CONDITIONS RELATED TO UPWELLING WHICH DETERMINE DISTRIBUTION OF TROPICAL TUNAS OFF WESTERN BAJA CALIFORNIA[1,2]

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ABSTRACT

Six oceanographic cruises were made off the west coast of southern Baja California in June through November, 1959–66, and some of the results were compared with contemporaneous fishery data on the distribution of yellowfin tuna, *Thunnus albacares,* and skipjack tuna, *Euthynnus pelamis.* The object was to test the hypothesis that the tunas generally do not aggregate in waters cooler than 20° C. even when suitable food is abundant, but do aggregate in warmer waters provided that suitable food is abundant. The measure of abundance of suitable food was the concentration of the pelagic red crab *Pleuroncodes planipes,* a herbivore which is the principal component of the tunas' diet in the Baja California region.

The results supported the hypothesis very well except on the cruise made in June. Then the coastal upwelling was still strong and some tuna entered waters as cold as 17° C., but no colder, where red crabs were abundant. Areas with temperatures 20° C. or over were very limited, and food was generally scarce in them, although it was plentiful in the extensive areas of upwelled water under 17° C. On each of the other five cruises, which covered the period of decay and disappearance of upwelling, extensive areas contained abundant food at temperatures at and over 20° C. Tunas aggregated in or very near those areas, and nowhere else in the cruise region. Red crabs were most abundant in places where their food, phytoplankton (measured as surface chlorophyll *a*), was most plentiful, and in the upwelling season these places were areas of cool upwelled water. The tunas aggregated at first around the edges of the cool areas, which were rich in chlorophyll *a* and red crabs. Later, when surface temperatures in the cores of the cool areas rose past 20° C., the tunas aggregated there as well. Eventually, after all upwelling had ceased, the distribution of surface chlorophyll *a*, red crabs, and tunas became rather uniform off the Baja California coast.

These relations are considered to support the following general statement of tuna ecology, for which there was some prior justification: temperatures set limits of total range, sometimes differently for different species, and food supply determines distribution within the range limits.

Tuna avoid the Cape San Lucas front when it contains water below 20° C., but otherwise the front may have no effect upon them. There is no evidence of aggregation of tuna prey in the front.

As a result of the association of red crabs with phytoplankton (surface chlorophyll *a*) tuna generally occur in the parts of the Baja California region where surface chlorophyll *a* concentrations are relatively high, provided that surface temperatures are not below 20° C. If the region could be thoroughly and frequently monitored for surface temperature and surface chlorophyll *a* during a tuna season, areas of probable tuna aggregation could be specified. It may eventually be practicable to do the monitoring from ships, aircraft, or satellites. It would not suffice to monitor surface temperature only.

Most species of tunas have a wide range in the world's oceans. Their distribution appears to depend mainly upon two oceanic properties: temperature, which sets limits of total range for each species; and standing stock of animals that tuna will eat, which determines distribution within the range limits. This opinion is reasonable, widely held, and supported by a large amount of information (Blackburn, 1965).

Much of the evidence for the hypothesis, however, is indirect. Because tunas are difficult subjects for experiments, tuna ecology depends upon

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comparisons between occurrences of tuna and distributions of properties as observed in the ocean. Many of these comparisons have been based on noncontemporaneous data. Distributions of tuna prey have been inferred from other property distributions more often than they have been observed. Different kinds of data on tuna occurrence, some of better quality than others, have been used. The tendency has existed to compare tuna data with environmental data on broad scales of space and time, a procedure which is more suitable for generating hypotheses than for testing them.

The hypothesis must survive tests of detailed close comparison between tuna and environment on narrow scales of space and time if it is to be accepted, but very few suitable tests have been made. The need for a good test became particularly evident about 5 years ago, when plans were being made for a series of oceanographic surveys of the eastern tropical Pacific Ocean (the EASTROPAC Expedition, 1967–68). One of the purposes of the expedition was to identify areas, outside the limits of existing fisheries, in which skipjack tuna, *Euthynnus pelamis*, might be abundant. It was necessary to know whether that purpose would be served by measuring standing stock of tuna prey routinely on the expedition.

The STOR (Scripps Tuna Oceanography Research) Program made a series of cruises off the west coast of southern Baja California to test the hypothesis. This paper gives the results of the test. The area off southern Baja California was selected for the following reasons:

1. It is the area closest to the Scripps Institution of Oceanography in which both yellowfin tuna, *Thunnus albacares*, and skipjack tuna occur regularly in abundance. These are the principal species taken in American tuna fisheries in the eastern tropical Pacific. The most detailed previous study of tuna ecology in the eastern tropical Pacific dealt particularly with yellowfin tuna (Blackburn, 1962, 1963), but the need is now pressing for work on skipjack tuna as well.

2. Yellowfin and skipjack tuna move seasonally from the tropics into the area west of Baja California and then back to the tropics. This shift has been shown by tagging experiments (Schaefer, Chatwin, and Broadhead, 1961; Fink, unpublished). The northern range limits of both species are generally in the area or south of it (fig. 1). Property distributions in the area should, therefore, show which properties correspond with range limits and which do not.

3. The food chain of yellowfin and skipjack tuna is shorter and simpler in the Baja California area than elsewhere in the eastern Pacific in ways that were expected to facilitate the study. In the other areas both tuna species consume a great variety of fishes, crustaceans, and cephalopods, most of which are presumably carnivores (Alverson, 1963). Off the west coast of Baja California, however, both tuna species feed mainly on the galatheid crab *Pleuroncodes planipes* (Alverson, 1963), which is a facultative herbivore and sometimes the dominant herbivore in the area (Longhurst, Lorenzen, and Thomas, 1967). *P. planipes*, frequently called red crab, is commonly pelagic, easy to collect in nets from a research ship, and conspicuous (easy to sort) in net catches. It is the principal species of the micronekton—about 80 percent of the total, by volume—in the area west of southern Baja California (Blackburn, 1968). Boyd (1967) recently published a good illustration.

