

What Has Been Accomplished

STUDIES OF THE SARDINE'S ENVIRONMENT

Physical Oceanography

The physical environment as it affects the sardine not only directly but indirectly is being investigated under the California Cooperative Sardine Research Program. The recruitment studies have shown that most spawning takes place within a narrow temperature range. Oceanographic data are being collected in the presence of sardine schools in an effort to correlate physical factors with sardine availability. The effects of temperature on sardine behavior are being studied in the laboratory. Much work is going into a fourth line of inquiry—how the physical environment affects the sardine indirectly by affecting its food supply.

The basic marine food supply, phytoplankton, live only in those upper few hundred feet of the sea that sunlight can penetrate. These minute plants produce organic matter from dissolved inorganic nutrient salts, using light for photosynthesis. The nutrients, which are produced by bacteriological decomposition, are often found in higher concentrations below the euphotic zone than in it.

By means of photosynthesis, solar radiation provides the energy that drives the life cycle itself; and it is solar radiation again that, through a completely independent chain of events, sets in operation the physical processes by which nutrients are restored to the euphotic zone.

Not all the energy emitted by the sun penetrates the atmosphere, but of that which does a major part is absorbed by the surface layers of the sea. A sizeable portion of this absorbed energy is re-emitted and/or given off to the atmosphere as latent heat. How much latent heat the atmosphere receives from the sea depends upon season, proximity to continents, and latitude. The variability in amount of latent heat given off induces the prevailing circulation in the atmosphere, that is, winds, clouds, high and low pressure areas, storms—the elements that make up weather in general. What we have here, however, is not a one-way process: the latent heat transmitted to the atmosphere by the sea largely controls the weather, but the weather also vitally affects conditions in the sea. It is true that the sea receives a major share of the solar energy and to some extent is influenced directly by it, but the atmosphere acting as a heat engine is the factor which effectively converts heat originally received by the sea into kinetic energy. And it is the drag of the prevailing winds on the ocean's surface that forces the waters in the upper layers to circulate. The Kuro

Shio current, the California current, and the Equatorial current all are part of a huge gyral maintained by the winds. But the winds do more than initiate great slow-moving horizontal currents; they set up waves, bring about vertical mixing of the upper layers of the water, cause the water over large areas to converge and sink or to diverge and rise. And these wind-induced phenomena to a large degree determine the physical environment of the sardine and other ocean life.

These facts have long been known, but our present program represents by all odds the most intense endeavor yet made to relate them to a practical problem—in this instance, the abundance and availability of sardines. We need to know not only the principles of the oceanic circulation but its details as they occur off the California coast and affect the Pacific sardine. Our ships in their routine cruises are getting that information for us.

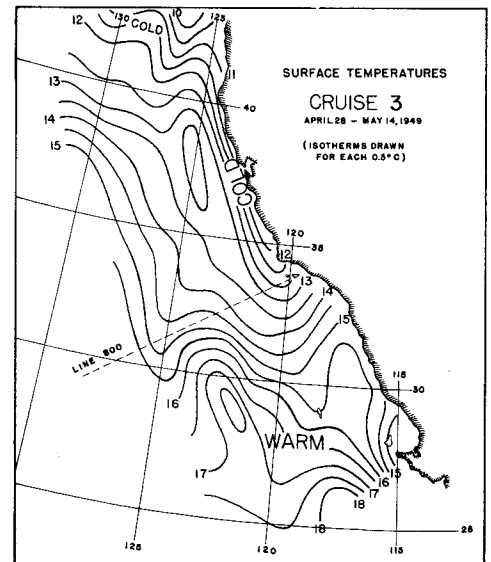
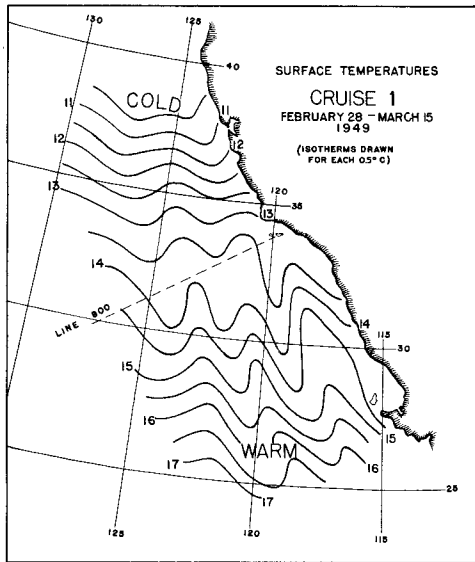
Upwelling

One of the significant advances made under the California Cooperative Sardine Research Program has been the accumulation of data relating to upwelling, which occurs when the surface waters diverge. Then deep water, rich in nutrients, is brought to the surface. It spreads throughout a wide area of the euphotic zone. The ascent of deep water is evidenced by a sharp decrease in temperature, an increase in salinity, and decided drop in oxygen concentration (Fig. 16). We have found that near the California coast, notably off Cape Mendocino and Point Conception, there is unquestionable evidence of the occurrence of upwelling.

This upwelling off the California coast, which brings about accompanying changes in the current pattern at the surface, is induced directly by the occurrence of winds having a strong northerly component. In the areas of Cape Mendocino and Point Conception, such winds are most frequently found during the spring and summer. In those seasons the Pacific atmospheric high-pressure cell intensifies and extends up along the coast. During the winter, on the other hand, when storms are moving in on us from the North Pacific, the winds are for the most part southerly and easterly; upwelling is suppressed. The occurrence of upwelling changes with changing weather conditions. Compare the apparent upwelling in 1941 with that in 1949 (Fig. 17).

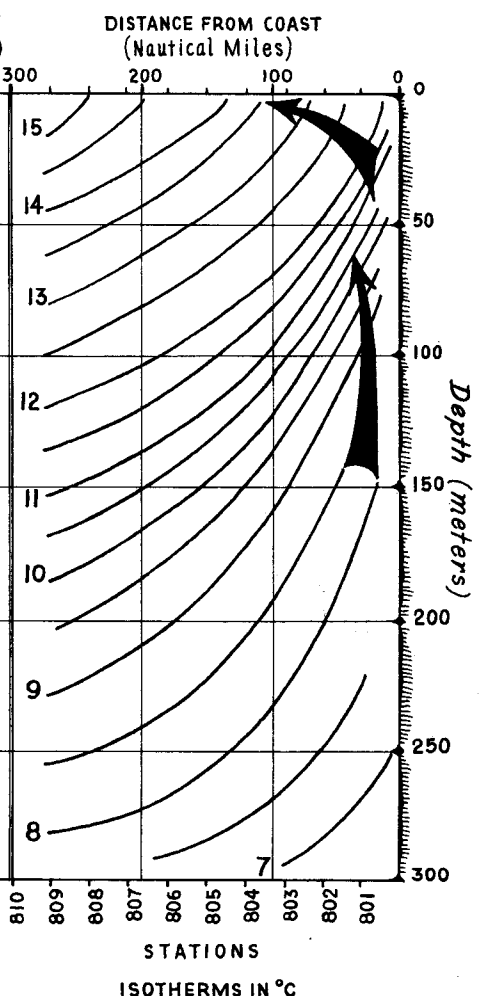
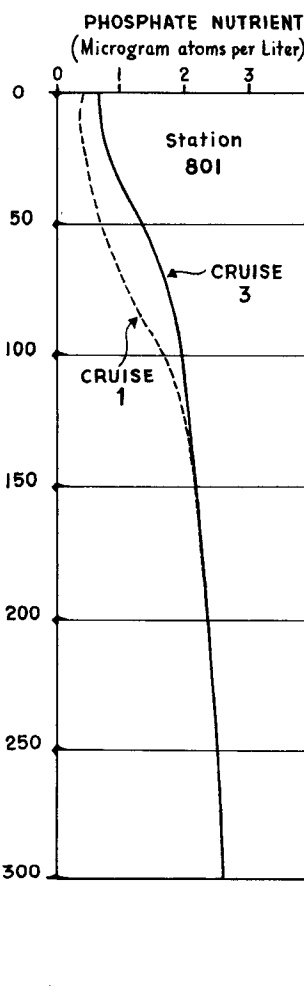
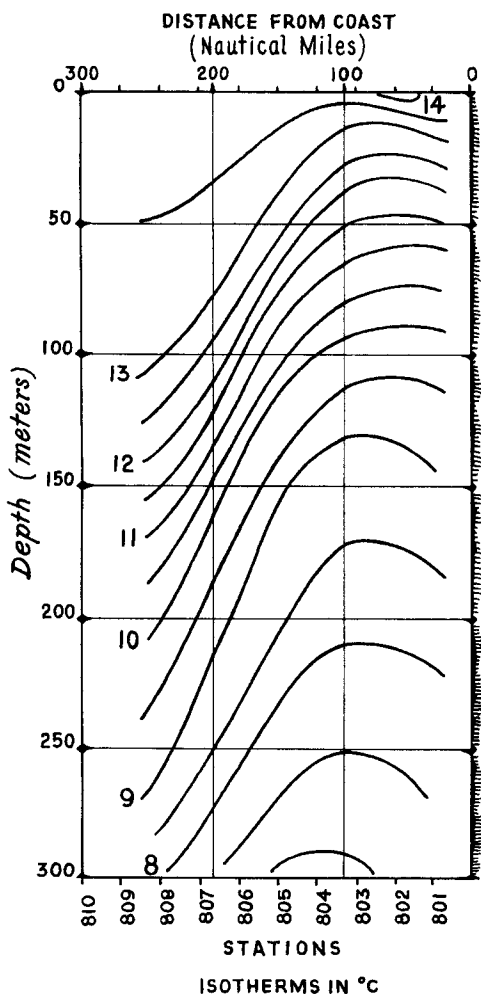
How the winds cause upwelling is shown quite well from an analysis of the data taken on Cruise 3 of the present program (Fig. 18). (In the figure, the data from Cruise 1, representing conditions where no upwelling was occurring, are included for comparison.)

CALIFORNIA COOPERATIVE SARDINE RESEARCH



LINE 800 CRUISE 1

LINE 800 CRUISE 3



Smoothed to eliminate internal wave effect

Smoothed to eliminate internal wave effect

FIGURE 16. Evidence of upwelling between Cruises 1 and 3. (UPPER LEFT) Surface temperatures, Cruise 1. (UPPER RIGHT) Surface temperatures, Cruise 3. (LOWER LEFT) Profile of temperature along line 800, Cruise 1. (LOWER RIGHT) Profile of temperature along line 800, Cruise 3. Note cooling adjacent to coast. Arrows indicate vertical circulation. (LOWER CENTER) Change in phosphate nutrient at Station 801 between Cruises 1 and 3. The enrichment of the upper layers of the water is a main feature of upwelling.

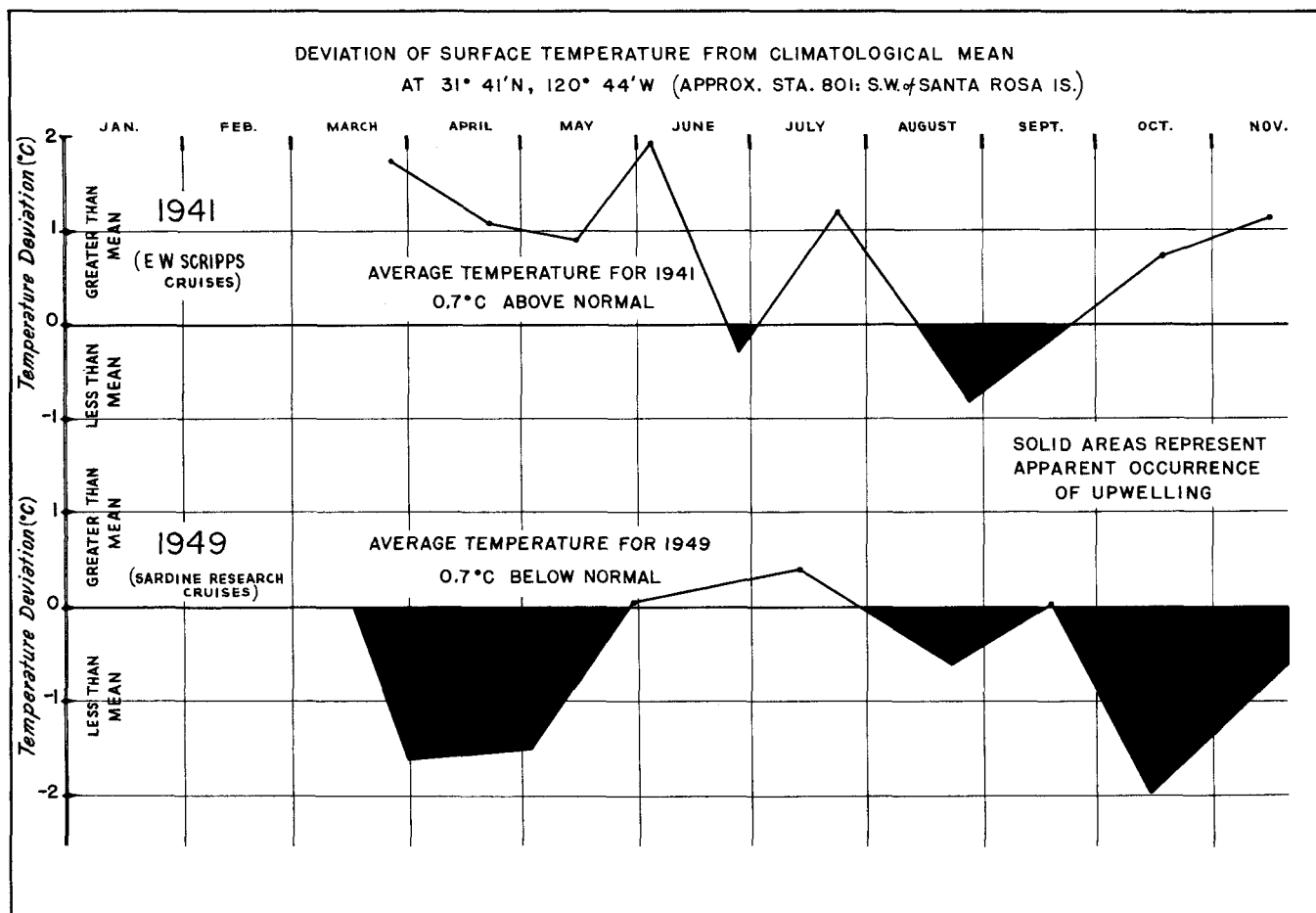


FIGURE 17. Apparent occurrence of upwelling in 1941 and 1949 at Station 801. Station 801 (old system of numbering) lay to the south of Point Conception, at approximately the location of the present Station 83.55. There are 659 surface temperature observations, ranging over several years, available for the area. The deviation of the surface temperature from the climatological mean shows that during 1941, when the average temperature was above normal, upwelling probably occurred briefly in June and during August and September. In 1949, when the average temperature was below normal, upwelling apparently occurred during March, April, May, and again from the first part of August through November.

During upwelling, the northerly winds push the surface waters away from the coast and cause the deeper waters from below to rise up to replace the warmer, lighter water. The result is not only that nutrients are brought up but also that the surface of the sea is lowered in the region of upwelling, owing to the greater density of the water which ascends. The actual lowering of the sea level is slight—usually not much more than 10 inches—but it is enough to cause the currents offshore to increase towards the south and even at times to reverse from north-flowing to south-flowing currents. All this evidence is in accord with theoretical considerations.

The currents induced by upwelling disperse the nutrients they have brought from depths and disperse also the minute plants and the sardine larvae. When the flow is directed towards the south, conditions are presumably right for spawning, for not only does the nutrient material come to the surface, thus facilitating the production of marine plants, but also these plants are swept into regions where temperature conditions are right for spawning (Fig. 19).

Mixing

Upwelling is not the only means by which nutrients can be replenished. The overturning, or mixing, of surface waters through the action of the winds may effectively keep the dead organic matter in the euphotic zone long enough for it to become converted into nutrient material. Mixing undoubtedly plays a part, though perhaps a slight one, in the process of enrichment. (The variability in abundance and productivity of the marine plants is more than can be explained by the variability in mixing.)

