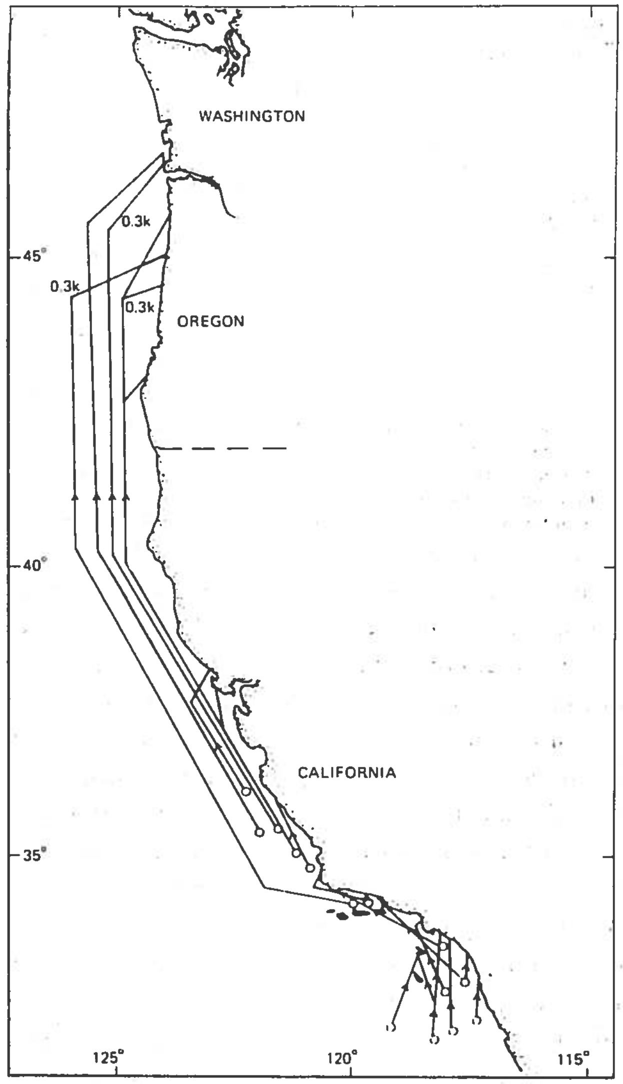

Figure 3. An unusually strong coastal countercurrent during November 1957. From Schwartzlose, 1963, fig. 11, p. 21.

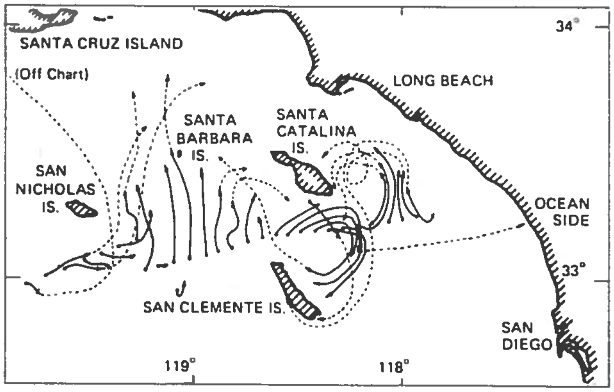

Figure 4. General water current circulation around the Channel Islands, 23-27 October 1958. Solid lines denote the paths of the 10 m deep drogues during the survey; the dotted line connects the last surveyed position with the location of final recovery. From SIO Report 62-27, 1962, fig. 1, p. 3.

drogues released east of a line connecting Santa Catalina and San Clemente Islands appeared to move in a circular manner with a minimum net transport. The period of motion around the circles is too slow for inertial motion and, in one case, is also moving in the wrong direction. Thus, it is assumed that these drogue paths represent small eddy motion, possibly associated with island topography.

Most of the year, the S-C Countercurrent is evident and flows with a velocity from 5 to 10 cm/sec. An order of magnitude calculation of the residence time of water in the Bight may be made by assuming a mean path of 500 km (around the southwest end of the gyre towards the shore south of the north Channel Islands and southeastward along the coast in Baja California) and a mean speed of 7 cm/sec. These values yield a calculated residence time of about 3 months.

A calculation of the surface warming may also be used to obtain an estimate of the residence time of surface waters in the Bight. Sverdrup and Fleming (1941) estimate that 39 days are required to account for the observed temperature rise in the summer from north of Point Conception (35°N. Lat.) to the southern extension of the S-C Countercurrent off Southern California (30.5°N. Lat.).

The estimated flow (Figure 5) for the summer season indicates that water enters the Bight from the offshore California Current from about 32.5° to 31.0°N. Lat. This results in a calculated mean travel time from Point Conception of about 25 days. A similar estimate is obtained by assuming a summer insolation capable of warming a column of water 10 m thick at the rate of 0.1°C/day (Roden, 1959).

As the water at the southern edge of the S-C Countercurrent turns towards the north to form the inshore countercurrent, the mean flow at the surface tends to parallel closely the surface isotherms (Figure 5). Thus, although the effective insolation has not changed, the surface waters display only a minor temperature increase. An explanation of this phenomenon is that the total heat received is balanced by evaporation and/or mixing of the surface water with colder, upwelled water. The amount of heat exchange with the atmosphere (primarily evaporation) would have to be three times its estimated value (Roden, 1959) to balance the radiative input. Hence, the absence of a temperature rise in the surface waters of the S-C Countercurrent as they move northward is assumed to imply a substantial mixing with colder upwelled water. This conclusion is supported by the collection of relatively high plankton volumes during most summer seasons in this area.

Some additional heating of the surface waters is noted from south of the north Channel Islands to the area immediately off the coast, south of San Pedro Bay to San Diego. From an observed temperature rise of about 3°C over a path of 150 km, a residence time of 30 days and a mean speed of 6 cm/sec may be calculated for water in this area of the Southern California Bight. Because of the probable advection of heat from the S-C Countercurrent, we are unable to provide a completely independent estimate of the residence time of water in the Bight. However, a month is a reasonable estimate of the mean travel time from the southern edge of the eddy to a location south of the north Channel Islands. The previous estimate of a 3-month mean residence time is not in conflict with this latter estimate, which is derived from the effects of surface heating.

The relationship of these values to the speed and path of flow at any time is not known. These estimates are not intended to represent average conditions, since the circulation is not understood to this broad detail.

Mean seasonal fluctuations are indicated by average geostrophic currents; Figures 5 through 8 indicate seasonal changes in the geostrophic surface

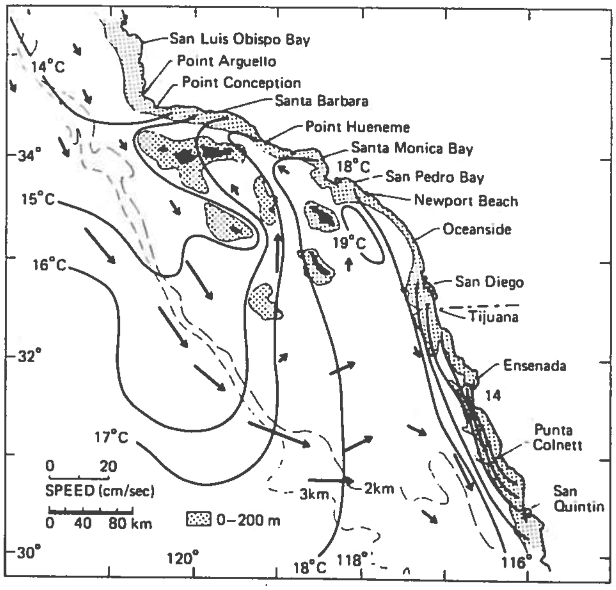

Figure 5. Average geostrophic surface flow (arrows) and surface isotherms (degrees C) in the Southern California Bight during summer (July).