CalCOFI (California Cooperative Oceanic Fisheries Investigations) has provided much oceanographic information about waters west of Baja California, through a program of seasonally repetitive cruises that began in 1949. IATTC (Inter-American Tropical Tuna Commission) has been recording commercial catches of yellowfin and skipjack tunas in the same area and elsewhere since the beginning of 1951. The IATTC tuna data were suitable for the proposed study, but the CalCOFI oceanographic data were not very suitable because they had been obtained for other purposes. The CalCOFI cruises generally covered only about half the area that yellowfin and skipjack occupy off Baja California (see example in fig. 7); they frequently missed the period when the tunas were most widespread in the area; and they seldom provided any information on phytoplankton or on animals eaten by tuna. It was necessary, therefore, to make special cruises for tuna ecology studies. Five such cruises, together with one CalCOFI cruise that was equipped to serve the same purpose, were made. They covered most of the period of the year (in different years) when tropical tunas occur off Baja California.

The hypothesis to be tested was that yellowfin and skipjack tunas generally do not occur in waters of surface temperature below 20° C., even

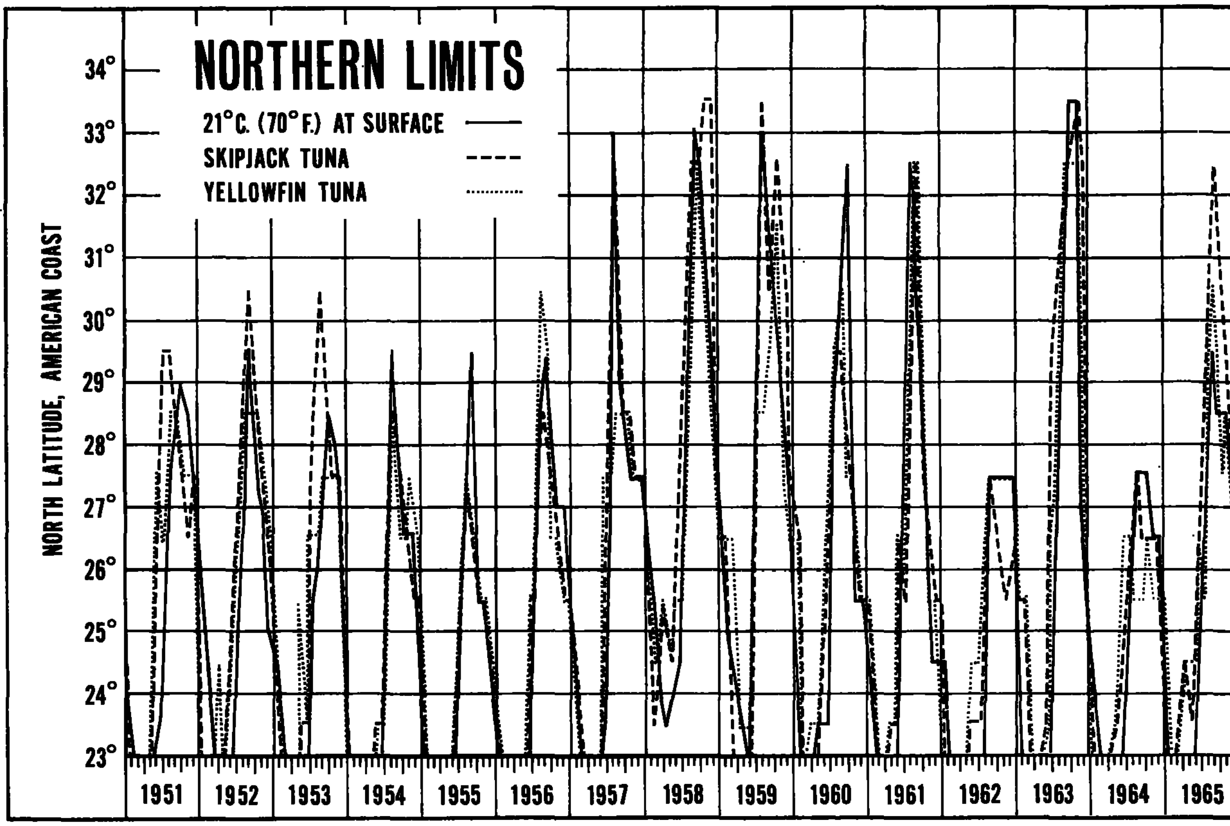

FIGURE 1.—Changes in latitudinal position of the 21° C. surface isotherm and of the northern limits of commercially caught yellowfin and skipjack tunas off the coast of Baja California and California, 1951–65.

when suitable food is abundant in those waters, but do occur in waters of surface temperature at and above 20° C., provided suitable food is abundant. "Suitable food" was defined as pelagic red crab, and "abundant" was defined as a concentration at or above 40 ml. displacement volume per 1,000 m.^{3} of water. The specified temperature, prey species, and concentration of prey are explained below.

The cruises were intended also to identify environmental properties that determine the distribution of the red crab, which is important in the diet of other commercial fishes as well as yellowfin and skipjack tunas (Boyd, 1967). Nothing was known about these properties except that temperature was not one of them (Longhurst, 1967). I thought that the properties would include standing stock of phytoplankton or of zooplankton, depending upon whether the red crab was predominantly herbivorous or carnivorous in the area studied; in the outcome it proved, as expected, to be predominantly herbivorous (Longhurst et al., 1967). Further, the cruises were intended to investigate possible relations between the tuna-connected properties—temperature, prey, food of the prey—and physical features of the environment such as upwellings and fronts. The results of those studies are included in this paper.

The range-limiting temperature was specified in the hypothesis as 20° C. for both species of tuna, but some deviation from it was expected. Range-limiting temperatures for yellowfin and skipjack have been discussed by Uda (1957), Blackburn and associates (1962), Laevastu and Rosa (1963), Broadhead and Barrett (1964), Blackburn (1965), and others. It is evident from these papers that successful commercial fishing, which requires a fairly high concentration of the fish, seldom occurs at temperatures below 20° C. for yellowfin tuna or below 19° C. for skipjack tuna. Both species can occur in waters as cool as 15° C. in some parts of the world, however. In the eastern Pacific the limiting temperature appears to be nearly always close to 20° C. for commercial concentrations of both species. Blackburn and associates (1962) found that the northern range limits of the species agreed in position with the 21° C. (70° F.) surface isotherm at almost any time. Broadhead and Barrett (1964) showed a similar agreement of both northern and southern range limits with the 20° C. (68° F.) surface isotherm.

