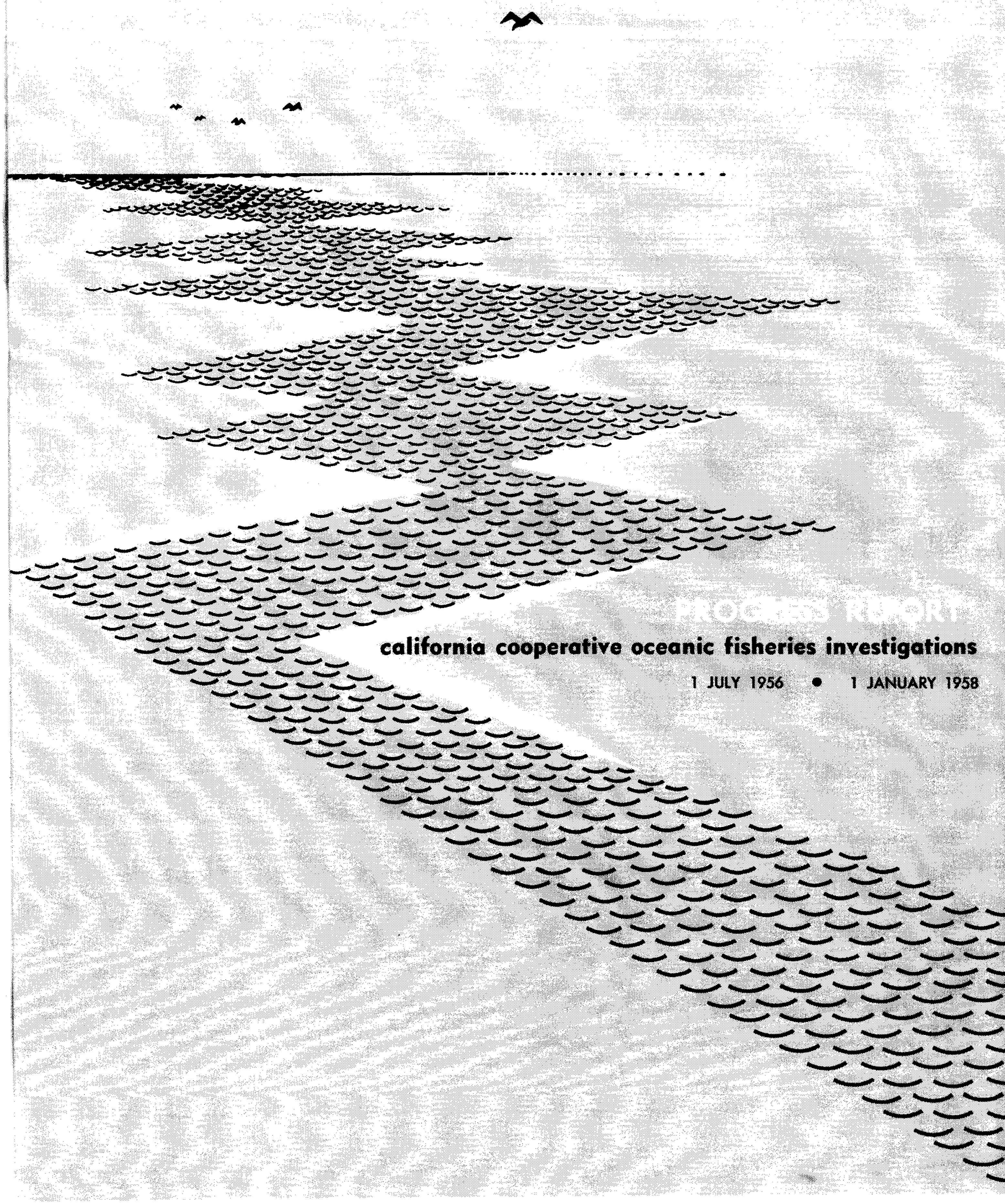

PROGRESS REPORT

california cooperative oceanic fisheries investigations

1 JULY 1956 • 1 JANUARY 1958

Inquiries concerning the California Cooperative Oceanic Fisheries Investigations should be addressed to the State Fisheries Laboratory, California Department of Fish and Game, Terminal Island, California

STATE OF CALIFORNIA
DEPARTMENT OF FISH AND GAME
MARINE RESEARCH COMMITTEE

CALIFORNIA COOPERATIVE OCEANIC FISHERIES INVESTIGATIONS

Progress Report

1 July 1956 to 1 January 1958

Cooperating Agencies:
CALIFORNIA ACADEMY OF SCIENCES
CALIFORNIA DEPARTMENT OF FISH AND GAME
STANFORD UNIVERSITY, HOPKINS MARINE STATION
U. S. FISH AND WILDLIFE SERVICE, SOUTH PACIFIC FISHERY INVESTIGATIONS
UNIVERSITY OF CALIFORNIA, SCRIPPS INSTITUTION OF OCEANOGRAPHY

1 January 1958

LETTER OF TRANSMITTAL

1 January 1958

HONORABLE GOODWIN J. KNIGHT
Governor of the State of California
Sacramento, California

DEAR SIR: We respectfully submit a report on the progress of the California Cooperative Oceanic Fisheries Investigations for the period 1 July 1956 to 1 January 1958.

The report consists of three parts: a Review of Activities for the period; a scientific paper, *Studies of the California Current System*, by Joseph L. Reid, Jr., Gunnar I. Roden, and John G. Wyllie; and a list of publications arising from the program.

Respectfully,

THE MARINE RESEARCH COMMITTEE
J. G. BURNETTE, Chairman
D. T. SAXBY, Vice Chairman
RAYMOND CANNON
JOHN HAWK
JOSEPH MARDESICH
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W. E. STEWART
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ABSTRACT

In the year 1957, oceanographic conditions along the western coast of the United States differed considerably from those in the past few years. Average temperatures at the shore stations were higher than at any time throughout the 1949-56 period. The winds in 1957 had less of a northerly component than at any time during the 1949-56 period.

Sea surface temperatures for the entire CCOFI area tell virtually the same story when compared with those for the period 1949 to 1954: warmer water, as much as 3° C., prevailed over much of the area from January through October.

These higher temperatures do not necessarily mean that southern water swept northward. The California Current continued to flow southward, although perhaps with reduced transport. Most probably the warm water came from offshore, from the west or northwest. One of the most striking features of the year, preliminary analysis shows, is that the warming extended to considerable depths.

Sardine spawning off northern Baja California and southern California during 1957 was also unique. On the usual offshore grounds, spawning was limited and discontinuous. Most of the spawning took place in a coastal band from Punta Baja to San Pedro. For the first time in several years, some sardine spawning occurred north of Pt. Conception, reaching at least as far as Monterey Bay.

The 1957-class of sardines soon made itself evident in the live-bait fishery. Preliminary figures indicate these "firecrackers" will account for at least 6.0 percent of the live-bait catch, as against 0.3 percent in the best previous year since 1949.

Survival of the 1957-class of sardines off southern California has undoubtedly been better than in recent years. It is possible that the 1957-class will prove to be large, but judgment should be reserved, since these juveniles may have been over-available during the year because of their inshore origin, and been over-sampled.

The year 1957 will unquestionably prove to be the best for the southern California anglers since party boat records were re-established in 1947. Equally as remarkable as the year's upsurge in landings of game fish by sportsmen is the fact that many species have been taken much farther north than in recent years.

To the agencies conducting research under the California Cooperative Oceanic Fisheries Investigations, the year 1957 presents both an opportunity and a challenge. In previous years, large amounts of data have been collected on the ocean and the fisheries, so that it has been possible to describe in considerable detail what has happened to oceanographic conditions since 1949. A comprehensive study of the California Current region from 1949 to 1956 appears as the central paper in this report, for instance. This material will now offer an invaluable basis of comparison with a year which differs strikingly from those immediately preceding, but which may have been similar to others in the past for which not so large an amount of data exists. Thus, 1957 may offer an opportunity to explain both the immediate past and perhaps throw further light on the years of the thriving sardine fishery.

CONTENTS

REVIEW OF ACTIVITIES
1 July 1956-1 January 1958

In April, 1947, representatives of the California Academy of Sciences, California Department (then Division) of Fish and Game, the South Pacific Fishery Investigations of the U. S. Fish and Wildlife Service, and the University of California's Scripps Institution of Oceanography met and drafted a document that has since served in a sense as the charter of activities under the California Cooperative Oceanic Fisheries Investigations.

To this enterprise they brought a distinguished history of research. As long ago as 1920, W. F. Thompson of the Division of Fish and Game had drawn up a long-term program of research on the sardine (W. F. Thompson, "The proposed investigation of the sardine," *California Fish and Game,* vol. 6, no. 1, pp. 10-12, January, 1920). The State's investigations along these lines revealed much information on the fishery, all of which has served as part of the strong foundation upon which the CCOFI program has been built.

From April, 1929, to September, 1932, the early life history of the sardine was subject to an intensive oceanographic-biological survey by the combined efforts of the California Division of Fish and Game and Hopkins Marine Station of Stanford University. A great deal was learned about the early life history of the sardine and the distribution of its eggs and larvae (Eugene C. Scofield, "Early life history of the California sardine (*Sardina caerulea*) with special reference to distribution of eggs and larvae," *Fish Bull.,* no. 41, 48 pp., 24 figs., 1934).

In 1937 the California Division of Fish and Game cooperated with the Scripps Institution of Oceanography in a study of surface currents off the southern California coast (Richard B. Tibby, "Report on returns of drift bottles released off Southern California, 1937," *Fish Bull.,* no. 55, 36 pp., 22 figs., 1939).

By the 1930s, the sardine fishery had become the largest in the country. In 1937, the U. S. Bureau of Fisheries (now a part of the U. S. Fish and Wildlife Service) established a laboratory at Stanford to work in this field. From this group came another influential paper on methods of studying the sardine (Oscar E. Sette, "Studies on the Pacific pilchard or sardine (*Sardinops caerulea*) I: Structure of a research program to determine how fishing affects the resource," U. S. Fish and Wildlife Service, *Special Scientific Report No. 19,* 1943).

From 1939 through 1941, the Fish and Wildlife Service cooperated with the Scripps Institution of Oceanography in additional combined oceanographic-biological cruises off our coast. Though small in scale as compared to the CCOFI cruises, all these earlier cruises have provided invaluable data to the present investigations (H. U. Sverdrup and the staff of the Scripps Institution of Oceanography, "Oceanographic observations on the *E. W. Scripps* cruises of 1940 and 1941," Univ. Calif., Scripps Inst. Oce., *Records of Observations,* vol. 1, nos. 3 and 4, pp. 161-408, and Oscar E. Sette and Elbert H. Ahlstrom, "Estimations of abundance of the eggs of the Pacific pilchard (*Sardinops caerulea*) off southern California during 1940 and 1941." *J. Mar. Res.,* vol. 7, no. 3, pp. 511-542, 4 figs., 1948).

The University of California's Scripps Institution of Oceanography was brought into the conference because of the recognition that it would be impossible fully to understand pelagic fisheries without a look at the ocean for an explanation of variations not explained by biology and the statistical analysis of the catch and fishery.

The California Academy of Sciences was represented in this conference since the facilities of Steinhart Aquarium could be used to study such matters as the schooling habits of sardines and their reactions to light and electricity.

In writing of such a meeting it is regrettably easy to ignore the fact that human beings, not cold institutional entities, were the participants. Three persons of remarkable abilities were the chief architects of the CCOFI program. None is connected with the Investigations now. Dr. Oscar E. Sette of the U. S. Fish and Wildlife Service is chief of the service's Ocean Research group. Dr. Frances N. Clark, for many years the Director of the Department of Fish and Game's State Fisheries Laboratory, retired in 1957. Dr. Harald U. Sverdrup, the world's greatest physical oceanographer, then Director of the Scripps Institution of Oceanography, died in his native Norway in August, 1957.

The program drawn up by these scientists has been printed before (Progress Report, California Cooperative Oceanic Fisheries Investigations, 1 July 1953-31 March 1955), but since it is germane to the present review, it is reprinted below:

BIOLOGICAL RESEARCH

I. Recruitment.
   a. Measurement of amount of spawning.
   b. Measurement of the abundance of larvae.

c. Measurement of the relative abundance of year-class before it enters the fishery.
d. Measurements of the sizes of year-classes in the commercial fishery.
e. Studies of the spawning stock on the spawning grounds.

II. Availability of the stock to the fishermen.
a. Analysis of the commercial catch.
b. Exploratory work on and off the fishing grounds during the fishing season.
c. Exploratory food studies.

III. Investigation of rapid methods of plankton collection and analysis.

IV. Physiological studies of behavior, feeding, and nutrition.

V. Dynamics of the sardine population and fisheries.

PHYSICAL AND CHEMICAL OCEANOGRAPHY

(No detailed program in oceanography was drawn up at this time.)

After the establishment of the Marine Research Committee, a Technical Advisory Committee was appointed by the Marine Research Committee. It consisted of one member from each of the four (later five) cooperating agencies. At a meeting of the Technical Advisory Committee on 10-11 June 1953 the following amplified consensus of CCOFI objectives and problems was reached:

CCOFI objectives:

To determine what controls variations in population size and availability in oceanic fishes off the west coast of North America.

The attendant problems, solution of which is necessary to attainment of these objectives, are, in brief:

(1) How many subpopulations are there?
(2) What is the size of each subpopulation?
(3) What controls variation in the growth rate of individual fish?
(4) What controls variation in year-class size?
(5) What controls variations in mortality rates of the adult fish?
(6) What controls variations in the availability of the fish to the fishery?

These objectives and problems are now being critically reviewed in the light of recent findings.

In 1951, the Hopkins Marine Station of Stanford University agreed to conduct studies of the oceanography of Monterey Bay, a type of highly detailed oceanographic study not feasible under the broader sort of investigations being conducted at the Scripps Institution.

In the ensuing paragraphs, each agency reports on its recent work under the CCOFI program.

CALIFORNIA ACADEMY OF SCIENCES

Effects of Light and Darkness on Schooling Behavior of the Pacific Sardine (Sardinops caerulea)

The experiments of 1955 and 1956, conducted in 1,000 gallon tanks, showed that maintenance of the school as a unit and the movement of the school in a circular path (so-called "circling" or "milling") are mediated through the fish's eye. Vision therefore appears to be the most important factor in schooling behavior of the sardine. Experiments showed that a sudden darkening of the tank at night would immediately result in breaking up the school, causing the fish to disperse in all directions. At such times the sardines, being scattered throughout the tank, seemed to swim about aimlessly at much reduced speed. Their swimming had no oriented direction, and resulted in complete disorganization of the school. At such times each fish seemed to be independent of any other as a point of reference. In total darkness any fish might occupy any stratigraphic position in the tank from the very bottom to the very surface. There was no concentration at any particular level.

A striking phenomenon of loss of body equilibrium has usually been noted immediately after turning off the light. Up to 90 percent of the sardines in a school have exhibited a definite effect of the sudden darkness. A series of flash photographs revealed them "standing on their tails" and slowly progressing head-upward toward the surface. This behavior lasted only a few minutes—up to 10 at a maximum—after which a normal swimming position was resumed. But in no case were they able to form a school in complete darkness. When illumination was again provided the sardines required from 5 to 10 minutes to resume normal schooling behavior, including the characteristic circling movement at normal speed.

Effect of an Intermittent Beam of Light

The experiment was tried of directing an intermittent beam of light of low intensity through the middle of a tank of sardines otherwise in total darkness. The light was directed from front to rear of the tank, and flashed at a rate of 60 times per minute. This appeared to frighten the sardines and effectively prevented their re-forming a school.

When a constant beam of light of the same intensity was directed through the tank, the sardines resumed normal schooling behavior almost as quickly as if the tank were fully illuminated. At first they avoided the direct beam of light, circling in areas of the tank dimly illuminated by light scattered or reflected from the beam, but gradually they moved more and more into the brightly illuminated area and soon were milling without regard to brighter and darker zones, passing freely through both.

The fact that sardines avoid a flashing beam of light is in accord with the practice of sardine fishermen of using a flashing light to prevent the escape of sardines from a purse seine as the net is being closed. The principle seems likely to be of considerably wider practical application in altering or directing the movements of fish.

Effect of Colored Lights on Sardine Behavior

Lights of the primary colors, red, blue, and green, of various measured intensities and of known wavelength, were experimentally applied to illuminate a tank containing sardines. Neither blue nor green light produced any significant change in behavior, but the red light, regardless of its intensity over the rather wide range used, produced an immediate reaction, initially similar to the behavior in total darkness described above. At the moment of switching from white to red light, the school came to a complete halt. This was followed by a state of confusion and loss of body equilibrium, referred to above as "standing on their tails."

At first it was surmised that the fish might simply be unable to see in red light, but this was not borne out by their subsequent behavior. The state of confusion as a rule rapidly disappeared and the school re-formed, but the fish appeared excited or alarmed. Although the experiments with the red light were continued an hour at a time, the school never settled down to normal behavior, but swam at an accelerated speed with frequent change of direction and pattern of formation.

This suggested a further experiment in which the sardines might have a choice of red, blue, green or white light, or darkness. Small groups of sardines (six at a time) were placed in a long tank, different segments of which were differently illuminated. Intensity and wavelength of the incident light were carefully controlled, although the factor of brightness as registered through the eye of the fish was not taken into consideration. At first three choices were permitted, then the several alternatives were carefully checked in pairs.

The series of experiments shows that sardines prefer blue or green light to white light, but they showed no preference for blue over green or vice versa. Red light was definitely avoided when offered as an alternative to blue, green, or white, but when the fish were offered only the alternatives of red light or darkness, they preferred the red light. It may be concluded that, under the conditions of this experiment, sardines are positively phototropic, and that they have at least some degree of color discrimination.

Behavior of the Sardine and Herring in an Electrical Field

In an earlier publication * it was suggested but not definitely proved that the current density required to produce controlled directional swimming of sardines in an electrical field varies inversely with the size of the fish. This has now been definitely demonstrated, using sardines ranging from 100 to 230 mm in length, and subjecting them to the effect of half-wave rectified 60-cycle alternating current, with an average current density from less than 1 milliampere up to 13 milliamperes per square inch of cross-sectional area of the water. The results are shown in the following table:

Length of fish	*Optimal current density*
100-114 mm	9-11 ma
140 mm	7- 9 ma
150-155 mm	6- 8 ma
170-180 mm	5- 7 ma
200-230 mm	3- 5 ma

Pacific herring (*Clupea pallasi*) tested in an electrical field displayed patterns of response closely similar to those of the sardine. The relationship between the size of the fish and the current density required to produce controlled directional swimming was found to be identical for the two species.

The northern anchovy (*Engraulis mordax*) behaved erratically and failed to show any consistent response to an electrical current. Only young fish 60 to 95 mm long were available for testing. Further experiments should be made with different size groups to determine the pattern of response in this species.

It is interesting to note that data obtained in these investigations have been used by Keith A. Smith * in a successful experimental catch of herring under sea conditions.

CALIFORNIA DEPARTMENT OF FISH AND GAME

The Department conducts investigations and collects catch statistics on almost all the commercial and sportfishes found off the California coast. The pelagic species, Pacific mackerel, jack mackerel, herring, squid, anchovies, and sardines, are investigated by the Department's Pelagic Fisheries Investigations. Therefore, this report of the Department's activities relating to the CCOFI program is essentially a report of the Pelagic Fisheries Investigations, coupled with pertinent information obtained from certain other investigations of the Department.

Since the start of the CCOFI, the activities of the Pelagic Fisheries Investigations have been directed toward obtaining information on the following phases extracted from the research outline given earlier:

(1) Measurement of the relative abundance of year-class before it enters the fishery.
(2) Measurements of the sizes of year-classes in the commercial fishery (in cooperation with Fish and Wildlife Service).

* Loukashkin, A. S., and N. Grant, 1954. Further studies on the behavior of the Pacific sardine, *Sardinops caerulea*, in an electrical field. *Proc. Calif. Acad. Sci.*, vol. 28, pp. 323-337.

* Smith, K. A. 1955. Use of an electric attracting and guiding device in experiments with a "fish pump." *Commercial Fisheries Review*, vol. 17, no. 2, pp. 1-7.

(3) Analysis of the commercial catch.
(4) Exploratory work on and off the fishing grounds.
(5) Exploratory food studies (begun by the Department, continued by Scripps Institution of Oceanography and now being conducted by the U. S. Fish and Wildlife Service).
(6) Dynamics of the sardine population and fisheries.

A description of the fishery and a report of the activities and some of the findings of the Department's Pelagic Fisheries Investigations since July, 1956 follows:

The Sardine Fishery in 1956-57

As in the previous two seasons, concentrations of sardines appeared off the Hueneme-Santa Barbara areas in August. However, by the middle of September 1956, the fish schools were less concentrated than during the same period in either 1954 or 1955. By September, 1956, the sardine schools were observed spreading out and moving down the coast. By the beginning of the sardine fishing season in southern California, 1 October, the southerly movement of fish was well developed.

Although the lack of a price settlement kept most of the San Pedro fleet from fishing until the night of 8 October, a few San Pedro vessels and some from the north fished with the Santa Barbara-Hueneme boats and by 8 October had landed over 5,000 tons of sardines. During this period there was a notable shift of fish toward the south; more and more catches were being made south of Hueneme.

On 8 October, after a price settlement had been made, the San Pedro fleet began fishing and catches were made at widely scattered locations from Hueneme to Oceanside. Commencing 10 October landings at Hueneme dropped markedly. Apparently a substantial portion of the fish from the Hueneme area had moved into the closed area of Santa Monica Bay.

During the night of 11 October the fleet converged on the sardines moving out of Santa Monica Bay and caught over 3,000 tons in the vicinity of Pt. Vicente. Although a large part of the fleet returned to the same area the following night, the catch dropped to less than a third.

After 12 October the fish were difficult to find. Landings were poor and catches were made from various areas, mostly south of San Pedro. On 16 October, the last night of the dark, catches totaling 5,000 tons, the largest of the season, were made just north of the Mexican Border from a southerly moving concentration of fish.