Evaporation

Another method by which nutrients ascend, and one which must play a considerable role off the California coast because of our unique geographical features, is by the action of evaporation. When excessive evaporation occurs over the sea, the water vapor takes with it to the atmosphere a large amount of heat in the form of latent heat of vaporization. A cooling of the surface waters and an increase in salinity are thereby brought about. Both cooling and the increase in salinity

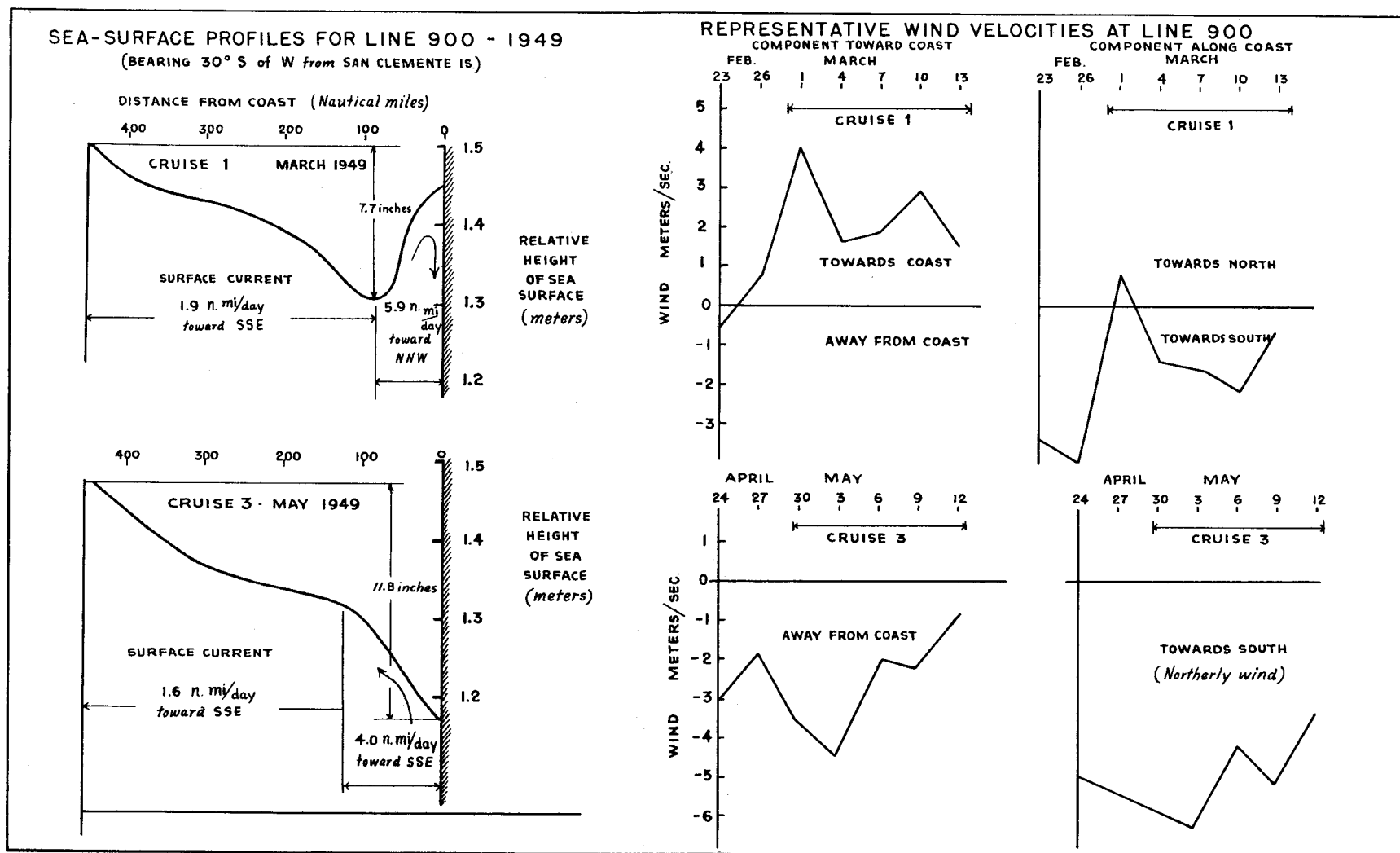


FIGURE 18. Sea-surface profiles and wind conditions at line 900, Cruises 1 and 3. During upwelling, northerly winds push the surface waters away from the coast. The deeper waters below rise and replace the warmer, lighter water. Note the lowering of the sea surface on Cruise 3, when there were strong northerly winds.

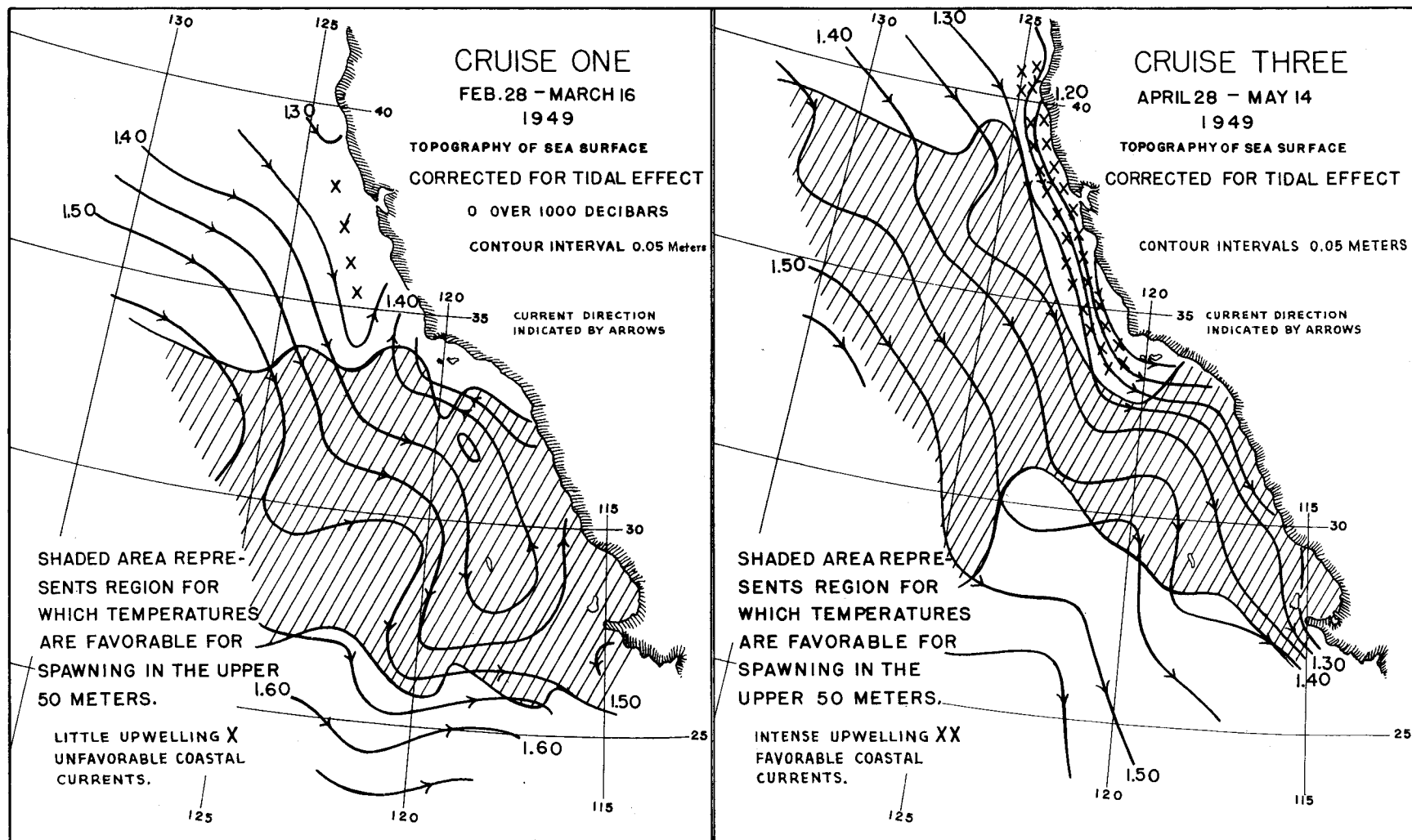


FIGURE 19. Currents induced by upwelling. (LEFT) On the first cruise, when there was no apparent upwelling, there was only a weak north-flowing current in the cooler water. (RIGHT) On the third cruise, when upwelling was apparently taking place, there was a strong south-flowing current in the cooler water. It has been induced by upwelling close to shore. Such currents sweep nutrients, plants and larvae into areas where temperature conditions are favorable for spawning.

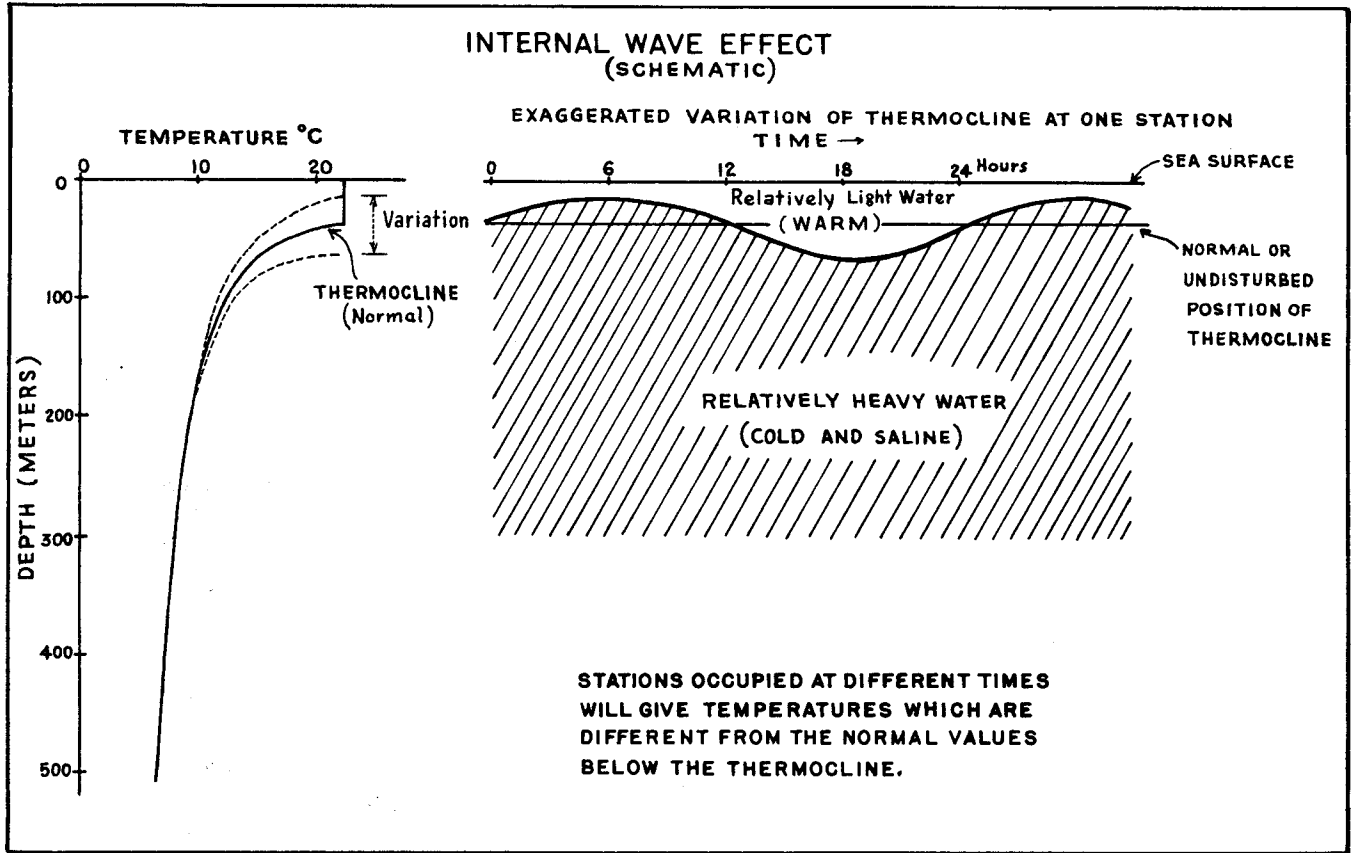


FIGURE 20. Schematic diagram of the internal wave effect. The depth of the thermocline (the region in which the temperature change is most pronounced) varies with time.

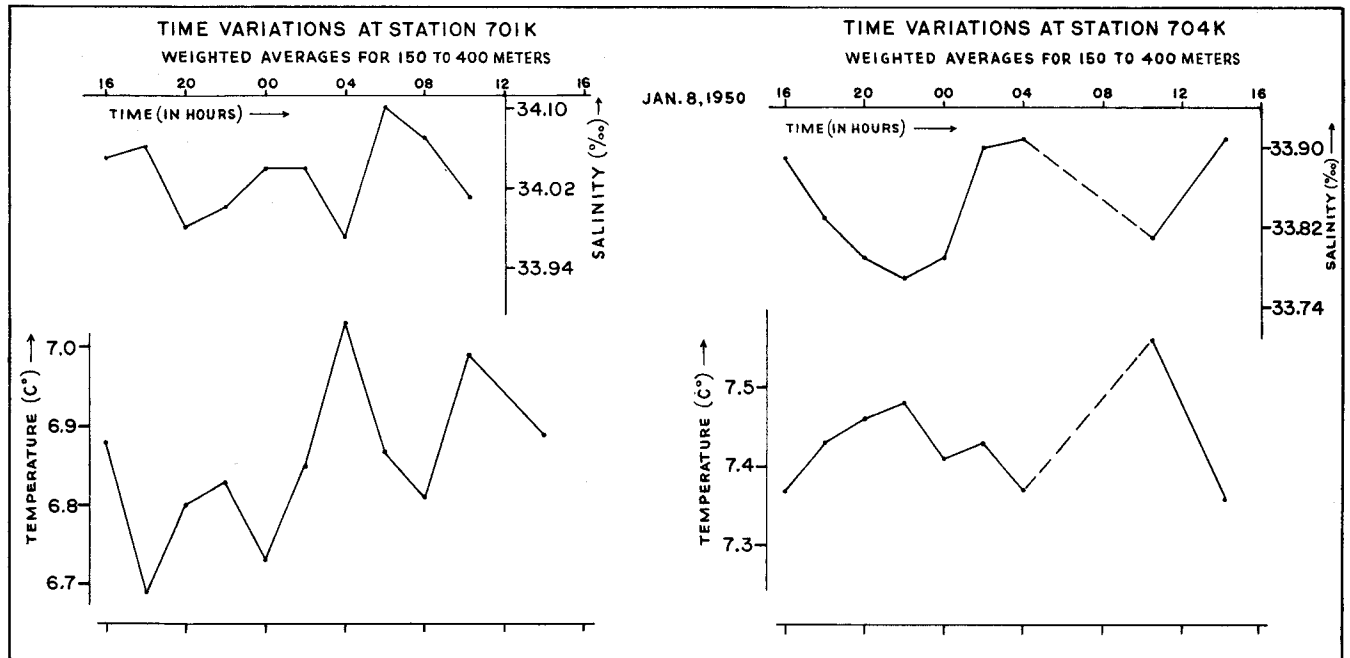


FIGURE 21. Time variations in salinity and temperature at fixed hydrographic stations. Note the decided differences in the two sets of curves at 0400.

work to increase the density near the surface and thus cause the water to become unstable. As a result, vertical convection cells are set up that extend down to and even below the lower limit of the euphotic zone. As the surface water sinks, deeper water must ascend to take its place. The water in the surface layers becomes thoroughly mixed and is replenished to some extent with nutrients from below.

The conditions for such large-scale evaporation as would bring about a significant increase in nutrients are provided by either strong winds or dry air (or both). The coming of Santa Ana winds in Southern California, occurring during the fall, presents optimum conditions. Santa Anas occur when the Pacific high extends into California and Nevada and stagnates. Very warm, very dry air is blown out towards the coast and to sea. The presence of large-scale evaporation is evidenced by the onset of fog all along the coast region following the Santa Ana regime.