Figure 1 shows the kind of data that Blackburn and associates (1962) presented for the period 1951–59, together with similar data for 1960–65. It gives the approximate latitudinal position, in each month of 1951–65, of the northern limit of commercially caught yellowfin tuna, the northern limit of commercially caught skipjack tuna, and the 21° C. surface isotherm. The latitudes shown are those along the entire west coast of Baja California and the southern part of the coast of California. Tuna range limits are based on IATTC catch data that are grouped by 1° squares. They have been graphed at the midpoint of the 1° range of latitude at which the most northern commercial catch (regardless of its amount) was made during the month. Temperatures for 1951–59 are from the series of monthly temperature charts published by Eber, Saur, and Sette (1968), except for August 1952 when CalCOFI cruise data showed a more northward penetration of the 21° C. isotherm. Temperatures for 1960–65 are from monthly temperature charts published by the BCF (Bureau of Commercial Fisheries) Biological Laboratory, San Diego, Calif. Because the BCF temperature data were contoured in intervals of 5° F., including 70° F. (21° C.), it was more convenient to compare tuna limits with 21° C. than with 20° C.

As mentioned previously, figure 1 illustrates the seasonal movement of yellowfin and skipjack tunas along the west coast of Baja California (and in some years, California). It is not a spawning migration for either species (Orange, 1961; Klawe, 1963). The tunas appear west of the southern tip of Baja California (lat. 23° N.) in late spring or early summer, extend their ranges northward during the summer, contract their ranges southward during the autumn and early winter, and leave the area (except in 1958) during the late winter and early spring. The 21° C. surface isotherm changes position in the same way. The positions of the isotherm and the range limits vary from year to year in the same month, but they generally agree closely with one another in any particular month. It is because of this agreement that I think temperature determines the range limits. Figure 1 shows a few disagreements which could have resulted from temperature data or tuna data that were unrepresentative of conditions within a month. The two kinds of data were not collected together. All temperature data apply to the sea surface or the upper 10 m., where yellowfin and skipjack tunas are generally seen and caught.

The range of skipjack tuna appears to be limited also by a high temperature, about 28° C., and the same temperature or a higher one may possibly limit the range of yellowfin tuna (Blackburn, 1965, and references there). Such temperatures seldom occur in extensive areas off western Baja California, however.

Nothing indicates that temperature plays any direct part in determining the patchy distribution of the tunas within their range limits (Blackburn, 1965). According to the hypothesis being tested, food supply is responsible for this aspect of the distribution. The principal food organism of tropical tunas off western Baja California is red crab, as mentioned above. Alverson (1963) sorted stomach contents of 567 yellowfin and 151 skipjack tunas taken off the west coast of Baja California and the coast of California. The composition of the stomach contents of yellowfin tuna by volume was 78 percent red crab, 10 percent northern anchovy, *Engraulis mordax*, and 12 percent other animals (euphausiids absent). The composition of the skipjack tuna stomach contents was 37 percent red crab, 28 percent northern anchovy, 19 percent euphausiids, and 16 percent other animals. Northern anchovies are much more abundant off California and northern Baja California than off southern Baja California, however (Baxter, 1967; Ahlstrom, 1967); in the latter area red crabs are, therefore, probably a larger component of the tunas' diets than Alverson showed. Northern anchovies were very seldom taken on the cruises described in this paper, probably because they were not common in the area. Euphausiids were taken on these cruises, but it was decided not to attempt to study their distribution in relation to that of the tunas, for the following reasons. Euphausiids are more difficult to sort and measure volumetrically than red crabs are; they are not routinely catchable or observable by some of the methods

TABLE 1.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10³m.³ of water strained, on cruise TO–64–1*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³m.³			*Ml./10³m.³*			*Ml./10³m.³*
3	M	32	24	Z	7	53	Z	865
4	Z	69	26	Z	62	54	Z	310
5	Z	34	27	Z	7	55	Z	35
7	Z	7	28	Z	18	56	Z	2,364
9	S	>40	29	M	7	57	Z	1,092
10	M,Z	>40	30	Z	26	58	Z	1,446
11	Z	17	34	Z,M	68	59	Z	614
12	Z	123	35	Z	6	60	Z	225
15	Z	7	36	Z	176	61	Z	108
16	M,Z	72	48	M	46	62	Z	492
17	Z	386	49	Z	5	63	Z	284
18	Z	316	50	Z	43	64	Z	1,142
19	Z	13	51	Z	6	65	Z	80
23	M,Z	36	52	Z	198	66	Z	3,437

that were useful with red crabs (high-speed net catches, and observations at the sea surface); and yellowfin tuna do not eat them. In any event, northern anchovies and some euphausiids are facultatively herbivorous like red crabs and might be expected to have a similar distribution.

I decided to distinguish between concentrations of red crabs that were greater or less than 40 ml./1,000 m.³, as mentioned above. Concentrations above zero ranged from 0.1 to 5,238 ml./1,000 m.³ (tables 1–6), with median 36 ml./1,000 m.³ It is implicit in the hypothesis being tested that tunas, which are highly mobile, encounter and aggregate around the highest concentrations of food in any area which they enter. It was, therefore, desirable, on the one hand, to use some value at least as high as the median to distinguish high concentrations from low. On the other hand, the frequencies at successive intervals of concentration declined sharply above the median, to the extent that charting would have been difficult if a value appreciably over 100 ml./1,000 m.³ had been used. Trial made it evident that the property charts presented later, and the conclusions of the study, were much the same at a value of 40 (just above the median) and at 100 ml./1,000 m.³ Therefore, the former value, which made more data available for drawing isograms of abundance of red crabs on the charts, was chosen.

MATERIAL AND METHODS

The following sections give information about the cruises and stations from which data were obtained; the methods used for measuring surface temperature, surface chlorophyll *a*, and concentration of red crabs; and the kinds and sources of contemporaneous data on tunas.

CRUISES AND STATIONS

The oceanographic data for this study were obtained in six cruises—one made in 1959, which generated the hypothesis mentioned above, and five made in 1964–66. The area of study was restricted to south of lat. 28° N., where the tunas (fig. 1) and red crabs (Longhurst, 1967) occur each year; these species appear farther north in some years, but not in all. Figure 2 identifies localities and topographic features to which I refer in this paper. The principal banks (underwater elevations of the bottom) within and beyond the 100-fathom (183–m.) line, and the small islands known as Alijos Rocks, are shown. Tuna fishermen consider that these features represent good fishing areas, a matter which is discussed later.