The end of the first dark virtually marked the end of sardine fishing, since 77 percent of the 1956-57 catch of 32,648 tons was taken during the first dark.

Approximately two weeks after the last night of the first dark, the Ensenada fishery experienced a brief flurry which subsided as abruptly as it began. Apparently, the sardines were still moving rapidly south as they passed Ensenada. During the California season 5,971 tons were landed at Ensenada.

The size of the fish caught during the 1956-57 season averaged about 11 mm longer than in 1955-56. An increase in the average size of the fish was not surprising; in fact it was predicted since almost half the fish caught in 1955-56 were the three-year-old 1952-class. As was expected the 1952-class remained dominant in the fishery as four-year-olds in the 1956-57 season. The 1952-class has been the strongest in the fishery since 1948.

The size of the San Pedro fleet is still decreasing, particularly in the number of larger purse seine vessels. In recent years there were additions to the fleet of smaller vessels employing either purse seines or lampara nets, but even the number of these vessels in the fishery decreased in 1956-57. Last season (1956-57) the San Pedro fleet consisted of 98 large purse seiners, 26 small purse seiners, and 36 lampara vessels. This was a decrease from the preceding season (1955-56) of 14 large purse seiners, 1 small purse seiner, and 5 lampara vessels.

Because of the recurrence of concentrations of sardines off the Hueneme-Santa Barbara area prior to the opening of the 1956 sardine fishing season and the abrupt decline in catch as the season progressed, the season was moved forward one month by the 1957 Legislature to start 1 September and end 31 December.

Despite the earlier starting date, a dispute on price has kept the San Pedro fleet idle, and as of 1 November 1957, a price settlement had not been reached; consequently, the vessels fishing out of Hueneme and Santa Barbara have landed almost the entire catch. The sardines have appeared to be widely scattered and not very abundant in 1957.

Anchovies

The commercial landings of anchovies fell short of the 35,000-ton limit during the season 1 April 1956 through 31 March 1957; the catch was 22,598 tons. The 1957 Legislature failed to renew the quota for the 1957-58 season. By late spring of 1957, the market demand for anchovies had improved, thereby giving impetus to substantial landings. In the first six months of 1957, approximately 12,500 tons of anchovies were delivered, almost 2,000 tons more than during the same period in 1956.

Routine sampling of the two principal fishing areas, central and southern California, indicated that in each area two-year-old fish contributed well over half of the numbers of fish caught. Of the incoming year-classes, the 1956 group does not appear to be out-standing off central California or off southern California. The 1955-class in the latter area appears very strong at present and should aid materially in maintaining a relatively high population of anchovies in the forthcoming season. Early indications point to a strong 1957-class of anchovies off central California.

Mackerel

During the season from July, 1956 to June, 1957 commercial landings of Pacific mackerel were approximately 28,000 tons—100 percent more than in the previous season. Landings of jack mackerel were over 46,000 tons—30 percent higher than in the 1955-56 season.

The heaviest landings occurred in the five-month period from October through February, when 70 percent of the tonnage of each species was taken. In comparison, 57 percent of the tonnage of each species was taken during the same five-month period of the 1955-56 season. The increase in landings in this five-month period is due to fluctuations of the market demand. The subsidiary role the mackerel play in relation to the sardine landings is quite apparent since the market demand for the two mackerel species is inversely affected by that of the sardine. During the sardine season, October through February, orders are placed for alternate species when sardines are not available in sufficient tonnage, thus distributing the daily workload at the processing plants.

During the first half of the season the price per ton of Pacific mackerel was $45.00 while that of jack mackerel was $42.50. On 4 January a new price of $42.50 per ton for either species was agreed on by the canners and fishermen.

Nearly half of the tonnage of Pacific mackerel was taken in the offshore areas between Pt. Fermin and Oceanside. About 20 percent was taken in the vicinity of Santa Catalina Island and about the same tonnage was taken in the area from Pt. Fermin north to Pt. Dume. The remaining 15 percent of the catch was about equally distributed, by point of origin, from Oceanside to the Mexican border, the area around Santa Cruz Island, Port Hueneme, and in the vicinity of San Clemente Island. This distribution of catch localities holds also, in a large measure, for jack mackerel.

Approximately 160 boats, using purse seines and lampara nets, caught the major portion, 84 percent, of the mackerel catch. The landings of the 50 or so scoop boats were composed almost entirely of Pacific mackerel, accounting for 16 percent by weight of the total deliveries of this species. About one percent of the mackerel landings was caught by nearly a score of assorted skiffs and power boats using hook and line.

Studies of the age composition of the catch, fecundity, and food of the Pacific mackerel are now being conducted.

Sauries

With the scarcity of sardines in the latter part of the 1956-57 season some fishing effort was directed toward anchovy fishing; however, the anchovy catch was limited by market demands, and other fish were sought. Therefore, it was not surprising, although certainly very interesting, that several small loads (from 1 to 20 tons) of Pacific sauries were delivered to at least two canners in the Long Beach-San Pedro area in January of 1957.

The fish were located by airplanes and caught by purse seiners. Although used almost entirely for pet food, the sauries, preliminary reports indicated, were substantially higher in protein value than most other cannery fish.

Previous progress reports of the California Cooperative Oceanic Fisheries Investigations have indicated that sauries are quite numerous and that they could support a substantial fishery. These reports also stated that the Japanese land considerable tonnages of this species annually. Much interest has been expressed in the possibility for future exploitation of this species off the California coast.

1956 Young-Fish Surveys

Five cruises were made to assess the relative abundance of sardines. Two thousand and eighty nautical miles were scouted during 76 nights. Three hundred and sixty-six light stations were occupied; 34 samples of sardines were obtained. The sardines were largely concentrated in the area between Ballenas Bay and Pt. Eugenia, Baja California. In this area 28 percent of all stations occupied yielded sardines. Preliminary age analysis of the fish reveals that about 70 percent were of the 1956-class.

As the survey progressed up the coast sardines appeared in less abundance. From Pt. Eugenia to the Border, sardines were sampled at only 17 percent of the stations occupied, and 64 percent of these fish were of the 1956-class. From the Border to Pt. Conception, sardines were quite scarce. Only 2.5 percent of the stations occupied yielded sardines; 20 percent of these were the 1956-class. Although spawning success was better south of Pt. Eugenia the fish of the year were less abundant in 1956 than in 1955. In 1955, 90 percent of the fish sampled in this area were fish of the year.

Pacific mackerel were sampled more often than any other species during the 1956 survey. They were present at 13 percent of all stations occupied, being most abundant along the Baja California coast, notably in Todos Santos Bay and the area from Pt. Eugenia to Ballenas Bay.

With the condemnation of the *Yellowfin* in May, 1956, experiments in electro-fishing were transferred to the *N. B. Scofield.* On 1 February 1957, work was begun installing and checking the electrical equipment and by 1 May experiments were under way at the level left off on the *Yellowfin.*

Wild schools of jack mackerel were night-lighted and successfully sampled with a new positive electrode. A gill net stretched over the electrode acted as a collecting device. Future work will be channeled toward development of a device to entrap fish about the electrode.

Aerial Surveys

Analyses of the first three years' airplane census data have proved most encouraging and the Department has intensified its aerial program. Methods of determining the area of fish schools from the air have been worked out. Results show that the large masses of fish that occur in the summer and fall are best measured by photographic methods, whereas the smaller, more uniform schools present in spring and any schools that are dim or barely visible are more efficiently measured by a telescope with a graduated reticle. Alterations are now being made to the Department's plane to accommodate special aerial photographic equipment.

The large anchovy concentration reported along the coast of California in the spring of 1956 continued to build up during the summer and fall in the southern California and Baja California areas. The peak of abundance in southern California occurred in late September. Results of the first two flights in 1957 showed a decrease of anchovies along the coast, especially in central California; however, there are good indications that the 1957-class should be a strong one, particularly off central California.

It is noteworthy that on Flight 57-2 (14-24 May) a school group of sardines appeared in the area around the Coronados Islands and Pt. Loma. These fish were reported about 1 May by commercial aerial spotters and samples of live bait collected at San Diego proved them to be nearly all of the 1955-class. Over the past three seasons sardines were not seen on aerial flights until late in June.

Bait Sampling

Although the Department has recorded the live-bait catch since 1939, it was not until 1949 that records were kept of the amounts of young sardines less than one year old that were caught for live bait. The reports from bait haulers indicate the numbers of "scoops" of various species taken and these values are converted to weights, based on the average scoop weight of each bait hauler. Young sardines less than a year old have been reported as "firecrackers" since 1949.

In general, adult anchovies and very young sardines (firecrackers) are the preferred live-bait fish. Species making up minor amounts of the catch such as white croaker, queenfish, and smelt are referred to collectively as "junk fish." Jack mackerel, Pacific mackerel, and Pacific herring also are frequently referred to as "junk fish" because of their relatively small contribution to the total live-bait catch.

In 1955, routine bait sampling was inaugurated to improve the estimates of species composition of the live-bait catch, to determine the size and age composition of the anchovies and adult sardines, and to attempt to obtain an index of the strength of the incoming year-class of anchovies and sardines in southern California. During the heaviest sportfishing months, April to October, a sample of bait has been received once each week from bait haulers operating from the major sportfishing ports between San Diego and Morro Bay.

The amounts and percentages of young sardines, adult sardines, anchovies, and miscellaneous species (junk fish) in the bait catch from 1949 through 1956 are shown in the following table.

SPECIES COMPOSITION OF THE BAIT CATCH

Year	Live-bait catch in tons	Young sardines (firecrackers)		Adult sardines		Anchovies		Miscellaneous fish percent
		Tons	Percent	Tons	Percent	Tons	Percent	
1949	4,535.0	0.5	.01	1,454.1	32.06	2,802.4	61.79	6.14
1950	5,528.9	2.1	.04	1,546.8	27.98	3,823.8	69.16	2.82
1951	6,614.2	1.9	.03	1,303.6	19.71	5,141.9	77.74	2.52
1952	7,182.4	12.8	.18	113.8	1.58	6,810.4	94.82	3.42
1953	6,488.9	5.7	.09	9.9	.15	6,391.5	98.50	1.26
1954	6,835.9	1.4	.02	68.8	1.01	6,686.0	97.81	1.16
1955	6,242.7	18.6	.30	40.5	.65	6,125.4	98.12	.93
1956*	6,364.1	0.1	.00	7.8	.12	6,331.8	99.49	.39

* Preliminary figures.

It is interesting to note that in 1949, 1950, and 1951, the percentage of firecrackers in the bait was very small and subsequently these year-classes were relatively weak in the commercial sardine catch. In 1952, the percentage of firecrackers in the live-bait catches increased materially and the 1952-class has dominated the commercial catch for the past two seasons.

In 1953, the percentage of firecrackers was somewhat less than in 1952 but better than in the years 1949 through 1951. Thus far, analyses of commercial landings reveal that the 1953-class is somewhat weaker than the 1952-class. It is too early to tell the contribution to the catch of year-classes since 1953 but, if percentages of firecrackers in the bait indicate the relative year-class strength, the 1955-class may be stronger than the 1952-class.

Since a substantial amount of the total anchovy catch is taken by the live-bait fishery, the bait sampling program inaugurated in 1955 should also prove to be a valuable asset in understanding the dynamics of the anchovy populations off California. The following table shows the tonnages of anchovies caught by the commercial fleet and the live-bait fleets since 1939.

COMMERCIAL LANDINGS AND LIVE BAIT

Catch of Anchovies in Tons in California, 1939-56

(Live-bait Catch 1943-45 Not Recorded)

Year	Commercial landings	Live bait	Total	Percent live bait
1939	1,073.9	1,503.2	2,577.1	58.3
1940	3,158.8	2,006.0	5,164.8	38.8
1941	2,052.6	1,581.7	3,634.3	43.5
1942	847.1	257.6	1,104.7	23.3
1943	785.4	--	--	--
1944	1,945.5	--	--	--
1945	808.4	--	--	--
1946	960.8	2,748.1	3,708.9	74.1
1947	9,470.2	2,854.0	12,324.2	23.2
1948	5,417.9	3,725.5	9,143.4	40.7
1949	1,661.1	2,802.4	4,463.5	62.8
1950	2,439.3	3,823.8	6,263.1	61.1
1951	3,477.4	5,141.9	8,619.3	59.7
1952	27,891.4	6,810.4	34,701.8	19.6
1953	42,917.7	6,391.5	49,309.2	13.0
1954	21,205.1	6,686.0	27,891.1	24.0
1955	22,345.7	6,125.4	28,471.1	21.5
1956*	22,598.0	6,331.8	28,929.8	21.9

* Preliminary figures.

In 1957, there has been an enormous increase in the percentage of young sardines (firecrackers) in the bait. Firm figures are not yet available, but it appears that firecrackers in the bait may exceed 6 percent (as against 0.30 for 1955, the best previous year). Even more significant is the fact that sardines of the 1957-class have been taken by the live-bait fleet off all sportfishing ports from San Diego north to Morro Bay. In addition, sardines of the year have been collected from Monterey Bay for the first time in several years.

It is apparent that 1957 is a year of unusually high water temperatures compared to the others since 1949. Aside from the obviously better survival of the 1957-class of sardines, there has been a phenomenal increase in the catch of many sportfish.

The Sportfishery in 1957

The year 1957, unquestionably, will be the best sportfishing year southern California ocean anglers have enjoyed since party boat records were re-established in 1947. Yellowtail have been caught off all southern California sportfishing ports and in large numbers south of Port Hueneme, and the barracuda catch has also increased greatly over the past several years. More bonito and yellowtail have been taken by party boat anglers than in any year previously recorded.

The following table shows the catch in numbers of several game species from 1947 through September of 1957:

TOTAL ANNUAL PARTY BOAT CATCH OF SEVERAL SPECIES IN NUMBER OF FISH FROM 1947 THROUGH SEPTEMBER OF 1957

Year	Barracuda	Yellowtail	Bonito	Yellowfin tuna	Skipjack	Dolphinfish	Angler days
1947	677,449	6,948	36,496	137	698	15	359,426
1948	384,056	13,028	14,519	18	460	0	407,757
1949	366,423	17,710	5,372	11	9	0	469,915
1950	256,367	6,971	2,359	6	31	1	544,264
1951	269,545	23,721	14,475	56	132	0	556,949
1952	336,550	59,263	7,649	34	38	2	562,898
1953	170,550	27,702	6,321	0	279	0	502,146
1954	282,552	40,872	70,078	0	50	12	532,190
1955	154,962	36,468	22,409	1	10	0	496,286
1956	87,603	29,198	61,404	78	13	2	523,063
1957 through September*	490,075	176,849	186,587	425	6,417	2,805	

* Preliminary report.

Even pier anglers were able to snag small (1957-class) sardines for bait with which to catch large numbers of bonito and occasional barracuda.

In addition to the good fishing for yellowtail, barracuda, and bonito, party boats also encountered skipjack and dolphinfish in greater amounts than during the past 10 years, and they occasionally landed yellowfin tuna.

Equally remarkable as this upsurge in landings of game fish by sportsmen is the fact that many species have been taken much farther north than in recent years. White seabass have been taken off the Golden Gate in fair numbers both by sportsmen and by commercial fishermen trolling for salmon. A rather substantial sport fishery for white seabass began in Monterey Bay. Meanwhile, commercial albacore fishermen were taking skipjack, dolphinfish, and bonito 30 to 80 miles off the Farallon Islands and as far north as Eureka.

Biologists from Oregon and Washington have reported bluefin tuna taken by commercial fishermen off Cape Flattery, skipjack as far north as Cape Blanco, dolphinfish off Grays Harbor, and white seabass off the Columbia River. Unusually high sea temperatures have been reported all along the coast by the albacore fishermen in the usual offshore albacore fishing areas. Marlin and sailfish have been reported seen in widely scattered areas and swordfish have been taken off Monterey Bay.

Following is a preliminary list of other warm water species taken in California waters in 1957:

Number taken in 1957	Common name	Scientific name	Years formerly reported	Location of capture in 1957
1	Bullet mackerel	*Auxis* sp.	1918 1919 1935	Coronados Islands
2	Sharpchin flyingfish	*Fodiator acutus*	1931	Long Beach
1	Tai or Porgy	*Calamus brachysomus*	1953?	Oceanside
1	Shortnose spearfish	*Tetrapturus angustirostris*	(Never previously taken off California)	60-Mile Bank
1	Spiny trunkfish	*Lactoria diaphanus*	1932 1933 1949 1951*	Santa Monica Bay
1	Pilotfish	*Naucrates ductor*	1926 1936 1945	San Clemente Island
3	Triggerfish	*Verrunculus polylepis*	1924 1931 1946 1950 1951*	Santa Monica Bay, Laguna Beach, and San Diego
1	Monterey spanish mackerel	*Scomberomorous concolor*	1931 1937 1939 1944 1947 1948 1949 1951*	Santa Barbara
1	Green jack	*Caranx caballus*	1858 1924 1945 1953 1955*	Belmont Shore

* Probably other years, also.

In addition to these warm water species, hammerhead sharks were seen frequently in California waters during 1957 and many were caught. Several green sea turtles were taken, especially by bait haulers in Los Angeles Harbor, and others have been reported sighted as far north as the Farallons.

At Pismo Beach the set of Pismo clams in 1957 was the best to occur at that locality in the past 10 years. This set compares favorably with the best sets since the Department's annual Pismo Clam census was inaugurated in 1923.

The year 1957 is, indeed, unusual compared with the last several, and sportfishing seems more nearly like it was in the years prior to World War II. The question seems to be whether 1957 is unusual or perhaps the only "normal" year in the past 10.

HOPKINS MARINE STATION, STANFORD UNIVERSITY

Monterey Bay is historically one of California's richest fishing grounds. It is broadly open to the sea, and conditions in the Bay therefore reflect to a large extent the conditions which occur in the offshore waters of central California.

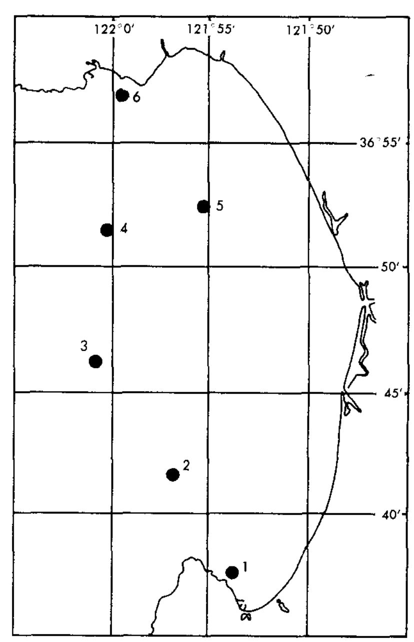


FIGURE 1. Stations occupied in regular oceanographic cruises in Monterey Bay. At each station the vessel records weather and water temperatures, and takes water samples and plankton hauls for analysis.

Since 1951 the Hopkins Marine Station of Stanford University has operated for CCOFI what amounts to an oceanographic "weather station" on Monterey Bay, with approximately weekly cruises that sample the water conditions and plankton organisms at several points in the Bay (Fig. 1).

In the continuing hydrobiological survey in the Monterey Bay area it has been found that the pattern of surface temperatures provides a good index of the water masses present and is closely correlated with the production of phytoplankton.

The upper series of bars in figure 2 depicts the deviation of the surface temperatures at the individual stations from the average of all of the stations on that particular day. (Data come from the winter of 1955-56 and summer and fall 1956.) For each day,

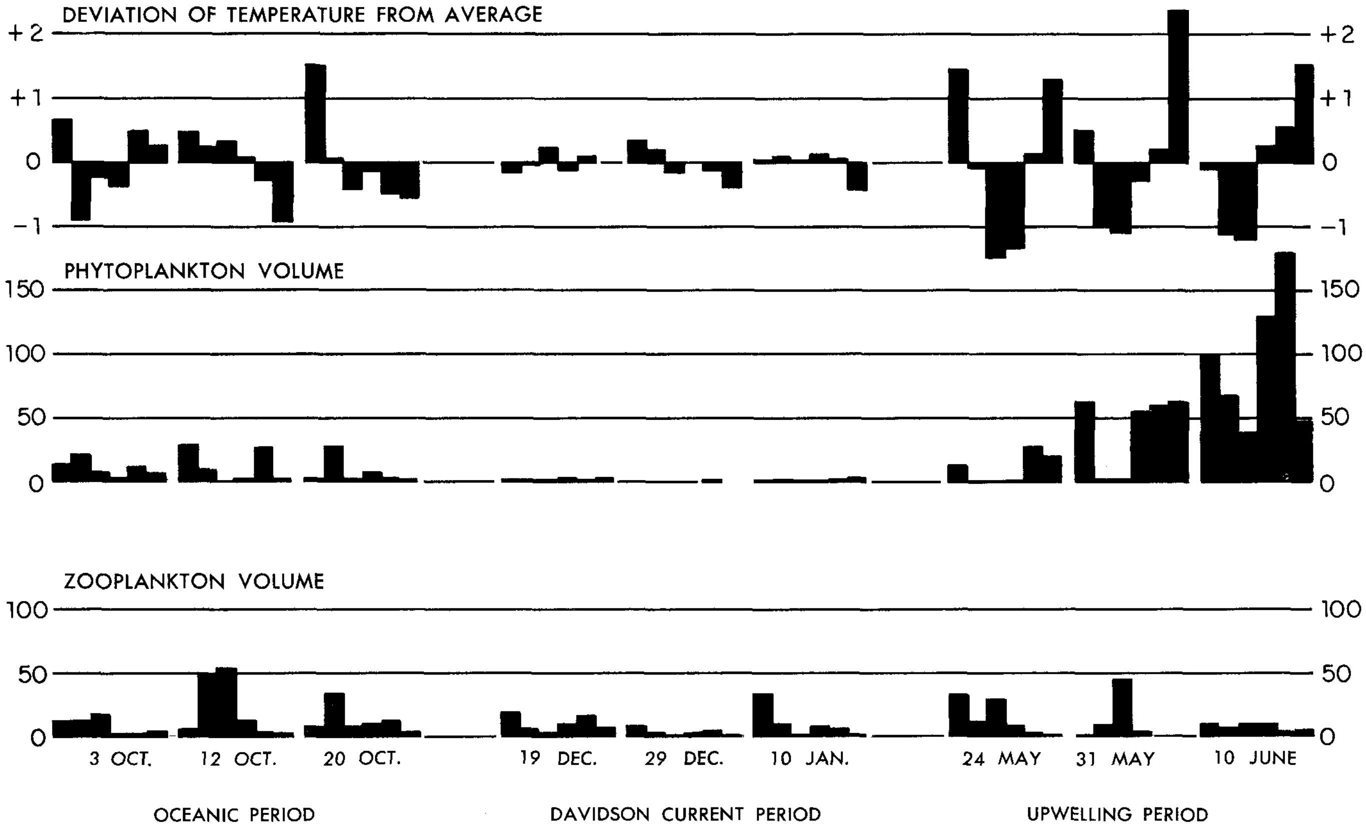


FIGURE 2. Deviation of temperature from average (in degrees Centigrade), phytoplankton and zooplankton volumes (in milliliters per liter) during three periods in Monterey Bay.