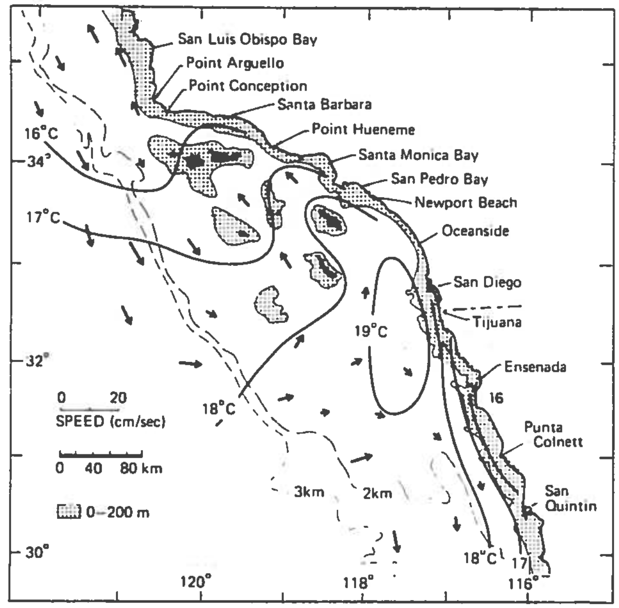

Figure 6. Average geostrophic surface flow (arrows) and surface isotherms (degrees C) in the Southern California Bight during autumn (October).

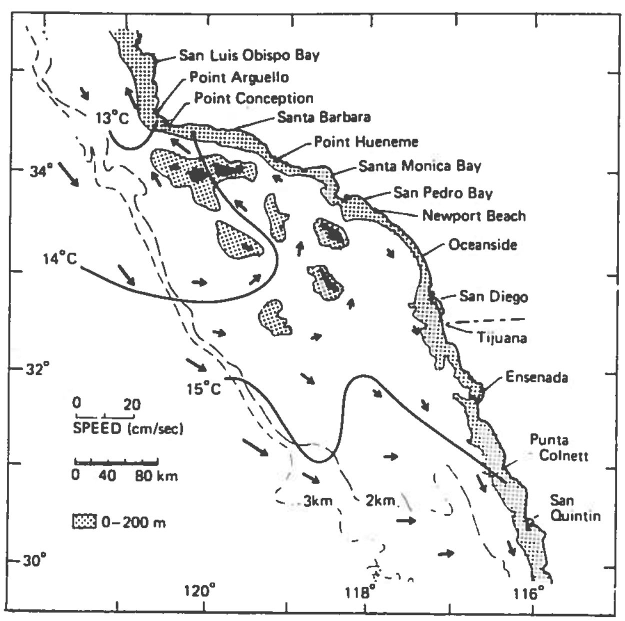

Figure 7. Average geostrophic surface flow (arrows) and surface isotherms (degrees C) in the Southern California Bight during winter (January).

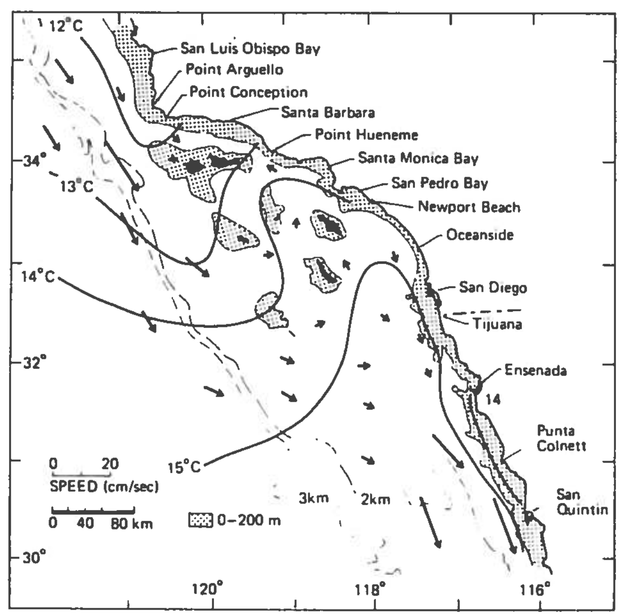

Figure 8. Average geostrophic surface flow (arrows) and surface isotherms (degrees C) in the Southern California Bight during spring (April).

flow for a 15-year average of the four seasons.

In summer (Figure 5), the S-C Countercurrent develops as the inshore side of the semipermanent counterclockwise S-C Eddy. The mean southeastward surface velocity is about 7 to 10 cm/sec, and transport estimates are nearly $10^7 m^3$/sec. Transport estimates in the S-C Countercurrent for this season (Pavlova, 1966) are about 90 percent of those in the California Current itself. Surface temperatures in the upper ten meters increase about 1°C south of Point Conception, with only minor changes obtained in other constituents at the surface.

During the 3 months of autumn, the surface flow is strong and toward the southeast, with the S-C Eddy still evident (Figure 6). According to Pavlova (1966), both the mean velocity and transport are, during this period, decreasing from the maximum noted in the summer. Drift bottles from the CalCOFI cruises have indicated that the Eddy flows westward from the Channel Islands region around Point Conception during this period and thus contributes to the Davidson Current off central California.

Taking January as representative of winter conditions (Figure 7), a broad southeastward flow offshore, with a weak development of the S-C Eddy, is in evidence during this season. The water contained in the California Current is primarily subarctic water with surface characteristics of low temperature and salinity and a high oxygen and nutrient content. Generally, the temperature and salinity at the surface increase as the water moves southward. This phenomenon is attributed to solar heating and lateral mixing with water to the west (central Pacific water), which is characterized by high temperatures and salinity and low oxygen and nutrients. The average surface speed and transport in the California Current during winter were estimated by Pavlova (1966) as 5 cm/sec and 5 x $10^6 m^3$/sec for a profile normal to the coast and extending seaward from the San Pedro area.

In the spring (Figure 8), the southeastward flow of the California Current comes closer to shore, with a weak cyclonic eddy extending around the north Channel Islands and contributing to the Southeast Coastal Current. Velocity and transport estimates remain about the same as previously discussed for the winter season, as do the mean estimates for surface temperature and salinity.

Occasionally, there is no apparent eddy structure in the southern California Bight during the spring months. A drift bottle study by Schwartzlose (1963) indicated that this condition existed in May 1958. In this study, some bottles were released west and south of San Clemente Island and none were recovered. This gives further evidence that an aperiodic flow regime can exist in this area where the California Current remains near the coast south of Point Conception to Baja California and where the S-C Countercurrent is not present. The year of 1958 was anomalous in many other respects and is discussed in the section of this report on aperiodic variations.

The dissolved oxygen distribution in the area of the California Current has been discussed by Reid (1958). Regardless of the consumption and evolution through photosynthesis, the surface waters are almost always near saturation in oxygen because of the constant contact with the atmosphere. The oxygen saturation values are inversely related to temperature and salinity. Hence, the cold, less saline water that is characteristic of the surface flow off Catalina Island is relatively rich in dissolved oxygen (4.5 to 7.0 ml/L). Beneath the mixed layer, oxygen values are decreased by consumption, and replenishment from the surface is inhibited by the stable stratification of the water column.

Figure 9 shows the seasonal variations of dissolved oxygen and percent saturation from 0 to 150 m depth at a station located approximately midway between Catalina and San Clemente Islands. Reid has indicated that, in the California Current system, an oxygen maximum exists beneath the summer thermocline. He has shown that this maximum occurs at a depth corresponding to the lower part of the winter-mixed layer and is caused by winter overturn and warmer temperatures in the summer (Reid, 1962b).

Phosphate-phosphorus (total PO_4-P) values at the surface are generally low and remain around 0.6 µg-atom/L (1.8 x 10^{-2} mg/L) in the California Current (Reid et al., 1958), although marked seasonal variations exist at some locations.