The tracks and station positions for the six cruises are shown in figures 3, 5, 7, 9, 11, and 13, which appear in later sections of this report. They were based on the CalCOFI basic station plan (since 1950), and most of the stations can be identified easily with CalCOFI station positions (Anonymous, 1963), although they have not been numbered in the CalCOFI way. Two of the cruises were devoted entirely to occupying a series of CalCOFI stations (figs. 7 and 9). On each of the other four cruises (figs. 3, 5, 11, and 13) a series of CalCOFI stations was occupied first (part 1 of the cruise, terminating in the southern part of the area) and the ship then returned northward by a different route, occupying special stations in areas of particular interest (part 2 of the cruise). The

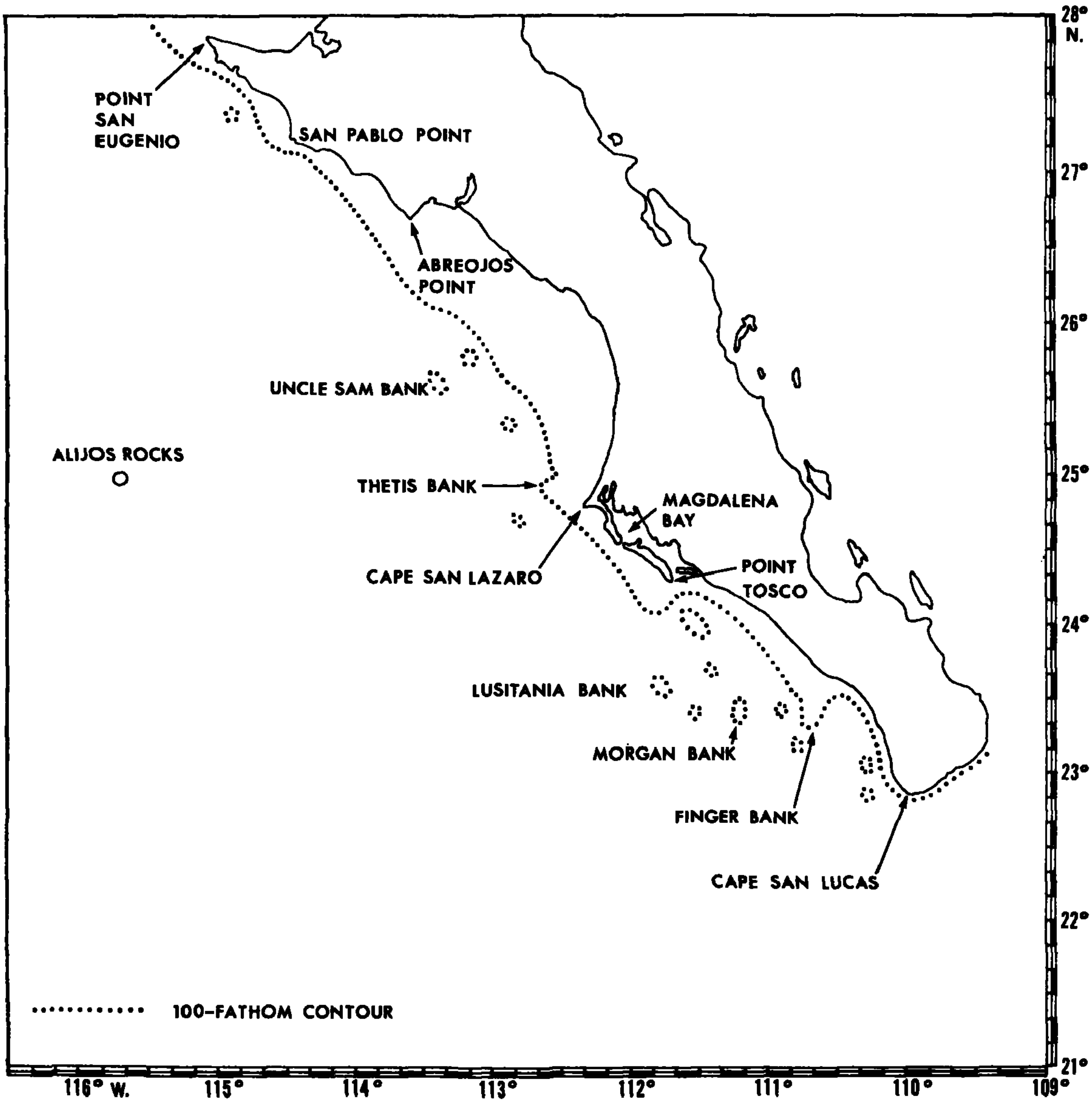

FIGURE 2.—Localities and topographic features referred to in the paper.

figures identify the stations that were occupied close to local noon and midnight so as to indicate approximately which portions of the track were covered in daylight and which in darkness.

Although many physical, chemical, and biological properties were measured at several depths at most stations, this paper is concerned only with data on surface temperature, standing stock of phytoplankton, pelagic crabs, and tunas, for reasons given earlier. The stock of phytoplankton was measured as concentration of chlorophyll *a*, and in this paper I discuss only surface concentrations, which were measured much more often than concentrations at other levels.

SURFACE TEMPERATURE

The term "surface temperature" is used for convenience, for the temperature data in this paper are not precisely from the sea surface. Mainly they are from 10 m. below the surface, where temperature was measured at almost every station with a reversing thermometer. Temperatures read from bucket thermometers, bathythermographs, and thermographs that recorded sea-water injection temperatures aboard vessels were used in charting isotherms between station positions. The data for cruises TO–59–2 (considered as part of CalCOFI cruise 5908), 6608, TO–64–1, and TO–64–2 have been published (Scripps Institution of Oceanography, 1961, 1968, 1969). The data for cruises TO–65–1 and TO–66–1 are available from the Scripps Institution of Oceanography.