Station 1 is shown at the left; the other stations follow in numerical sequence to Station 6 at the right. Three consecutive weeks have been selected to show the typical conditions during each of the three phases of the annual cycle. The middle and lower series of bars indicate the comparative size at each station of the phytoplankton and zooplankton populations respectively. They are based on samples obtained by drawing standardized plankton nets vertically through the upper 15 meters of water. The preserved plankton is allowed to settle to constant volume in graduated cylinders and its wet volume recorded in milliliters.

These studies show that the yearly cycle of events in the bay may be divided into three fairly distinct periods: the Oceanic Period (September and October), the Davidson Current Period (November through February), and the Upwelling Period (March to August).

During the Oceanic Period the differences in temperature to be found between the most divergent pairs of stations average about 1.9° C (3.4° F), but it may be as little as 1.4° C (2.4° F) or as great as 3.0° C (5.4° F). The northernmost and southernmost stations are usually the warmest ones, owing to heating of the relatively stable water in the eddies over the sand flats at the extremities of the bay during the clear sunny days typical of fall. On occasion the surface water at one end of the bay or the other may be washed out by winds of short duration and replaced by water from slightly deeper layers. Since at this season the vertical temperature gradient is very abrupt in the upper 10 meters, the station at which the water has thus been replaced is characterized by the lowest temperatures. This situation prevailed at Station 6 on 12 October.

During the Davidson Current Period temperatures are exceedingly uniform. The extreme difference between any pair of stations averages a little less than 0.5° C (0.9° F). At times it may be as little as 0.3° C (0.5° F), and on rare occasions it may approach 0.8° C (1.4° F). No regular pattern of temperature distribution is discernible.

During the Upwelling Period the temperature pattern is strikingly characteristic. Station 3, located directly over the Monterey Canyon, yields the lowest temperatures about 70 percent of the time; this indicates the importance of this topographic feature in channeling the deep waters toward the surface. Whenever Station 3 does not yield the lowest values of the day, these are invariably obtained at either Station 2 or Station 4, the particular one showing whether the trend of the upwelling water is toward the north or the south within the bay. During this period the amplitude of the temperature differences between stations is high but variable, the magnitude of the difference reflecting the magnitude of the upwelling. Differences of 3.0° C (5.4° F) between Station 3 and Station 1 or 6 are normal.

Phytoplankton volumes during the Oceanic Period are relatively low and variable, and there is no evident correlation between temperature and productivity.

At the onset of the Davidson Current Period phytoplankton production is reduced to a minimum. It is a very rare station that yields as much as 5 milliliters, and sometimes most or even all of the stations are negative. The figure shows that on 29 December only Station 5 yielded a measurable catch.

Production, reflected in larger phytoplankton volumes, shows a marked increase about three weeks after the onset of upwelling as indicated by the expansion of the temperature differences between the various stations to more than 1.0° C. The period of 24 May to 10 June, which was selected as representative of the Upwelling Period, shows clearly the development of a typical plankton bloom. The first upwelling of the season extended from 27 February to 9 April. It was of minor strength and resulted in a small bloom which reached a peak on the latter date. As the upwelling slackened the phytoplankton declined, apparently because of the browsing by an increased number of small copepods, by dense masses of euphausiids which come from deep water to swarm at the surface during April, and by a heavy influx of the pelagic tunicate *Doliolum* during the latter part of this month. By early May the phytoplankton was at a low level, but a second and much more massive wave of upwelling water, shown by the drastically lowered temperatures at Stations 2, 3, and 4, resulted in a new and heavy phytoplankton bloom. Its development, well illustrated by the figure, is typical. On 24 May the freshly upwelled cold water at Stations 3 and 4 was rich in plankton nutrients but had only recently been inoculated with elements of the phytoplankton through admixture with surface water; its population was very low. At Stations 1, 5, and 6, where the higher temperatures indicate that the water had remained on the surface for an appreciable period, the floating microscopic plants had had time to multiply and the plankton volumes were considerably greater. On 31 May the upwelling stream had shifted its position slightly to Stations 2 and 3, while an additional week of growth had resulted in a marked increase in the standing crop in the warmer parts of the bay. By 10 June the shift of the upwelling stream toward the south had progressed so far that the temperature at Station 1, although still markedly above those at Stations 2 and 3, was depressed below the average for the bay as a whole. The phytoplankton had again more than doubled, providing an extremely high value at Station 5, and the heavy concentrations had spread to such an extent that even Stations 2 and 3, in the center of the upwelling stream, yielded very respectable values. The comparatively small amount of phytoplankton taken in the warm water at Station 6 on this day probably indicates a decline of the bloom as a result of depletion of nutrients in a relatively stable eddy at the northern extremity of the bay.

Except for the fact that there is a general tendency for the zooplankton volumes to be comparatively low in winter and high during the summer, little can be said about the relationship of the floating animals to the floating plants. The zooplankton volumes are very irregular and do not appear to be correlated with specific fluctuations of the phytoplankton. High values are obtained at isolated stations at irregular intervals. Sometimes the sudden increases occur when the phytoplankton is rich, at other times when it is poor. It has not been possible to clarify the picture by an attempt to find a time lag such as might be expected between phytoplankton and zooplankton peaks. In most cases the high values can be ascribed to injection into the plankton of larval forms as the result of mass spawning of bottom invertebrates, or through the invasion of the layers being sampled by organisms which normally live in deeper waters, or more rarely by swarms of oceanic organisms from the open sea.

The plankton samples indicate that fishes tend to avoid the freshly upwelled water for spawning. At Stations 1, 5, and 6, fish eggs, although somewhat irregular in occurrence, are on the average the second most abundant element in the zooplankton. At Stations 2, 3, and 4, on the other hand, fish eggs rate fourth, and at Station 3 even this position is not secure. It appears that most fishes spawn in water which has "matured" on the surface and in which the developing larvae will have a good chance of finding adequate food.

Warmer Water Conditions

Monterey Bay and the ocean beyond have shown a definite trend toward warmer conditions since 1955. The year 1955 was cold, with surface temperatures rarely rising above 14° C, even in inshore waters (Fig. 3). September and October, nearly always the two warmest months of the year, showed monthly average temperatures on the bay of 13.1° C. The year

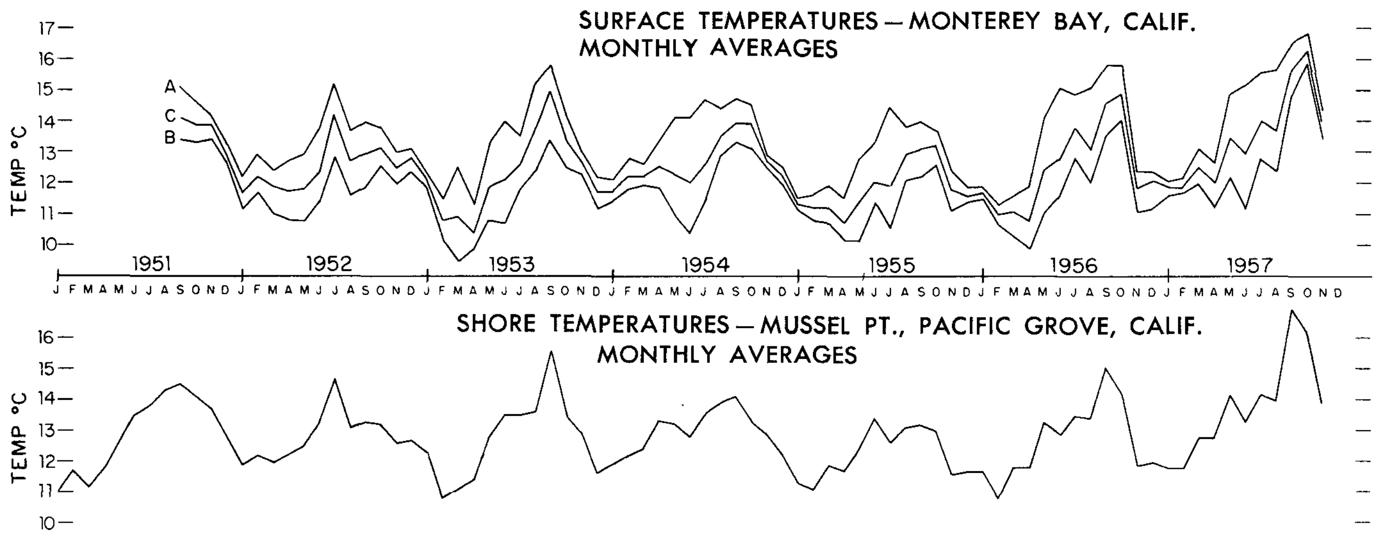


FIGURE 3. (Top) Surface temperatures, Monterey Bay (monthly averages in degrees Centigrade). Curve A—Monthly averages of the highest surface temperature recorded during each weekly cruise. Curve B—Monthly averages of the lowest surface temperature recorded during each weekly cruise. Curve C—Monthly averages of all surface temperatures recorded during each weekly cruise. (Bottom) Shore temperatures, Mussel Point, Pacific Grove (monthly averages in degrees Centigrade). Curve D shows monthly averages of the shore temperatures at the southern end of Monterey Bay, based on daily measurements recorded by Hopkins Marine Station for the Scripps Institution of Oceanography.

1956 was warmer, with September and October average surface temperatures of 14.6 and 14.9° C. The year 1957 has been warmer yet, with September and October monthly averages of 15.7 and 16.4° C, some two and a half degrees warmer than in 1955. Changes in other seasons parallel those indicated above, though differences in winter temperatures are not as large as those given above. For oceanographic conditions this represents a fairly conspicuous change.

SOUTH PACIFIC FISHERY INVESTIGATIONS, U. S. FISH AND WILDLIFE SERVICE

Descriptive studies have progressed to the stage where it is now possible to suggest a working hypothesis that appears to be in accord with what is known of the biology of the sardine and the history of the fishery. Briefly, the features of this hypothesis are:

(1) Sardines produced off southern California migrate as far north as the Pacific Northwest and support the fishery in that region, as well as the winter fishery at San Francisco, Monterey, and San Pedro.

(2) Sardines produced off central Baja California migrate as far north as central California and enter into the fall fishery in San Francisco, Monterey, and San Pedro.

(3) Lack of spawning success on the southern California spawning grounds since 1943 could account for the observed changes in the fishery.

(4) This lack of spawning success is attributed to lower (suboptimal) spring temperatures on the southern California spawning grounds.

It is interesting to remark on the possibility of a larger than usual year-class being produced off southern California in 1957 (see below), a year in which spring temperatures approached pre-1943 conditions.

Most of the projects of the South Pacific Fishery Investigations are continuing ones and are carried out in cooperation with other agencies participating in the California Cooperative Oceanic Fisheries Investigations. Age analyses of the commercial landings of sardines and anchovy are carried out cooperatively with the California Department of Fish and Game. Oceanographic-biological survey cruises are made in cooperation with Scripps Institution of Oceanography.

The oceanographic-biological cruises during the past year were of four kinds:

(1) Egg and larval survey cruises designed to determine the distribution and abundance of sardine spawning and the rate of survival of sardine larvae and those of associated pelagic species.

(2) Hydrographic-biological survey cruises in the Gulf of California.

(3) Cruises for the collection of sardines on the spawning grounds.

(4) Cruises made in conjunction with the commercial sardine fleet to study factors influencing the availability of sardines to the fishermen.

Egg and Larval Survey Cruises

The egg and larval survey cruises off California and Baja California cover an area that has been continuously surveyed since 1949. During both 1956 and 1957, the extensive survey cruises were confined to the first seven months of the year, January through July, with the widest and most intensive coverage being made in April through July. The January, April, and July cruises had complete hydrographic coverage of the area as well as biological coverage; the other cruises were primarily egg and larval survey cruises, with limited hydrographic observations. Hydrographic observations on egg and larval cruises consist of the following: temperature and salinity observations at 10 and 50 meters depth at each station, bathythermograph casts at and between stations, continuous record of surface temperature, geomagnetic electrokinetograph observations on some vessels.

A preliminary estimate has been obtained of the amount of sardine spawning in 1956: 206×10^{12} eggs. This value is a preliminary estimate only, but the comparative figures for the two preceding seasons are the final estimates. These are:

	No. eggs	*No. spawning fish*
1954	355×10^{12}	7.1×10^{9}
1955	163×10^{12}	3.3×10^{9}
1956	206×10^{12}	4.1×10^{9}

In 1956, about 43 percent of the spawning occurred in the "northern" spawning center off southern California and adjacent Baja California, the remainder in the "southern" center off central Baja California. (Sardine spawning in the Gulf of California is not considered in this connection.) The 1956 distribution was rather similar to that found in 1954 and 1955, except that a larger portion of the spawning in the "northern" center occurred to the south of Ensenada.

Preliminary results for 1957 indicate that it was an unusual year off southern California and, indeed, over the area from Peru to Alaska and as far westward as the Hawaiian Islands. Locally, 1957 has been one of the warmest years on record. Coincident with this sharp change, certain sportfishes such as yellowtail, barracuda, and white seabass have been exceptionally available and many southern forms have been found far north of their usual range.

Sardine spawning off southern California has also been unique. Spawning on the usual, offshore grounds was limited and discontinuous. The larger portion of the spawning took place in a coastal band from Punta Baja to San Pedro (Station lines 90-107).

For the first time in several years, some sardine spawning has occurred to the north of Pt. Conception. Sardine eggs and/or larvae were taken at five stations on lines 67 to 77 in June; spawning north of Pt. Conception was observed in July. The northernmost locality was off Monterey Bay.

Early in the year, sardines of the 1955-class were taken in the southern California live-bait fishery. Later in the year, sardines of the 1957-class have been taken in the live-bait fishery and have been commonly observed by sardine fishermen fishing out of Port Hueneme. Sardines of the 1957-class have also been reported from north of Pt. Conception, at least as far north as Monterey Bay.

Survival of the 1957-class of sardines off southern California has undoubtedly been better than in recent years. It is possible that the 1957-class will prove to be a large one. Judgment should be reserved, however, since these juveniles may be over-available owing to their inshore origin.

As already noted, the peculiarities of sardine spawning and survival off southern California in 1957 have been associated in time with an unusually warm year. Oceanic conditions in 1957 represent the greatest change yet observed by CCOFI.

A number of plankton samples collected off California during the June and July cruises of 1957 have been examined in order to determine if there was anything unusual about the distribution of plankton organisms during this period. Inasmuch as there had been marked incursions of warm water fish into the area, it was of interest to ascertain whether there were incursions of plankton animals associated with tropical or central Pacific water. These preliminary investigations indicate no evidence for the incursion of a tropical water mass into the area during June and July. At some stations in June a species with affinities for central Pacific water was collected. This species may approach close to the coast at times, but its presence supports the physico-chemical evidence of an incursion of central Pacific water. Except for this species, the plankton in the area off California was made up of species associated with the California Current, and hence did not differ materially in June and July 1957 from the plankton of these months in other years.

Hydrographic-biological Survey Cruises in the Gulf of California

Except for a cruise of the *Black Douglas* into the southern part of the Gulf of California in late 1952, no work had been done on sardine spawning in the Gulf prior to February 1956. Since then cruises have been made in February, April, and December, 1956 and February, April, June, and August 1957.

The station grid in the Gulf consists of 12 lines on which stations are spaced 15 miles apart, together with a fairly large number of inshore stations located between station lines. On some cruises, between-line stations are placed in the "deeps" rather than inshore.

Sardine spawning in the Gulf is heaviest in the middle third, between Carmen and Tiburon Islands, although it has been shown to occur more or less throughout the Gulf. Interestingly, the distribution of spawning in February 1957 was strikingly similar to that found in February 1956, with the heavy spawning occurring on the two station lines immediately to the south of Guaymas.

Gulf cruises were spaced at bi-monthly intervals during the spawning season in order that an estimate of the amount of sardine spawning in the Gulf could be obtained. It is evident from the results of the 1956 surveys that the spawning population in the Gulf must be a large one.

Although the Gulf of California has been proved to be an important spawning area for the sardine, Pacific mackerel, and other species, no cruises are presently planned into the Gulf in 1958. The relationships of the fish of the spawning areas off southern California and Baja California to each other and to the fishery must first be determined. Once answered for these groups, the same questions can be asked concerning the sardines spawning in the Gulf. In the meantime, only monitoring activities, if any, will be continued in the Gulf.

Collection of Spawning Sardines

The August and September 1956 cruises were devoted in part to the sampling of adult sardines for use in fecundity and subpopulation studies, in part to egg and larval surveys of fall sardine spawning. During both months, sardines were sampled in the area between Pt. Eugenia and Pt. Abreojos, mostly by gill nets.

A large percentage of the sardines have developing gonads, and several females were approaching spawning condition. In August the females that contained yolked eggs were between 177 and 222 mm in standard length; in September, they were between 160 and 188 mm. The fish were mostly one and two years of age. In fact, less than 5 percent of the fish collected were older than two years.

The fish were markedly smaller in size than fish of the same age taken in the California commercial catch. Two-ring fish, 1954-class, in the commercial catch ranged in standard length from 208 to 242 mm, with an average length of 224 mm; the same year-class in ''spawning'' sardine collections ranged from 162 to 226 mm, with an average length of 182 mm. This is 42 mm smaller, on the average, than the two-ring fish taken by the California commercial catch. The marked difference in size between sardines from the two areas is evidence that they did not enter into our commercial catch in any numbers in the 1956-57 season. It also adds support to the thesis that the fall-spawning sardines constitute a separate subpopulation.

Availability Studies

In October, November, and December 1956, the *Black Douglas* made nightly plankton and temperature collections in areas scouted by the San Pedro sardine fleet. As soon as the area of most intense fishing was ascertained on any given night, the *Black Douglas* executed a pattern of observations that included the fishing area as well as some portion of the surrounding area that had been scouted without success. Once started, each pattern was continued until a half-hour before dawn.

This survey is a field approach to the problem of sardine availability. Large concentrations of sardines do not necessarily appear in the same spot on successive nights. It is reasonable to hypothesize that such fluctuations are related to variations in one or more features of the environment. Since it was not known at the outset which environmental factors might be critical, it was decided to measure plankton and temperature, which have been related to fish distribution in a few other fisheries. Plankton was collected with a Hardy continuous plankton recorder, approximately one and one-half linear miles being sampled for each two-inch length of the collecting silk. Surface temperature was recorded continuously, and bathythermograms were taken at frequent intervals.

The plankton collections and the temperature data are now being studied. Small copepods are by far the most numerous organism, and they fluctuate by a factor of three or four during the course of one night. In one case, the area of highest density for the more abundant categories appears to be associated with a geographical feature of the adjacent coastline. The center of fishing, however, was in an area of lower plankton density about four miles away.

Since the 1956-57 season was relatively poor, no really large sardine catches were made while the *Black Douglas* was operating. Obviously, the significance of plankton and temperature distributions as factors in sardine availability cannot be determined until collections are obtained on some number of good as well as poor nights of fishing.