At the surface, the processes of upwelling enhance the concentration of phosphate. Under non-upwelling conditions, the surface waters are relatively low in phosphate and other nutrients because of the consumption in the photic zone by the phytoplankton. Phosphate and other nutrients increase with depth due to regeneration by decay. Upwelling is thus considered to be the primary process whereby nutrient-rich waters are brought to the surface in the California Current region. Figure 10 presents a composite of surface phosphate values near Point Arguello. The wide variation in values may be attributed to the presence of the coastal countercurrent (no upwelling, and hence, low values) and periods of upwelling, as well

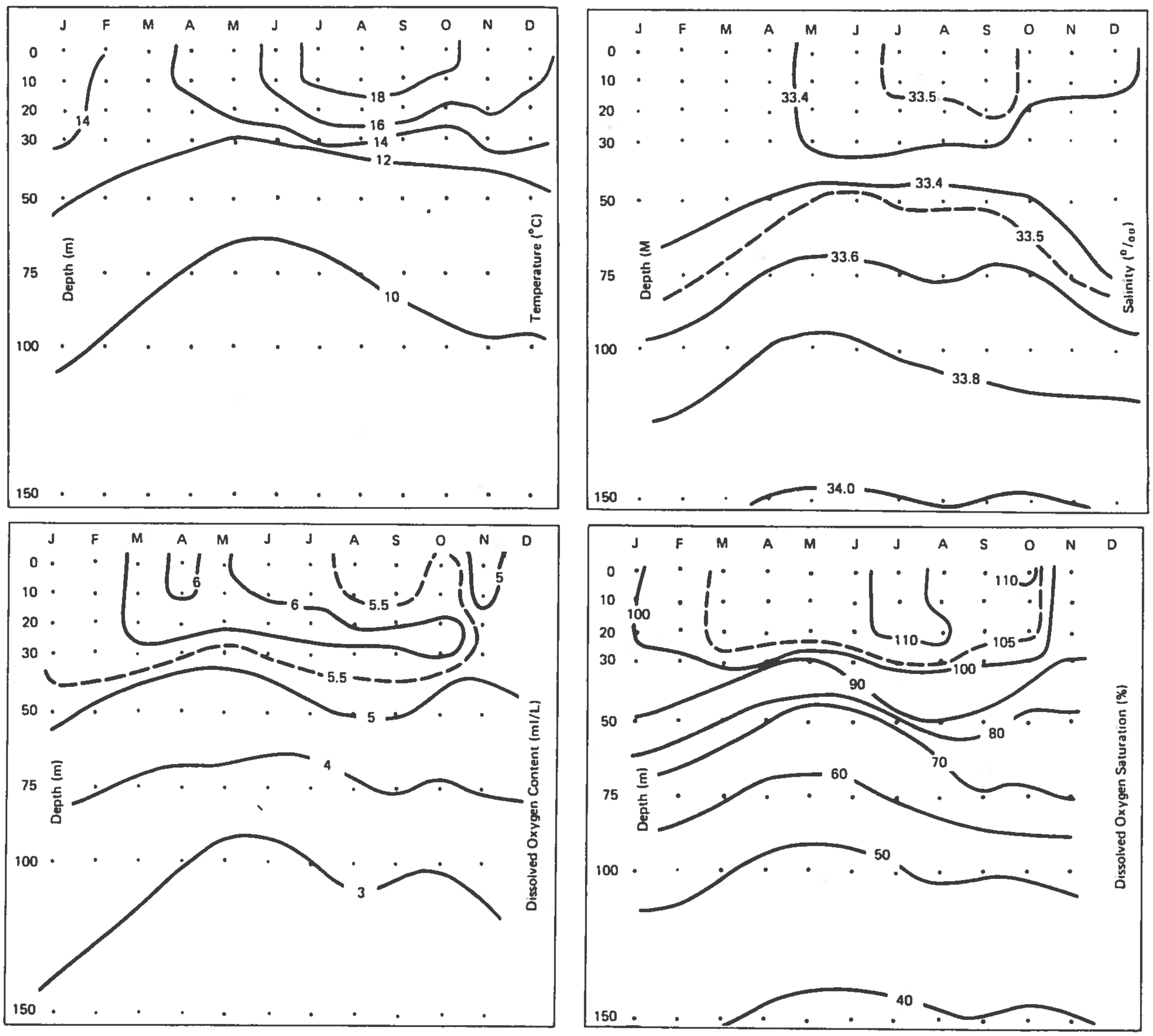

Figure 9. Average seasonal variations of temperature, salinity, and dissolved oxygen content and saturation in the upper 150 m at 33°, 12' N., 118° 24' W. (in the Channel Islands area). From Reid, 1965b, fig. 32.

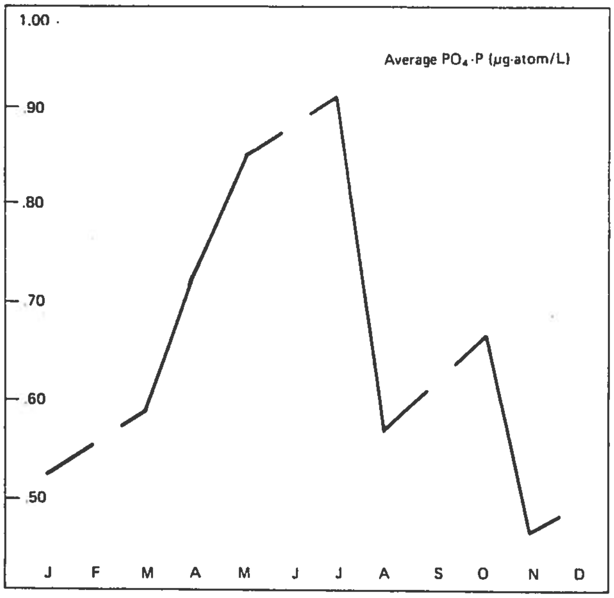

Figure 10. Average phosphate-phosphorus (µg-atom/L) ratio at the sea surface 29 km southwest of Point Arguello. From data collected in various years during the period from 1949 to 1964. From Reid, 1965b, fig. 33.

as year-to-year variations and plant consumption. Further offshore, the mean values, as well as the range, are much reduced.

The surface current pattern off southern California shows approximately an annual variation, with the maximum southeastward transport and velocities occurring in the summer and the minimum in the winter. Reid et al. (1958) have suggested that the pressure differences between the mainland and the north Pacific high characterize the large-scale variations of the California Current. These differences are greatest in the summer and smallest in the winter, in agreement with estimates of velocity and transport within the current. Munk (1950) has further related the water flow west of Catalina to the curl of the wind stress in order to explain the seasonal variations observed in the California Current and the coastal countercurrent. Pavlova (1966) and others have also indicated an apparent positive correlation between the strength of the California Current and the presence of the S-C Countercurrent.

Temperature and salinity variations are related to changes in the current flow. On the average, the nearshore temperature in the Southern California Bight reaches a maximum of about 20°C in August-September and a minimum of about 13°C in March-April. Salinity variations are considerably less and average about 33.3 to 33.6°/oo in the Bight, which indicates that the direct effect of evaporation and precipitation is minimal. In the summer months, a 6°C temperature difference exists between the warm waters off southern California in the vicinity of Santa Catalina Island and the waters some 150 km west of Point Conception. In the winter months, this difference is less than 1°C.

Changes in the dissolved oxygen concentration near the surface appear to be due to variations in the surface flow and the subsequent temperature and salinity variations rather than to biological processes. Surface phosphate concentrations also are related to the flow, primarily through the mechanism of the upwelling of nutrient-rich water.