SURFACE CHLOROPHYLL *A*

On cruise TO–59–2, concentrations of chlorophyll *a* were determined by spectrophotometric measurement of optical density of acetone extracts by use of the equations of Richards with Thompson (1952). These data have been published (Blackburn, Griffiths, Holmes, and Thomas, 1962). On cruises TO–64–1 and TO–64–2, concentrations were determined by measuring the fluorescence of acetone extracts (Holm-Hansen, Lorenzen, Holmes, and Strickland, 1965; Lorenzen, 1966). The data have been published (Scripps Institution of Oceanography, 1969). On the other three cruises, determinations were made by measuring the fluorescence of acetone extracts or in vivo suspensions (Lorenzen, 1966) or both. The data for these cruises are available at the Scripps Institution of Oceanography. All available surface measurements were used in this study, irrespective of the time of day or night at which the material was collected. Concentrations are given in mg./m.^{3}

PELAGIC RED CRABS

The pelagic red crab was collected or observed and its concentration in the water estimated in several ways. Tables 1–6 list stations and localities between stations where red crabs were collected or observed on the six cruises and give the estimated concentrations in milliliters (displacement volume) /1,000 m.^{3} These data refer to adults and juveniles (postlarvae), but not larvae.

One method of collection (M in tables 1–6) was the standard micronekton net haul, which was made usually once each night. The net was the 1.5-m. (5-foot) net described by Blackburn (1968); it was hauled obliquely at a ship speed of 5 knots (9.3 km./hour). On cruises TO–59–2, TO–65–1, and TO–66–1, the hauls were made to a depth of about 90 m. with 350 m. of wire. On cruises TO–64–1 and TO–64–2 they were made to about 140 m. with 500 m. of wire. Wire was paid out at speeds of 20 to 30 m./minute and retrieved at speeds of 10 to 15 m./minute. This method was not used on cruise 6608; other methods, mentioned below, were employed on that cruise. The volume of water strained on each haul was estimated from the distance traversed in meters, the mouth area of the net in square meters, and an empirical filtration coefficient, 0.76 (Blackburn, 1968). Crab volumes were measured directly.

Another method (Z in tables 1–6) was the standard zooplankton net haul with the CalCOFI 1-m. net, which was usually made at each station. These hauls were made obliquely to a depth of about 140 m. at a ship speed of less than 2 knots (3.7 km./hour). Thrailkill (1956) described the net and hauling procedure. A flowmeter measured the volume of water strained on each haul. Volumes of red crabs were measured directly for cruises TO–64–1, TO–64–2, and TO–65–1. For the other three cruises the volumes were estimated from counts of crabs, using an empirical average volume of 3.0 ml. per crab, or 1.0 ml. per crab if they were recorded as small. Some crabs probably avoided these slowly moving nets, even at night. At 46 night stations both standard micronekton hauls and standard zooplankton hauls were made and red crabs collected. Volumes per 1,000 m.^{3} were equal in the two hauls at 3 stations, greater in the micronekton hauls at 31 stations (including 18 when the zooplankton haul was negative), and greater in the zooplankton haul at 12 stations (including one with a negative micronekton haul).

A third method (H in tables 1–6) was the high-speed micronekton net haul described by Blackburn (1968). This net is hauled horizontally at about 10 m. below the surface at the ordinary cruising speed of the ship. Such hauls were made, usually at night, on all cruises except TO–64–1. Their duration was from 2 to 3 hours on cruise TO–59–2, from ½ to 1½ hours on cruise TO–64–2, and 1 hour on other cruises. The volume of water strained was estimated from the distance traversed, the mouth area of the net, and an empirical filtration coefficient, 0.94 (Blackburn, 1968). Crab volumes were measured directly. I showed earlier (Blackburn, 1968) and found again in this study that volumes per 1,000 m.^{3} from these hauls average much smaller than those from standard micronekton hauls made at about the same time and place; the ratio, high-speed net volume/standard micronekton net volume, is of the order 1:10. The reasons are unknown; possibly red crabs are scarcer in the upper 10 m. than at greater depths, or they may tend to avoid a fast-moving ship. The concentrations shown for this method in tables 1–6 have all been multiplied by 10 to make them broadly comparable with those from the other hauls.

The remaining sources of information about red crabs were sightings of aggregations at the sea surface and occurrences in the stomachs of predators that were captured from the ship. The concentration for each sighting was obviously over 40 ml./1,000 m.³ and is listed accordingly (see S in tables 1–6). On four occasions the stomachs of predators contained crabs. The predators were yellowfin tuna, dolphin, *Coryphaena hippurus*, and an unidentified turtle. Three of these occurrences were represented by only one predator individual; it was not then safe to assume that red crabs occurred at a concentration over 40 ml./1,000 m.³ In the other occurrence, three predator individuals (yellowfin tuna) containing red crabs were captured and many others seen; here it was reasonable to assume that a high concentration of red crabs was available (see P in table 5).

For stations at which two or more estimates of concentration were available, the highest one was listed in tables 1–6. In charting the isogram of 40 ml./1,000 m.³ concentration for each cruise, I used the data of tables 1–6, together with the zero concentrations recorded for the remaining stations. In view of the opinion of Boyd (1967) and Longhurst (1967) that red crabs make diurnal vertical migrations, I occasionally ignored estimates of low or zero concentrations based upon daytime catches or observations when other evidence suggested the probability of high concentrations in the area—for instance when surface chlorophyll *a* was high, and high concentrations of crabs were encountered during one or both of the adjacent nights. An additional justification for this procedure is that most of the daytime information was obtained from zooplankton hauls, which frequently yield low estimates of concentration as shown above. On the other hand, if a series of night observations all yielded low estimates of concentration I concluded definitely that red crabs were not abundant in the area examined, whatever the other circumstances were; I sometimes ignored an occasional low concentration in a series of high ones obtained during the same night.

Stations 60–66 of cruise TO–64–1 were occupied very close to each other, in an area of about 5 nautical miles (9 km.) radius, during a period of about 3 days. The odd-numbered stations were occupied about noon, the even-numbered stations about midnight. Table 1 shows the crab concentrations measured in zooplankton hauls at these stations which were all much higher than 40 ml./1,000 m.³ Concentrations were lower at noon than at midnight, as expected. Concentrations in consecutive hauls differed by a factor of about three in both the noon and midnight series. I have found similar differences for other kinds of organisms in noon and midnight series of micronekton hauls that were closely adjacent in space and time (Blackburn, 1968). Concentrations of red crabs estimated from single net hauls might, therefore, differ by a factor up to three from concentrations actually present in the water. I tried to allow for this possibility in charting the isogram of 40 ml./1,000 m.³ for each cruise.