The Scripps research vessel *Orca* covered a regular grid of hydrographic-biological stations off southern California each month during the period that the *Black Douglas* was working with the commercial fleet. A striking fact brought out by the *Orca* cruises was the marked lowering in temperature that occurred in the southern California area between the October and November cruises, amounting to about two degrees over much of the area. This cooling was associated in time with the southward movement of sardines from

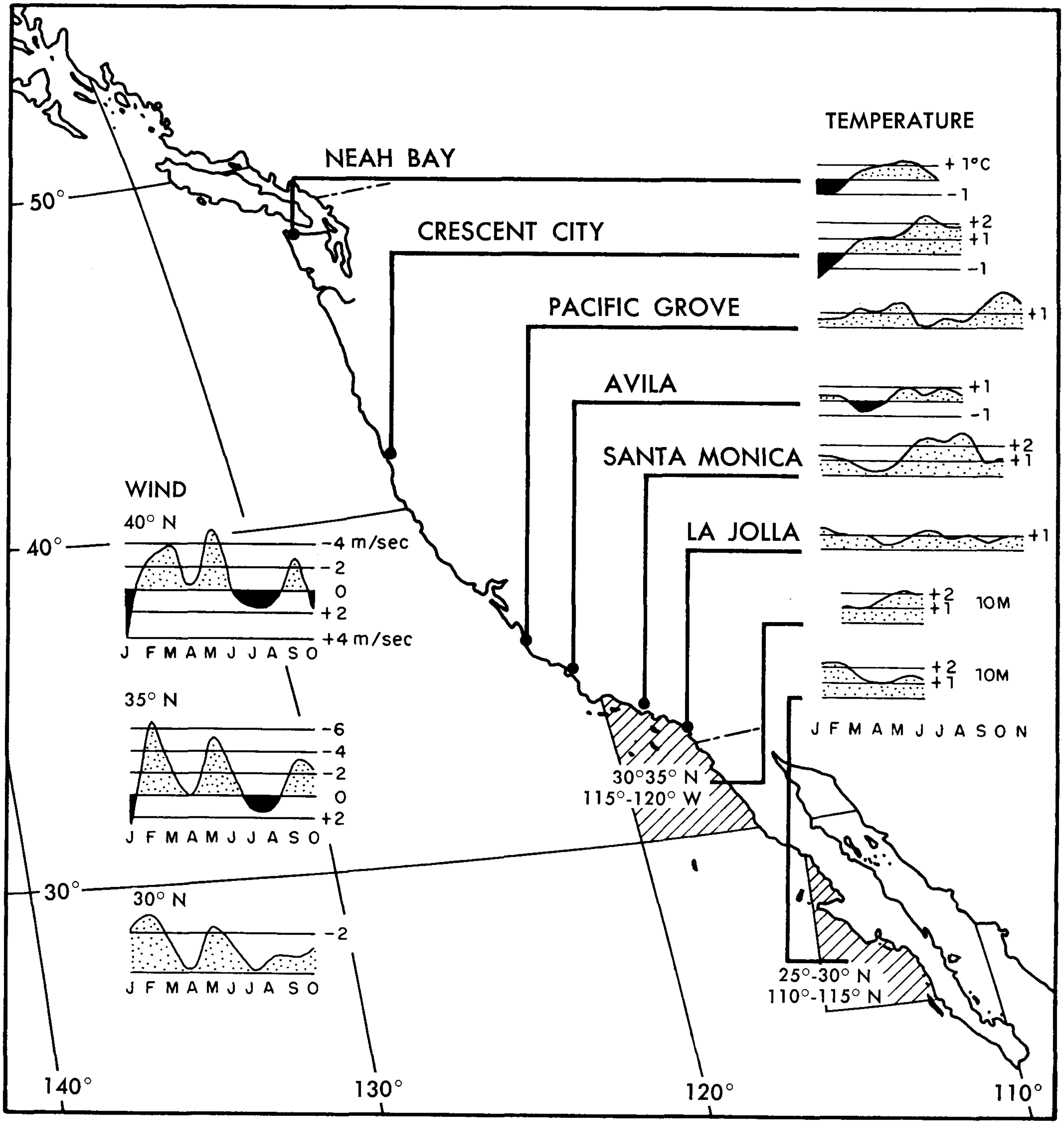


FIGURE 4. Temperature and wind anomalies at shore stations, 1957 compared to the 1949-56 means. Wind anomalies show variations in the northerly component of the geostrophic winds (computed from pressure charts). A negative anomaly means that the northerly component was weakened. Positive temperature anomalies indicate warmer water.

the southern California fishing grounds to areas off the coast of Baja California in 1956.

Genetic Studies

Genetic studies of subpopulations of sardines have been initiated. Research is directed toward determining whether genetically isolated or partially isolated groups exist along the Pacific coast. The approach is through a serological study. A large body of precedental information is available in this field, mostly developed on domestic animals. Several species of fish have also been investigated and individual differences

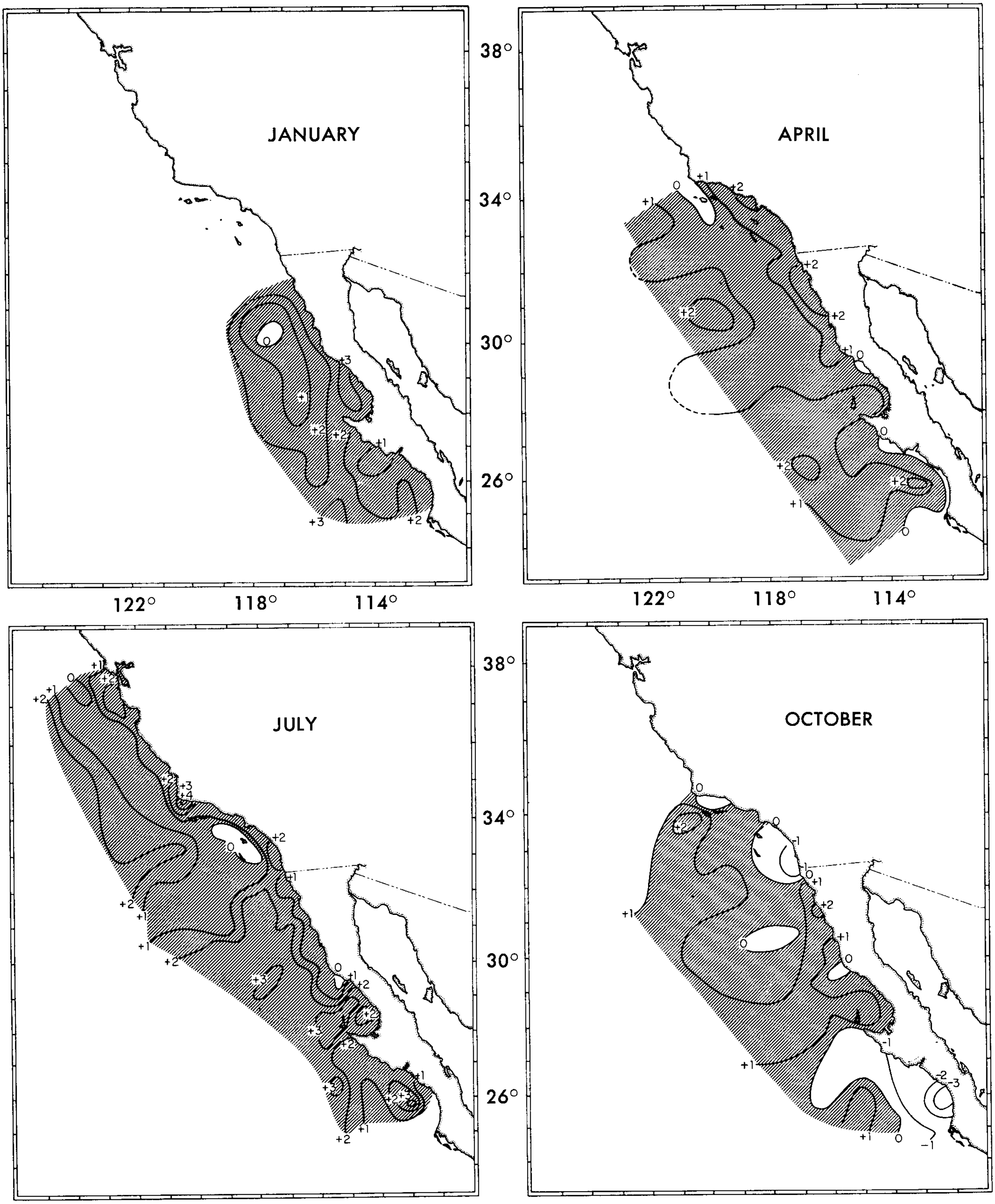


FIGURE 5. Differences between sea surface temperatures in 1957 and in earlier periods. Upper left, January 1957 compared with the 1949-55 average. Upper right, April 1957 compared with 1949-54 average. Lower left, July 1957 compared with 1949-54 average. Lower right, October 1957 compared with 1949-54 average. Differences are expressed in degree centigrade. Shading indicates warming.

with respect to erythrocyte antigens have been shown to exist. The existence of discrete individual differences with respect to erythrocyte antigens already has been demonstrated for the Pacific sardine (*Sardinops caerulea*) by means of antibodies found in the serum of certain wild and domestic animals.

The investigation has not proceeded far enough as yet to determine whether such differences can be used to characterize subpopulations.

Other Species

The 1956 collections of fish larvae have been sorted, identified, and standardized. Anchovies continue to be the dominant species in the collections and other species follow in about the same order as in 1955. A comparison of the standard haul totals of fish larvae for 1955 and 1956 follows:

	1956		*1955*	
Species	*Number*	*Percent*	*Number*	*Percent*
Anchovy	134,931	33.06	140,183	39.03
Hake	89,857	22.02	60,090	16.73
Rockfish	29,144	7.14	29,341	8.17
Sardine	15,523	3.80	14,121	3.93
Jack mackerel	8,027	1.97	13,246	3.69
Pacific mackerel	1,519	0.37	1,950	0.54
All others	129,139	31.64	100,224	27.91
Total	408,140	100.00	359,155	100.00

There is a small decrease in number of anchovy larvae taken in 1956, as compared to 1955. There are interesting differences in the distribution of anchovy larvae in these two years. In 1955, over 40 percent of the anchovy larvae occurred in the area between Pt. Conception and Punta Baja (Station lines 80-107), while only 20 percent of the larvae were taken in this area in 1956. In both years, about 60 percent of the anchovy larvae were taken off central Baja California (Station lines 110-137). A marked increase in abundance occurred in the area off southern Baja California in 1956; 19 percent as compared with 0.05 percent in 1955.

The 1955 totals do not include NORPAC (August cruise). In 1956, 36,715 larvae were taken in August. Hence if this number is subtracted from the 1956 total, to make the two years more exactly comparable, the totals are remarkably close (359,155 and 371,425).

Since 1957 has been unusual in the abundance of warmer water fishes off California, larval collections made off California during June and July 1957 have been examined to determine if there were similar occurrences of the larvae of these fishes. No such occurrences were noted. However, an exciting finding was the unusual abundance of larger jack mackerel larvae (between 5 and 10 mm in length) in the collections. The survival to these sizes is better than in any recent year. Barring unusual mortality during the juvenile period, the 1957-class of jack mackerel should be a successful one.

UNIVERSITY OF CALIFORNIA, SCRIPPS INSTITUTION OF OCEANOGRAPHY

In 1957 the climate of the ocean in the CCOFI region changed in sharp contrast to the 1949-56 period. The primary change was warming of the sea water in some areas a depth of more than 400 meters. This short report on the physical changes is only a preview of what took place. Much more time is needed to analyze the data in a comprehensive manner.

The data from the shore stations indicated that warming began south of Port Hueneme as long ago as December 1956. It progressed northward to Monterey Bay in January and reached Puget Sound in March (Fig. 4). The warming along the coast averaged 1° C.

The surface temperature anomaly charts for each cruise show the warming to have covered the entire CCOFI region during the year (Fig. 5). Here the differences between 1957 and the 1949-54 average have been plotted. Warming in various places along the coast and offshore amounted to more than 3° C. A few spots of cooler than average water do appear, but these were small in size and presumably were caused by local upwelling and decreased mixing. In October there was a fairly large area of cooling from Pt. Eugenia southward.

A preliminary analysis has been prepared of the average temperature from the surface to 200 meters and from four selected hydrographic stations. The station locations are given in figure 6. Stations 80.90 and 100.70 were chosen as representative of offshore conditions, Stations 80.60 and 90.45 of inshore conditions. The physical and chemical properties for the months April, July, and October were analyzed and were compared with the average values obtained at the same stations in the same months in the years 1950, 1952, 1953, 1954, 1955, and 1956 for April; 1950, 1952, and 1953 for July; and 1952, 1954, 1955 for October.

April

The average temperature from the surface to 200 meters increased over most of the region. A warming of more than 1° C covered about 50 percent of the cruise pattern, with most of it being along the Baja California coast 100 miles offshore and beyond. An area of 2° C increase occurred to the west of Guadalupe Island.

The two inshore stations showed warming in the upper 50 meters. The salinity did not change significantly from earlier years. The two offshore stations showed warming down to 75 meters in the north, 150 meters in the south. The salinity at both these latter stations down to 125 meters increased 0.2 to 0.3 parts per mille. At 200 meters at Station 100.70, there was an average of 0.3 parts per mille less salinity than in

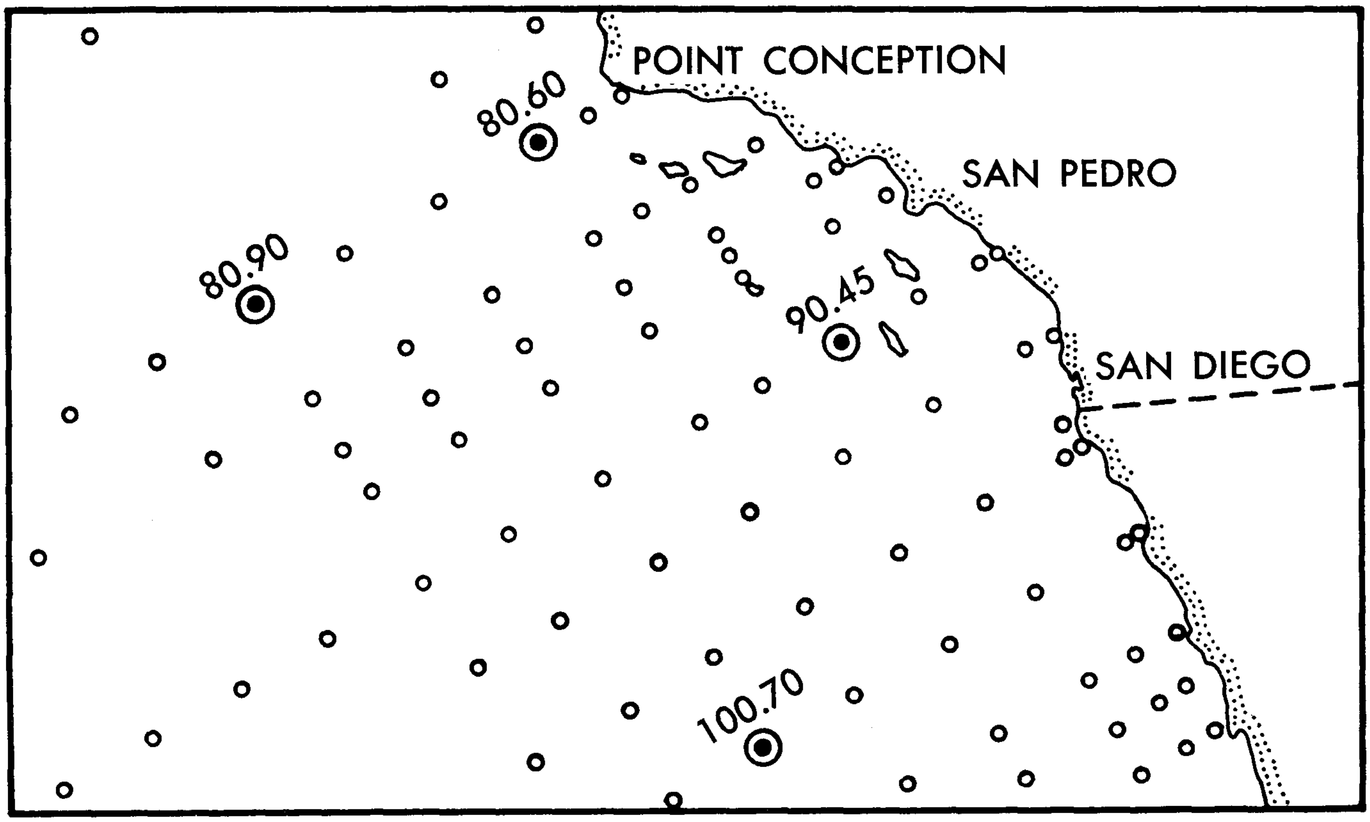


FIGURE 6. Location of four hydrographic stations for which 1957 data have been analyzed.

former years. The depth of the mixed layer and the thermocline—the region where temperature decreases most rapidly—were much the same as in the past years for all four stations.

July

In the entire region, the average temperature from the surface to 200 meters was only a little higher than in past years. In comparing a few stations with past data, over the entire region from San Francisco to southern Baja California, the warming was slightly less than 1° C.

Warming occurred in the upper 75 to 100 meters for Stations 80.60, 80.90, and 90.45. The salinity for the two inshore stations was little changed. At Station 80.90, offshore, the salinity increased an average of 0.35 parts per mille from the surface to 100 meters, and 0.15 parts per mille from 100 to 150 meters. At 200 meters the salinity decreased over the other years by an average of 0.1 parts per mille. The oxygen values at Station 80.90 at 200 meters was much higher than usual, 4.0 milliliters per liter. The depth of the mixed layer was the same as in past years.

October

By October a very noticeable change had occurred from Pt. Conception to Pt. Eugenia. The average temperature from the surface to 200 meters indicated warming over the whole region. Offshore 150 miles and beyond there was warming of more than 2° C.

The temperatures at the four stations increased as deep as 400 meters with Station 80.90 having the largest increase. At 50 meters, the depth of the mixed layer, the temperature was over 2° C higher than the average, and at 150 meters it was 1.8° C higher. The salinity also increased for all stations except 90.45, where it was slightly less than in former years. The increase in salinity was the greatest at Station 80.90, averaging 0.4 parts per mille to 125 meters. Again at this station the salinity was less at 200 meters, by an average of 0.2 parts per mille. The oxygen value at Station 80.90 was 4.6 milliliters per liter. The mixed layer was the same as in previous years at all stations.

The geostrophic wind taken from monthly average pressure charts indicates that there was less northern component to the wind than the mean for the years 1949-56 (Fig. 4). In February the pressure charts indicate that the geostrophic wind had a southern component rather than the usual northern component.

There appears to have been upwelling during the period in which upwelling normally occurs. The amount of upwelling has not yet been determined. The higher surface temperatures indicate that the upwelled water did not come from as deep or that the water in the lower layers was warmer than usual.

At present, clues to the currents during the year come only from the drift bottle experiments, as the hydrographic data must be processed before the standard current computations can be made. Other clues will come from the further analysis of the plankton.

The drift bottle experiments indicate that the eddy often found off southern California was in existence during November and December 1956, and during June, July, October, and November 1957. The eddy was not observed during February, March, April, and May. There are no data for January, August, and September.

The Davidson countercurrent, which sweeps along the central California coast during some months, usually in the winter, was apparently active during November and December 1956 and February, March, July, October, and November 1957. This is indicated by the fact that drift bottles released off Pt. Conception were found to the north. The two previous years of drift bottle experiments had shown the presence of the countercurrent only in November and December.

Though warming began in the south and shifted northward in time, there is no indication that southern water moved northward. Study of the zooplankton shows no species from other areas. The northerly winds were greatly reduced in the first part of the year. This may have retarded the normal transport of water along the coast, allowing advection of warmer offshore water into the region off southern California and Baja California. The slight increase in salinity at Station 80.90 in April and the larger increase at Station 100.70 indicate that water from farther west than usual was in fact present. By July, Station 80.90 more clearly shows the presence of a different water mass. The higher temperature and salinity and the higher oxygen at 200 meters indicate that this water mass was not from the south; it must have come from the west or northwest. Indeed, the shape of the T-S (temperature-salinity) curve and the values of higher temperature and salinity at Station 80.90 strongly resemble those of water that was found along a line from 40° N-145° W to 35° N-125° W during the NORPAC expedition in August and September 1955. By October the water mass had affected the inshore Station 80.60 and appears to have been present at a station one mile offshore from Scripps Institution.

We may summarize our conclusions to date by saying that the water was warmer, the northerly winds reduced, and that the warm water did not seem to come from the south, but at present we do not have sufficient data analyzed for 1957 to understand the combination of the oceanographic and meteorological mechanisms by which these changes took place.

The major effort of the Scripps Institution in the CCOFI goes into investigations of the physics and the chemistry of the waters off our coast. That work is reported briefly above for 1957, in detail for earlier years in the scientific paper, "Studies of the California Current System," by Joseph L. Reid, Jr., Gunnar I. Roden, and John G. Wyllie, which makes up the body of this report.

However, other research studies connected with the Investigations are under way. Studies of the marine zooplankton, the floating animals of the sea of which the sardine is one in its earlier stages, are being conducted.

Significant studies are being conducted of the role that ocean currents can play in the life history of such floating or feebly swimming creatures. One of these projects concerns itself with the pelagic phyllosoma larval stages of the California spiny lobster, *Panulirus interruptus*. Plankton collections from the CCOFI area have been utilized in this study. The project required the complete description of all the hitherto unknown developmental stages—there were eleven. The last stage metamorphoses into the puerulus stage. At this time the animal deserts the planktonic existence to assume the morphological features and benthic habit of the adult. As an essential part of this study the phyllosoma larval stages of the pinto spiny lobster, *Panulirus gracilis*, have also been identified since the range of that species overlaps that of *Panulirus interruptus*.

With this information at hand the plankton samples for six years (1949 to 1954) have been sorted and the developmental stages recorded with a view to determining the duration of the pelagic life, the major areas of larval concentration, and the pattern of dispersal and drift in the water currents off the coast. The seasonal distribution of the successive larval stages points to a pelagic life of several months' duration. The major larval concentrations occur off Baja California. Evidence is accumulating that there may be cross-current transport of larvae.

Another project is concerned with the search for compounds in the sea which encourage or inhibit growth. The identification of such compounds would be the first step towards actual "farming" of the sea.

The concept of a particular nutrient limiting the growth of a population dates back to 1840. The obviousness and simplicity of the idea, as well as its repeated experimental verification, have given it strong intellectual appeal, and have led to its acceptance as a basic ecological concept. As a result many attempts have been made to interpret the abundance of natural populations whose food requirements primarily consist of simple and/or soluble substances in terms of growth-limiting nutrients. Particular emphasis has been placed on this concept in relation to the dynamics of marine plankton populations.

However, studies with cultures of certain bacteria have shown that the growth-limiting nutrient is not necessarily the same as the nutrient that determines the rate at which a population grows, *i.e.*, the rate-limiting nutrient.

If this applies to bacteria in the sea, then there is a possibility that the distributions and abundances of phytoplankton and other populations are primarily controlled by rate-limiting nutrients.

Additional results from this study show that a population in a given environment may respond differently to different rate-limiting nutrients. Thus whether a certain nutrient is rate-limiting is not obvious from its concentration. Further, different species can respond differently to the same nutrient. As a result, in a specific environment the abundances of different species may not be determined by the same nutrient.

Studies are now being made to elucidate further the role of rate-limiting nutrients in the population dynamics of microorganisms and to ascertain the effects of such environmental factors as temperature and salinity on the growth response of various species to selected nutrients. If successful, these studies should not only give us further understanding of factors controlling the development of microbial populations in the sea, but they should give us increased insight into the population dynamics of other organisms as well.