NEARSHORE CIRCULATION

IV

Very near to the California coast, the currents are caused primarily by a combination of wind, tide, and surf. The circulation pattern caused by surf along a beach consists of transport along the shore inside the breaker zone to a zone of outward flow (called a rip current), returning water to a location seaward of the surf zone. The rip current usually terminates in a rip head, completing the return flow of water. This circulation is local in character. Although it may be important in a discussion of the sediment or floatable transport and accumulation on a coastline, it is a special condition and is best treated as a separate topic in a more detailed discussion of the nearshore flow.

Off the west coast of North America, the tides are both diurnal and semi-diurnal, producing a mixed tide in which, generally, two high tides and two low tides occur each day. The primary generating forces causing the tides are the gravitational attractions of the moon and sun on the earth. The actual day-to-day variation is a result of these forces, as well as the general topography of the ocean shelf. The precise height at any time is, however, only partly predictable by tidal theory. Other causes of sea-level variations (of the order of a few centimeters) are winds, temperature, and salinity changes and atmospheric pressure fluctuations. The tidal heights along the southern California coast range from about 30 cm to more than 2 m. The time between successive high (or low) tides varies from about 10 to 14 hours.

The tidal wave causing the rise and fall observed at coastal stations along the California coast is a progressive wave known as a Kelvin edge wave, which has a maximum amplitude at the coastline and decreases progressively to seaward. Beneath each crest, fluid parcels move forward in the direction of wave propagation; beneath each trough, they move backward. It is this motion of fluid particles that causes the tidal currents observed at coastal stations.

Off the coast of southern California, the tide wave moves from the southeast to northwest, following the coastline at such a rate and incident angle that high tide reaches Point Conception about ½ hour after passing San Diego. Although the wave speed is nearly 400 km/hour, the associated motion of fluid particles (the tidal current) is a very small fraction of the wave speed (of the order of 20 cm/sec). Observations made near shore indicate that the current velocity vector at one point tends to describe an ellipse approximately every 12.5 to 25 hours, depending on the relative strength of the main tidal components. The long axis of the ellipse is parallel to the coast. The "head" of the vector moves clockwise or counterclockwise (principally the latter), probably depending on local topographic influences.

The wind-induced currents, which are superimposed on the tidal motion, usually have a strong diurnal component in response to the local observed wind pattern. Thus, short-term observations of the currents near the coast often show complicated flow patterns as a result of the combined wind-induced and tidal motions. Theoretical studies of wind-induced currents are usually limited to deep-ocean conditions, away from boundaries, and in steady-state conditions. Because none of these conditions apply to a coastal situation (i.e., depths less than a few hundred meters and diurnal winds), observations are generally very difficult to interpret. The surface water in the Bight may also respond to other than just the local winds. A strong wind out to sea or near Point Conception, associated with a stationary front, might be just a mild breeze in Santa Monica Bay. However, the waters in the Bay will rapidly respond to the movements of the more distant water.

A study by Gaul and Stewart (1960) off San Diego has indicated that the short-term variations in movement of water below about 10 to 15 m were primarily tidal, while above that depth they were mainly wind-induced. Because, in the absence of strong winds, the thermocline is located near this depth most of the time, such a result is not unexpected. The thermocline is also a region of maximum stability, which results in a decoupling of the water movement below from that above.

Up to the present time, most studies examined are too limited in time and in synoptic observations of winds and currents to be useful in determining the various causes of nearshore circulation or in stating its general nature. It is this circulation, however, that is most critical to the initial dispersion of any nearshore discharge.

CIRCULATION AND WATER CHARACTERISTICS BELOW 100 M DEPTH

V

The deeper circulation off southern California appears to be somewhat less complex than that of the surface currents. The most outstanding characteristic is a northwestward flow of 25 cm/sec (or less) found near the coast at depths greater than about 150 m. Off northern Baja California, this water has a temperature-salinity relationship characteristic of equatorial Pacific water. In particular, it has higher temperature, salinity and phosphate, and lower oxygen values than the deeper water in the California Current, located at the same depth but farther offshore (Reid et al., 1958). This southern water normally does not appear at the surface in southern California. Because of the presence of the Channel Islands and the relatively shallow Santa Rosa-Cortez Ridge, the deep flow is influenced by the bottom topography of the southern California continental borderland. Figure 11 shows the average flow below 200 m in the region of the Southern California Bight.

North of Point Conception, in the late fall and early winter, a northwest surface flow is in evidence on the inshore side of the main flow. In this area, the northwest flow is called the Davidson Current (Figure 1). The Davidson Current may be a surface expression of the California Undercurrent, which has been noted off Baja California (Wooster and Jones, 1970). However, the detailed measurements to connect the two currents are lacking. This is especially true in the region of the Southern California Bight. Sverdrup and Fleming (1941) identified the water contained in this northwest current as southern water. In their analysis, they discussed the processes whereby this water mixes with the water carried into the southern California region from the north. Figure 12 summarizes their technique, based on a temperature-salinity diagram, for estimating the percent of southern water contained in the water mass.

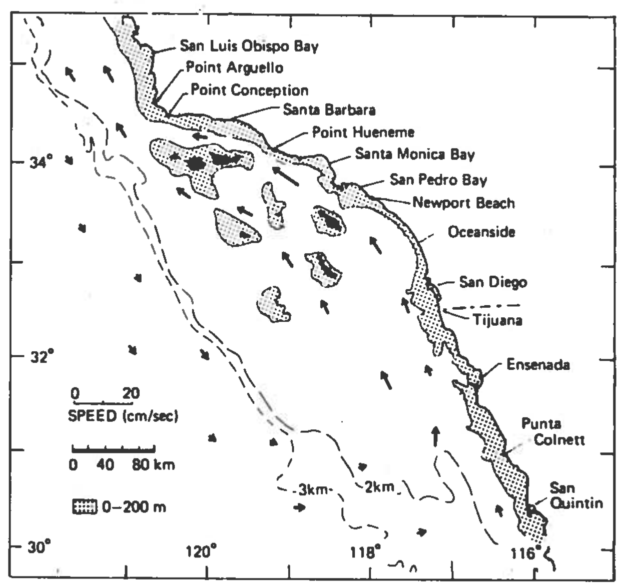

Figure 11. Mean geostrophic flow at 200 m depth in the Southern California Bight. Arrows show direction and magnitude.

Emery (1960) has proposed that the water in the Southern California Bight is 50 percent southern water and 50 percent northern water at depths between 200 and 300 m, with higher percentages of southern water occurring with increasing depth. Figure 13 indicates the percent of southern water between 200 and 400 m. Small temperature inversions are frequent in the Bight at this depth range and are probably indicative of mixing processes at the boundaries of the water masses. Recent investigations, with a continuous profiling salinity/temperature/depth (STD) instrument, have revealed that both temperature and salinity inversions are a common feature when two different water masses coincide and are presumably mixing (Roden, 1964; Reid et al., 1964).