Internal waves

Another mechanism which might be responsible for the mixing of coastal waters is the action of internal waves (Fig. 20). These waves are extremely high (sometimes 50 feet or more). Since they are present below the surface, they are unobservable by eye from a ship. They occur at the interface between layers of different densities. Such an interface can be identified as the depth of maximum temperature change (thermocline). To some extent, internal waves occur in all oceanic regions. They have been observed by making serial measurements of temperature and salinity at fixed hydrographic stations. Figure 21 shows the results of such data, as taken on Cruise 10 at two stations north of Point Conception. In the Mediterranean, internal waves have been observed to break in shallow water very much as ordinary surface waves do. The breaking is accompanied by an overturning and mixing of the subsurface waters, and consequent lifting of some nutrients to the surface layer.

If the sea were a static environment the dead organic matter would sink out, the oxygen of the deeper water would become virtually exhausted, and since small amounts of nutrients would be produced by aerobic bacteria, much less would be brought back to the surface; the present type of life in the sea would be at a minimum. When the sea tends toward such a static condition, when it "slows down," life in the sea slows down as well, although there may be a large time-lag in the response of the living creatures to their environment. This natural lag would be a rather critical thing if it were about the same as the time between successive regimes of full replenishment, such as by upwelling or other intermittent phenomena.

Delineation of spawning areas

The physical data collected on the sardine research cruises provide the answer to such questions as the

frequency of upwelling, extent and amount of replenishment. Because sardine spawning occurs within relatively narrow temperature limits, the data can also be used to delineate areas where spawning might take place. In the end, it should be possible to estimate from the weather data of a previous year, together with supplementary oceanographic data, what the total bulk of nutrient replenishment has been as well as the frequency of its occurrence. Then from a knowledge of the nutrients' effectiveness on production of organic matter (which enables larvae to live) one phase of the success of spawning can be dealt with on a rational, measurable basis. However, the very important factors of mortality by predation or by disease will have to be considered jointly with the question of food supply.

Problems of processing

The problems that have been encountered in the work of adequately describing the physical environment should not go unmentioned. First, there is the problem of obtaining sufficiently accurate data on temperature and depths. Much time and effort have gone into this. Second, there is the problem of setting up a smooth, efficient scheme for recording and processing all data, and making final plots of temperature, salinity, and current charts. Third, there is the problem of checking the calculations of currents from the dynamic topography of the sea surface; trajectory studies, using specially designed equipment, are being carried on for this purpose. Fourth, there is the problem of eliminating from the data the confusing effects of internal waves. It has been found in the oceanographic work that because the stations were occupied at different phases of the internal waves, large eddies in the current pattern were apparent. These eddies have no real, physical existence in the sea; they must be eliminated before any sense can be made from the data.

These and other problems in the processing techniques have been solved to some satisfaction. But it is important to remember that even with the greater efficiency of the present techniques of processing, the data collected from a single year's cruises are far in excess of those taken by any other oceanographic expedition. The *Carnegie* occupied more than 160 hydrographic stations in both the Atlantic and Pacific during a single year. It was about a decade before the data could be published. The three ships usually employed on the present program occupy more than 120 stations in two weeks. So far about 1,200 stations have been occupied each year. At each station there are 15 levels of observation. The first year's physical and chemical data have already been issued in mimeographed form to the interested agencies.

Much of the time spent to date in the physical oceanographic program has been devoted to processing. It is naturally expected that additional time will be necessary in order to analyze these data thoroughly and correlate them with the biological data.

Chemical Oceanography

The chemical studies under the sardine research program are concerned with an investigation of variations in the distribution of nonconservative chemical constituents of sea water and their relation to physical processes as well as to the distribution of phyto- and zooplankton. On all cruises routine measurements are made of chlorinity, dissolved oxygen, and inorganic phosphorus.

Dissolved inorganic nutrient salts, such as phosphate, can be considered the first link in the food chain—nutrients, phytoplankton, zooplankton, fish, man—and a study of their distribution is a study of the supply of food available to phytoplankton, the primary producers of organic matter in the sea. Dissolved oxygen is another useful chemical parameter, being produced during photosynthesis and consumed during respiration and oxidation of decaying organic matter. As oxygen is consumed, nutrient salts are released to become again available for use. Chlorinity data are essential to the calculation of density, and hence to the dynamic computation of currents.

Because of the great numbers of analyses to be run, a great deal of time and thought have gone into the improvement of these methods, both to increase accuracy and to increase the rapidity of analysis. An improved setup for manual titration of chlorinities has been designed, and the development of an automatic chlorinity titrator has been pushed. The method for oxygen determination has been streamlined, so that all of the samples collected on a station can be analyzed in less than an hour.

Existing methods for phosphate analysis were found to be unsatisfactory. A study of the method showed that reagent concentrations had to be changed, the time between addition of reagents and reading carefully controlled, and temperatures of samples and standards measured. Automatic reagent dispensers were developed for the careful measurement of small volumes of reagents at sea. A new seagoing photoelectric colorimeter, simple and accurate in operation, was developed. Duplicate phosphate samples from all depths on a station can now be run in less than an hour.

The pressure of routine processing of cruise data has forced interpretation of the data to play a secondary role. Charts of the horizontal distribution of oxygen and phosphate are being prepared, and a few studies of the data have been made.

Recently work has been done on the "high-oxygen" layer. This layer was arbitrarily defined as the greatest depth at which oxygen saturation is 90 percent or greater if shallower than 75 meters, or 80 percent or greater if deeper than 75 meters. Topography of the surface of 80 percent saturation would be equally useful and requires fewer calculations. Topographies of the bottom of the high-oxygen layer were plotted for the six cruises of *E. W. Scripps* in 1938 and compared

with the dynamic topographies. These data show that a deep high-oxygen layer is associated with clockwise circulation, or convergence, and a shallow high-oxygen layer with counterclockwise circulation, or divergence. Thus the depth of this layer is a useful indication of the location and extent of divergences and convergences. The presence of a shallow high-oxygen layer is a more reliable criterion for upwelling than is the presence of a low dissolved oxygen content at a fixed depth.

Correlation of the logarithm of average diatom count with depth of the high-oxygen layer yielded a low but significant negative correlation. In general, low diatom counts were associated with deep layers and high diatom counts with shallow layers, probably owing to the mechanical effect of vertical circulation on the vertical distribution of phytoplankton.

Another study of *E. W. Scripps* data showed no correlation between diatom counts and surface oxygen content. Counts of diatoms retained by a silk net give a poor estimate of the effective phytoplankton crop. Furthermore, other processes controlling the distribution of oxygen are superimposed on the effect of photosynthesis and tend to obscure any apparent relationship.

Under way at present are studies of the effect of internal waves and of the wind and evaporation on stirring in the euphotic zone. An explanation for the observed variations in distribution of deep phosphate is being sought. An attempt is being made to relate distributions of chemical factors with those of physical and biological factors, so that an understanding of the interrelationship of physical, chemical, and biological processes can be gained.

Additional studies of analytical methods are being made. A wet-ash method for determination of carbon has been developed; it is hoped to establish the relationship between measured chlorophyll content of phytoplankton in this region and their content of organic matter, as indicated by carbon.

Although the rates of utilization and regeneration of nitrate may be quite different from those of phosphate, nitrate analyses are made only infrequently because of the difficulty of the present method. A study of an improved method has been started. A study is also being made of methods for determination of hydrogen ion concentration. Some measurements of silicate distribution have been made, and more silicates will be run if the data prove to be useful.

Biological Oceanography

Marine botany

Phytoplankton, the floating plant life of the sea, is measured in an effort to determine what and how much there is available for creatures of the sea to eat, and how these organisms vary throughout the season and from year to year. And since phytoplankton makes new organic matter, it is measured so that some estimate

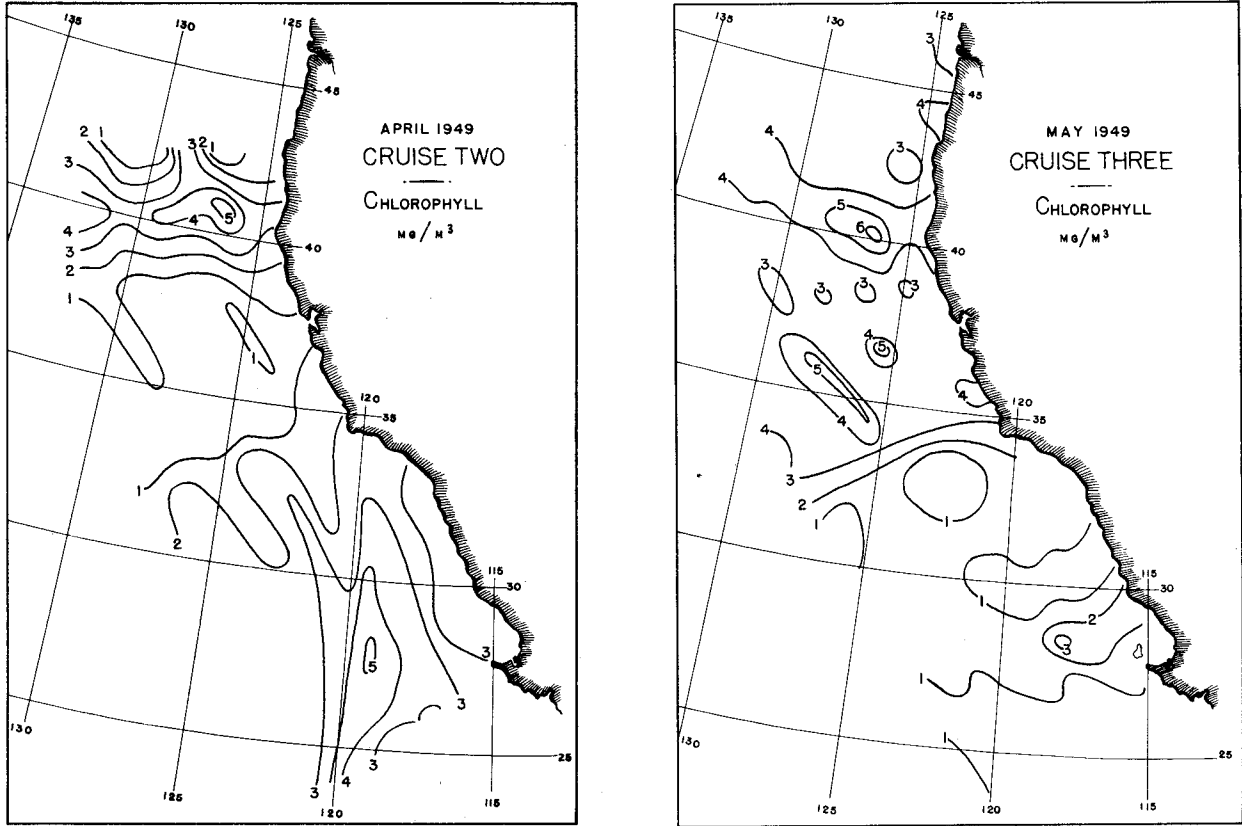


FIGURE 22. Distribution of chlorophyll, April and May, 1949.

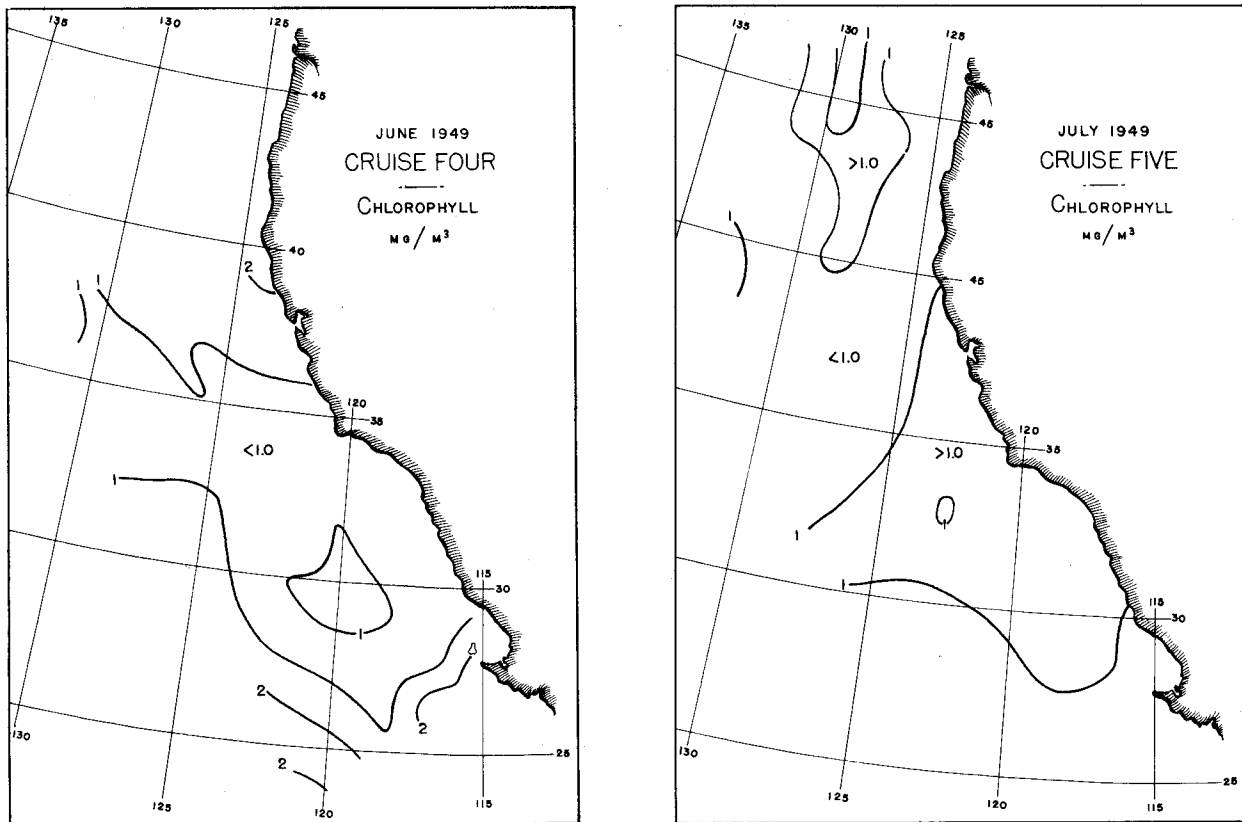


FIGURE 23. Distribution of chlorophyll, June and July, 1949.

can be made of the amount of machinery for the production of organic matter. A difficulty crops up here; different types of phytoplankton have different rates of production of organic matter. Chlorophyll is the likeliest factor by which the production of new organic matter can be measured, but the rate of chlorophyll production is variable.

What can be measured at present are the numbers and kinds of living cells in a sample of sea water. It is hoped some day to measure the amount of organic matter present, but the possible methods are complicated.

The steps in measuring phytoplankton are, briefly, these:

(1) A measured quantity of sea water is filtered through a fine paper filter or centrifuged,

(2) The material collected is extracted with a solvent,

(3) The absorption of light in the solution is measured. With some qualifications and exceptions, we can use this final value as a measure of the amount of chlorophyll present in phytoplankton. Figures 22 to 24, inclusive, show the distribution of chlorophyll in the top 70 meters of the sea during Cruises 2 through 7, April through September, 1949.

Several features stand out on these charts. In the first place the stations are close enough together to give some indication of the topography of the distribution. Although earlier in the program we drew only generalized charts, we have more recently come to have some faith in the details. There are still too many contours based upon a single value, but the majority of the contours are related to each other in ways that indicate real features.

In 1949 the chlorophyll content, and hence the phytoplankton population, reached its highest over-all levels in April and May and in September. During each of these months chlorophyll concentrations of five to six or more milligrams per cubic meter occurred at some stations. Concentrations as high as three milligrams per cubic meter occurred at more than one-third of the stations occupied. During June and July no concentration as high as three milligrams per cubic meter occurred anywhere. During August, higher concentrations than this were found at only two stations. Seasonal cycles of phytoplankton populations with spring and fall maxima occur in many waters and have been observed locally at the Scripps pier for 30 years.