Two studies in marine genetics at the Scripps Institution bear on the program of CCOFI:

In one of these studies, one of the marine bacteria is subjected to ultraviolet irradiation to produce mutants which are unable to synthesize some item from their natural diet. As must human victims of diabetes, they must obtain the substance from external sources. The organism is *Serratia marinorubrum*, a bright red pigmented bacterium which normally grows when supplied solely with inorganic salts and glycerol (a simple carbohydrate). Irradiation of this organism by ultraviolet light has produced three mutant strains thus far. These differ from the normal parent strain in that one biosynthetic process has been eliminated in each, thus leading to requirements for certain specific growth factors, to-wit, Biotin, Uracil, and a non-specific Purine requirement.

The vitamin mutant will respond to concentrations of Biotin as small as 0.002 ug/ml (two one-millionths gram per liter, supporting 10 billion cells) while both the Purine and the Pyrimidine mutants require about tenfold more of their specific supplement. The reason for emphasizing the minute amounts of these biochemical substances which are required to produce a response in the bacterial mutants is to indicate the value of these biochemically deficient cells for a bioassay.

The utilization of biochemical mutants for the bioassay of sea water for its content of various growth factors has been prompted by the suggestion that these growth factors might be partially responsible for the discontinuous distribution and the high degree of localization of some marine flora and fauna. This theory gains support from an increasing number of reports concerning growth factor requirements in marine algae and the effect of external metabolites on feeding and on other responses.

In a preliminary test of the validity of the bioassay system, some 29 samples of sea water were taken. These were tested with the mutant organisms (ability to grow indicates presence of specific biochemical supplement; amount of growth indicates concentration). Biotin was found in 55 percent of the samples, Uracil in 21 percent, and Purine at only one location (less than 5 percent). These results emphasize the utility of the technique as well as the desirability of expanding both testing facility and the scope of the tests.

The search continues for more mutants with diverse biochemical requirements. Ultimately it is hoped that a broad spectrum of mutants will be available so that the bioassay will become even more meaningful.

The character of the non-specific Purine requirement has posed the question of the mechanism of biosynthesis of Purines—the bases of which nucleic acids are composed. This pathway is being examined by the use of enzyme chemistry, chromatography, and spectroscopic analysis. It seems likely that other biosynthetic pathways will prove amenable to test as future mutant strains are isolated.

The second project in the field of marine genetics is concerned with *Tigriopus*, a tiny tide-pool crustacean. These creatures are hardy, reproduce rapidly, and are easily handled in the laboratory. One problem studied is that of sex determination. Contrary to the common concept of numerical equality of the two sexes at the time of conception, *Tigriopus* showed a very marked deviation in favor of the males. Analysis of the situation, both cytological and experimental, suggested a relatively primitive mechanism where a number of genes are involved in determining the sex of the organism in a manner analogous to other quantitative characters, such as crop yield or weight in cattle. Apparently this mechanism is not triggered by a sex chromosome (as in human beings, for example) which would basically assure a 1:1 ratio of the two sexes. It has thus been possible to select and maintain families, at will, with as high as 80 percent or as low as 0.5 percent females.

Additional work with *Tigriopus* includes a cytogenetic study on British, Japanese, and California species, and an intensive morphological study on samples from all over the world.

How rich in plant and animal life are the waters off southern California? The determination of this has been the aim of another project at the Scripps Institution of Oceanography.

This past spring an attempt was initiated to relate phytoplankton (plant) abundance, as reflected by chlorophyll "a" concentration, to zooplankton abundance and to the physical and chemical regime in the waters between Pt. Conception and Ensenada. The analysis of the data has not been completed as yet, but several generalizations may be made from a consideration of the data thus far analyzed.

The area encompassed by this study may be divided into two regions on the basis of the amount of chlorophyll "a" present at the surface: stations located on or inshore of the .60 stations (*e.g.* 80.60, 83.60, 87.60, etc.) exhibit relatively high but variable concentrations, while those offshore are generally lower and less variable. Within both regions there occurs a gradual decrease in chlorophyll "a" in the southerly direction. An additional difference between the two regions is the manner in which chlorophyll "a" is distributed vertically. In the mixed layer, the offshore stations show very little in the way of gradients, being essentially homogeneous, while the inshore stations show a marked increase in chlorophyll "a" at about 20-30 meters.

The concentrations of chlorophyll "a" observed in this area compare favorably with those observed in the waters off Central America and Mexico, which are known to support a large tuna fishery.

The relationship between chlorophyll "a" and zooplankton volume is difficult to understand at present. Generally speaking the maximum zooplankton concentration is observed in the regions of low chlorophyll concentration. It has been suggested that this may result from the general southern drift of zooplankton from the rich waters north of Pt. Conception. If the zooplankton is not produced locally, then the suggestion is probably correct and accounts for the anomaly. This possibility is currently being examined.

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

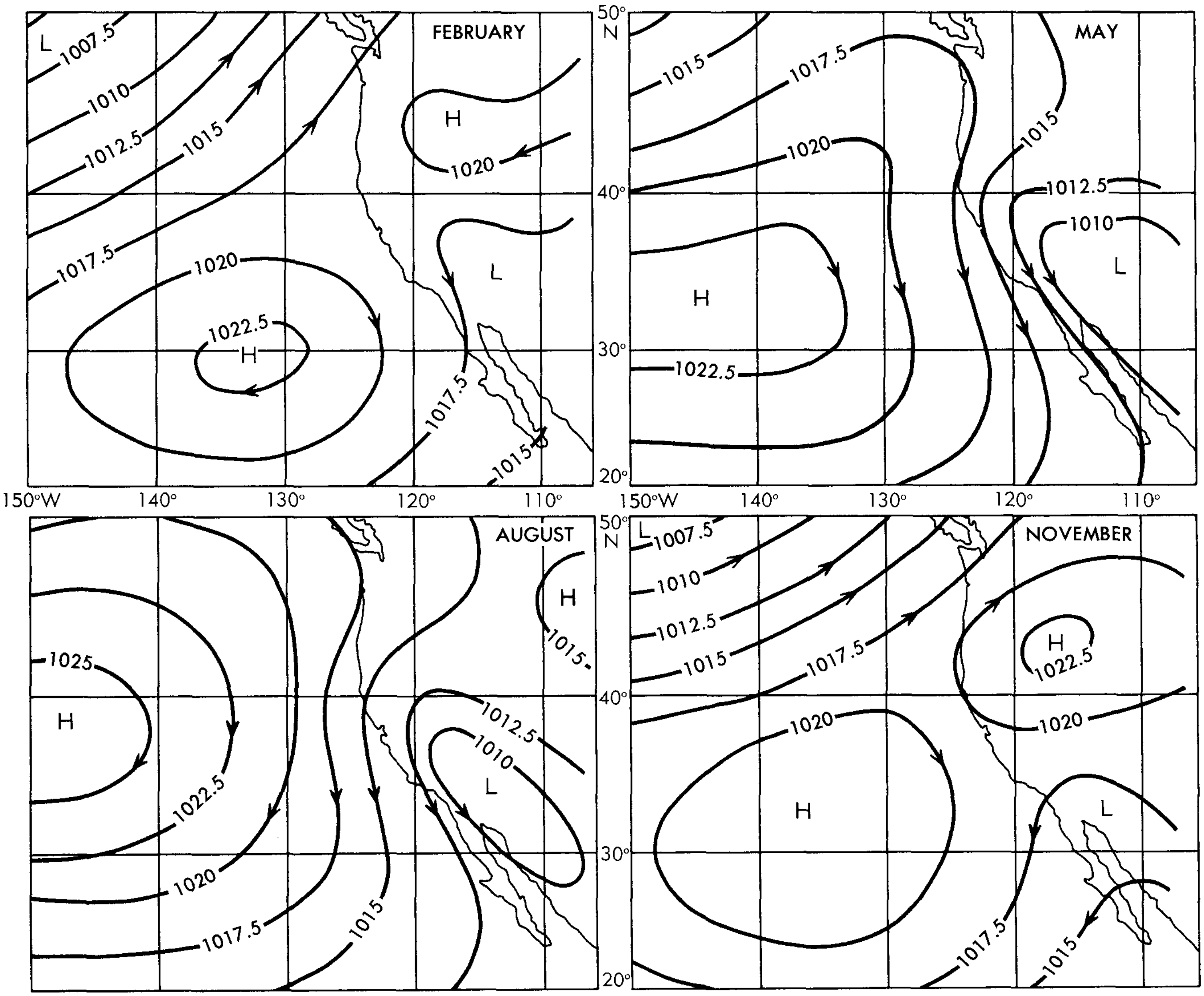


FIGURE 1. Average monthly atmospheric sea level pressure (in millibars) over the eastern North Pacific Ocean and the western coast of North America during four months of the year.

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.

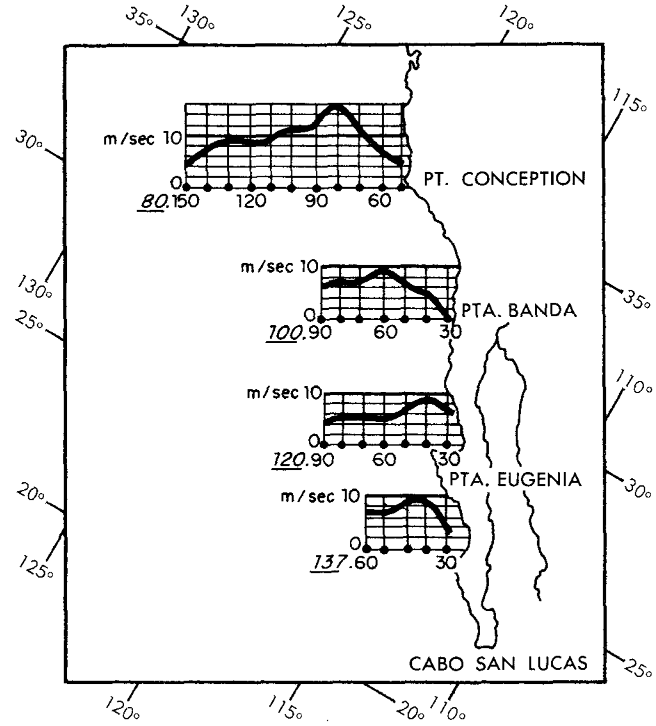


FIGURE 2. Variations of wind speed with distance from coast, May 1953. Measurements made along Station Lines 80, 100, 120, and 137, on CCOFI Cruises. Wind expressed as meters per second. Strongest winds occur off Point Conception.

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

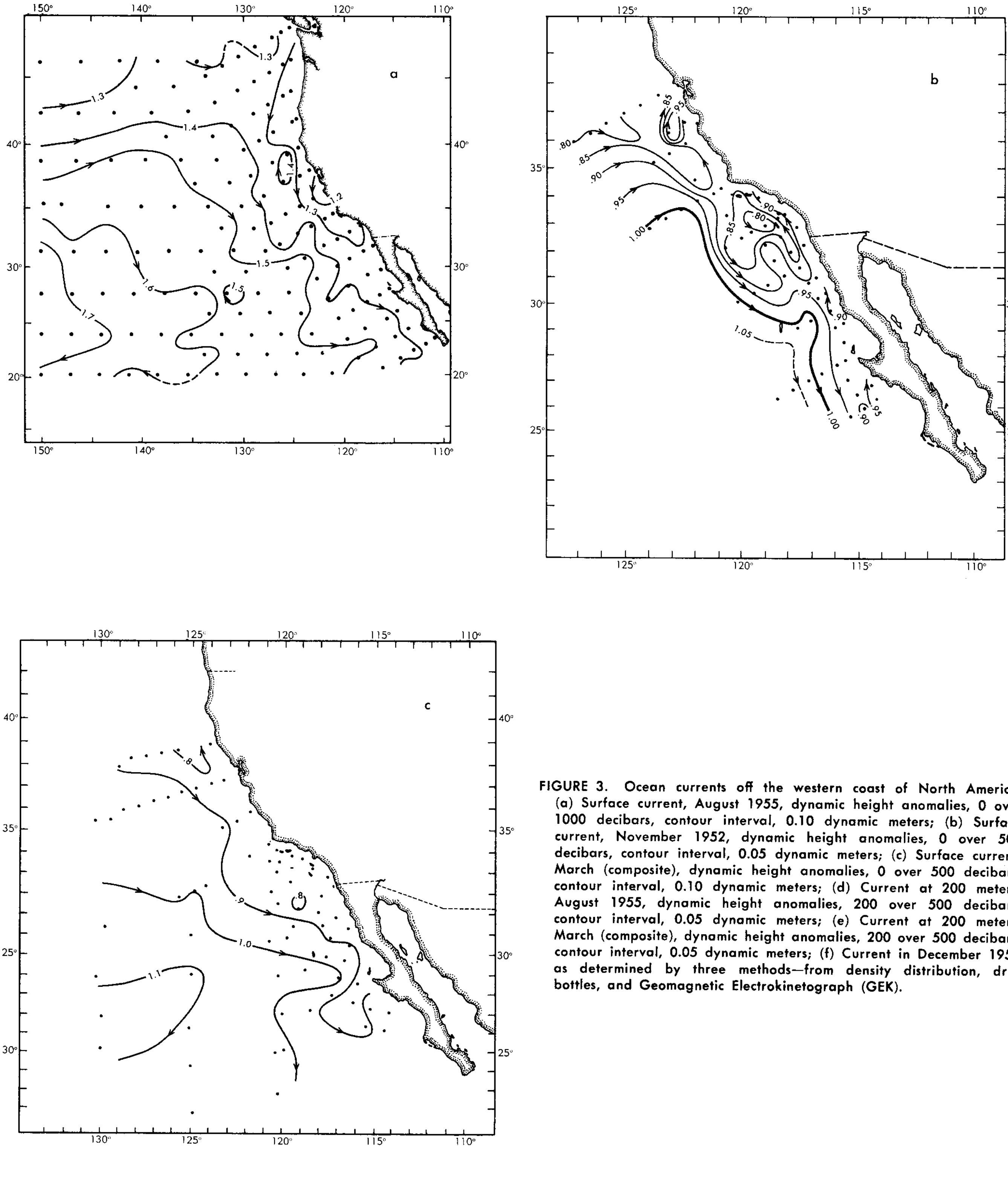
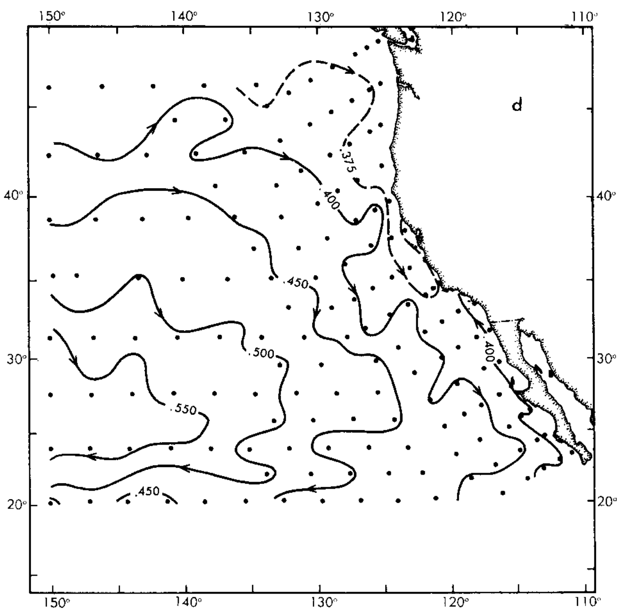


FIGURE 3. Ocean currents off the western coast of North America. (a) Surface current, August 1955, dynamic height anomalies, 0 over 1000 decibars, contour interval, 0.10 dynamic meters; (b) Surface current, November 1952, dynamic height anomalies, 0 over 500 decibars, contour interval, 0.05 dynamic meters; (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).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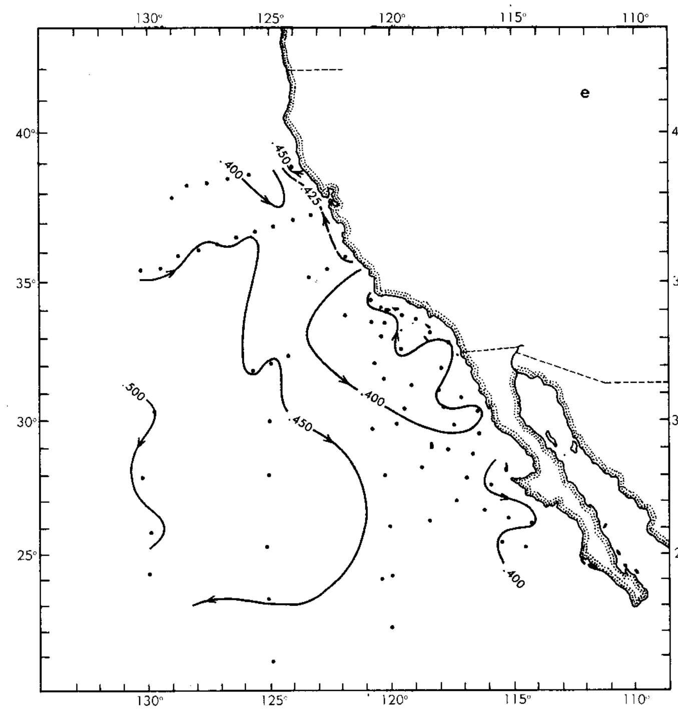
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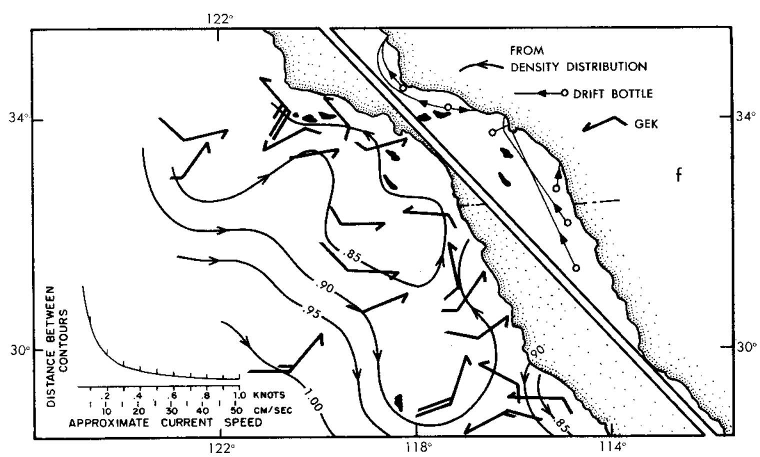
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DRIFT BOTTLE
GEK
f
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.90
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.90
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DISTANCE BETWEEN CONTOURS
.2 .4 .6 .8 1.0 KNOTS
10 20 30 40 50 CM/SEC
APPROXIMATE CURRENT SPEED
122°
118°
114°
34°
30°

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.

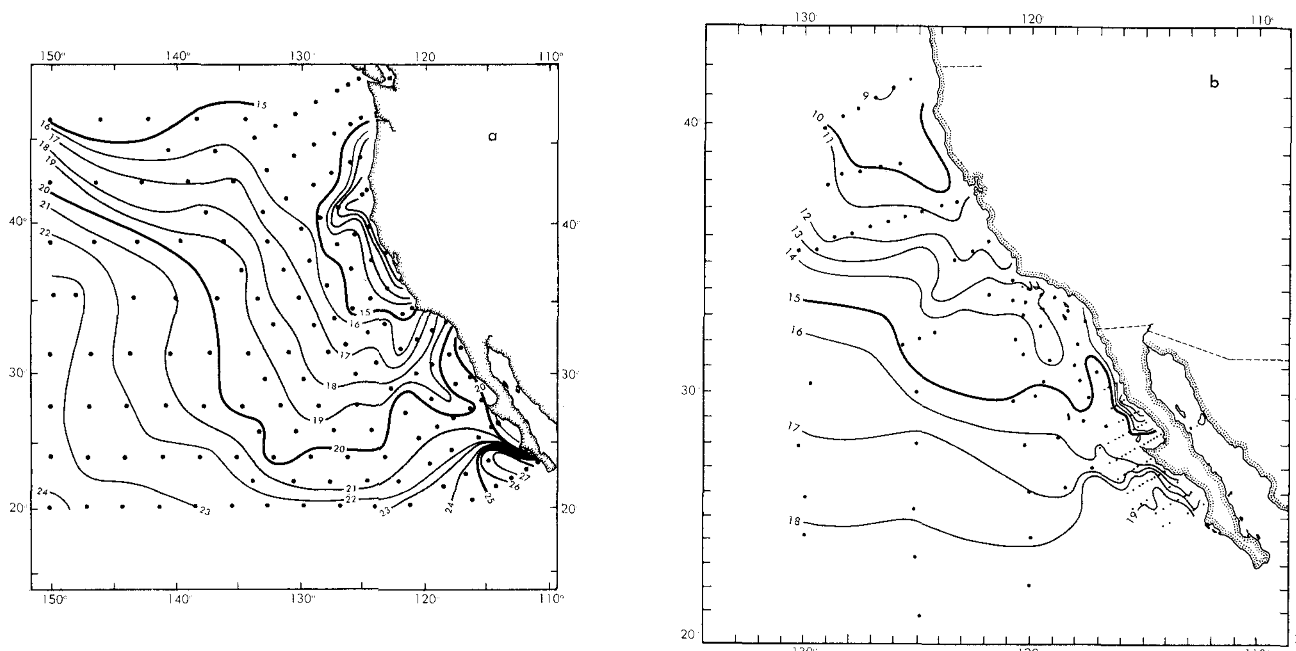


FIGURE 4. Ocean temperatures at 10 meters (degrees Centigrade). (a) August 1955. (b) March (composite).