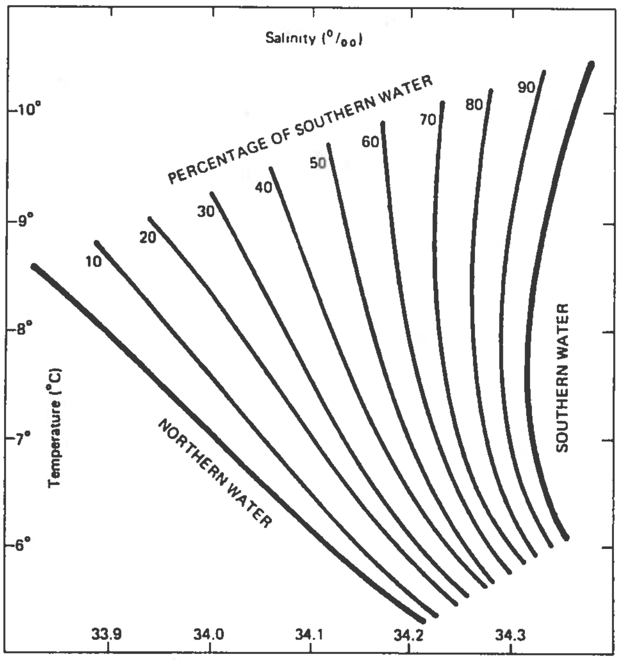

Figure 12. Diagram showing T-S curves of types of water containing 10% southern water and 90% northern water, 20% southern water and 80% northern water, and so on. The diagram has been constructed on the assumption that the intermediate types are formed by processes of isopycnal mixing. From the diagram, the percentage content of southern water can be read off when temperature and salinity are known. From Sverdrup and Fleming, 1941, fig. 20, p. 279.

At a depth between 300 and 600 m, the water in the Bight is characterized by temperatures of 6 to 9°C, salinities of 34.1 to 34.4°/oo, and relatively low oxygen and high phosphate content. The low oxygen and high phosphate levels are indicative of water that has been away from the surface for a considerable time. Because these properties are distinctive from those of the northern water, it is possible to infer percentages of these two water types in a mixture from oxygen-temperature or phosphate-phosphorus-temperature plots (e.g., Emery, 1960, figures 93, 94, and 95).

The California Undercurrent has recently been investigated by Wooster and Jones (1970). A detailed STD survey was made off northern Baja California of the temperature and salinity structure associated with this flow (Figures 14 and 15). The abrupt nature of the transition between waters of the Undercurrent, present in a narrow zone next to the continental slope, and in the California Current offshore, can be seen from these figures. The transition between the two waters was marked by temperature and salinity inversions below 150 m.

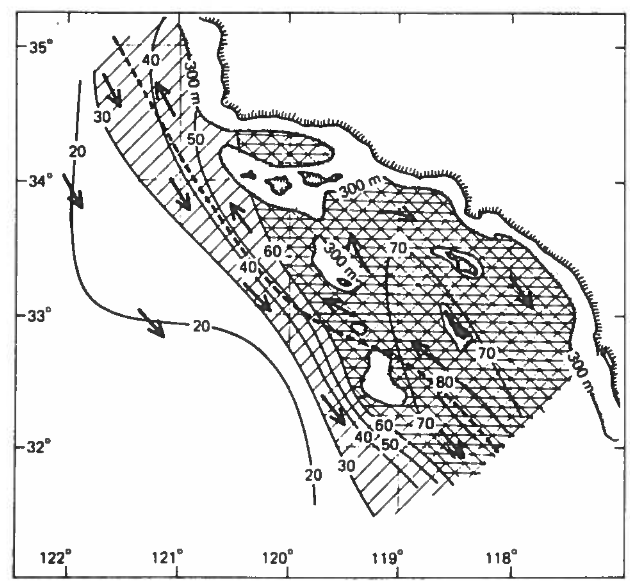

Figure 13. Horizontal distribution of southern water between 200 and 400 m depth. The 300-m isobath has been plotted to indicate the possible effect of the topography on the flow of southern water east of Cortez Ridge. The heavy dashed line separates flow to the south from flow to the north. The cross-hatched area indicates waters made up of more than 60% southern water. From Sverdrup and Fleming, 1941, fig. 34, p. 295.

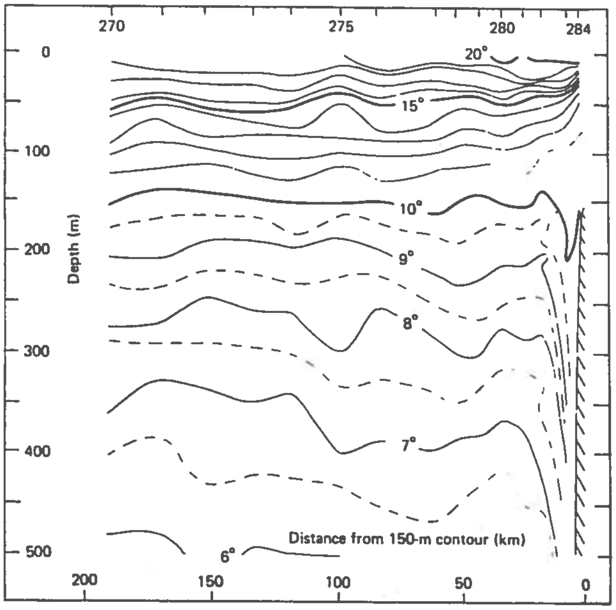

Figure 14. Distribution of temperature (degrees C) on a section normal to the coastline off northern Baja California.

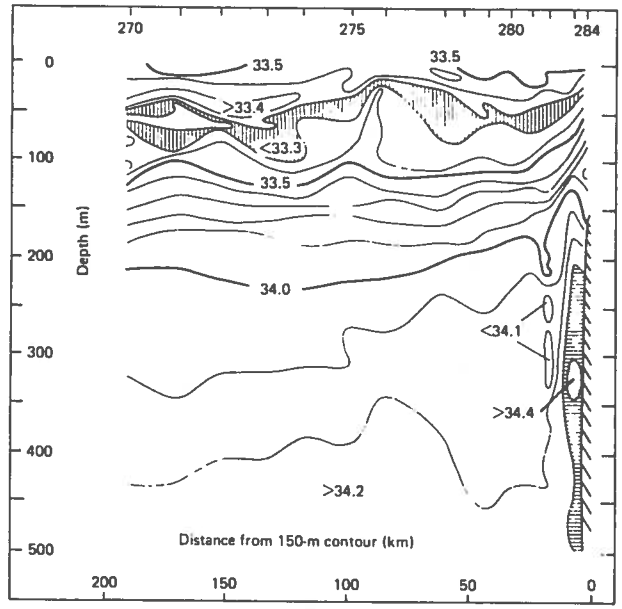

Figure 15. Distribution of salinity (°/oo) on a section normal to the coastline off northern Baja California.

UPWELLING

VI

The term "upwelling" is generally used to mean an ascending motion of some minimum duration and extent, by which water from subsurface layers is brought into the surface layer and is removed from the local area by horizontal divergence, usually accompanied by solar heating. Upwelling is a conspicuous phenomenon along the eastern boundaries of the oceans where prevailing winds carry the surface water away from the coast (Sverdrup, 1938). Because upwelling brings subsurface water into the surface layer, it induces horizontal anomalies in the distribution of physical and chemical properties. These anomalies are most often used as indicators of upwelling, but the effects of upwelling and the physical processes involved should not be misinterpreted. Effects similar to those produced by upwelling can be caused by wind-induced mixing or by an adjustment of the density field associated with an increase in the geostrophic transport of a current (Smith, 1968). The correlation between areas of upwelling and high organic productivity serves to emphasize the importance of upwelling on marine life.

Upwelling is a markedly seasonal phenomenon in the California Current system. The northwesterly winds, which blow more or less parallel to the coast, are strongest off Baja California and southern California in the spring and drive the surface waters offshore. Since upwelling is a result of these winds, the most intense upwelling usually occurs in the region of the Bight during April, May and June. Upwelling begins somewhat later to the north of Point Conception. There are also nonseasonal occurrences of upwelling and, occasionally, upwelling in the Bight will continue into the summer months. These variations in occurrence and strength are also wind-related (Reid, 1960).

In the autumn and winter, when the north winds are weak, the California Undercurrent appears to be strongest. At this time the Davidson Current, which may be a surface manifestation of the California Undercurrent north of Point Conception, is also strongest. The presence of a coastal countercurrent may be considered the antithesis of an upwelling situation.