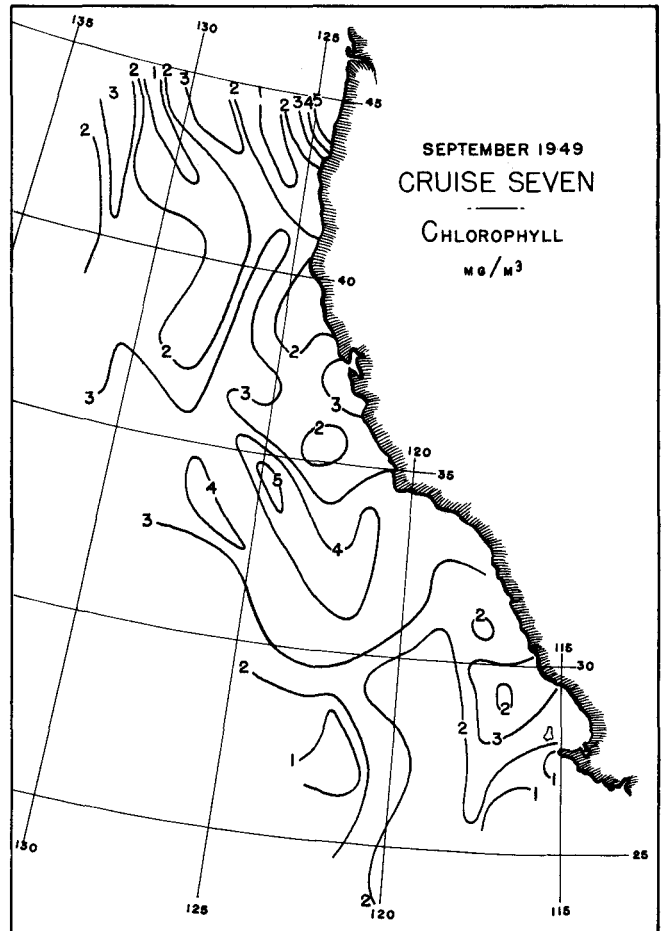
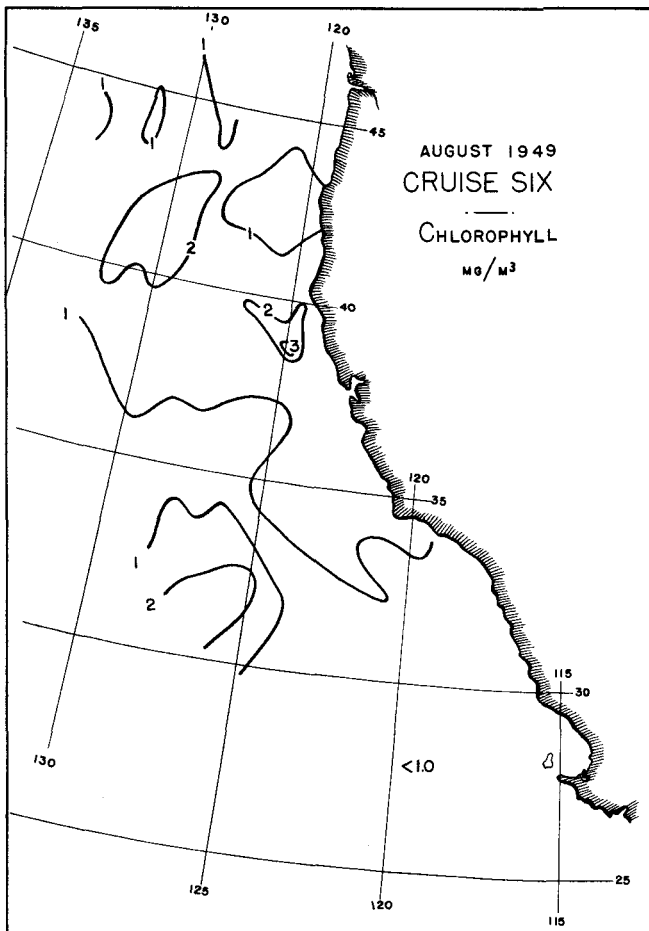


FIGURE 24. Distribution of chlorophyll, August and September, 1949.

The general population level, equivalent to nearly three milligrams per cubic meter of chlorophyll during the spring and fall cruises and little more than one milligram per cubic meter during the summer, is comparable with that on the high seas over large parts of the world. However, population levels equivalent to four or five times the highest chlorophyll content observed during the 1949 cruises (6.4 milligrams per cubic meter at station 404 in May) have been observed in other waters. There is good reason to believe that populations of this magnitude occur locally. Many of the largest populations observed in 1949 were at off-shore stations, and only a few (e.g., during May at Stations 201, 401, 402, and 701 and during September at Stations 201, 501, 1101, 1102, and 1103) at stations close to shore. Many earlier investigations along this coast have indicated that the largest populations are usually found close in. We believe therefore that although the station network is close enough for a general survey, detailed studies of some small areas may uncover centers of large phytoplankton populations which could be critical for an understanding of the sardine problem.

Another conspicuous characteristic of the 1949 situation is that there seem to be at least three different centers of population. In the whole area north of the latitude of Cape Mendocino, the chlorophyll concentration was relatively high during all the cruises. Far to the south, in the neighborhood of Guadalupe Island, there were relatively large populations during most cruises. In between these is an area west of Point Conception in which very large populations occurred during May and September.

Marine invertebrate plankton

In order better to understand the biological environment of the sardine and other fishes, especially those with planktonic eggs and larvae, the Scripps Institution is engaged in a study of the invertebrates collected with the fish eggs and larvae in the net samples.

The task of analyzing the plankton qualitatively to determine the relative importance of the myriads of constituents progresses only slowly. The samples currently being collected, together with past collections along the coast, are providing a picture of the occurrence of species that are believed to be important for reasons of their (1) abundance, and, therefore, significance in the life of the sardine and general biological economy of the coastal area; (2) probable use as indicators of degree and pattern of dispersal of free-living floating life; (3) fluctuations in geographic range of species shown to be characteristic of either the southern or northern sections of the coast, or of inshore or off-shore situations. Any marked increase in southern species to the north or northern species to the south can be an indication of the relative strength of the

prevailing water currents or movement of water masses off our coast.

Crustacean plankton—In the samples examined, copepods are usually overwhelmingly dominant numerically and usually also in bulk. They, together with the euphausiids, form most of the more "substantial" plankton and will accordingly be given a great deal of attention in the analysis of the plankton.

Especially significant because of their abundance or because of characteristic geographic range are the following species of copepods:

Acartia clausi—inshore

Acartia danae—offshore

Calanus finmarchicus—abundant over whole range, but less frequent at far offshore stations

Calanus minor—moderately abundant in the southern range

Calanus tonsus and *C. cristatus*—sometimes exceedingly abundant in northern sections and extending southward to latitude of about Point Conception

Candacia spp.—on the basis of earlier collection some of the six or more species show a restricted range, but more study is needed to determine the relationships

Eucalanus bungii californicus—abundant over the whole of the southern range, but diminishing noticeably along the coast in north

Eucalanus bungii bungii—abundant in the north, but diminishing towards the south where it is apparently completely replaced by the southern variety off the Southern California coast

Metridia lucens—sometimes abundant

Other genera of large calanoids that occur in sufficient numbers to enter the routine counts of aliquot samples of each haul include especially *Euchirella* (six species), *Scolecithrix*, and *Centropages*.

There are many characteristically deep-water species (especially of the genus *Pleuromamma*), some of which are numerous in night hauls. These await further analysis together with the deep-water samples being taken on the more recent cruises.

The small copepods are being studied from separate hauls which have thus far been taken only at pattern II stations. They include a large array of microcalanids, and among the cyclopoids especially the genera *Oithona*, *Oncea*, and *Corycaeus*.

These microcopepods (especially *Oithona*), their larvae, and the larvae of larger species must be highly important in the diet of the sardine larva following absorption of the yolk sac.

Charts that are being prepared for copepod distribution show a varying degree of southward extension of typically northern forms offshore to the regions of about San Francisco to Point Conception or a little

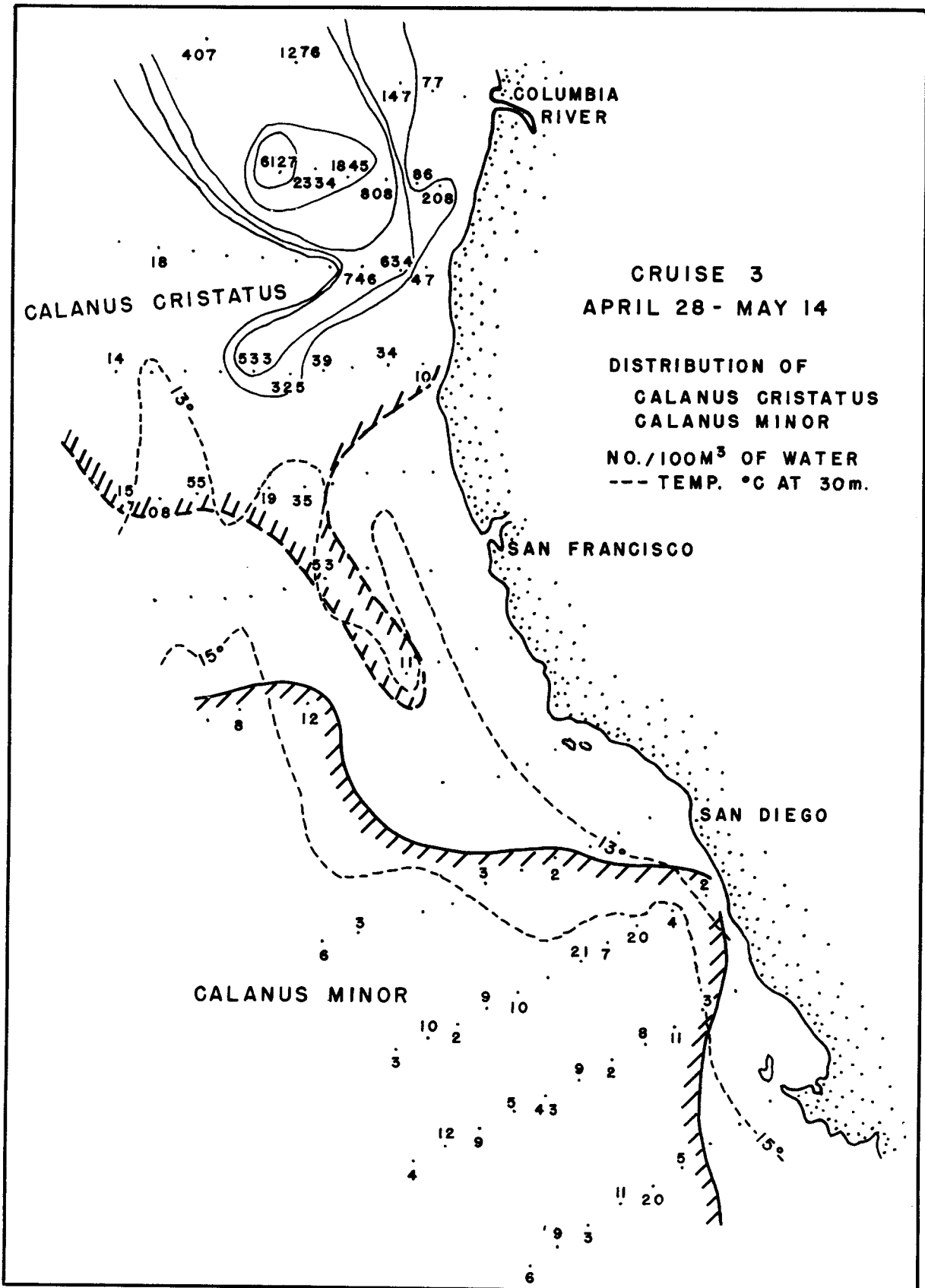


FIGURE 25. Distribution of *Calanus cristatus* and *Calanus minor* on Cruise 3. The 13° and 15° C. isotherms in general follow the northern and southern lines of distribution.

farther south. There is also some indication that as the season progresses there is a gradual "retreat" northward or that deeper water is sought below the relatively shallow range of the nets. The typically southern species, for example *Calanus minor* or *Mecynocera clausi*, have their greatest northward extension in the offshore waters.

In Figure 25 is given an example of the distribution of two species of copepods with geographical ranges that are characteristic of several other species. The numbers given at each station are based on aliquot samples of the total catch at the station and therefore represent the areas of principal population density. A more detailed examination of the total catch shows a considerable overlapping of the populations by stragglers of *Calanus cristatus* to the south and *Calanus minor* to the north. The line of greatest demarcation between northern and southern forms appears to fall most noticeably between the 13° and 15° C. isotherms at a depth of 30 meters.

From a study of the euphausiids, it appears that *Euphausia pacifica*, a north temperate neritic species, is the numerically dominant species and is important because of its abundance in the plankton community. There are in the area about 17 other species in seven genera. Some of these are mainly deep-water forms which are probably only night-time visitors to the surface stratum sampled by the regular hauls. The following tentative list includes the more outstanding examples of species thus far appearing to be either southern or northern in geographical range in the area under survey:

Thysanopoda aequalis—southern, oceanic form—straggler

Euphausia eximia—entirely southern, mainly oceanic—promises to be a good indicator of southern water

E. gibba—straggler from southern waters

E. hemigibba—southern, oceanic form

Thysanoessa longipes—rare straggler from northern waters—possibly very good indicator

T. gregaria—bipolar form, found at greater depths in the tropics—15.5° C. is apparently the upper limit of thermal tolerance.

The season of recruitment of the more abundant species is being considered through study of the occurrence of larval and juvenile stages.

The enumeration and plotting of the geographic range of the more abundant euphausiid species suggests a region of overlapping or division of ranges between northern and southern species in the area between the 14° C. and 15° C. isotherms at 30 meters depth.

The biology of several other invertebrate groups is being considered in more or less detail. Among these

are included especially the amphipods, chaetognaths and zoea larva of sand crabs.

Fifty-seven species of pelagic amphipods have been identified. The frequency of occurrence and numerical abundance of many of these are too limited to allow conclusions relative to their distribution. The genus *Parathemisto* appears to be the dominant amphipod wherever it occurs. It may reach considerable numbers and its predacious habit makes it important in the plankton community.

Dispersal by water currents—The degree of dispersal of fish eggs and larvae together with other planktonic organisms is difficult to determine. In an attempt to obtain evidence along this line, a special study is being made on the horizontal distribution of the planktonic zoea larvae of the sand crab *Emerita analoga*. The adults of *Emerita* live intertidally from whence the larvae must originate. The plankton hauls taken during the present and the 1940-41 cruises off Southern California demonstrate a surprisingly wide dispersal of the larvae in offshore waters to distances of about 200 miles seaward. This can be illustrated by reference to cruises 10, 11, and 12 of 1940 when respectively 73, 78, and 74 percent of the stations yielded *Emerita* larvae, a few occurring at the outermost stations of the lines and in numbers ranging up to 150 per standard haul at more coastal stations.

This study may provide useful information on the degree of dispersal that can occur and on the extent of lateral water mixing and type of flow.

Plankton volumes—Measurements of the displacement volume of zooplankton (after the larger forms such as jellyfish, salps, etc., have been removed) were made for each station by the U. S. Fish and Wildlife Service. As mentioned earlier, a qualitative study of these data usually shows a preponderance of copepods and euphausiids. Thus far no attempt has been made to evaluate the contribution to the volume of the more watery forms such as chaetognaths and the small salps, siphonophores and medusae.