TUNAS

Data on the recorded occurrence of yellowfin and skipjack tunas were obtained from IATTC, which has such data in various forms, one of which gives average catch per unit of fishing effort by species, by fishing method (live-bait and purse-seine), location by 1° squares, and by months. Such information had been very useful in previous work on tuna ecology in the Gulf of Tehuantepec (Blackburn, 1963) but was rather unsatisfactory for this study. The isograms of temperature, chlorophyll *a*, and red crabs intersected the parallels and meridians in a way that was frequently very complicated (e.g., fig. 6), and it was evident that their position did not always remain unchanged for the whole of the calendar month in which they were observed.

I used IATTC data on tuna occurrences that had definite dates and positions. Figures 4, 6, 8, 10, 12, and 14 (see later sections) show these occurrences separately for each species and for mixed catches of the two species. They refer either to the whole period when the ship was in the area of the charts or to some part of that period, as explained later for each cruise. The original data were available from baitboats and purse seiners separately, but the distributions of tuna from these two sources were generally similar and are not distinguished in this paper. Data were available on the amounts of tuna captured at each of the charted positions, but they are not given here because size of catch is not necessarily a measure of abundance. Catch per unit of fishing effort can be considered as a measure of abundance, but it would be difficult to establish the amount of effort expended at each of the individual points shown on the charts. For this study, any commercial catch of tuna indicates an aggregation of the fish, and the main interest lies in the general distribution of the aggregations.

In areas where no occurrences are shown, there was either no significant fishing effort (hence tuna distribution unknown) or no fish, at the period of the cruise. Data showing absence of fish are few; they refer to combinations of 1° squares and months in which at least 5 boat-days of fishing effort yielded no catches. These examples of unproductive effort are mentioned later for the individual cruises.

A few catches and observations of yellowfin and skipjack tunas made from the oceanographic vessels have been included in the charts.

RESULTS OF INDIVIDUAL CRUISES

In the following sections, six cruises are discussed in the order that best represents the typical seasonal change during the period of the year when yellowfin and skipjack tunas occur west of Baja California. The distributions of surface temperature, surface chlorophyll *a*, red crabs, and tunas are described and explained for each cruise, with special reference to their relations with the seasonal cycle of coastal upwelling.

CRUISE TO-64-1

This cruise showed environmental conditions that are probably typical of the beginning of a yellowfin and skipjack tuna season off western Baja California (see fig. 1). Figure 3 shows the track and station positions, omitting individual positions of two clusters of stations that were occupied for special purposes. Figure 4 gives the essential features of the distributions of the properties previously discussed; this and similar figures show only selected isograms of surface temperature and surface chlorophyll *a*. The isotherms in figure 4 refer only to the temperature distribution on part 1 of the cruise, June 9–15, 1964. At the few stations that were re-occupied on part 2 of the cruise, temperatures averaged about 2° C. higher than on part 1. Figure 4 includes only those tuna occurrences that were recorded for the period June 9–15. The charted distributions of chlorophyll *a* and red crabs are based on all available data from the entire cruise, as they are also for the other cruises. The red crab data are given in table 1.

Along the Baja California coast below Point San Eugenio the coastal upwelling typically begins about April, is strong from April through June, and ceases about August (Reid, Roden, and Wyllie, 1958; Wyllie, 1961; Lynn, 1967). CalCOFI stations 123.37 and 143.26, which are the same as stations 2 and 18 in figure 3, are considered to be the centers of the two principal coastal upwelling areas (Lynn, 1967). These areas, one along the coast south of Point San Eugenio and the other south of Cape San Lazaro, are indicated by the 15° C. surface isotherm in figure 4. In the northern area, surface temperatures below 13° C. were recorded off San Pablo Point. The 16°, 17°, and 18° C. isotherms lie generally parallel to the coast, rather than in the wavy configurations described later for certain offshore isotherms on subsequent cruises. This parallel orientation appears to be normal in June (Anonymous, 1963).

Off Cape San Lucas a well-defined temperature front existed at the sea surface, oriented in much the same way as in May 1960 and April 1961 (Griffiths, 1963, 1965). Surface water below 17° C., in part below 16° C., lay in a narrow band just west of Cape San Lucas; it was probably upwelled farther north, where temperatures were similar. Eastward from this cold area along the south coast of the peninsula, surface temperatures rose to above 25° C. The 17° to 21° C. isotherms trended more or less to the southeast from Cape San Lucas, whereas the 22° to 25° C. isotherms trended parallel to the south coast of Baja California. The front, therefore, was very strong close to Cape San Lucas but split about 15 nautical miles (28 km.) offshore into two weaker parts. Some 60 miles (110 km.) southwest of Cape San Lucas, a tongue of water over 19° C., mostly over 20° C. (the two isotherms are close together), protruded north-