No direct measurements of vertical velocities associated with upwelling are available. Steady-state models (Sverdrup, 1938; Hidaka, 1954) and transient-state models (Yoshida, 1955; Saito, 1956) give values of the vertical velocity of the order of 10^{-3} cm/sec. These calculations are in qualitative agreement with estimates inferred from the displacement of the isolines of physical properties. Sverdrup and Fleming (1941) have shown the changes in density that occurred during an upwelling period during April 1937 off Port San Luis (Figure 16). The time interval between the two sets of observations was about 40 days.

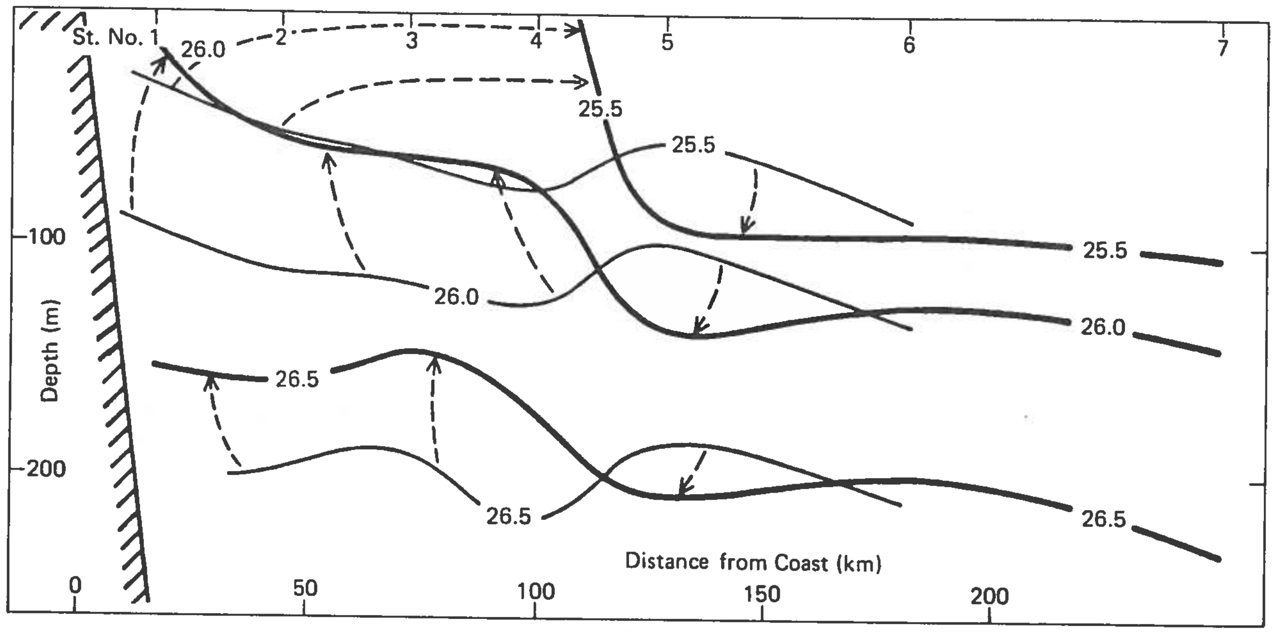

Figure 16. Density distribution of water above a depth of 250 m in a selected area of the Southern California Bight during April 1937. Data were collected during two separate observations: cruise 1, denoted by light lines on the graph; cruise 2, denoted by heavy lines. The elapsed time between the two observations was 40 days. From Sverdrup and Fleming, 1941, fig. 51, p. 319.

Coastal upwelling is known to have a major influence on the high biological productivity in eastern boundary currents. Such upwelling is often intense enough to alter significantly the surface concentration of nutrients. (According to Wooster and Reid (1963), oxygen saturation values in most eastern boundary currents are also significantly affected by upwelling, but not apparently to any great extent in the California Current.) Using the carbon-14 dating method, quantitative studies of the rate of production of organic matter in the oceans have revealed that, over large parts of the ocean, the average rate of carbon fixation is less than 0.2 gm-cal/m^2/day. In the California Current, the average rate is more than twice this value (Wooster and Reid, 1963).

APERIODIC VARIATIONS AND NEARSHORE TEMPERATURE FLUCTUATIONS

VII

Several researchers (e.g., Reid et al., 1958; Hubbs, 1948) have presented information on nonseasonal variations in the California Current region. Reid (1960) has pointed out that certain periods, sometimes lasting for years, have remarkably cold temperatures while others are quite warm. The warm periods have been given as 1926, 1931, 1939-40, 1941 and 1957 to mid-1958 (the end of the published data), and the cold periods as 1924, 1933, and 1955-56. In general, higher salinities and surface phosphate levels correspond to periods of lower temperature. Reid et al., (1958) have stated that the major temperature anomalies seem to continue for several months, which implies that monthly averages appear to be an adequate technique for analysis of these data. They also found a significant correlation between wind anomalies and temperature and salinity anomalies.

Long-term temperature variations are known to be associated with large effects in the regional distribution of marine organisms. Berner and Reid (1961) have given a description of the very large changes in regional populations occurring in a temperature-limited plankter (the pelagic tunicate *Doliolum denticulatum*) during a period of warmer than average surface temperatures in the California Bight region. Reproduction of this particular organism is limited below temperatures of 14 to 15°C. The major concentration of this organism occurs in the upper 50 m. *D. denticulatum* normally lives in the southwestern part of the California Current system, with influx from the northwest and efflux to the south in response to the prevailing currents. Its normal, seasonal pattern of movement, observed from 1949 through 1955, is to the north in summer and to the south in winter, following the seasonal temperature fluctuations. Processes of lateral diffusion and mixing will tend to spread the species outward and, if inshore temperature conditions are favorable, the species will tend to spread inshore.

During the winters of 1957-58, 1958-59 and 1959-60, temperature conditions inshore in the region of the Southern California Bight were such that large populations of *D. denticulatum* flourished near the coast. Berner and Reid (1961) have suggested that the unusually warm water off southern California during 1957 to 1958 caused the species concentration to cross the area west of the islands off southern California usually occupied by a cold tongue of water and to survive in the inshore area. A further result of this change in areal redistribution of the plankter was that the inshore population moved northward in winter and southward in the summer, in response to the seasonal temperature fluctuations observed there.

It should be noted, however, that inferences of surface current patterns from the distribution of plankton can be very misleading. The plankton are not simple drift bottles. All that is needed for population growth is a seed population and suitable conditions. The source of the seed population may be resident or transported, and the difference can be difficult to determine.

In regard to the distribution of the pelagic crab *Pleuroncodes*, Berner and Reid (1961) state that the larvae do not normally live north of San Diego. However, during April 1958, they were found near shore as far north as Monterey, which gives further evidence that 1958 was anomalous with respect to a long-term temperature norm.

Hubbs (1948) presented information concerning nearshore temperature anomalies and resultant changes in fish fauna during the period from 1850 to 1947. In his examination of historic records (e.g., Pacific Railroad Survey from 1853 to 1857), he reports strong indications of a warm-water regime off southern California from 1850 to 1870. During this period, fish fauna that were characteristic of waters south of Point Conception were found as far north as Monterey. In 1859, considerable numbers of these pelagic crabs were washed ashore at Monterey, although this species is uncommon north of central Baja California. More recently, this species was found in abundance off southern California in the spring and summer of 1941. The lowest salinities on record were also observed at Scripps' pier in La Jolla during the spring of 1941.