In Figure 26 is given the distribution of displacement volume adjusted to 1,000 cubic meters of water filtered by the 1.0-meter net towed obliquely in steps from 70 meters to the surface. It is seen that the volume of plankton in the northern sections of the survey tend to be well above the average for the whole area, while those in the southern section are quite consistently below average. In both northern and southern areas there is a general decrease in volume at the stations situated at the outer (seaward) ends of the lines. While it is possible to discern major areas of greater or lesser plankton concentrations, still there is within these areas a great deal of patchiness. Night hauls are usually more voluminous than day hauls in the same areas owing to upward migration of some forms to the surface at night. Data from deeper hauls might change the picture but it is believed that the

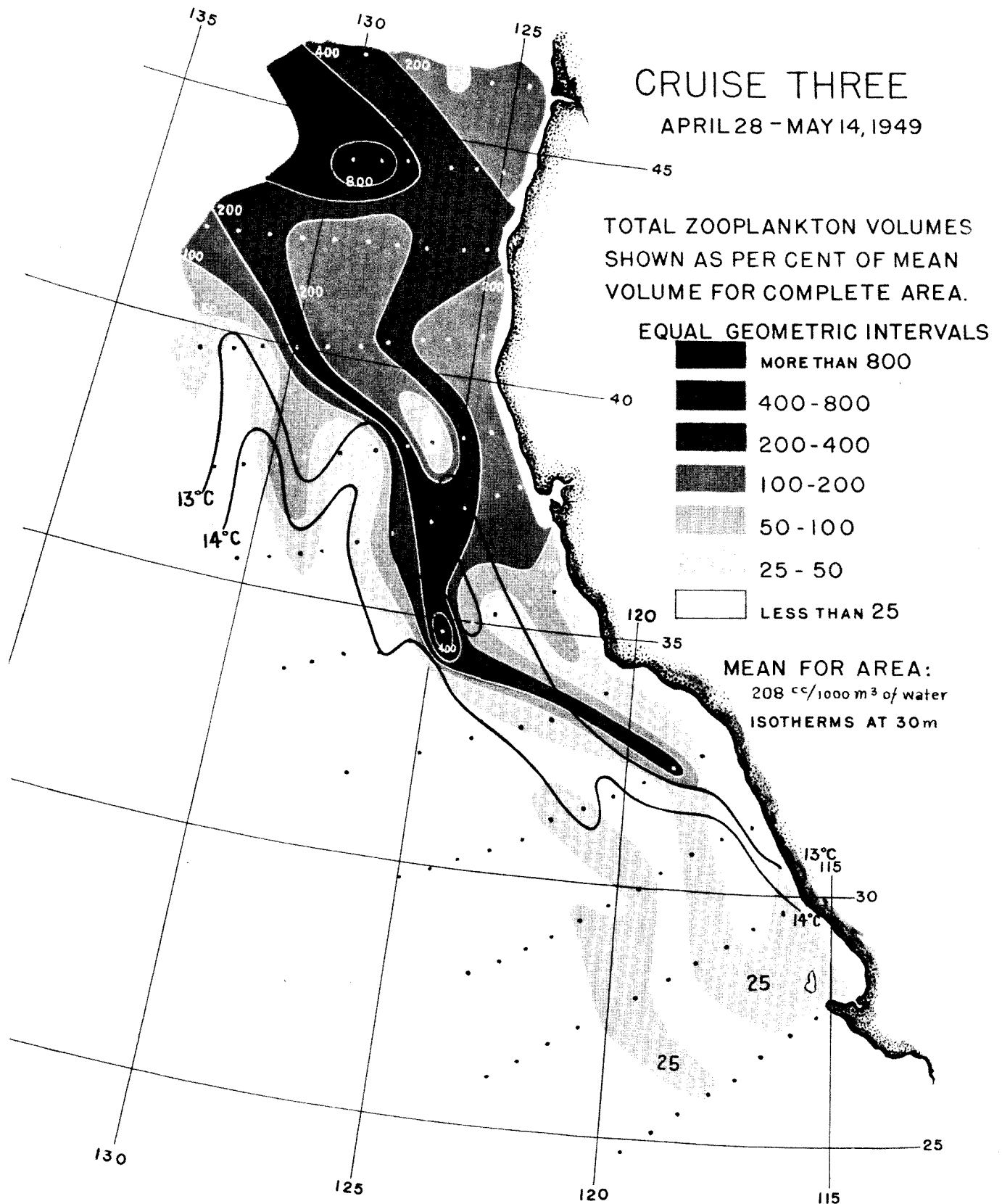


FIGURE 26. Total zooplankton volumes shown as percent of mean volume for complete area. The volume of plankton in the northern sections of the survey area tend to be well above the average for the whole area; those in the southern section are quite consistently below average. In both areas there is a general decrease in volume at the stations at the seaward ends of the lines.

figure given depicts rather well the plankton population in which the sardine must live by day and by night, provided these fish do not normally go below the depth of the hauls taken during the daylight hours.

RECRUITMENT RESEARCH

An important phase of investigation in the program is directed toward determining the factors underlying the success or failure of year classes of sardines. A solution to this problem is a prerequisite if we are to attain one of our primary goals—the prediction of the strength of year classes in advance of their entry into the commercial fishery. The investigation of sardine recruitment is primarily the responsibility of the U. S. Fish and Wildlife Service.

The immediate objectives of the recruitment research are: (1) the determination of the extent and time of sardine spawning; (2) the determination of the amount of spawning, i.e., the number of eggs spawned, and, as a corollary, the estimation of the size of the spawning population; (3) the determination of the rate of survival of the young fish; and (4) the correlation of all of the above with environmental conditions—physical, chemical, and biological.

Given enough data, it should be possible to predict year-class strength one to two years in advance of the time the year class would be of importance in the commercial fishery. But, as has been emphasized re-

peatedly, prediction is a long-range objective. Its attainment will require: (1) intense coverage during the spawning season of the whole spawning area of the sardine, and (2) such coverage over a sufficient period of years so that a norm can be established.

Sardine eggs are spawned in the open sea near the surface, and the young sardines after hatching remain in the upper water layers (usually above 50 meters). They can be sampled quantitatively by using very fine-meshed silk nets. Occurring with the sardine eggs and larvae in the plankton collections are the eggs and larvae of other fish, as well as many kinds of small animals. The collections are analyzed at the laboratory on Point Loma, where the fish eggs and larvae are first separated from the other constituents of the plankton and then are identified and enumerated. The sardine larvae are measured to determine the number of larvae of successive stages present in each collection. The sardine eggs are separated into the several days' spawning present in each sample. The development of the egg to the post-larval stages is shown in Fig. 27.

The first task has been to find out where and when the sardines spawn. This must be known if we are to estimate either the amount of spawning or the survival rate of the young sardines. Investigations during the 1949 and 1950 spawning seasons have shown that there are, at present, two major areas of sardine spawning: a compact area of intense spawning around and to the south of Cedros Island, central Baja California, and a much larger area of diffuse spawning off Southern California and adjacent northern Baja California. In the waters separating these two spawning centers very little spawning has been encountered during either season, and this little has been confined to a coastal strip.

The 1950 Sardine Spawning Season

The times of occurrence of sardine spawning in different parts of the spawning area have been quite similar during the two seasons covered by survey work. At the beginning of each season, sardine spawning has been confined to the southern portion of the area being surveyed, then has gradually progressed northward as the spawning season advanced. This can be illustrated by following the distribution of spawning month by month during the 1950 season.

FEBRUARY: On this, the first cruise of the 1950 season, sardine spawning was confined to the southern portion of the survey area, around and to the south of Cedros Island (Fig. 28).

MARCH: Although still confined to Baja California, spawning was found to extend somewhat farther north (Fig. 29).

APRIL: The most intense spawning of the season was encountered during this month (Fig. 30). The spawning extended as far north as Southern California, occurring in a coastal belt about 520 miles long and 100 miles wide. During this month spawning was especially intense off central Baja California.

MAY: Although fewer sardine eggs were taken in May than during the previous month, the abundance of sardine larvae reached its peak during this month. The larvae

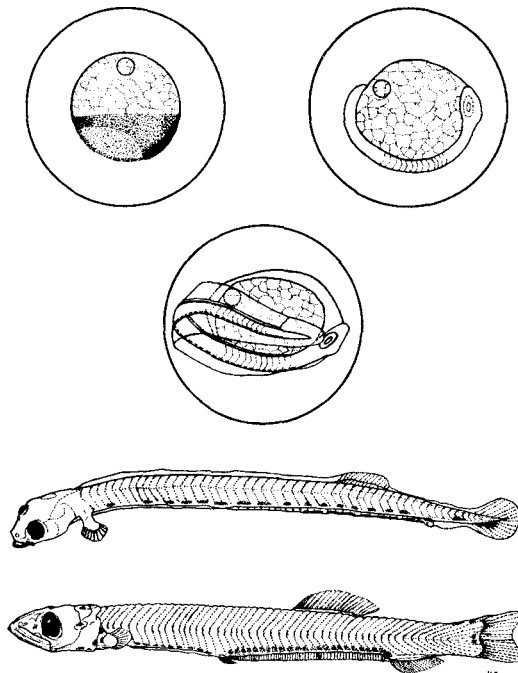


FIGURE 27. Successive stages in the life of the sardine. (UPPER LEFT) The egg 12 to 18 hours after spawning. (UPPER RIGHT) The egg about a day and one-half after spawning, midway between spawning and hatching. (CENTER) The egg just before hatching. The yolk sac remains attached to the larva and is absorbed as food. (LOWER) Postlarval sardines. The upper of these sardines is about 10 mm. long, the lower about 25 mm. long. In these stages, it is impossible to determine their ages with any exactitude.

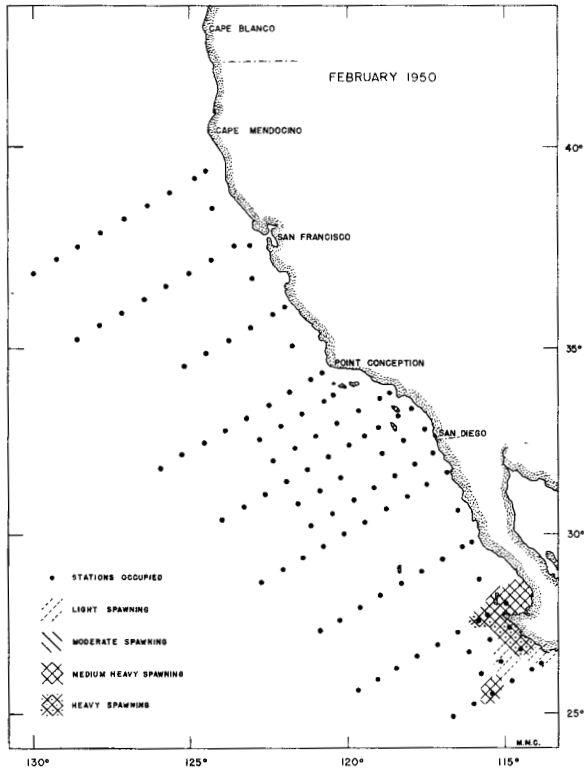


FIGURE 28. Spawning in February, 1950. Spawning was confined to the southern portion of the survey area, around and to the south of Cedros Island.

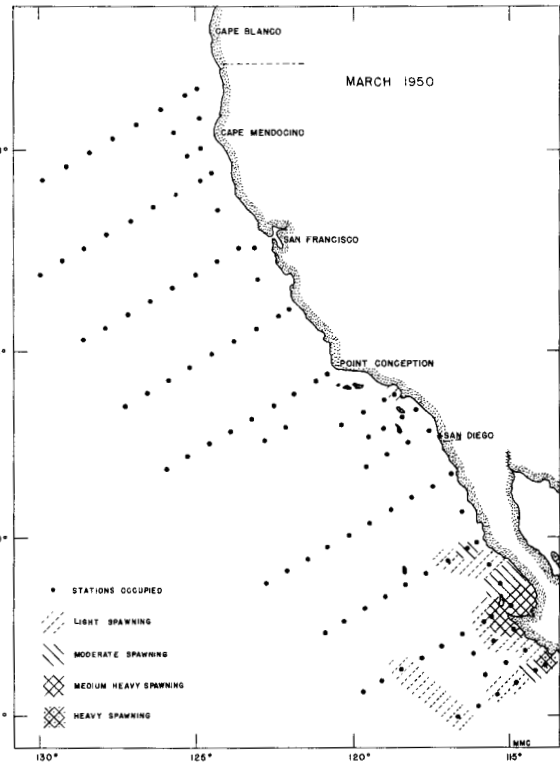


FIGURE 29. Spawning in March, 1950. Although still confined to Baja California, spawning was spreading northward.

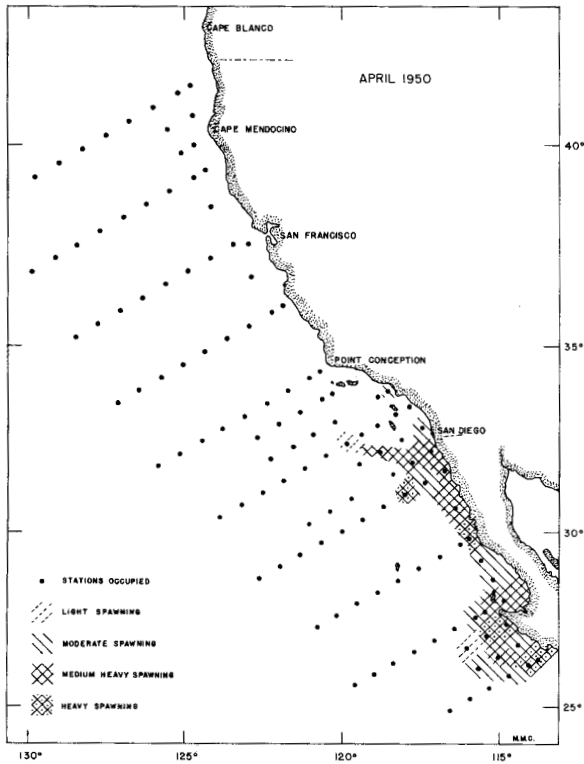


FIGURE 30. Spawning in April, 1950. The most intense spawning of the season was encountered during this month. Spawning extended as far north as Southern California; it was particularly heavy off Baja California.

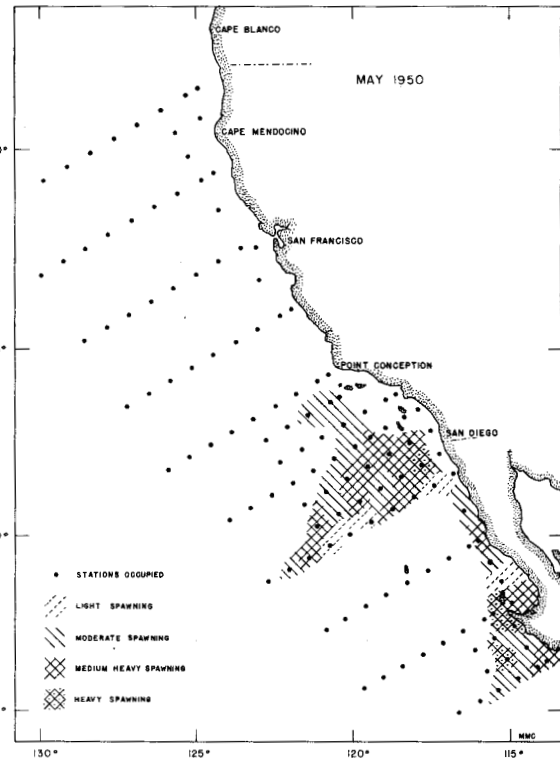


FIGURE 31. Spawning in May, 1950. Fewer sardine eggs were taken, but sardine larvae were at their peak abundance in this month.

were abundant in both centers of spawning. Off Southern California and adjacent Baja California the larvae were found over an extensive area, occurring as far seaward as 330 miles on one line of stations (Fig. 31). No evidence of spawning was encountered to the north of Point Conception.

JUNE: Spawning had progressed farther northward during June, occurring off San Francisco (Fig. 32). However the spawning to the north of Point Conception, although rather wide in extent, was very small in amount. The Cedros area, for the first time during the season, had fewer eggs or larvae per collection than elsewhere. The collections in the Southern California area still showed moderately heavy spawning, although sardine larvae were more important in the collections than sardine eggs.

JULY: The collections taken during this month contain the tag end of the spawning (Fig. 33). Although sardine larvae occurred in collections from Cedros to off San Francisco, their abundance amounted to only 2 or 3 percent of the number taken during May.

AUGUST: The survey cruise extended as far north as the Columbia River. No evidence of sardine spawning was obtained off Oregon, and a negligible amount off California.

Relation of Sardine Spawning to Oceanographic Conditions

The sardine apparently seeks out water masses having favorable temperatures. During the 1949 survey all sardine eggs were taken in water of 13.3° to 16.2° C. This is a temperature range of less than three degrees. Our accumulated observations, made during a number

of spawning seasons, on the temperature of spawning show that this temperature range is somewhat too narrow: a more inclusive range would be 12.5° C. to 16.5° C. During the 1950 spawning season 98.4 percent of all sardine eggs sampled were taken within a 3½ degree temperature range, 12.5° to 16° C.