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

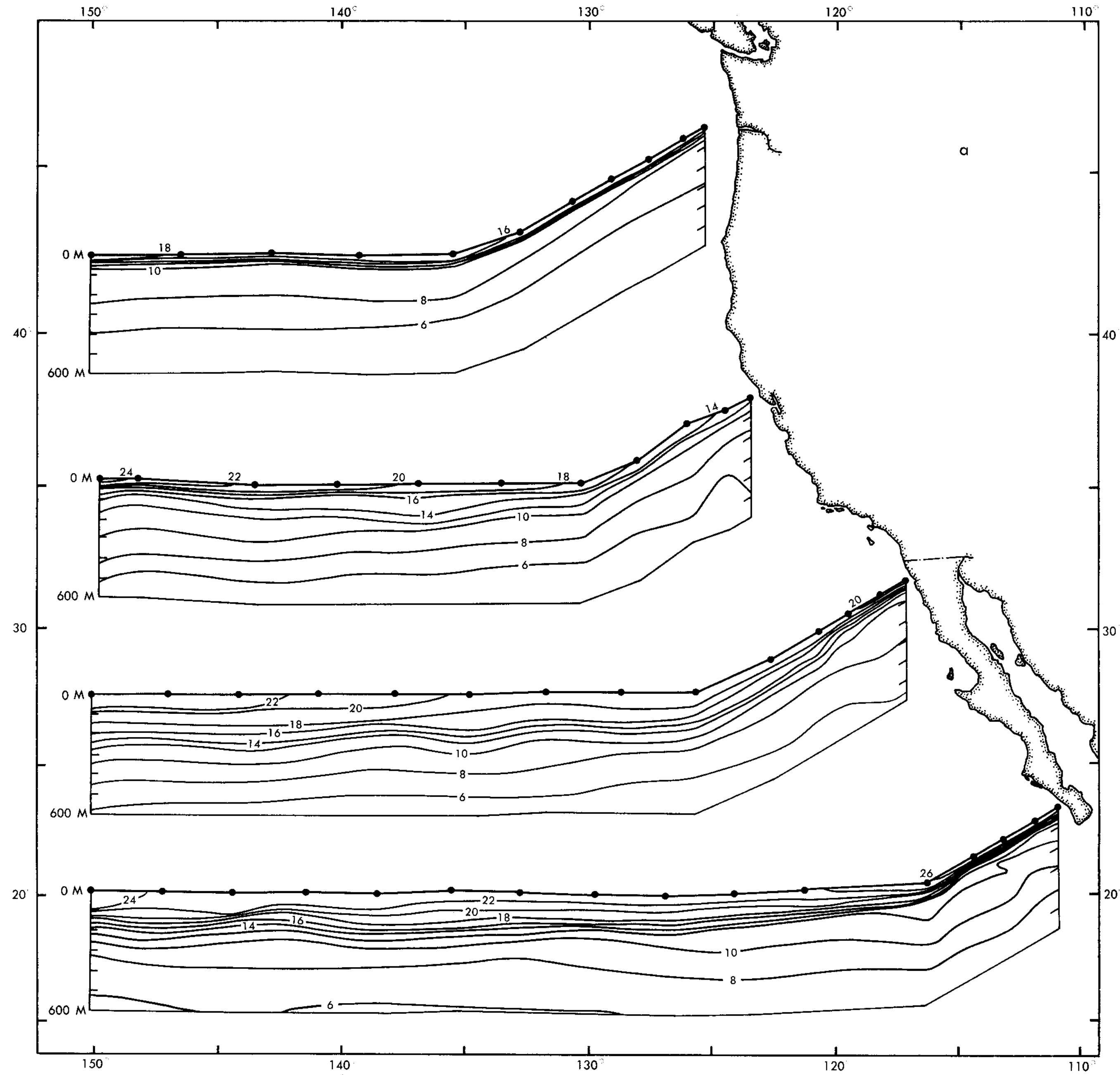


FIGURE 5. Vertical profiles of temperature, salinity, oxygen and phosphate from the surface to 600 meters, August 1955.
(a) Temperature, degrees Centigrade.

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 dèeper 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

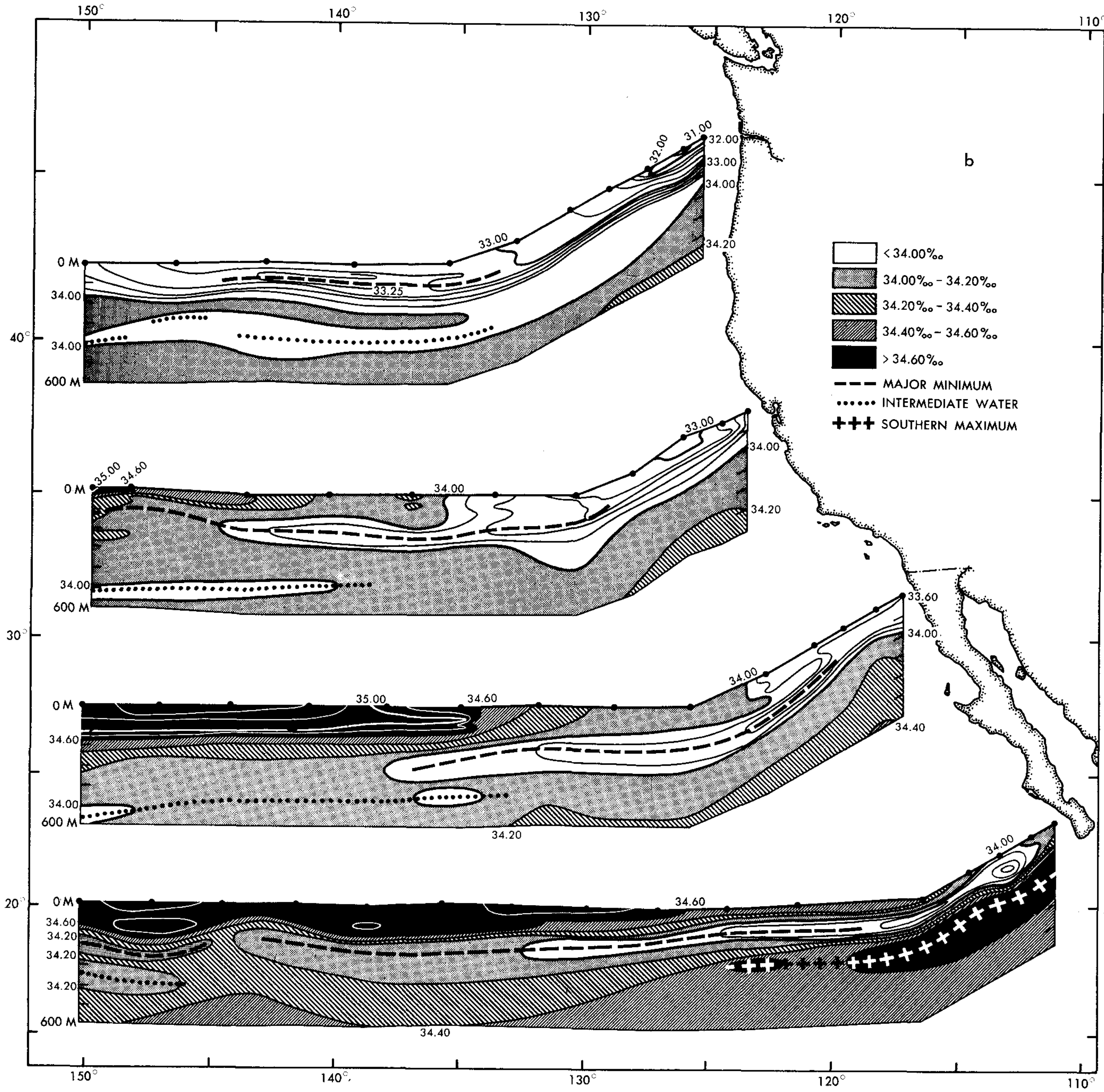


FIGURE 5—Continued

(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

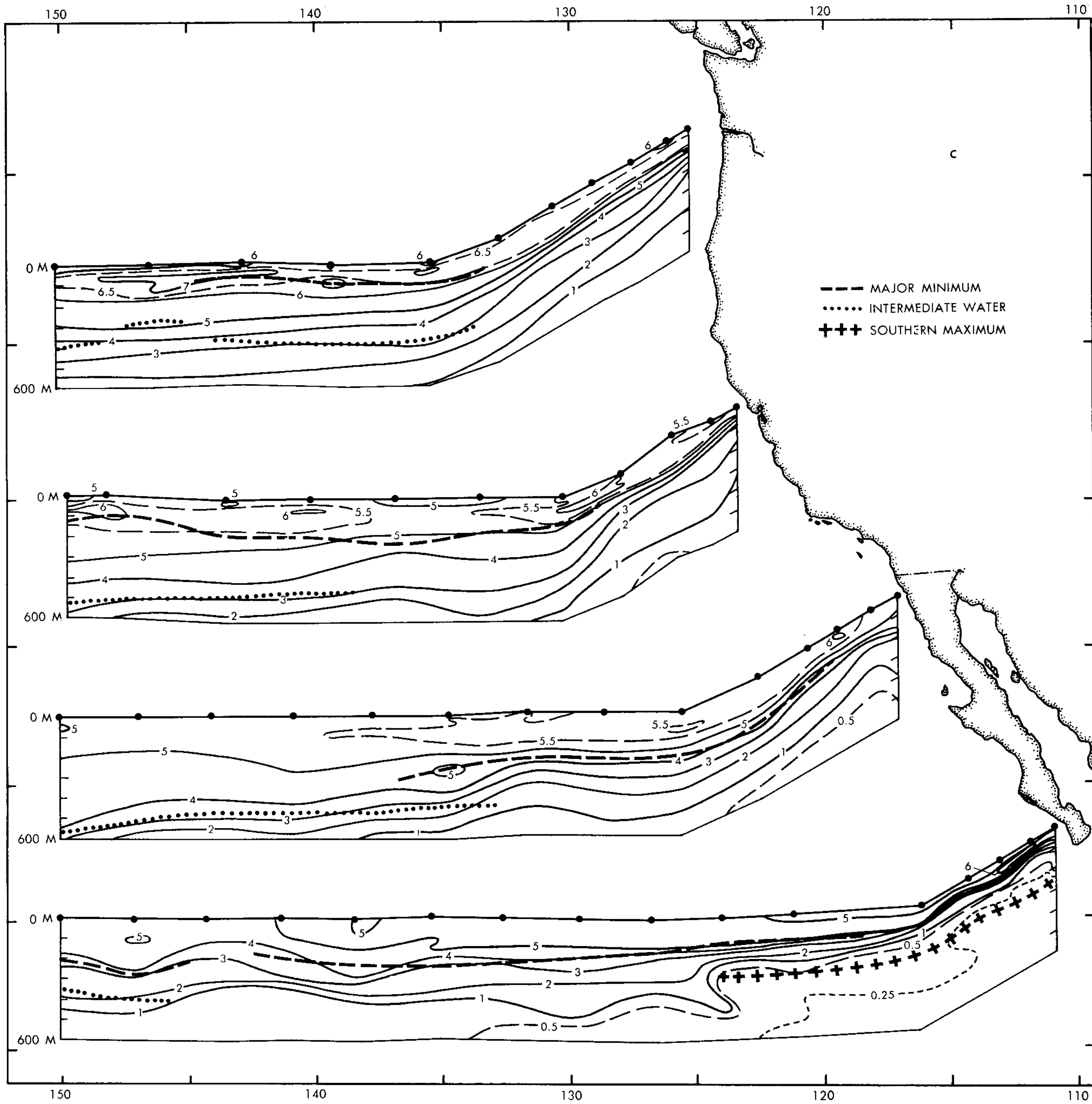


FIGURE 5—Continued

(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.

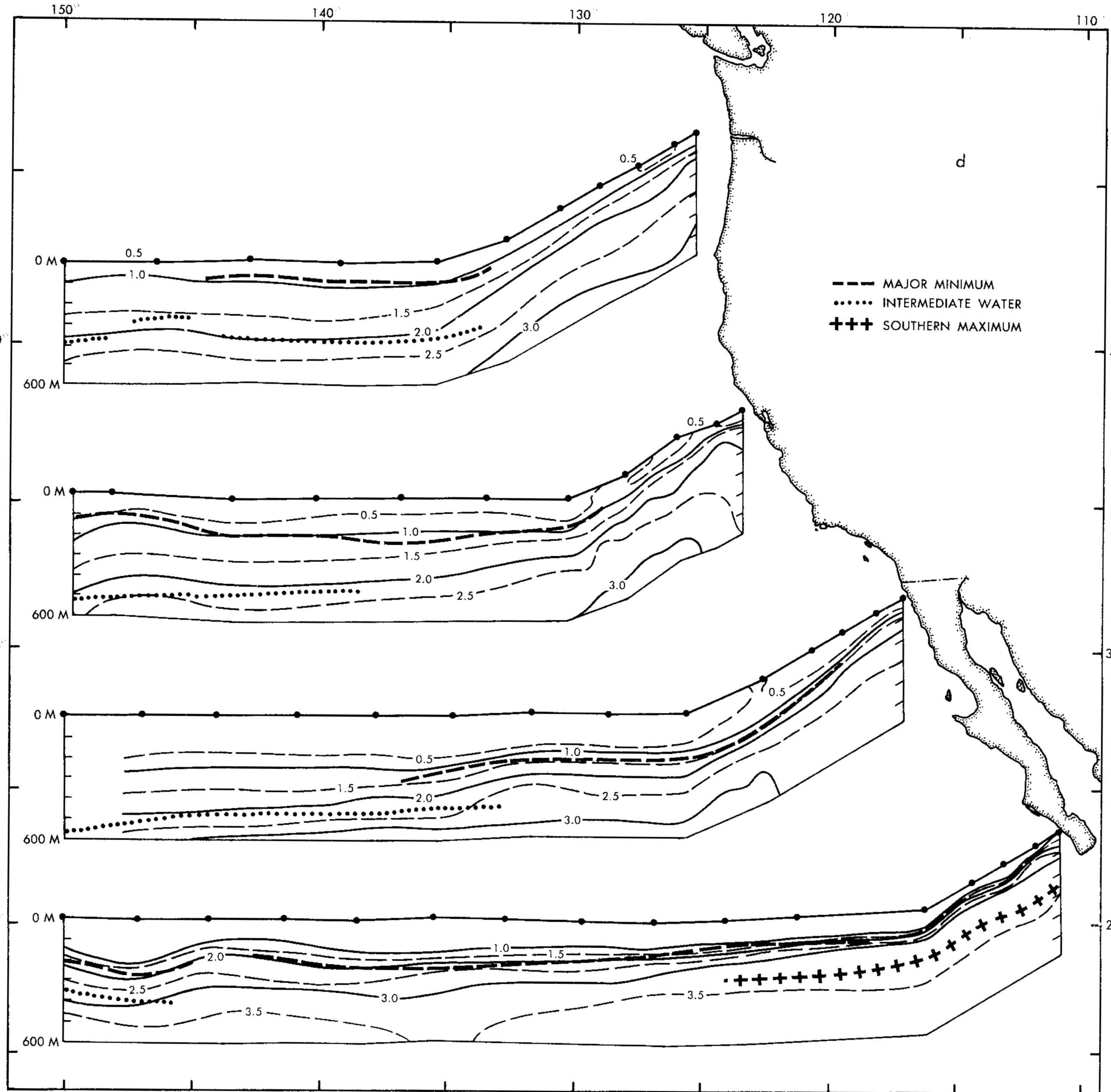


FIGURE 5—Continued

(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.)

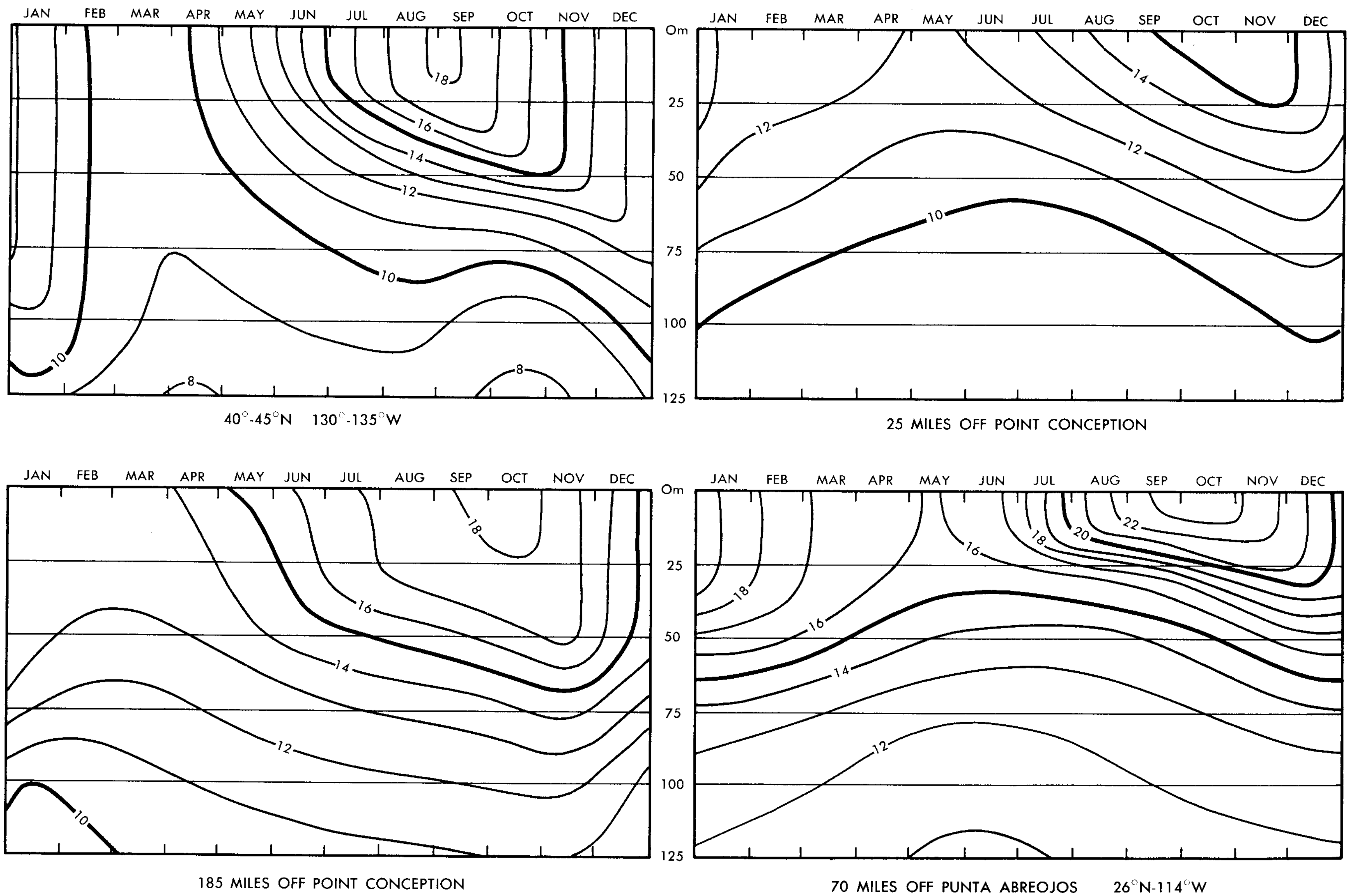


FIGURE 6. Seasonal variation of temperature in the upper 125 meters at four locations. Temperature in degrees Centigrade, depth in meters. The upper left-hand section is from Robinson (1957); the other sections are from CCOFI data, 1949-55.

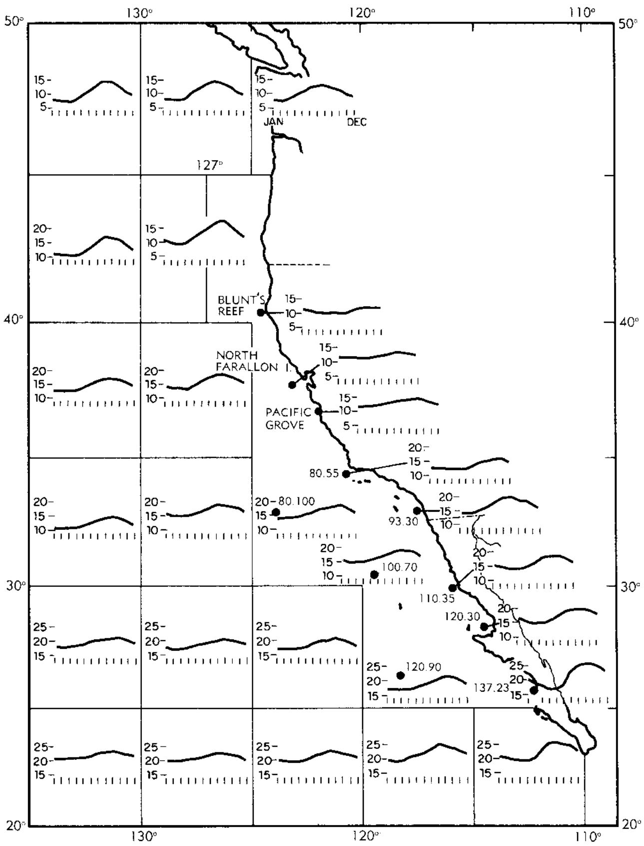


FIGURE 7. Seasonal variation of temperature at the surface off the western coast of North America. Temperature in degrees Centigrade. Values over five-degree squares are from Robinson (1957); values at Blunt's Reef, North Farallon Island and Pacific Grove are from U. S. Coast and Geodetic Survey (1956);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

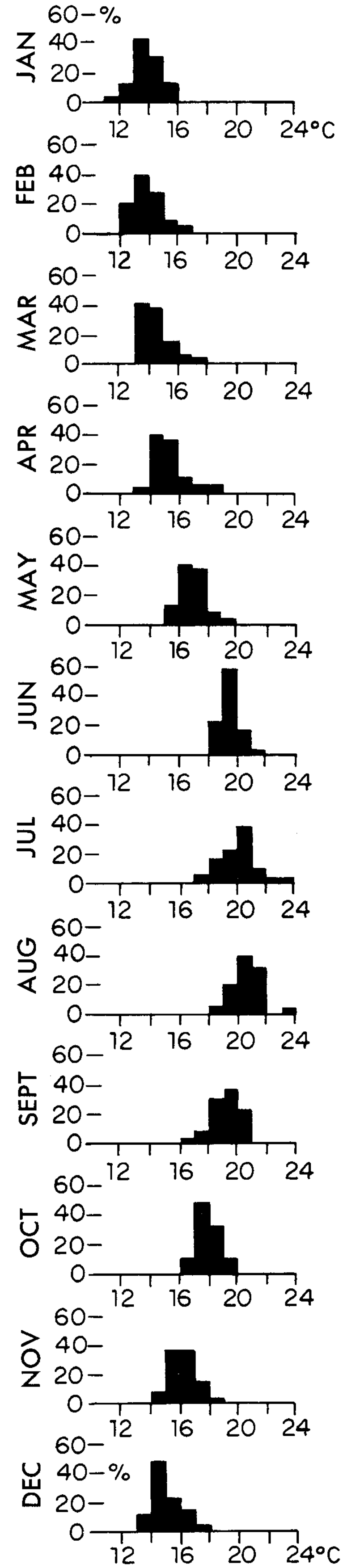


FIGURE 8. Frequency distribution of monthly average temperature at Scripps Pier, La Jolla, from 1917 to 1956. Temperature in degrees Centigrade.