During occasional warm years, unusual numbers of free-swimming fishes and other pelagic animals appear along the Pacific Coast far north of their customary habitat. Hubbs and Schultz (1929) reported that an occurrence of this nature took place in 1926. Many southern forms (*Velella, Mola mola, Germo alalunga* [albacore]) were found in the nearshore waters of Oregon and Washington, and many hammerhead sharks were caught in southern California coastal waters. All species are either rare or absent from these areas under normal conditions. Five years later, in 1931, an unusual number of southern fish species were taken off the coast of southern California (Walford, 1931). *Velella* were again common off the Oregon coast in June 1971 (J. D. Isaacs, personal communication).

Hubbs (1948) has found that the trend of surface (5 m) sea temperature at La Jolla (Scripps' pier) has remained nearly level, with the exception of the warm years of 1926 and 1931. This correlated with the observations of a northward displacement of some of the marine biota.

The unusual warm period of 1957-58 was the subject of a 3-day symposium at Rancho Santa Fe in June 1958, entitled "The Changing Pacific Ocean in 1957 and 1958" (Sette and Isaacs, 1960). The following pertinent quotations are taken from the summary of the published proceedings:

> "The year 1957 terminated a remarkable and unprecedentedly monotonous decade . . . which involved low temperatures and high northerly winds in the coastal eastern North Pacific . . .; a low stand of sea level . . .; warmer conditions in the Western Pacific . . .; possibly cold conditions in the Equatorial Pacific . . . and in Hawaii."
>
> "The first act of 1957 opened in the winter of 1956-57 with the occurrence of water much warmer than normal over much of the North Pacific . . . and on the Peruvian Coast . . ., and a surprising drop in the velocity of the westerlies of the North Pacific."
>
> "In the meantime, the biota had been affected by these events. As early as the spring of 1957, there was evidence of a northward encroachment of warm water species of fish and possibly a retreat of the northern species along the California Coast . . ."
>
> "The trend intensified over the year and into 1958, with southern fish migrating even into Alaskan waters . . ."
>
> "Both zoo- and phytoplankton exhibited a similar change with an essentially tropical population extending far to the north of their usual habitat. The conclusion was that these species originated to the south and did not represent encroachment from the west."
>
> "Other evidence, such as the dynamic height and the movement of drift bottles [See Figure

3] . . . indicated the development of strong, narrow countercurrents along the California Coast during the winter of 1958, but which was not observed in March 1958."

"Although the change in 1957-58 was conspicuous by any standards, it was not remarkably different from year-to-year changes in the fifty years previous to 1947, during which period hot and cold years, and years with other types of variations, were common. Indeed, looking at the events of 1957-58, these climatic and oceanographic changes are not so remarkable *as is the monotony of the decade that they terminated.*"

"The persistent period of conditions during 1946-1956 holds alarming implications for certain types of engineering studies where the normal is determined by brief surveys, for the design and guidance of such relatively irrevocable acts as locating sewer outfalls, . . ."

There exists another type of aperiodic variation that cannot properly be classified with the phenomenon discussed above, and that is extreme seasonal variations. It was brought out in some of the discussions in the 1958 conference that the year 1939 represented one of these types.

Sea surface temperatures were unusually low in the first few months of the 1939 year and unusually high in late summer and autumn (the warmest autumn on record, Roden, 1961). It is also the only time in this century during which a tropical hurricane reached southern California. In addition, the lowest sea level on record since 1897 (most probably a consequence of the low temperatures) was observed early in 1939. An unusually large seasonal variation of this nature could have profound effects on the breeding habits of marine fish in the affected area.

For many years, records have been kept of sea surface temperature and salinity at various stations along the west coast of the United States. Records at stations on the California coast have been maintained from 1916 at the Scripps Institution of Oceanography, from 1924 at the Newport Beach (Balboa) Pier, from 1920 at Pacific Grove, and from 1919 to 1961 at Port Hueneme. Figure 17 indicates the monthly temperature deviations at these four locations computed by taking the differences between the monthly mean and the long-term mean of the same month. This technique eliminates the regular seasonal variations and highlights the nonseasonal or aperiodic variations.

The observations are made at a random hour during each weekday, but in many cases, the monthly means are computed from less than 20 daily values. The accuracy of individual temperature readings is estimated to be within 0.05°C for stations in southern California. The mean monthly salinity deviations are not included because the values are not as reliable as the temperature observations. In addition, the deviations clearly indicate those years of heavy rainfall and little else (Roden, 1961).

Let us assume that a monthly deviation of ±2°C from the long-term average at the Scripps' pier is the criterion for defining an unusually warm or cold period. From Figure 17 then, the warm periods occur in 1916, 1926, 1931, 1939, 1941, 1957, and 1959. The cold periods occur in 1916, 1924, 1932, 1933, 1939, 1964, and 1965.

A comparison of the records presented in Figure 17 shows that these variations are common to all four stations with only minor differences. It is clear that some warm and cold periods last much longer than others. An extended warm period such as that from 1957 to 1960 (Berner and Reid, 1961) seems to have occurred only once before, from 1939 to 1941. The extreme variations previously noted for 1939 apparently also occurred in 1916. Unusually cold periods lasting for many months are less frequent than extended warm periods. The records indicate only one conspicuously cold period that lasted for more than 12 months; this occurred in 1932-33.

The monthly mean temperature values are computed on a regular basis from the daily observations. In addition to the mean, the maximum and minimum values and the range for the month are recorded. These records are not published, but the data are available at the Scripps Institution of