The northward progression of spawning during both the 1949 and the 1950 seasons was associated with the northward progression of favorable spawning temperatures, while the gradual elimination of spawning from the southern part of the spawning area coincided with the rise in temperature above the favorable range for spawning.

It is noteworthy that the two centers of heavy spawning previously discussed are in areas enriched by upwelled water. Upwelling appears to be important not only because of the nutrient enrichment associated with it, which increases the food supply available to the sardine larvae, but also because the temperature of upwelled water is likely to be favorable for spawning, especially in the warmer southern part of the spawning range.

The extent of the two spawning centers appears to be influenced by the manner in which the upwelled water is dispersed by the currents in the two areas.

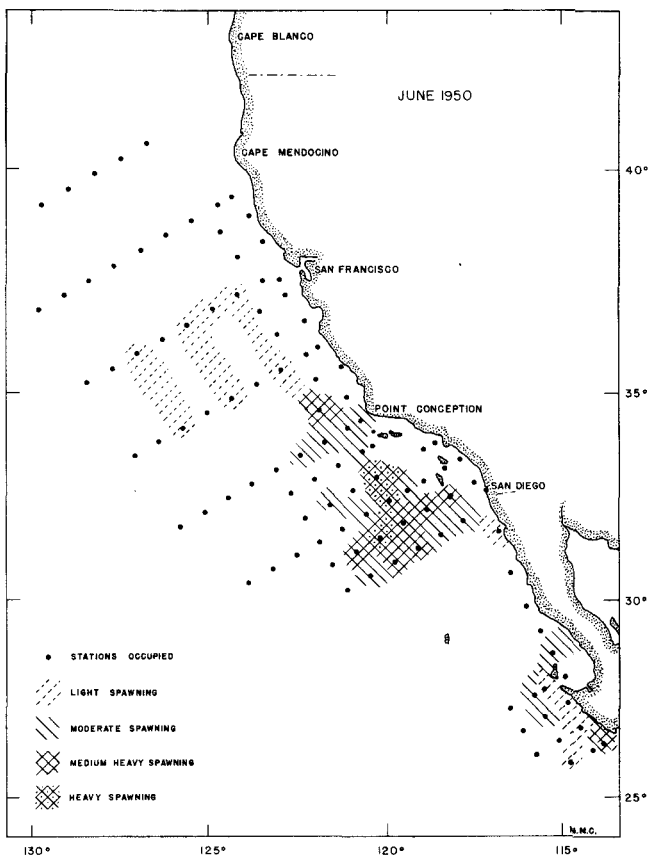


FIGURE 32. Spawning in June, 1950. Spawning had progressed to the north of Point Conception, although it was light there. For the first time in the season, the Cedros Island area had fewer eggs or larvae per collection than did other areas.

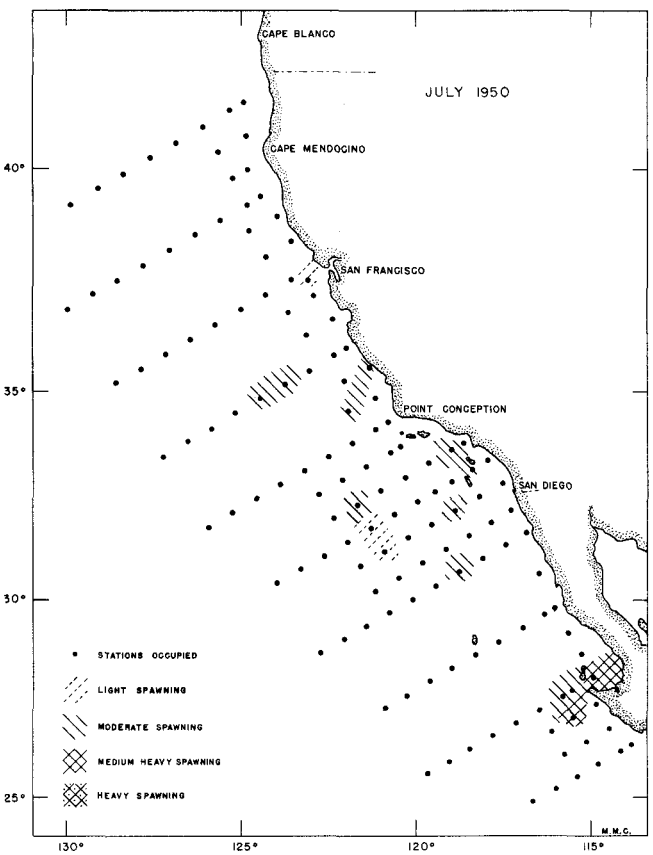


FIGURE 33. Spawning in July, 1950. Though spawning was widespread, the collections taken during this month contain the tag end of the season (only 2 or 3 percent of the number of eggs and larvae taken during May appeared in the collections).

Currents carrying upwelled water from above and around Point Conception sweep seaward in a broad area before bending inshore off Baja California. In this area spawning occurs offshore, mostly beyond the island area of Southern California, and may extend as far seaward as 300 miles or so. In the Cedros area, on the other hand, the currents are much closer to shore; as a result, spawning is concentrated within a coastal strip 60 or 80 miles wide.

From the data available for the 1949 and 1950 seasons, it is difficult to assess the success of spawning. For one thing, the coverage of the major spawning areas during the 1949 season was not intensive enough for an adequate determination of the amount of spawning. This fact was known and carefully considered when laying out the 1949 survey plan. However, before the areas of major spawning could be surveyed intensively, it was first necessary to determine their location, and this was achieved by the wide coverage of the 1949 survey. During the 1950 season a much more intensive coverage was made of the major spawning areas, while at the same time an extensive coverage was effected by shifting the survey northward as the spawning season progressed.

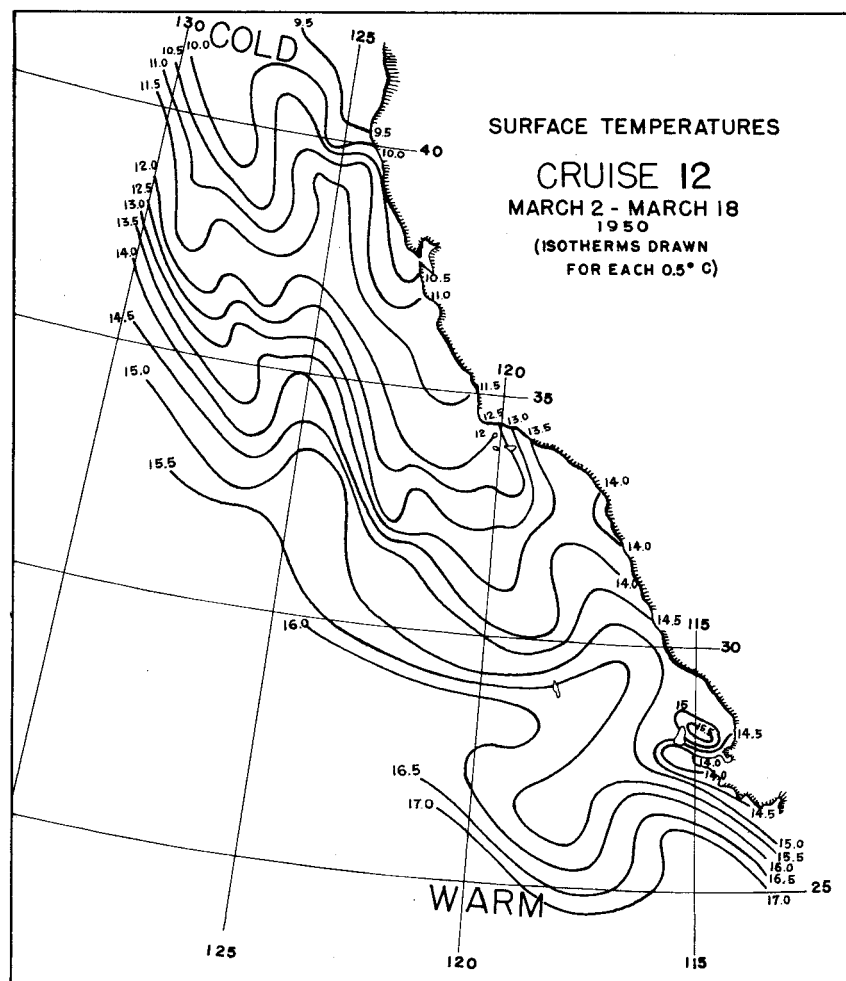
One difference between the two seasons that may have bearing on the success of the two spawnings will be noted. Water temperatures were lower during the 1950 season (Fig. 34), and it is likely that this was due, at least in part, to more intensive upwelling during the 1950 season. Walford¹ has presented evidence in support of the thesis that good year-class survival occurs during seasons when upwelling is more intense than usual. However, a few words of caution should be inserted at this point. We have not carried on our surveys over a long enough period to establish a norm for upwelling. Until this is done, any comparisons such as the one noted above must be tentative. For we still do not know whether the 1950 season was above average, average, or below average with respect to upwelling intensity.

WORK ON OTHER FISHES

There are two reasons why work on other fishes is an integral part of the cooperative sardine program: (1) many species compete with the sardine for available food and living space, while others prey upon

¹ Walford, Lionel A., 1946, *Correlation Between Fluctuations in Abundance of the Pacific Sardine (*Sardinops caerulea*) and Salinity of the Sea Water*, Journal of Marine Research, Vol. VI, No. 1, 31 December 1946, pp. 48-53.

FIGURE 34. Surface temperatures, Cruise 12, March, 1950. During the spring, surface temperatures were somewhat cooler than they were during the spring of 1949 (compare with Fig. 16, upper left). The decrease may have been due to more intense upwelling during the 1950 season.



the eggs and young of the sardine; (2) some of these fish may constitute fishery resources of considerable potential value. If the sardine catch were to remain very low, it might be possible to use the same equipment to catch and process some other species. As a matter of fact, the anchovy has been suggested for this purpose. A few are canned at present. No reduction has been permitted. Just after World War II there was a boom of sorts in the canning of squid—which is not a fish, of course—for export. However, there has been relatively little investigation of the abundance, availability, and possible uses of much of our marine food resources.

Some of the basic scientific work on fishes other than the sardine is now being undertaken, with special attention being paid to other herring-like fishes. This work is only partially supported by sardine funds. The studies are being made jointly by personnel of the Scripps Institution of Oceanography and of the U. S. Fish and Wildlife Service. The same scientists are also cooperating on a study of another food fish of proven importance, the albacore, dealing with the food of the species and the relation between catches and surface temperatures.

Young of Other Fishes Associated with the Sardine

Plankton hauls for sardine eggs and larvae also contain eggs and larvae of other fishes spawning in the area. These eggs and larvae are removed from the plankton collections along with those of the sardine and are identified and tabulated. Larval fishes often differ greatly from the adults. As the young of most species have never been described, study has been necessary in order to identify correctly the younger stages. Fortunately, we are now able to identify almost all fish larvae occurring in our collections.

Jack mackerel

Of considerable interest is the information, gathered incidentally to the sardine cruises, on the abundance and distribution of young jack mackerel. The spawning season is similar to that of the sardine, but the jack mackerel spawns over a large area. The larvae of the jack mackerel are exceedingly abundant, with the center of their distribution well offshore.

Anchovy

The anchovy is another species of considerable importance in our study, since it occurs in about the same localities as the sardine and seems equally as abundant. The anchovy spawns over a longer period than the sardine. Unlike the sardine, the anchovy larvae are fairly abundant over the whole north-south extent of the area being surveyed. This species constitutes one of our most important latent fishery resources.

Saury

Another species of exceptionally wide distribution is the saury. The species has been sampled at almost every station occupied, being attracted readily to a

light hung over the side of the vessels at night. However, the saury is not abundant in waters close to shore and less than 20 fathoms deep. The Japanese fish this species, landing a considerable tonnage. It is a fish of excellent quality, which might make a pack at least equal to or better than the sardine if methods can be developed for taking it in commercial quantities. Large numbers of these fish do, however, carry a parasitic copepod which may affect their utilization as food. The saury may also prove to be a desirable bait species. The occurrence of small young at all times of the year indicates that spawning is not restricted to a definite season, although variations in spawning intensity may occur in time and space. Some progress has been made in the determination of age and rate of growth. It would appear that growth in length is more rapid than in the sardine or anchovy.

Other food fishes

Space does not permit listing all of the species taken that are of present or potential importance to the commercial fishery. Although studies of these fishes are not being specifically undertaken under the sardine program, the presence of the young in the plankton hauls is, of course, noted. The hake is an example of a species abundant off our coast that is not considered particularly desirable as a food fish in our area, although related species are prized in other parts of the world. Rockfish larvae also occur in considerable numbers, and surprisingly enough are regularly taken as far as 300 miles at sea off Northern California.

Fodder fishes

Of less immediate interest to the fishery, but of fundamental importance in the economy of the sea are the "fodder" fishes, particularly the lantern fish and deep-sea smelts. Most of the larvae taken in the net hauls belong in this category. While usually small in size, the fodder fishes are so exceedingly abundant that they must provide much of the food of carnivorous species. The analyses of stomach contents of albacore and jack mackerel have indicated this to be true. The role played by fodder fishes has not been sufficiently appreciated. Lantern fishes have been considered as curiosities rather than as one of the most abundant kinds of fishes in the ocean. More interest is being taken in this group, however, and the possibility of their use as bait may soon be explored.

Adults of Other Fishes

Northern anchovy

The stocks of northern anchovy (*Engraulis mordax mordax*) inhabiting the coastal waters from British Columbia to Baja California have been found to be segregated into several populations, between which intermingling is limited or absent. At least three such populations have been identified. These inhabit the regions from British Columbia to Northern California, Southern California and northern Baja California, and southern Baja California, respectively.

The mean number of vertebrae, the character used most widely in detecting the presence of fish populations, is not sufficiently precise for this purpose in the anchovy. Using vertebral counts alone as a criterion it is not possible to distinguish between adults from British Columbia south to northern Baja California. On the basis of dorsal, anal, or pectoral fin-ray counts, however, marked differences are indicated between anchovies taken to the north and to the south of Point Conception (Fig. 35). Anchovies from Northern Cali-

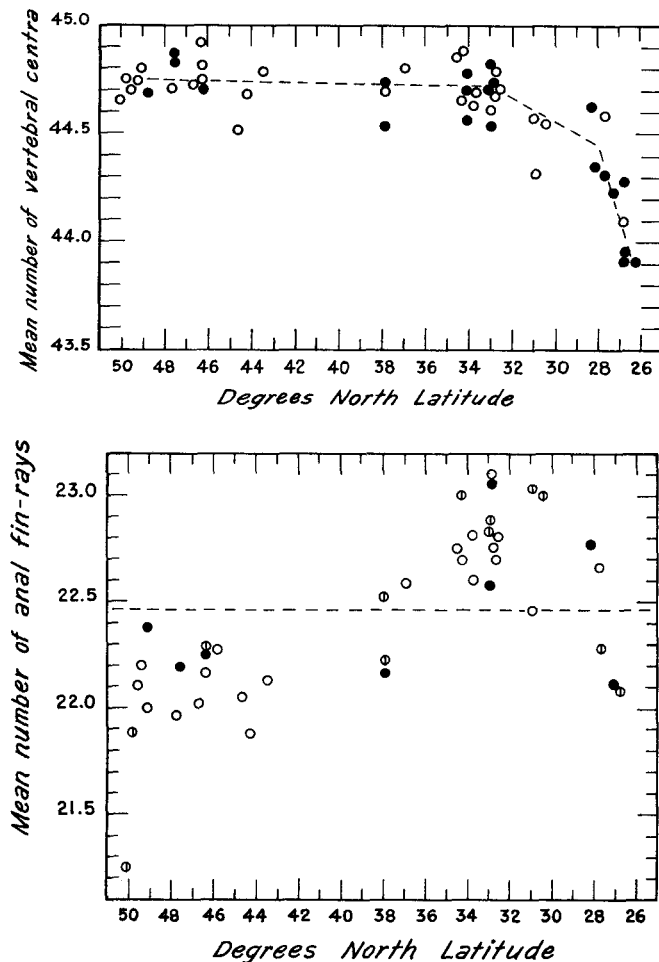


FIGURE 35. Mean number of vertebral centra and mean number of anal fin-rays of the anchovy. (UPPER) Counts of mean number of vertebral centra show few differences between anchovies off coast except in southernmost part of region, where consistently smaller number may indicate separate population. Open circles are adults, filled circles are postlarvae and young. (LOWER) Counts of mean number of anal fin-rays reveal a different picture; on this basis, separate anchovy populations may be presumed to inhabit waters off (1) British Columbia to Northern California, (2) Southern California and northern Baja California, (3) southern Baja California. Open circles, adults; filled circles, larvae; partially filled circles, young.

fornia and the Pacific Northwest have fewer fin-rays on the average than do those from Southern California. The results of this study are in process of publication.