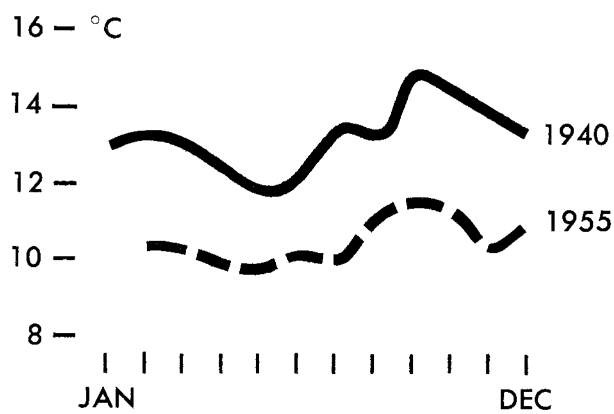


FIGURE 9. Monthly average temperature at North Farallon Island in 1940 and 1955. Temperature in degrees Centigrade.

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

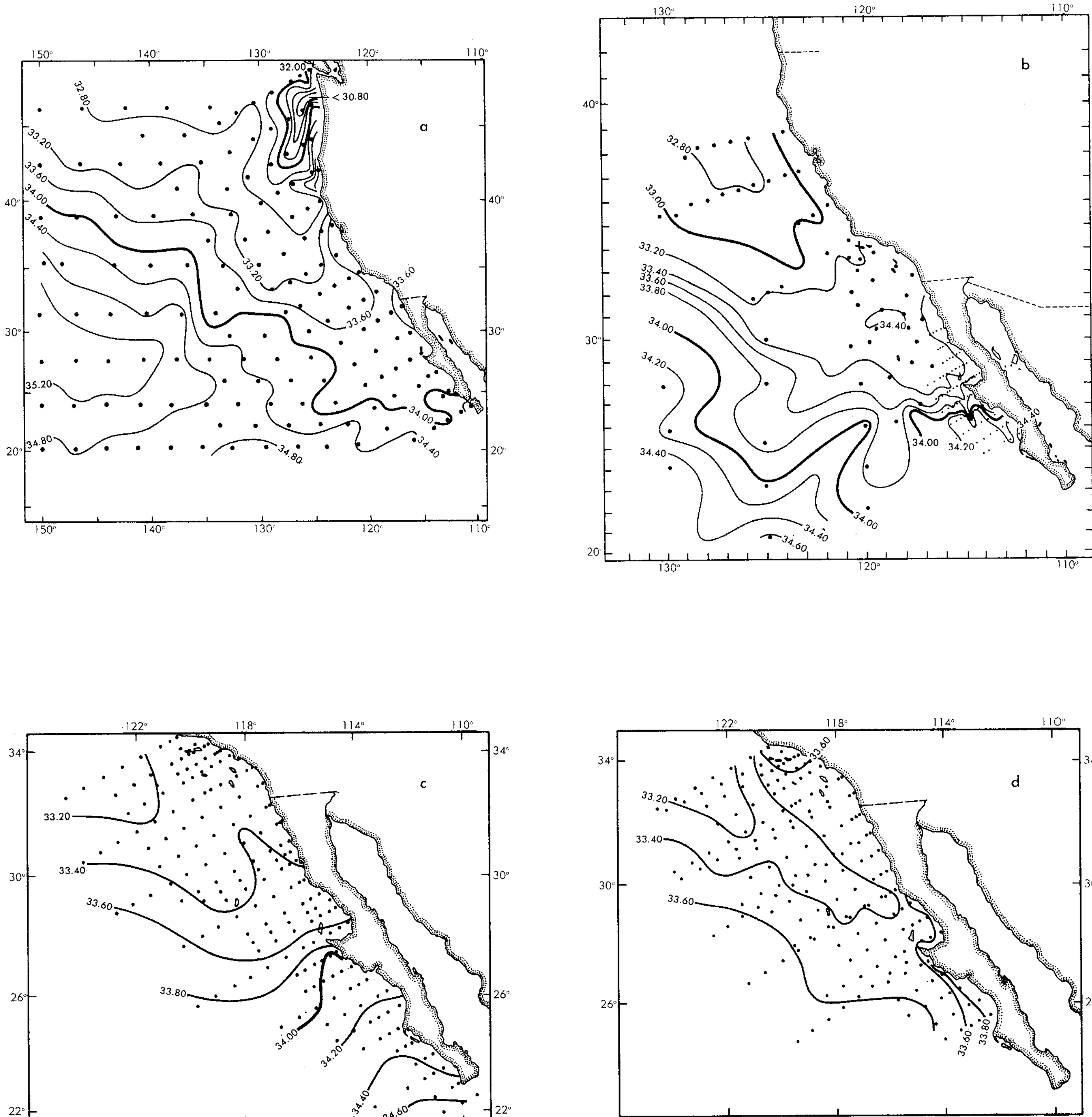


FIGURE 10. Salinity at 10 meters, in parts per mille. (a) August 1955. (b) March (composite). (c) January (average of three years). (d) June (average of three years).

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

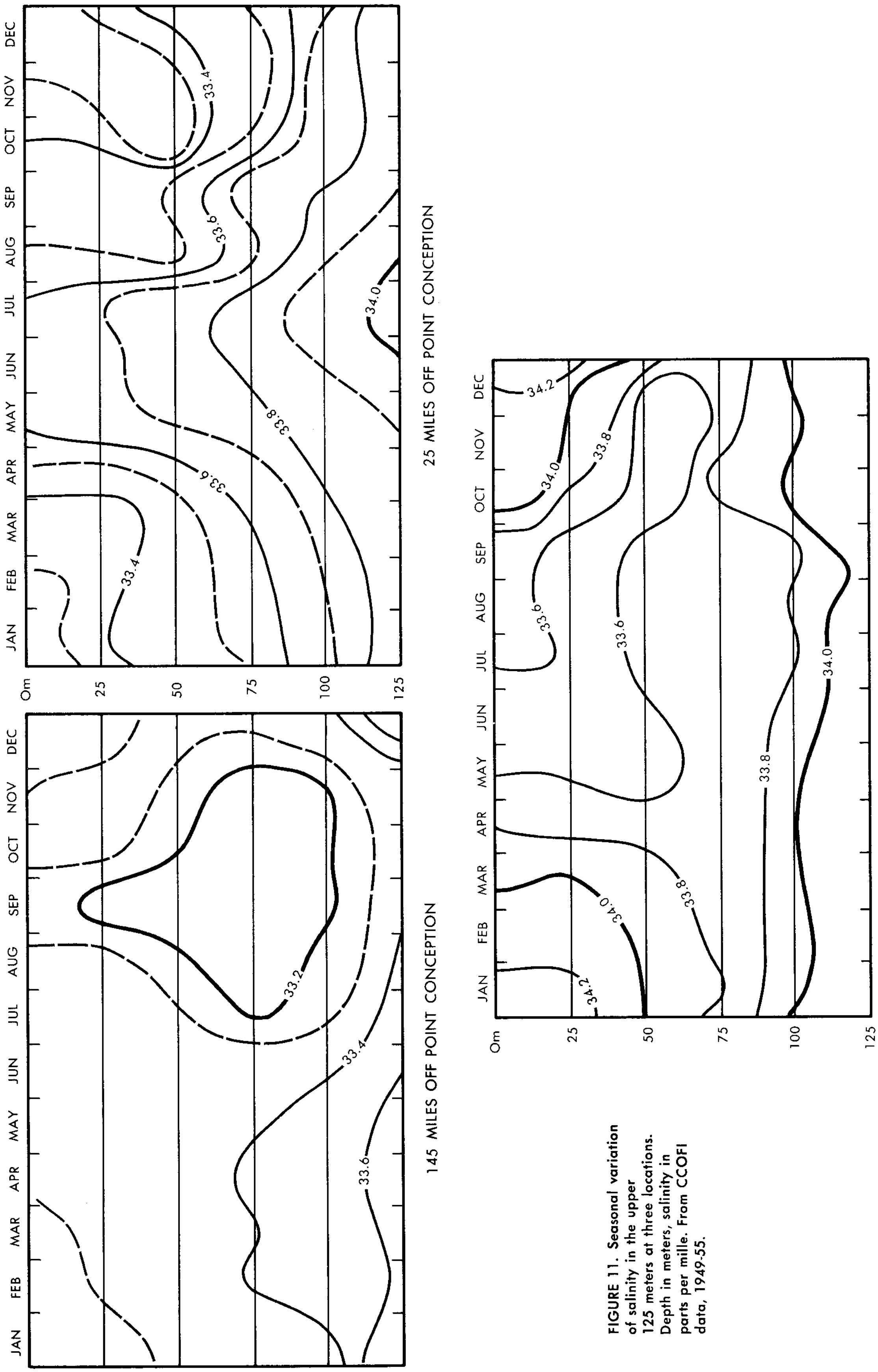


FIGURE 11. Seasonal variation of salinity in the upper 125 meters at three locations. Depth in meters, salinity in parts per mille. From CCOFI data, 1949-55.

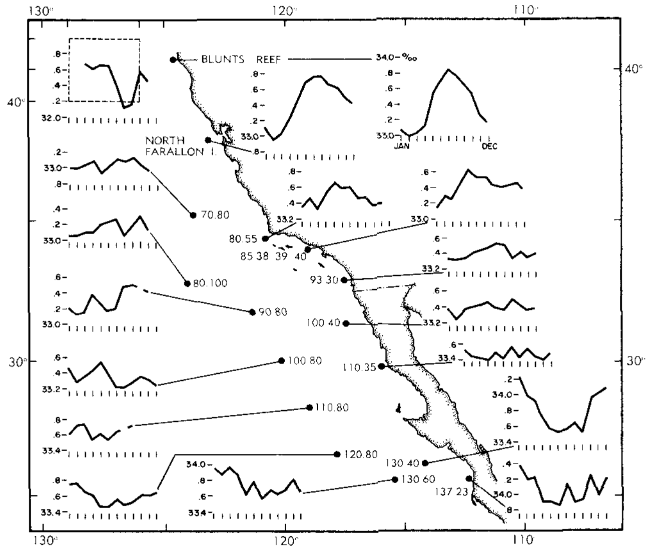


FIGURE 12. Seasonal variation of salinity at the surface off the western coast of North America. Salinity in parts per mille. Values at Blunt's Reef and North Farallon Island are from U. S. Coast and Geodetic Survey (1954); all other values are from CCOFI data, 1949-55.

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.

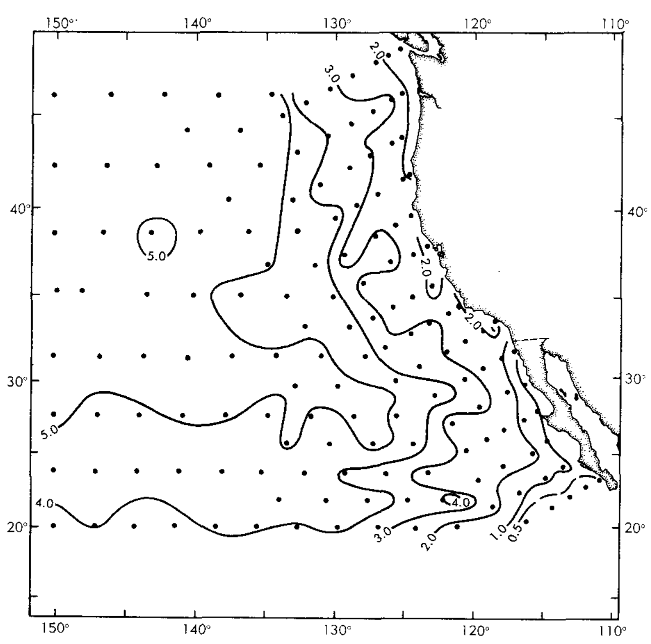


FIGURE 13. Dissolved oxygen, in milliliters per liter, at 200 meters, August 1955.

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

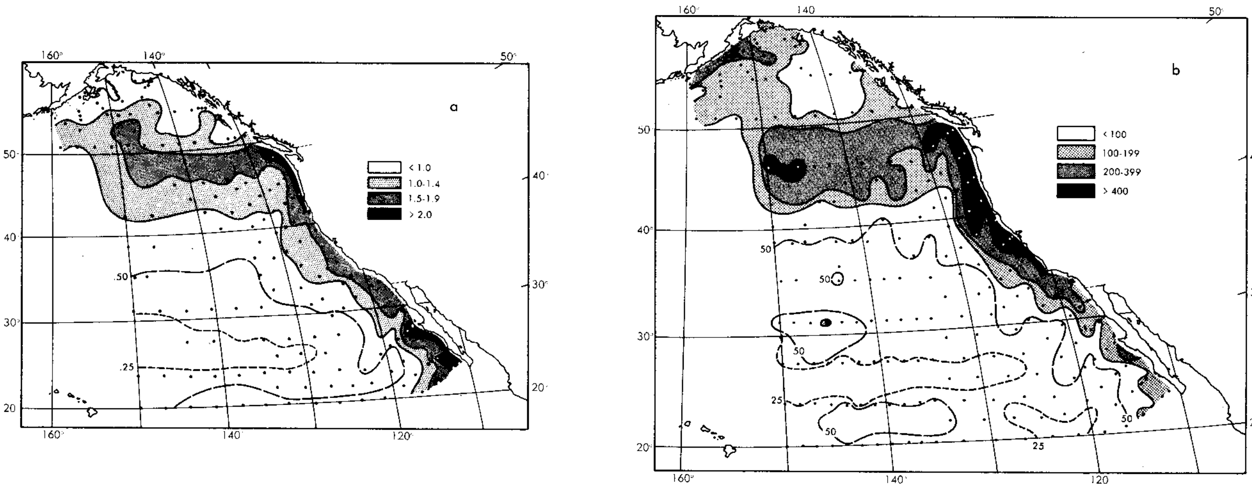


FIGURE 14. Distribution of phosphate-phosphorus and zooplankton volumes, August 1955. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

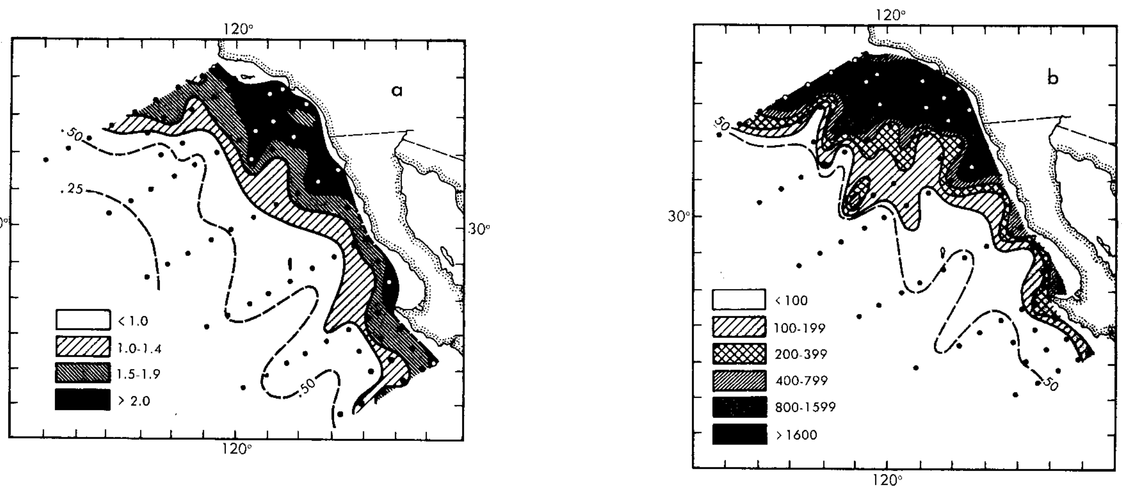


FIGURE 15. Distribution of phosphate-phosphorus and zooplankton volumes, April 1950. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

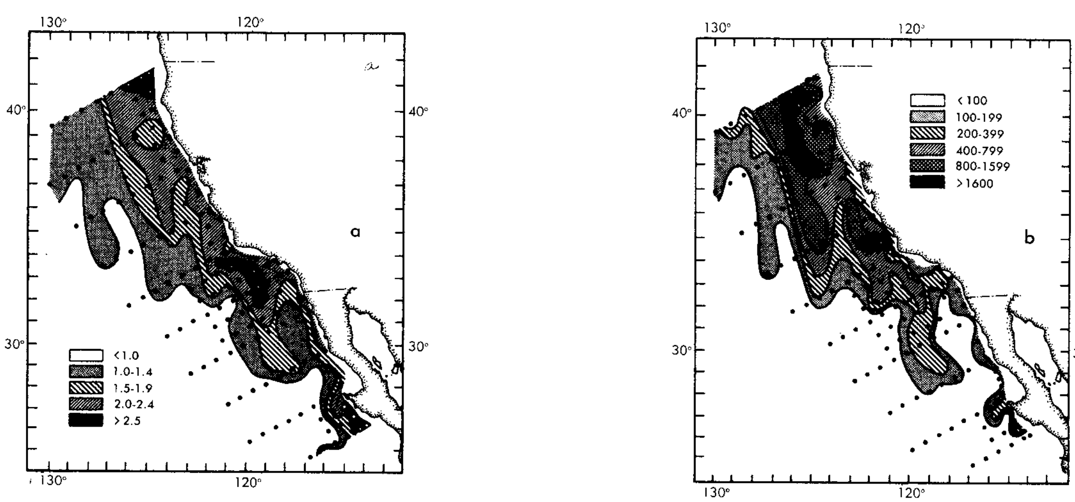


FIGURE 16. Distribution of phosphate-phosphorus and zooplankton volumes, July 1950. (a) Phosphate-phosphorus, microgram atoms per liter at 100 meters. (b) Zooplankton volumes, cubic centimeters per 1000 cubic meters.

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.

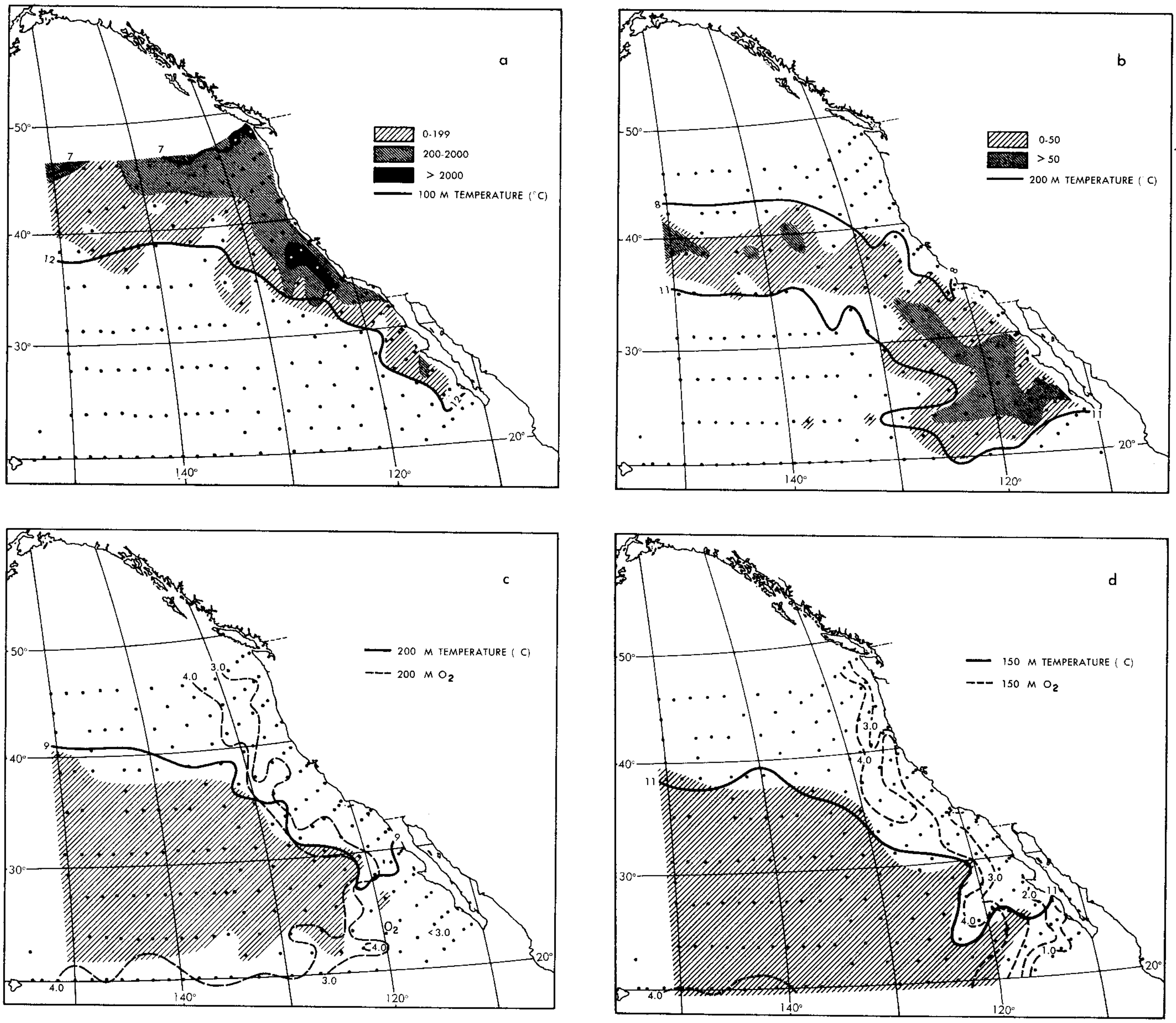
The requirements of the organisms shown are not well enough understood for us to conclude that the properties illustrated at the boundaries are the effective ones. The euphausiids, in particular, are difficult to understand since they undergo a diurnal migration, and are deep in the daytime and near 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



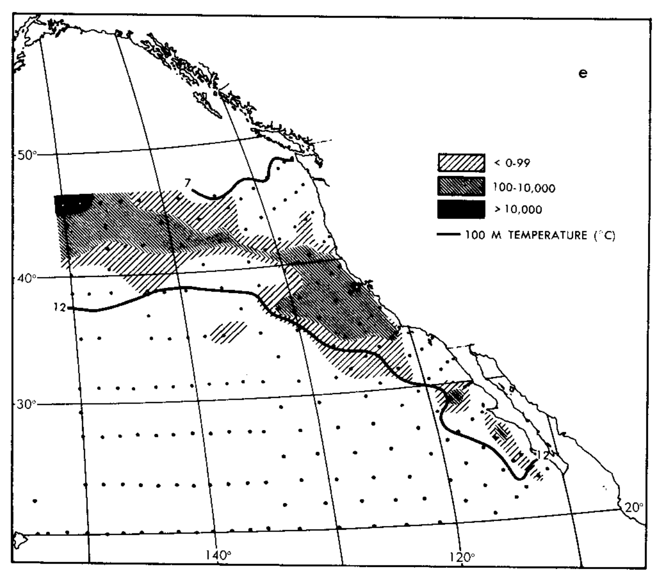


FIGURE 17. Distribution of certain zooplankton and certain temperature and oxygen values, August 1955. (a) *Euphausia pacifica* and temperature (in degrees Centigrade) at 100 meters. (b) *Euphausia gibboides* and temperature (in degrees Centigrade) at 200 meters. (c) *Nematoscellis atlantica* and temperature (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) *Doliolettα 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.)