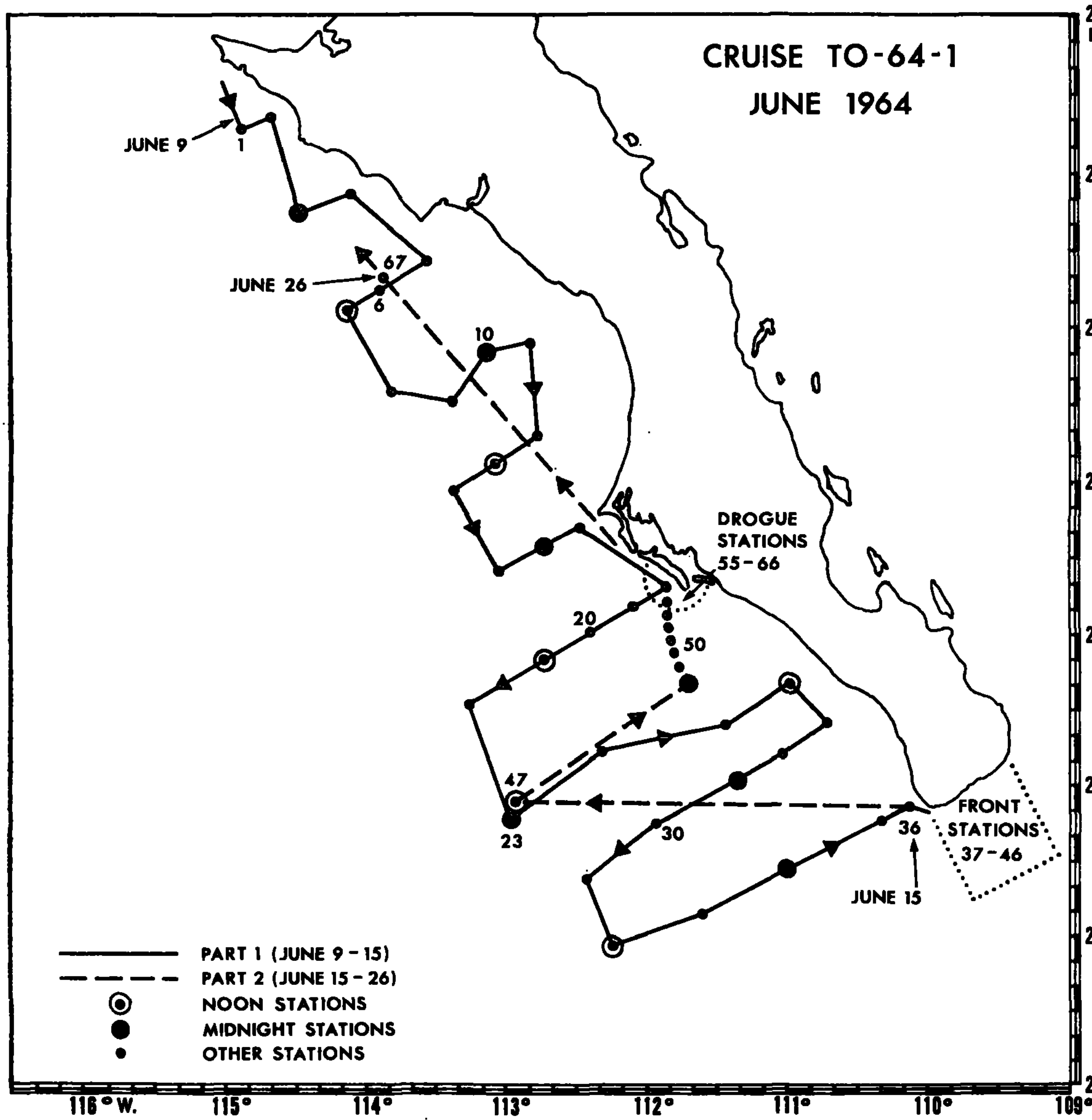

FIGURE 3.—Track and station positions for cruise TO–64–1.

ward into the cruise area. Such a warm tongue appears frequently at this time of year; for example, it occurred in June 1951 and June 1957 (Anonymous, 1963) and is shown in several of the BCF June temperature charts.

The standing stock of surface chlorophyll *a* was highest in the cold coastal water (upwelling or recently upwelled water), as expected. The 1.0 mg./m.^{3} isogram follows the coast and includes the principal upwelling areas, where some concentrations exceeded 6.0. Concentrations below 0.1 mg./m.^{3} were confined to the offshore region in the extreme south of the area (stations 31–34), and none of these values was below 0.06.

The area of red crab concentration over 40 ml./1,000 m.^{3} was large and broadly similar to that of chlorophyll *a* concentration over 1.0 mg./m.^{3} Thus, the red crab and its food supply had the same distribution. A separate small area of high concentration lay near Cape San Lucas, and another one farther offshore.

The tuna occurrences were in two groups in the southern part of the area—one (yellowfin tuna only) east of the front along the south coast of