These anchovy population studies are being continued in order to gain further knowledge of the differences between California and Baja California fish.

Progress is also being made in developing methods of age-determination.

The work on anchovies has posed the question of whether similar studies on the Pacific sardine might establish the existence of several relatively independent local populations.

The distribution of mean vertebral number in adult sardines had been investigated before the present studies were commenced; there is no evidence from vertebral counts that more than one population occurs from British Columbia to northern Baja California. Studies of other characters, such as the numbers of fin-rays and of gill-rakers, now under way, so far suggest that intermingling is not complete between Southern California and the regions to the north. It is too early to state definitely that these differences in the sardine are as clearly marked as has proved true for the anchovy.

In the central section of the coast of Baja California, mean vertebral number in postlarval sardines varies significantly with season. If vertebral number can be used in this area to define populations, it would seem that the ranges of the northern and southern populations overlap at this point. The northern fish may spawn here in winter and spring and the southern group may migrate northward to spawn in the same region in summer and early fall. This problem is being given considerable attention.

Similar investigations of the herring stocks in California waters indicate that, as is true in waters of Alaska, British Columbia and Washington, several populations occur along the California coast. North-south migration in this species is probably more restricted than in the anchovy and sardine.

Herring-like fishes

Along the Pacific Coast, from Alaska to the southern tip of Baja California, at least 20 species of sardine-like and anchovy-like fishes are known to occur. Information on the distribution and abundance of these species is being gathered, and studies are progressing on the identification of the larval stages of many.

The sardines of the Japanese, Peruvian, South African, Australian, and New Zealand coasts, though considered distinct species, are known to be closely related to the Pacific sardine. Opinion is not unanimous as to the degree of relationship between these species, primarily because no adequate studies have been made. A project has been under way for some time to compare these forms critically. The results to date indicate that the differences, if any, are extremely slight. This work, when complete, will be of value in understanding the past history and movements of the sardines of the world.

Albacore

Records of albacore caught on jig-lines during survey cruises have provided valuable information on the temperatures at which the species occurs in the

surface waters. In general, the average temperature at which catches are made is higher than the average surface temperature for all stations occupied during the cruise. This may not indicate that temperature directly governs the presence of fish, since albacore are not normally taken close to shore, even when the temperature appears favorable. Furthermore, the average temperature at which catches are made increases from north to south, and also increases in each area as the season progresses.

Studies of albacore stomach contents show that a wide variety of organisms is eaten. Organisms living near the surface constitute the most important food in terms of volume. However, forms are commonly found that occur normally at considerable depth. Often the state of digestion indicates that the albacore must have recently come to the surface; however, since the surface-living organisms are in general better preserved in the albacore stomach, their importance as an element of diet is probably overemphasized. Species commonly found are the red swimming crab *Pleuroncodes planipes*, squid, and Euphausiids. Many fish species are eaten, those most usually found being *Vinciguerria lucetia*, sauries, anchovies, hake, and rockfish.

THE 1950 YOUNG SARDINE SURVEYS

It is necessary, if we hope to predict sardine catches, to know not only the rates of natural and fishing mortality, but to know the rate of recruitment to the population. A direct approach to determining the rate of recruitment is to measure—relatively or absolutely—the size of the successive year classes. Preferably this measurement should be made at some stage in the life history before the sardines enter the fishery. The California Division of Fish and Game has undertaken assessment of the abundance of sardines in their first year of life, after they have passed the larval and postlarval stages.

Methods of Approach

The division has for several years collected statistics of the live bait fishery of Southern California. These include records of the capture of young sardines, when they are available. Young sardines ("firecrackers") are a preferred bait. It is evident from experience, however, that in some years young sardines representing strong year classes are not available to the Southern California bait fishery. Therefore a reconnaissance of the total area where young sardines might be found should give a more reliable measure of the numbers comprising each year class.

A reconnaissance of young fish within their entire possible geographic distribution would present formidable difficulties. Adult sardines have been taken from southeastern Alaska southward along the Pacific Coast to the tip of Baja California and northward into the Gulf of California, a lineal distance of over 3,000

miles. Young sardines have been taken from Vancouver Island southward. A single research vessel, the *Yellowfin*, was available for the work. There is information at hand, however, which lends support to two assumptions which bring the geographical limits of such a survey closer to the ability of a single vessel to conduct it:

Scofield (1934)¹ compared the distribution of very young (up to 10 mm.) sardine larvae with the oldest larvae (20-35 mm.), and concluded that the main movement was inshore and to the south. Godsil (1930)² demonstrated that in 1928 and 1929 in the La Jolla-San Diego area all the young fish (20-100 mm.) were taken by the commercial fishery in water less than 100 fathoms deep. By far the greatest number of these young fish were taken in water less than 10 fathoms deep. On this evidence the first assumption was drawn for the young sardine survey—that the significant majority of sardines in their first year of life will be found inside the 100-fathom curve.

Clark (1947),³ on the basis of a summary of vertebral counts of sardines, concluded that sardines from British Columbia to Point San Eugenio, central Baja California, comprise a mixture of populations, and that sardines south of Point San Eugenio probably comprise a distinct group which does not mix with the northern fish, or, if mixture occurs, the proportion of southern fish to the northern population is small. This conclusion permitted establishment of the southern limit of the survey in the vicinity of Point San Eugenio. Later information indicates this limit is not so clearly defined. The southern boundary was extended to Point San Juanico, 180 miles south. To keep the scope of the survey within the abilities of one vessel the northern limit for 1950 was placed at Point Arena, Central California.

It is known, however, that significant spawning and survival of young have occurred to the north of California. It is thought that the largest contribution to the great 1939 year class may have originated there. Sardines with maturing eggs were taken off Oregon and Washington in the summer of 1939. Great numbers of young began to appear in the inlets of British Columbia the following May. Because these young fish did not appear in shallow water until the following spring, survey of northern waters may yield more accurate results in the spring months. A reconnaissance of this area is projected, therefore, for May-June, 1951, if there is evidence of a significant spawning there in 1950.

¹ Scofield, Eugene C., *Early Life History of the California Sardine (Sardina caerulea) With Special Reference to Distribution of Eggs and Larvae*, Fish Bulletin No. 41, California Division of Fish and Game, 1934.

² Godsil, H. C., *A Discussion of the Localities in Which the California Sardine (Sardina caerulea) Was Taken in the San Diego Region, 1928-1929*, California State Fisheries Laboratories, Fish Bulletin No. 25, pp. 40-44, California Division of Fish and Game, 1930.

³ Clark, Frances N., *Analysis of Populations of the Pacific Sardine on the Basis of Vertebral Counts*, Fish Bulletin No. 65, California Division of Fish and Game, 1947.

Methods of Collection

Sardines are attracted by a light suspended over, or underneath, the surface of the water. Also, schools of sardines can be located at night by the bioluminescence. Schools of young sardines were located by these means or by use of the recording fathometer as described earlier. They were taken by use of a small explosive charge dropped into the school. All the work was done at night.

Limitations

Before any conclusion can be drawn from the young fish survey the limitations of such a survey must be understood:

- (1) Any measure of year-class success derived from the work must be relative. The relative measure must be compared for several years.
- (2) Any change of efficiency in locating and identifying schools of young fish must be noted, and a correction applied.
- (3) Proof of validity of the survey method is a comparison of values obtained from the survey with the relative measures of year-class strength of the same year classes obtained later from the commercial fishery. The 1950 year class will not appear in the commercial fishery for some time.

The 1950 Work

Four young sardine survey cruises were completed in 1950. The area from Point San Juanico, Baja California, northward to Bodega Head, central California, was surveyed. Of the many schools of fish sampled, 23 contained young sardines. The first cruise of the survey began 17 July, the last ended 20 October. Location

of schools of young fish appear in Figure 36. The results of the cruises are indicated in Table I.

AVAILABILITY

There are several reasons why sardines can fail to appear in the usual numbers on proven fishing grounds. There can simply be fewer sardines, a decreasing

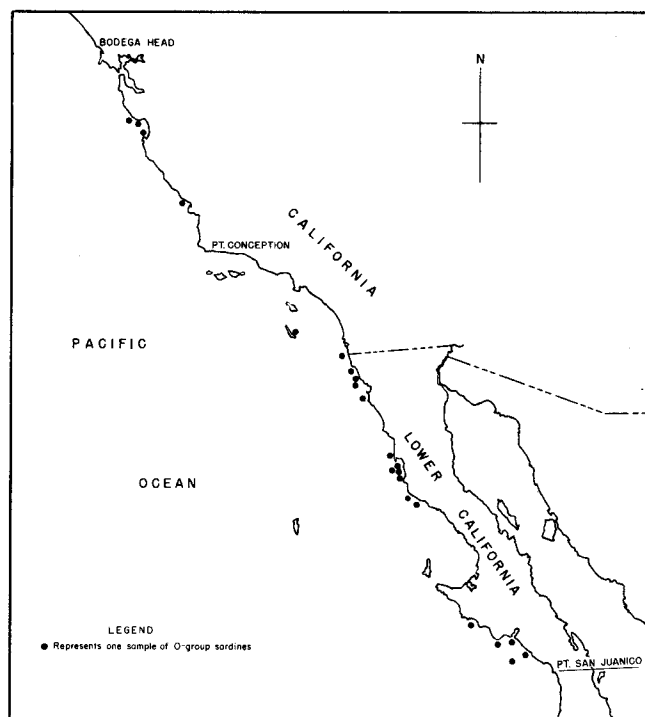


FIGURE 36. Location of schools of sardines during 1950 young-sardine surveys. Each circle represents one sample of 0-group (1950 year class) sardines.

TABLE I. YOUNG SARDINES FOUND IN 1950 YOUNG FISH SURVEY

Date	Time	N. Latitude	W. Longitude	General location	Depth of water (feet)	Number of fish	Standard length range (mm.)	Surface temperature (°C.)
26 July	2240	26° 41.6'	113° 34'	Ballenas Bay	45	1	40	18.5
27 July	0020	26° 39'	113° 16.5'	2.5 mi. S Punta Holcombe	90	3	68-79	19.0
27 July	0345	26° 24'	112° 52.5'	12 mi. NW Punta San Domingo	90	2	80-87	18.95
28 July	0440	26° 15'	113° 15'	33 mi. SE Punta Abreojos	280	62	52-89	20.0
28 July	2300	26° 28.5'	113° 35'	3 mi. S Punta Abreojos	140	47	91-127	18.3
29 July	0445	26° 59.5'	114° 05.5'	12.6 mi. SE Asuncion I.	210	100	100-182	15.5
2 Aug.	2310	29° 27'	115° 16'	4 mi. NW Punta Canoas	100	1	88	13.5
3 Aug.	0135	29° 35'	115° 27'	3 mi. SE Punta San Carlos	60	3	51-56	11.7
17 Aug.	0015	30° 00'	115° 50'	3 mi. NW Punta Baja	80	28	73-122	13.1
17 Aug.	0300	30° 03'	115° 49'	6 mi. N Punta Baja	78	2	83-118	13.2
17 Aug.	0350	30° 03'	115° 55'	8 mi. NW Punta Baja	210	63	109-125	13.6
17 Aug.	2150	30° 13.5'	115° 51'	10.5 mi. SE Cabo San Quintin	120	1	109	13.45
18 Aug.	0410	30° 29'	116° 04.5'	1 mi. E San Martin I.	70	4	56-81	14.75
21 Aug.	0305	31° 35.5'	116° 40.5'	Soledad Bay	105	24	106-128	17.3
22 Aug.	2230	31° 56'	116° 47'	1.7 mi. N Punta San Miguel	150	39	78-109	18.8
23 Aug.	0000	31° 54'	116° 46.5'	1 mi. SW Punta San Miguel	120	10	84-97	
23 Aug.	2120	32° 13.2'	116° 58'	Steamboat Rock, Descanso Bay	130	2	75-96	19.2
10 Sept.	0320	32° 31.5'	117° 09.5'	2 mi. off Mexican Boundary	80	4	84-111	18.4
11 Sept.	2235	32° 47.6'	118° 24.3'	1 mi. SE China Pt., San Clemente I.	220	5	51-88	17.75
9 Oct.	0350	36° 57.3'	121° 56.5'	1 mi. off Capitola	50	206	59-82	14.7
9 Oct.	2030	36° 56.5'	122° 00'	1.2 mi. E Pt. Santa Cruz	50	18	68-83	14.9
13 Oct.	1915	36° 36.5'	121° 53.2'	Monterey Harbor	30	292	69-89	13.7
18 Oct.	0110	35° 24'	120° 53'	1 mi. W Morro Beach	120	3	75-80	13.2

abundance. But the nonappearance can also be due to the sardines moving offshore, schooling at subsurface levels, occurring in less compact schools—there is a long list of possibilities. It was, of course, the possibility that these reasons are intimately connected with changing oceanographic conditions that led to the establishment of the present program. The study of availability—how many sardines are where the fishermen can catch them—is a major aspect of the present research. It is being attacked by the Division of Fish and Game and the U. S. Fish and Wildlife Service.

The Division of Fish and Game is trying to determine the environmental factors which influence the geographical distribution of the sardine schools. It is hoped to measure the effect of variations in physical, chemical, and biological oceanographic conditions on the availability of sardines to the fishing fleet.

The plan of the work is to measure the environmental conditions where sardines are found. A part of the work of the *Yellowfin* has been the collection of oceanographic data from waters where sardines are present. The methods of location (visually and by means of echo-ranging and echo-sounding apparatus) have been described under Instrumentation.

The *Yellowfin* was placed in service in September, 1949. By the end of October, 1950, a total of 249 pelagic schools of fish had been sampled from the vessel. Of these 249 schools, 57 percent contained more than one species of fish. Since the schools could not be identified from the sounding trace, it was necessary to collect samples. Three methods have been tried: (1) gill nets, (2) trawling, (3) explosives. The last method has proved most successful. Gill nets of a mesh size calculated to capture sardines have been very useful in areas where the fish could not be taken by other means, but the nets are highly selective with respect to the size of the fish captured. They probably do not take a random sample from the school. The trawl, which had a 12-foot opening, was towed at depths as great as 100 fathoms. At shallower depths, it was towed at speeds up to eight knots. It did not prove effective; no sardines were captured. Other species, including lantern fish and rock fish, were taken, however.

Once a school of sardines has been located and identified by a sample, the following environmental information is collected: (1) temperature (by a bathythermogram to 900 feet); (2) salinity (by water sample); (3) amount and kind of animal food (by plankton tow); (4) amount and kind of plant food (by water sample). The sardines themselves are measured, the scales are removed for age determination, and the stomachs removed for analysis of food. The gonads are saved for analysis of sexual maturity by the U. S. Fish and Wildlife Service as part of the work on spawning.

Since the *Yellowfin* was placed in service, 15 sardine cruises have been completed. They covered an area along the coast from Bodega Bay, north of San Francisco, southward to Magdalena Bay, in southern Baja

California. To 1 November 1950, a total of 216 days had been spent at sea. Samples had been taken from 145 schools containing sardines.

The schools containing sardines were found in waters ranging from 11° to 20.4° C. (51.8° to 68.7° F.). The relation of salinity to the presence of sardines cannot as yet be stated; shoreside analysis is not complete.