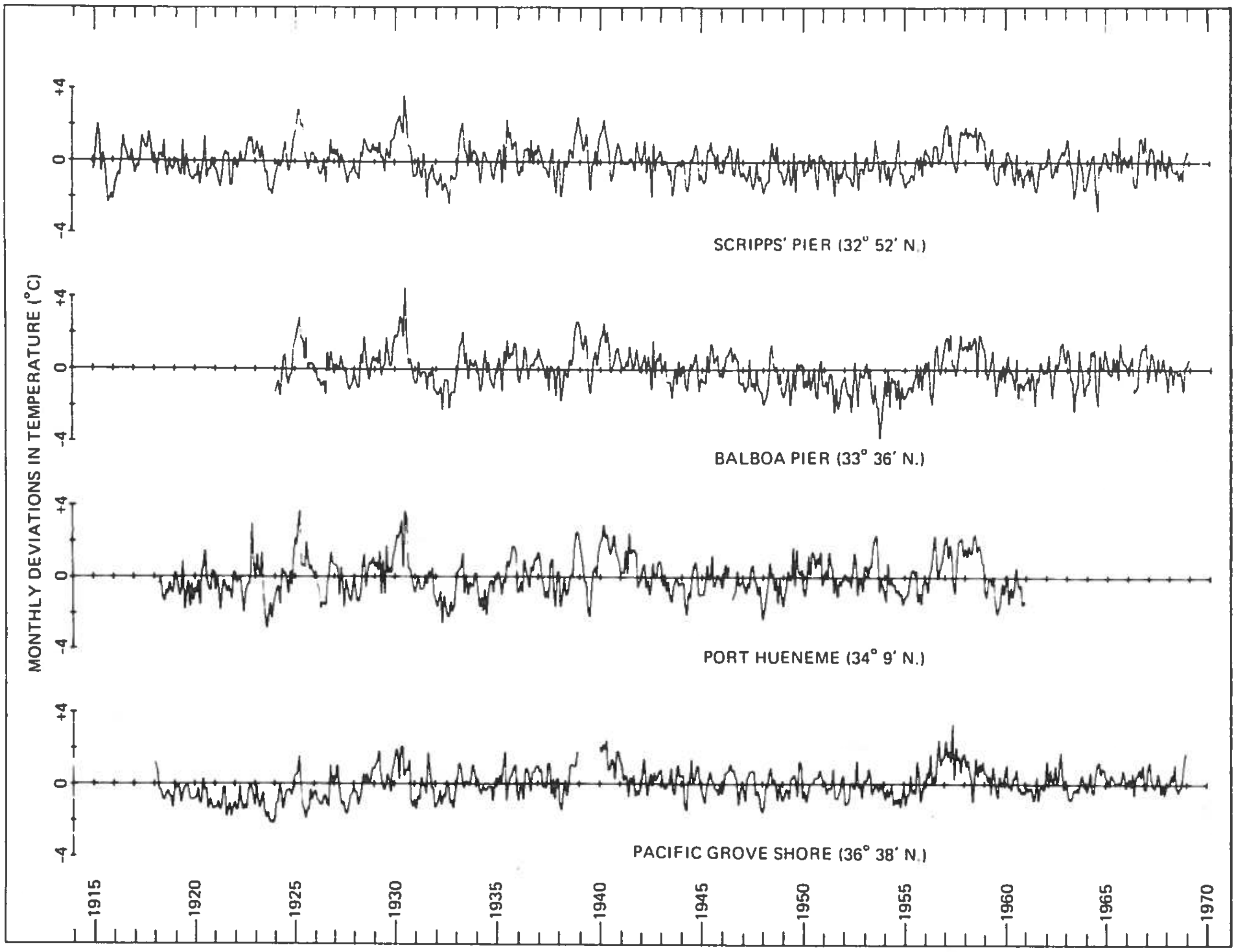

Figure 17. Temperature variations in sea-surface waters as recorded at four different stations on the California coast from 1915 to 1970.

Oceanography. Data collected for a period of 40 years (1919 to 1961) were examined for maximum and minimum ranges and seasonal occurrence. In most years, the minimum range in daily values occurred in the winter season. This minimum range was between 1 and 2°C. The daily records indicated that this range was usually not spread throughout the month, but normally occurred within a period of 10 days or less.

Two types of maximum monthly ranges are observed in the records. The first is a bimodal distribution, where a monthly range of 5 to 6°C has been observed during the times of maximum heating (spring) and maximum cooling (autumn). During the summer season, the monthly range decreased to about 3°C. The second type of maximum range variation in the surface temperature was a single peak occurring usually in July or sometimes in August. These two types of range distribution occurred with about equal frequency.

During those periods in which the monthly temperature range was about 4°C or greater, it was not uncommon for a 1° change per day to be observed. The surface temperature seems to change abruptly, in relatively large increments, rather than gradually and evenly over a period of days.

These large incremental changes in surface temperature might be the result of sporadic eddy-like movement of pools of constant surface temperature water drifting slowly past the observation point with the mean current. If the mean drift is 10 cm/sec (0.2 k), then a 1° change per day implies a horizontal temperature gradient of 1°C per 8 km. Horizontal temperature gradients of this magnitude have often been observed in the vicinity of the California Current, as well as in the Bight itself.

No long-term trends in the ranges or the range distributions were obvious in the 40 years of daily records examined.

SUMMARY AND CONCLUSIONS

VIII

The California Current, typical of eastern boundary currents, is best described as a meandering, diffuse southeastward flow, with short-term variations in speed that are of the same order as the mean speed itself. The current originates near the Canadian border and initially contains water characteristic of the subarctic. As this water moves southward, the surface characteristics are modified by solar heating and by the effects of river inflow and exchange with estuaries and embayments. The flow generally follows the coastline until it reaches the northern limit of the Southern California Bight—Point Conception. Here, the coastline turns abruptly towards the east, and the flow of water departs from the coast, generally continuing in a southeastward direction. Further south, off the coast of northern Baja California, the main portion of the current turns toward the land, and the flow divides into two branches. One branch, known as the Southern California Countercurrent, turns northward and flows through the Channel Islands, forming the inshore side of the Southern California Eddy. The second branch turns southward and continues down the coast of Baja California, where it eventually turns westward and contributes to the North Equatorial Current.

The residence time of water in the Bight may be estimated by assuming a mean path and speed or by estimating the effects of surface heating. Much of the data necessary for an accurate estimate is lacking; however, a mean residence of 2 to 3 months is in reasonable agreement with the available information.

The water entering the Bight reflects a northern origin by surface characteristics of low temperature and salinity and high oxygen content. The Southern California Eddy, a nearly permanent feature of the flow pattern, is seasonal in character. The Eddy is usually well developed in summer and autumn and weak (and occasionally absent) in winter and spring.

Seasonal variations in the surface winds are the primary cause of variations in the surface flow; these wind variations are also responsible for the vertical movement or upwelling of water to the surface. The strong northwest winds off southern California in late winter and spring drive surface waters offshore and cause the upwelling of cold, nutrient-rich water to the surface. This phenomenon contributes significantly to the productivity of water in the Bight. The most intense upwelling usually occurs in the months of April, May, and June, although significant upwelling occasionally continues into summer.

The presence of the coastal countercurrent, known as the Davidson Current, north of Point Conception may be considered the antithesis of upwelling. When the dynamics of the circulation are such that a strong Davidson Current is in evidence, no upwelling is likely to occur in the Point Conception area. The Davidson Current is strongest in autumn and winter—the seasons of the weakest northwest winds.

Surface temperatures in the Bight vary seasonally from 14°C to nearly 20°C. However, historical records indicate that, in some periods, temperature variations that are not related to seasonal changes occur. These aperiodic fluctuations, which may last for years, are characterized by temperatures that deviate from the long-term average by 2°C or more. Fluctuations of this nature may profoundly affect the distribution of the marine biota in the Bight. Aperiodic temperature fluctuations also occur on a much shorter time period: Daily temperature records have revealed changes as great as the annual variation occurring in the space of one month.

Most of the present knowledge about the circulation in the Southern California Bight is based upon information from programs not specifically intended to deal with the dispersion of pollutants as they enter the ocean environment. We have knowledge of the average seasonal variations of some oceanographic parameters, and some data on the monthly variations are available. However, pertinent information is missing regarding the small-scale, horizontal eddy structures, which are important in describing lateral mixing, as well as in determining the residence time of a parcel of water or the half-life of a pollutant in the Bight. Valid estimates of these parameters must await specialized oceanographic field programs and dynamic models of the circulation in the Southern California Bight.

The literature examined has provided intriguing information concerning the historical occurrence of aperiodic phenomena off the coast of southern California. However, these studies are primarily related to one or two isolated phenomena and, with the exception of Rancho Santa Fe Conference on the warm period of 1958 to 1959, rarely encompass enough oceanographic and meteorological aspects. To provide not only the average conditions but the maximum expected deviations, a detailed survey of aperiodic phenomena is needed; this survey should include an examination of all historical documents and personal observations of changes in ocean conditions, including marine flora and fauna, fisheries, weather, ocean temperature and salinity, and nutrients.

Evidence has indicated that the flow in the California Current is highly responsive to the influence of the winds. Much of the information necessary to document the response of the Current to changes in the wind is available. However, no complete study aimed at predicting changes in the flow pattern has been attempted to date.

Much useful oceanographic information has been collected by the CalCOFI program during the last 20 years. While some of this information has been examined in detail with regard to special studies, a major portion of it has not. A complete study of these data would be appropriate, with a view towards understanding the inputs and variations that occur in the Bight and its contributing waters. The study would further provide an evaluation of residence time and mixing of water in the Bight area under various oceanographic and meteorological conditions.

The nature of the California Undercurrent, especially off southern California, is not at all well understood. A study conducted in the summer of 1966 indicated a northward subsurface flow off Baja California, approaching a speed of 1 knot. It has even been suggested that the Davidson Current is a surface manifestation of this flow occurring north of Point Conception. Further understanding of the vertical properties and the northward transport of biota into the region of the Bight is necessary.

A basic understanding and subsequent forecasting of the fluctuation of conditions related to water quality off southern California can best be achieved by a study of the nearshore and offshore circulation. This should be guided by criteria for environmental sampling based on existing knowledge of physical processes within the area.

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