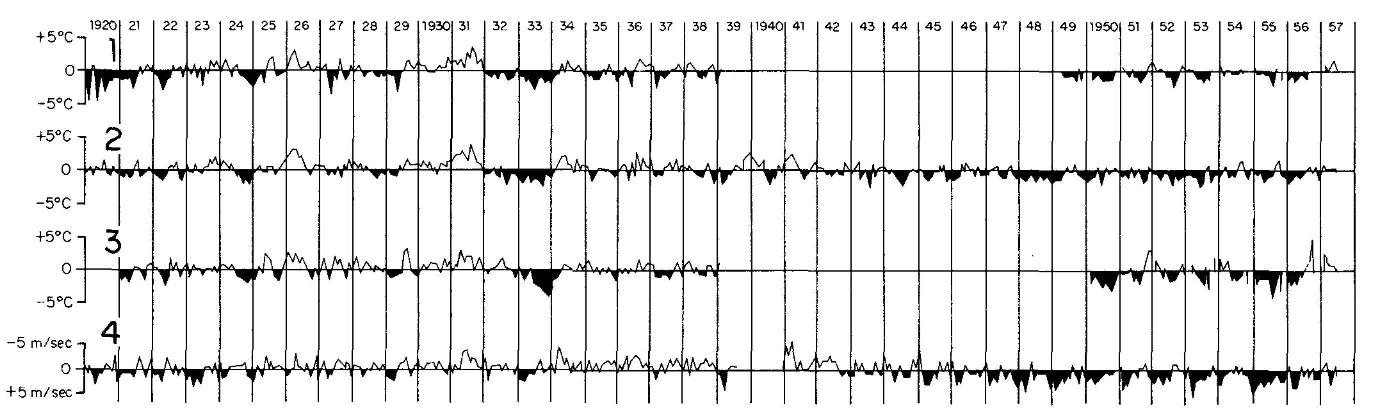


FIGURE 18. Monthly differences from average sea surface temperatures (degrees Centigrade) at (1) 30°-35° N, 115°-120° W, (2) Scripps Pier, and (3) 25°-30° N, 110°-115° W; and (4) monthly differences from average northerly wind component (in meters per second) at 30° N, 110°-130° W.

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

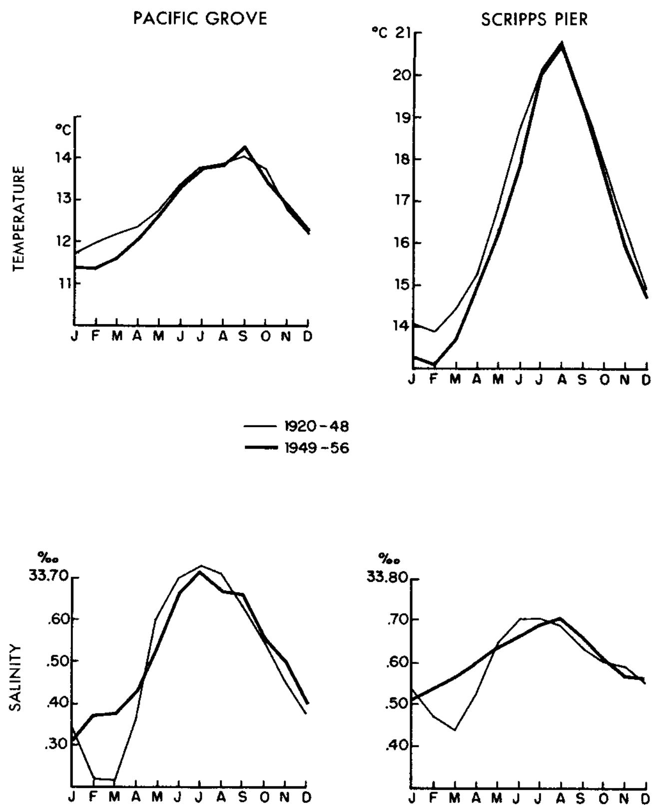


FIGURE 19. Average surface temperature (degrees Centigrade) and salinity (parts per mille) at Pacific Grove and Scripps Pier for the periods 1949-56 and 1920-48.

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

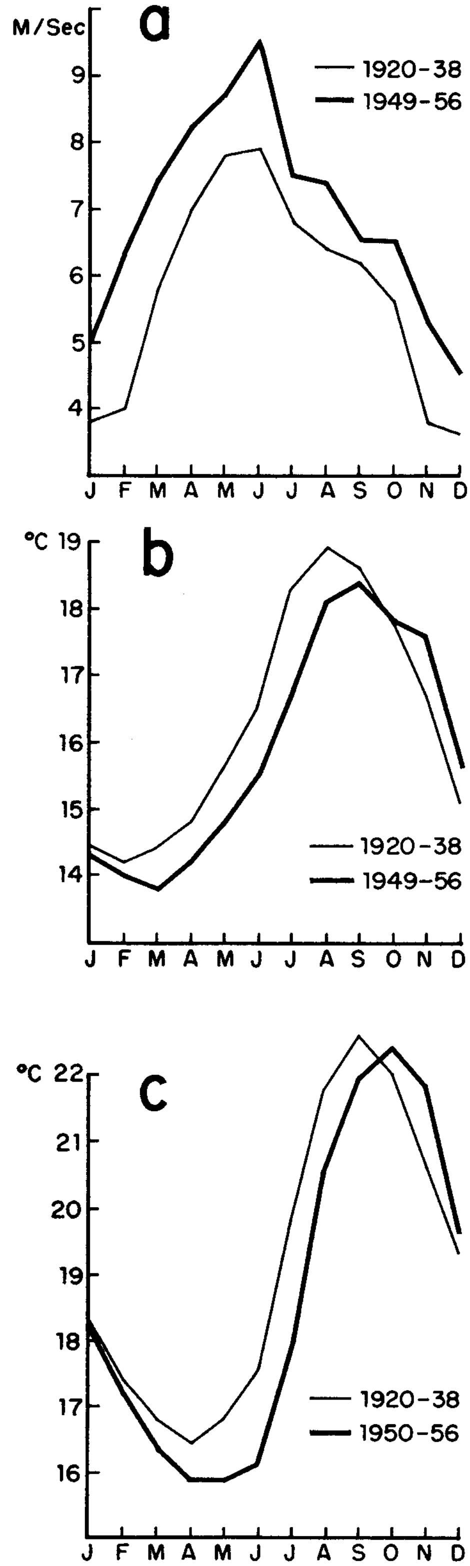


FIGURE 20. Average northerly wind component and temperature in recent period compared to averages for 1920-38. (a) Northerly wind component in meters per second at 30° N in years 1949-56. (b) Temperature in degrees Centigrade at 30°-35° N, 115°-120° W, 1949-56. (c) Temperature in degrees Centigrade at 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

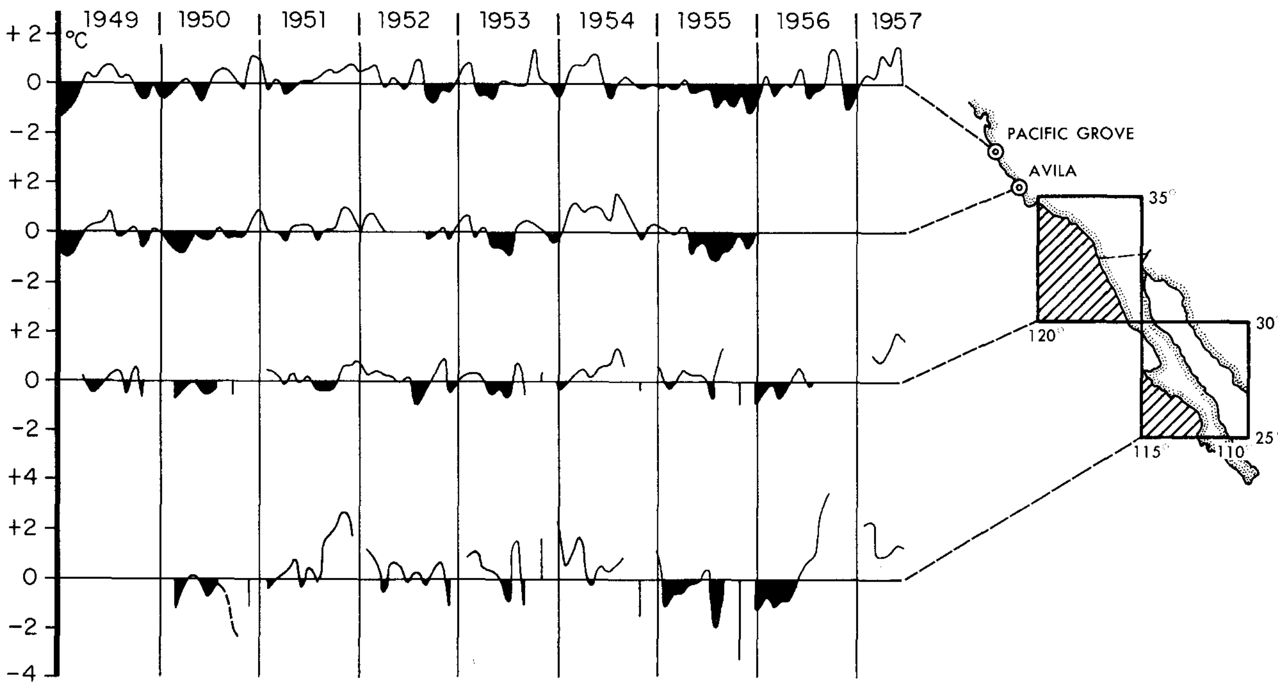


FIGURE 21. Temperature anomalies, 1949 to 1957, at four locations as referred to 1949-56 mean. Temperature in degrees Centigrade.

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.

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

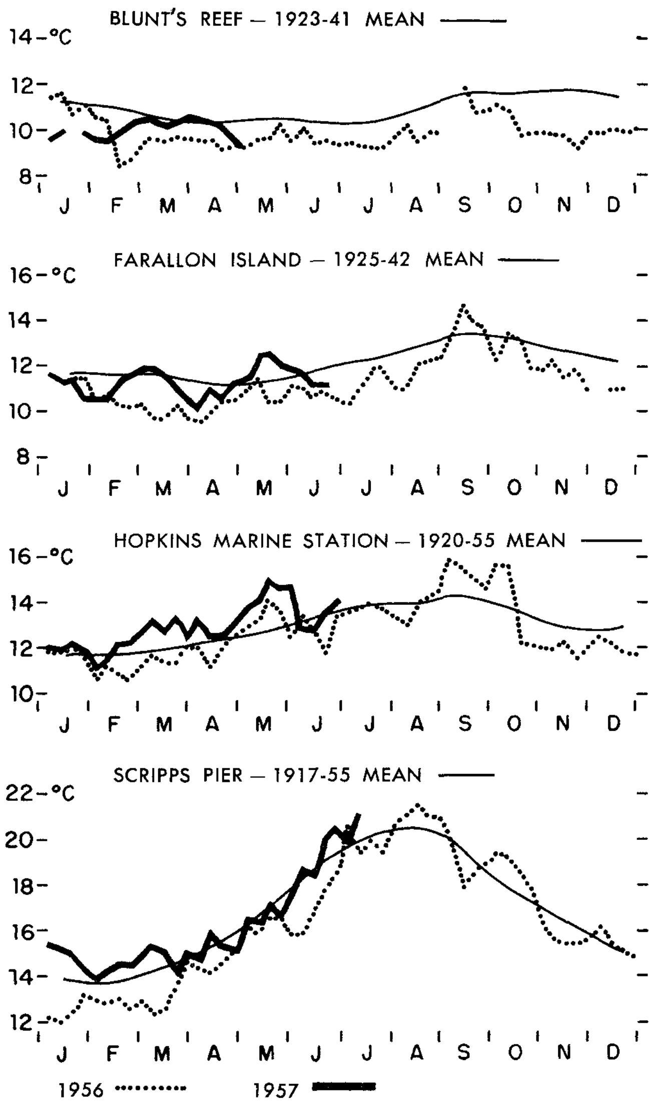


FIGURE 22. Temperatures in 1956 and 1957 at four locations as compared to long-term means. Temperature in degrees Centigrade.

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.

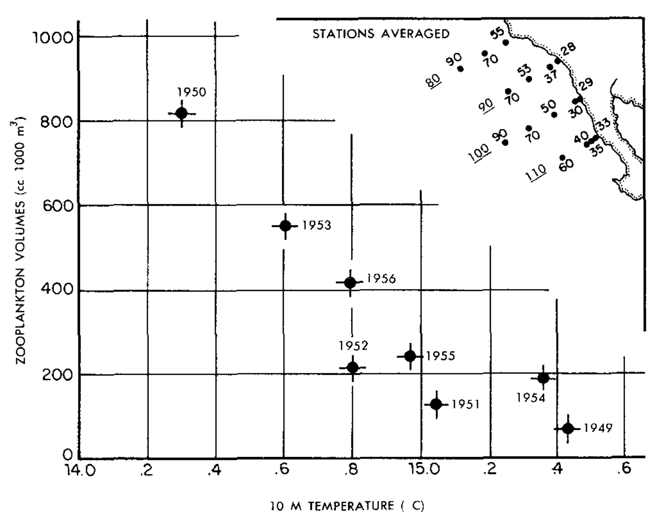


FIGURE 23. Temperature at 10 meters (in degrees Centigrade) and zooplankton volumes (in cubic centimeters per 1000 cubic meters) averaged from February through August for each year from 1949 through 1956.

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.

PUBLICATIONS

(Annotated list of publications arising from the California Cooperative Oceanic Fisheries Investigations, 1 July 1956 to 30 June 1957)

Ahlstrom, Elbert H., and Harold D. Casey

1956. Saury distribution and abundance, Pacific coast, 1950-55. *U. S. Dept. Interior, Fish and Wildl. Service, Spec. Sci. Rept.: Fisheries*, no. 190, 69 pp.
Information on the saury, obtained on CCOFI cruises, is of two kinds: (1) collections of saury eggs in plankton hauls and (2) visual observations of saury abundance. This report gives the basic data on saury eggs for six years, 1950-1955, and on visual observations of saury abundance at night stations for the period September 1951 through December 1955.

Ahlstrom, Elbert H., and David Kramer

1956. Sardine eggs and larvae and other fish larvae, Pacific coast, 1954. *U. S. Dept. Interior, Fish and Wildl. Serv., Spec. Sci. Rept.: Fisheries*, no. 186, 79 pp.
Basic data on abundance of sardine eggs and larvae in the area surveyed on CCOFI cruises during 1954. Also included are records of abundance of the larvae of northern anchovy (*Engraulis mordax*), jack mackerel (*Trachurus symmetricus*), hake (*Merluccius productus*), Pacific mackerel (*Pneumatophorus diego*), and rockfish (*Sebastodes* spp.).

Barham, E. G.

1957. The ecology of sonic scattering layers in the Monterey Bay area. Technical Report No. 1 under N6onr 25127, NSF G911 and NSF G1708, 182 pp., 31 figs.
This report is primarily concerned with deep sea ecology investigated on other programs. However, it does utilize and discuss briefly phytoplankton data accumulated on the CCOFI program and the influence of productivity in modifying and shifting the deep scattering layer.

Bieri, Robert

1956. A method for the microscopic examination and manipulation of plankton on board ship. *J. Cons. Int. Explor. Mer*, vol. XXII, no. 1., pp. 38-41, 3 figs..
The under-way plankton tray, a device for the microscopic examination of plankton on board ship, is described.

Dales, R. Phillips

1957. The pelagic polychaetes of the Pacific Ocean. *Univ. Calif. Scripps Inst. Oce., Bull.*, vol. 7, No. 2, pp. 99-168, 64 figs.
The author has examined many of the CCOFI collections, among others, in this paper, which described the distribution and life histories of several species of marine worms.

Farris, David A.

1956. Diet-induced differences in the weight-length relationship of aquarium fed sardines (*Sardinops caerulea*). *J. Res. Bd. Can.*, vol. 13, no. 4, pp. 507-513.
Sardines which were fed two markedly different types of diet—one a high protein diet, the other a carbohydrate diet—showed differences in weight-length relationship.

Holmes, Robert W., and Theodore M. Widrig

The enumeration and collection of marine phytoplankton. *J. Cons. Int. Explor. Mer*, vol. XXII, no. 1, pp. 21-32, 2 figs.
Methods of enumerating and collecting phytoplankton are discussed in this study, which arose directly out of the CCOFI program.

Johnson, Martin W.

1956. The larval development of the California spiny lobster, *Panulirus interruptus* (Randall), with notes on *Panulirus gracilis* Streets. *Calif. Acad. Sci., Proc.*, vol. XXIX, no. 1, pp. 1-19, 22 figs.
The author draws on data from the CCOFI cruises to describe stages of the spiny lobster larva.

Joseph, David C.

1956. New techniques in ocean electro-fishing are developed. *Outdoor Calif.*, vol. 17, no. 9, p. 13, September.
A report on the preliminary series of electro-fishing experiments conducted by personnel of the Marine Fisheries Branch, California Department of Fish and Game. Reasons for the work, obstacles to using this gear in salt water, and other items are briefly discussed in a non-technical report.

Knauss, John A., and Joseph L. Reid

1957. On the accuracy of the GEK for measuring surface current. *Amer. Geophys. Un., Trans.*, vol. 38, no. 3, pp. 320-325, 2 figs.
The GEK (geomagnetic-electrokinetograph) is one of the standard tools used in the CCOFI program to measure surface currents. The authors made simultaneous observations of GEK measurements and of drifting drogues in order to test the validity of the GEK for surface current measurements. Good agreement was obtained.

Marine Research Committee

1956. *California Cooperative Oceanic Fisheries Investigations, Progress Report, 1 April 1955 to 30 June 1956.* Sacramento: The State Printer. 1 July 1956. 44 pp., 21 figs.
This progress report consists of a review of activities for the period and separate sections on the anchovy, jack mackerel, Pacific mackerel, and eggs and larvae of these species. Publications for the period are listed.

Miller, Daniel J.

1956. Anchovy study shows gain in Southern waters. *Outdoor Calif.*, vol. 17, no. 12, p. 3, 8-9, December.
A short discussion of the anchovy situation in Californian waters has been presented. Catch, population densities, aerial surveys, laws, spawning populations, and movements are mentioned in a non-technical terminology.

Robinson, Margaret K.

1957. Sea temperature in the Gulf of Alaska and the northeast Pacific Ocean, 1941-52. *Univ. Calif. Scripps Inst. Oce., Bul.*, vol. 7, no. 1, pp. 1-98, 61 figs., 1 chart.
In her study of sea temperatures in the northeast Pacific Ocean, the author has utilized data collected in the course of some of the CCOFI cruises.

Thrailkill, James R.

1956. Relative areal zooplankton abundance off the Pacific coast. *U. S. Dept. Interior, Fish and Wildl. Serv. Spec. Sci. Rept. Fisheries*, no. 188, 85 pp.
Contained in the report are distribution charts showing abundance of zooplankton for every CCOFI hydrographic-biological cruise during the seven-year period 1949 through 1955. In addition, there are yearly distribution charts showing the average plankton volumes obtained at each station.

United States Fish and Wildlife Service, South Pacific Fishery Investigations

1956. Zooplankton volumes off the Pacific coast, 1955. *U. S. Dept. Interior, Fish and Wildl. Serv. Spec. Sci. Rept.: Fisheries*, no. 177, 32 pp.
This report deals with zooplankton volumes obtained on 1955 CCOFI survey cruises. This is the sixth report in a continuing series, which, with this report, covers the period 1949-1955. In addition to wet plankton volumes (reported as volume per 1000 cubic meters of water strained), this report contains the basic data on all plankton hauls made during the year, including location, date, duration of haul, depth of haul, and volume of water strained.

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