The analysis of the food contents of the stomachs of the sardines taken is proceeding, as is analysis of the plant and animal food found in the presence of schools. Approximately 700 stomach samples have been collected to date. The examination is necessarily a laborious job, and will take some months to complete. The studies to date have not demonstrated a tendency for the sardines to seek or avoid specific groups of organisms for food. Representatives of more than 35 groups of plants and animals, including larval fish and fish eggs, have been identified from the stomachs. The smallest organism found in the stomachs so far was 0.02 mm. in length, the largest 14.7 mm. In general those forms comprising the greatest bulk in the stomachs of the fish also comprised the greatest bulk in the water where the fish were taken.

Parasitic worms, trematodes of family Haemirudiae have been found in the digestive tracts of all fish examined to date. The role of these parasites in the life history of sardines is not yet known. They may constitute a serious handicap to the sardine or they may be tolerated without injury to the host.

Another line of investigation of availability is being followed by the U. S. Fish and Wildlife Service. The work involves the examination of previous catch records with respect to the deviations of the observed catch from the catch that would have been predicted on the basis of the age composition of the previous catches.

The advantages of this method include the use of a large number of data which are immediately available. It is also, compared to work at sea, inexpensive. But at present it can be considered only as an adjunct to the work at sea, not as a substitute for it. One disadvantage in the work thus far is the fact that the deviations observed include the effects in changes in rate of natural deaths as well as changes in availability.

Information on these deviations are now available from the 1941-42 through the 1948-49 seasons. The catches in the 1941-42 through the 1944-45 seasons were greater than would have been predicted. The catches in the 1946-47 through 1948-49 seasons were lower than would have been predicted. A manuscript describing the methods used and discussing the results obtained is in preparation.

Indirect evidence strongly suggests that sardine behavior, and hence availability, is influenced by temperature. The idea is borne out by the experiments on schooling behavior carried out by the California Academy of Sciences and described later in this report, and by observations on spawning. An extremely suggestive

relationship between the deviations in catch mentioned earlier and water temperatures off San Francisco has been observed. More adequate data are now being obtained so that this relationship may be investigated more thoroughly.

Data on the age composition of the catch indicate that about 25 to 50 percent of the decline in landings in the 1946-47 through 1948-49 seasons may be roughly attributed to the fish being less available or to their suffering a greater natural death rate during this period. About 50 to 75 percent of the decline may be attributed to reduced spawning success since 1939. As we see it now, this reduced spawning success is not directly related to the number of spawning fish. Therefore, the fluctuations in spawning success are apparently natural fluctuations. A manuscript on this work has been completed.

BEHAVIOR AND PHYSIOLOGY

Experimental work on the behavior and physiology of the sardines has been conducted at the California Academy of Sciences. The following results have been found:

Feeding Behavior

Preference for living (brine-shrimp) over non-living organisms as food was displayed in the experiments.

Smaller sardines, averaging 75 mm. in length, exhibited a selective feeding habit. They displayed a rising motion to catch individual shrimp. Larger sardines (200 mm.), on the contrary, exhibited "seining" feeding, while swimming forward or circling about through the cloud of brine-shrimp. These were feeding regularly on adult brine-shrimp measuring around 8 mm. in length, but showed no response to newly hatched brine-shrimp measuring less than a millimeter.

In addition to sight, a chemical sense was used in locating food.

Schooling Behavior

Temporary isolation of a part of the school (up to 25 days) did not affect schooling tendency. Upon return to the original holding tank, isolated sardines joined and intermingled with the larger part of the school.

Three larger sardines (approximately 200 mm.) when added to a school of 50 smaller sardines (approximately 75 mm.) did not show any evidence of leadership in the movements of the school.

With reduction of the same school to 10 fish, the three larger sardines led the school and appeared to determine movements of the sardine school. Response, incidentally, seems greater to a single leader.

A minimum school unit was well exhibited by a pair of fish prior to their complete adaptation to aquarium conditions.

Definite increase in tendency to form close schools was observed at water temperature from 12° down to 6°C. Reduction in this tendency is effected by the higher water temperature, from 12° to 25 °C.

Clockwise swimming of the school was most frequently observed. However, when school of dummy (rubber) sardines was run counterclockwise, the sardines joined it.

Miscellaneous Observations

Reaction to the change in direction of water current was found to be negative.

Constant swimming is not necessary for respiration of the sardine, as it is for certain other pelagic species.

Bacteriological tests using pathogens failed to reveal any antibiotic activity of sardine slime.

Electrical Stimulation of Fish in Sea Water

Conditions of experiments

Wooden tanks of the following dimensions were used: 24" x 40" x 6", water 5" deep; 12' 7½" x 20" x 12", water 5" and 6" deep. By using glass barriers this tank in certain experiments was reduced to 10' 6" in length in one case, and approximately to 7' in another.

Both carbon and steel electrodes were used with no apparent difference in effect upon the fish. Polarity of electrodes was reversible to eliminate as far as possible other environmental factors.

Types of fish tested and their standard lengths were: sardine 200-300 mm., top smelt 110-120 mm., and shiner, about 28 mm.

Types of electrical current applied: All the experiments carried out were made with different types of D. C. current. They are as follows:

A. A. C. rectified current using full wave rectifier which delivers a current with low pulsating peaks of 120 cycles per second.

A-1. This current was also used in on-and-off pulsations from 3 to 30 cycles per second.

B. A. C. rectified current using half-wave rectifier which delivers pulsating current equal to A. C. frequency.

B-1. The same current with frequency varying from 45 to 68 cycles per second.

C. Straight D. C. current supplied by D. C. welding set.

C-1. This current was cut on and off or made pulsating from 3 to 12 pulsations per second.

C-2. These pulsations were used with current on two or three times as long as off, and current off two to three times as long as on.

C-3. In some cases current was cut off to zero point between pulsations, in others current was reduced to one-half ampere only between pulsations.

D. Condenser discharge using approximately 50-mf. condenser with voltage (pressure) varying from 100 to 600 volts. Frequency of discharge was varied from four to eight discharges per second.

Definition of terms

Directional effect is immediate involuntary orientation and movement of all the fishes tested toward positive pole in the tank. Slight directional effect is immediate involuntary orientation toward positive pole, but without, or with only slight, movement in that direction.

Confusing effect is any movement induced by the current different from those listed above.

Negative effect is one when no visible response to the current was observed.

Tabulation of records and results

Total number of experiments carried out—eight.

Species	NUMBER OF FISHES BY SPECIES PER ELECTRICAL TYPE-TEST APPLIED							Total
	Type of electrical test							
	A	A-1	B	B-1	C	C-1,2,3	D	
1. Smelt	15	5	4	4	12	11	4	55
2. Sardine	2	0	0	0	10	3	1	16
3. Shiner	2	0	0	0	0	0	0	2
Totals	19	5	4	4	22	14	5	73

NUMBER OF TESTS PER TYPE OF ELECTRICAL STIMULATION

Type A	36 tests
Type A-1	15 tests
Type B	5 tests
Type B-1	10 tests
Type C	37 tests
Type C-1,2,3	85 tests
Type D	14 tests
Total	202 tests

TEST RESULTS BY TYPE, AND TOTAL

Effect	Type of electrical test							Total
	A	A-1	B	B-1	C	C-1,2,3	D	
1. Directional	1	0	0	0	1	31	0	33
2. Slight directional	11	7	4	2	21	23	3	71
3. Confusing	5	6	0	1	0	17	4	33
4. Stunning	1	1	0	5	4	4	0	15
5. Negative	18	1	1	2	11	10	6	49
6. Not recorded	0	0	0	0	0	0	1	1
Totals	36	15	5	10	37	85	14	202

Conclusions

As a result of these tests the type of electrical current found to be most effective in directional and controlled stimulation and the least injurious to the fish was direct current, three to four pulsations per second, the current being on two to three times as long as it was off.

A current density in sea water higher than 35 milliamperes per square inch seemed to have a detrimental effect on the fish in the form of temporary paralysis or death, depending on duration of the current and the size of the fish. This was especially true when non-pulsating current was used.

Strength of the current most effective in producing directional movement was inversely related to the size of the fish. For example, a current of three amperes was most effective with sardines of approximately 200-300 mm., whereas a current of four amperes was necessary to stimulate top smelt of approximately 110-120 mm. in length.

Because results in the above experiments have been encouraging, plans are being developed for similar tests in larger bodies of sea water.

CONTINUING STUDIES

Length Frequencies

A very useful tool for the measurement of what is happening to the sardine population is a record of changes of size of fish in the commercial catch. Since 1919 the Division of Fish and Game has made weekly measurements of the size of the sardines taken by the fishermen at Monterey and in Southern California. Similar records have been collected for the San Francisco fishery since the mid-thirties.

These measurements of the sizes of sardines, termed length frequencies, have told us that in the twenties fish taken in both Central and Southern California were smaller during the fall months and that larger sardines moved onto the fishing grounds during the winter. The winter fish appeared off Central California in December and off Southern California in January. There are now very few of these larger fish in the population. There is at present little size difference between the sardines taken in the fall and in the winter.

The length measurements also told us that in certain seasons an unusual number of young fish appeared in the fall fishery and in the succeeding seasons the sardines in this abundant group increased in size. We were thus able to trace the progress of the group through the fishery. These abundant groups have been interpreted as representing year classes in which survival from a given season's spawning was unusually successful and are termed dominant year classes. Prior to the mid-thirties the dominant year classes appeared in the fishery at intervals of two to four years. This marked variation in spawning success plays a very important role in the total abundance of the sardine population and in turn in the success of the fishery. This has been especially true in the last decade because the larger fish have largely disappeared from the catch and the fishery has become more and more dependent on the smaller sardines. As a result, when there are several seasons in which spawning success is below average, the recruitment of young sardines is poor, and fewer fish appear on the fishing grounds.

The dominant year classes, which have been identified in the fishery by the length measurements, have also given us a measure of the migrations of sardines along the coast. With one or two exceptions, a super-abundant group has first appeared in the Southern California fishery, a year later in Central California, and two to four years later in the Pacific Northwest.

Age Determinations

During the latter part of the thirties the U. S. Fish and Wildlife Service developed methods for determining the age of the sardine by an examination of its scales. The age analysis of a fraction of the length samples was started on a systematic cooperative basis

between the federal agency and the Division of Fish and Game in 1941. The work is continuing, and effort is being made to improve sampling procedures. Samples are obtained by the state agency from boats making landings in San Pedro and Monterey. The San Francisco catch is sampled by the federal agency, and scale samples are sent to its Stanford laboratory from the Oregon Fish Commission, the Washington Department of Fisheries, and the Pacific Biological Station (when there is a fishery in the Pacific Northwest).

The age and length studies have demonstrated that very good spawn survival occurred in 1939 but that during the next five years spawning success grew progressively worse. Conditions were better in 1946, and in 1947 a fairly abundant year class was produced.

The percentage distribution of the Pacific Coast sardine catch by year class for 1948-49 and 1949-50 was as follows:

Year class	Percentage	
	1948-49	1949-50
1948	0.1	7.8
1947	32.8	51.4
1946	49.9	27.9
1945	10.8	8.2
1944	3.9	4.0
1943	1.4	0.5
1942	0.5	0.1
1941	0.2	0.1
1940	0.3	---
1939	0.1	---
Totals	100.0	100.0

It is evident that in both seasons the major support of the fishery came from the 1946 and 1947 year classes, fishes one and two years old in 1948-49 and two and three years old in 1949-50. Fish older than three years were scarce and contributed less than 10 percent to the catch. There were no indications that the 1948 and 1949 year classes will appear on the fishing grounds in exceptional numbers. The 1946 and 1947 groups will presumably have to supply much of the tonnage taken in the next two or three years.

The collected data on age distribution are of value in several different lines of inquiry. Their part in availability studies has already been mentioned. They are also used in racial studies and form the basis for the study of vital statistics.

Racial studies

Racial investigations may be carried out by studies of physical characteristics, by studies of physiological characteristics, and by an appropriately designed tagging program. Ideally it would best be done by all three approaches. High costs usually eliminate tagging work.

Some preliminary collections have been made for studies of physical characteristics, but major emphasis has been placed on physiological characteristics—especially growth characteristics as revealed by the study of scales. The U. S. Fish and Wildlife Service uses as a method whereby it is believed the year-to-year fluctuations in growth caused by favorable or unfavorable environmental fluctuations can be distin-

tinguished from the inherent or heredity-connected differences in growth. This study indicates that there is a "northern type" of sardine—which grows faster and attains a larger size—and a "southern type"—which grows more slowly and does not attain such a large size. The northern type is found wherever the fishery is carried out. The southern type is most abundant on the San Pedro fishing grounds and is found in decreasing abundance to the north.

One explanation of these observations is that there are two races of sardines: one ranging from Southern California to British Columbia, the other occurring to the south of this area, but spreading north over the southern portion of the range of the northern race.

During the 1949-50 season, more fish of the groups spawned in 1943, 1944, and 1945 were caught than would have been predicted from previous catches of these year classes. According to the hypothesis just stated, this "surplus" could represent an influx of the southern race into the California fishery. Further, fish of the 1944 year class caught in 1949 were smaller than expected. This difference cannot be explained by the emigration of the larger fish of that year class; it must represent an influx of smaller fish. It should be emphasized that this is only one possible hypothesis. At least part of the observations could be explained on the basis of changes in availability.

The question whether there are one or more races of sardines is by no means settled. The above observations are only contributing pieces of evidence. This question must be answered, however, for the interpretation of all other sardine data will be influenced accordingly. A preliminary report on this work is in preparation.

Vital statistics

Since 1919 the Division of Fish and Game has collected detailed records of the daily deliveries of individual boats. These have been supplied by the dealers, who furnish the division with a copy of the original receipt given the fishermen. From these records the average monthly or weekly catch of the fishermen has been calculated each season since 1932-33. These measures of fishermen's success give us the most reliable available estimates of the abundance of sardines on the fishing grounds and of the differences in numbers of fish in each individual year class; they are therefore of inestimable value in determining the condition of the sardine population.

The fishing success in 1948-49, based on average monthly catch, was twice that of 1947-48. It doubled again in 1949-50. The greater abundance of the 1946 and 1947 year classes largely accounted for this increased success of the fishermen. However, although the catches increased in the past two seasons, they appeared highly successful only in comparison with the very lean years in 1946-47 and 1947-48. They were on a par with the catches of 1945-46.

With the vital statistics we now have it is impossible to assess the relative importance of the two death rates, that from fishing and that from natural causes.

While estimates of relative abundance of the population may be obtained from catch per unit-of-effort studies, we need estimates of absolute abundance of the population. Under present conditions, it is probably only possible to obtain such estimates from a tagging program or from trying to determine the total number of eggs spawned during a season and calculating the number of fish required to produce those eggs. Only the latter approach is being developed now.

Once an estimate of the absolute abundance of the population is obtained, information from samples of the commercial catch can be analyzed to yield the death rate from fishing and the death rate from natural causes. These results will supplement theoretical studies presently being carried out.

Compilation and analysis of data that will give information on the age composition of the catch from 1932 to 1938 (before scale samples were taken) has been undertaken by the U. S. Fish and Wildlife Service and is nearing completion. This information will add six years to the data series pertinent to vital statistics and availability studies.

MARINE BIRDS AND MAMMALS

As a matter of routine, counts of black-footed albatrosses have been made at each hydrographic station since cruises began in 1949. As indicated by the regular northward progression of the region of maximum abundance in spring, a strong northerly migration of birds took place during the spring and summer of 1949, followed by a southward and offshore movement in late fall. In 1950, on the other hand, no such regular shift in the distribution patterns has been detected. It is possible that this change may reflect differences in the oceanic circulation in the two years that affected bird movements. In 1949 it was noted that the pattern of albatross distribution corresponded in general with the annual northward migration of sardines. In that year, sardine fishing was considerably better off San Francisco than it has proved to be in 1950. Possibly the movements of sardines and birds are subject to similar influences.

Routine observations on the occurrence and abundance of whales, porpoises, and seals are being recorded. In general, whales and porpoises, as well as seals, are more abundant in the inshore areas. Certain regions of dominant abundance have been noted, for example, in the area north of Point Conception.



FIGURE 37. The occurrence and abundance of seals, other marine mammals, and marine birds are noted during the survey cruises.