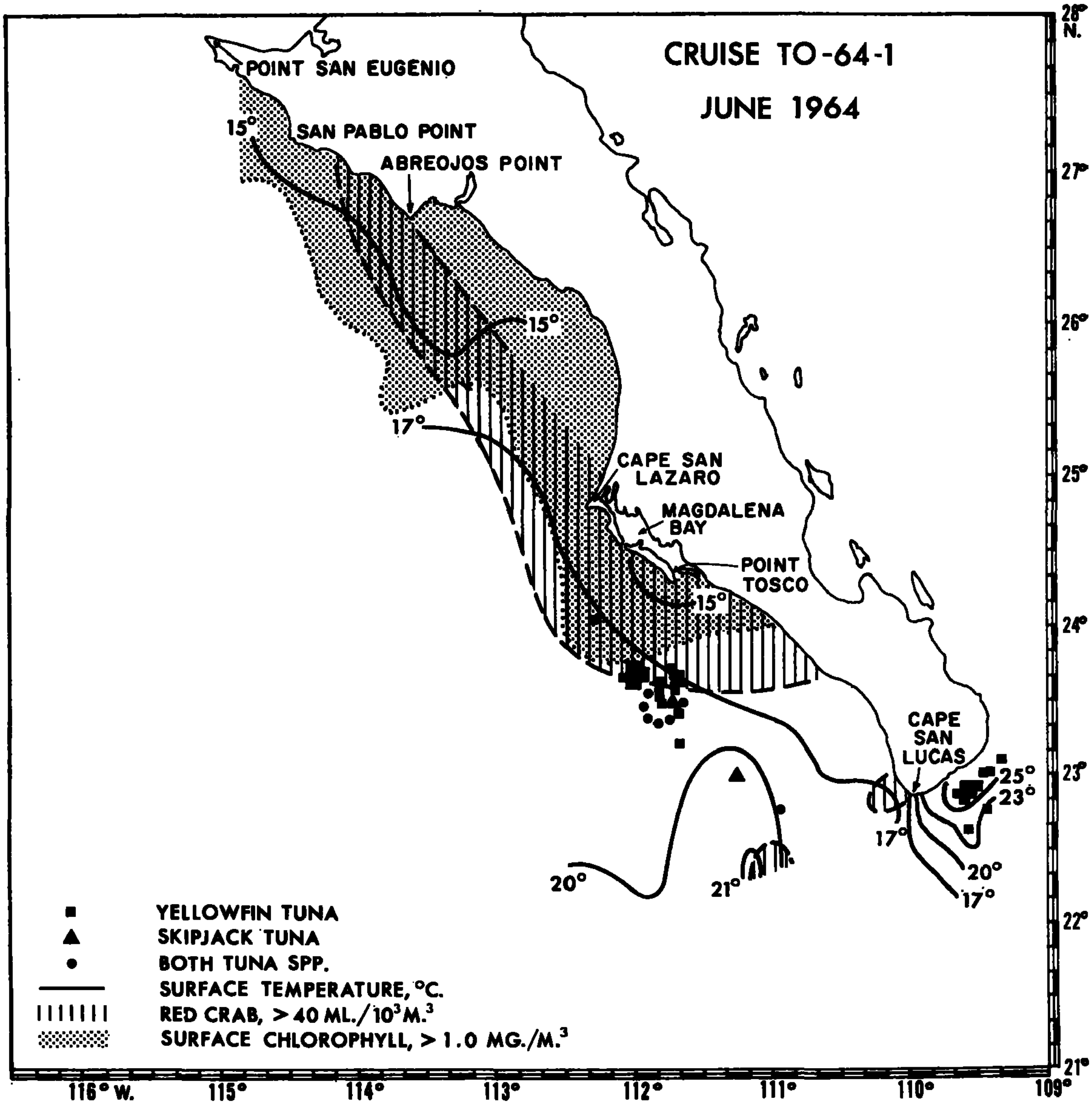

FIGURE 4.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO-64-1 and locations of contemporaneous tuna catches.

Baja California, and the other (both species) in and northwestward of the warm offshore tongue. Neither of these groups of tuna was in the area of highest concentration of food, although the second group reached the edge of it. In the front area virtually no red crabs were caught in three standard night micronekton hauls, and concentrations of all animals in these hauls (i.e., all potential tuna prey) ranged only from 9 to 16 ml./1,000 m.³ In the other tuna area concentrations of red crabs were 7 and 46 ml./1,000 m.³ at stations 29 and 48, and concentrations of all other micronekton were 14 and 10 ml./1,000 m.³ Some of the tuna aggregations in each of these areas were only about 25 nautical miles (46 km.) from a much richer food supply (over 100 ml./1,000 m.³ of red crabs—e.g., at station 52), but the fish would have had to encounter temperatures below 17° C. to reach it. Figure 4 shows that the tunas will tolerate 17° C. and suggests that lower temperatures are not acceptable.

A reasonable interpretation of figure 4 is that both tuna species prefer some temperature at or over 20° C., will move into adjacent water as cool as 17° C. if food is more plentiful there, and will not enter water below 17° C. even if food is extremely abundant. If so, tuna will not round Cape San Lucas from the east as long as water under 17° C., and perhaps under 20° C., remains there; data from Griffiths (1963) indicated that 20° C. was the limiting temperature in May 1960. Under those circumstances their entry into the area west of Baja California will be by the offshore tongue of warm water, as suggested by figure 4. The area enclosed by the offshore 20° C. isotherm in figure 4 was well occupied by both species in the second half of June and the first half of July, although there were still no records of tuna caught between that area and the coast (between long. 110° and 111° W.). Tuna were not recorded in the latter area until the second half of July, when they suddenly became widespread; these fish were all yellowfin tuna, and probably the same aggregations as shown to the east of the front in figure 4. Probably the 20° C. isotherm moved northward from Cape San Lucas about mid-July and permitted the yellowfin tuna to round Cape San Lucas; this isotherm was located at about lat. 25° N. during the last 10 days of July (Scripps Institution of Oceanography, 1966). Thus, tuna appear to follow two pathways from the tropics into the area west of Baja California at the beginning of a tuna season, both determined by the distribution of surface temperature. One is from the east around Cape San Lucas, and the other is from the south. The former is mainly for yellowfin tuna, and the latter is for both species; skipjack tuna are much less common than yellowfin tuna to the east of the meridian of Cape San Lucas in most years (Joseph and Calkins, 1969).

Cruise TO–64–1 was the only one of this series in which tuna occurred at temperatures substantially lower than 20° C. They probably can tolerate temperatures down to 17° C. to obtain a larger food supply, as indicated above. Lee (1952) found that cod will enter waters over 2° colder than those in which they usually occur if food is plentiful. On cruise TO–64–1 only one small area had more than 40 ml./1,000 m.^{3} of red crabs in water at 20° C. or over (station 34, with 68 ml./1,000 m.^{3}). On all the later cruises, such areas were extensive and the concentrations of red crabs in them were generally over 100 ml./1,000 m.^{3}

Several tuna boats were fishing off the south coast of Baja California at the time the front was surveyed, and their operations were watched to see if their fishing success bore any relation to the position of the front. The only obvious relation was that they worked mainly to the east or north of the front and occasionally on its warm edge. They were probably avoiding water under about 20° C., and the front itself, as distinct from the limiting isotherms located in it, seemed to have no effect.

Various authors have suggested that tunas may aggregate in fronts in response to aggregations of prey organisms. Griffiths (1963, 1965) found that some kinds of zooplankton were more abundant in the middle of the Cape San Lucas front than on either side of it, but, on the other hand, micronekton (potential tuna forage) was most abundant on the warm side. On cruise TO–64–1 micronekton hauls were again made on both sides of the front and in the middle, all on the same night; the highest concentration was on the warm side, as in Griffiths' series, but all three concentrations were similar (16.3 ml./1,000 m.^{3} warm side; 9.1, middle; 11.8, cold side).

All the foregoing observations were made in the part of the front that is oriented parallel to the south coast of Baja California. Another series of seven micronekton hauls, made across the stronger part of the front near Cape San Lucas on cruise TO–64–1, showed highest concentrations in the upwelled water on the cold side. The evidence, therefore, does not support the idea of a concentration of tuna forage in the Cape San Lucas front. This front may have no special attraction for tunas and is probably avoided by them when unsuitably cold water occurs in it.

CRUISE TO–64–2

The results of this cruise, which was made in August of a rather cold year (see fig. 1), are probably typical of conditions in the early part of the tuna season, including July, when the fish rapidly expand their range northward. Figures 5 and 6 show cruise coverage and property distributions. The isotherms in figure 6 refer to the temperature distribution on part 1 of the cruise, August 5–16, 1964. At the few stations that were re-

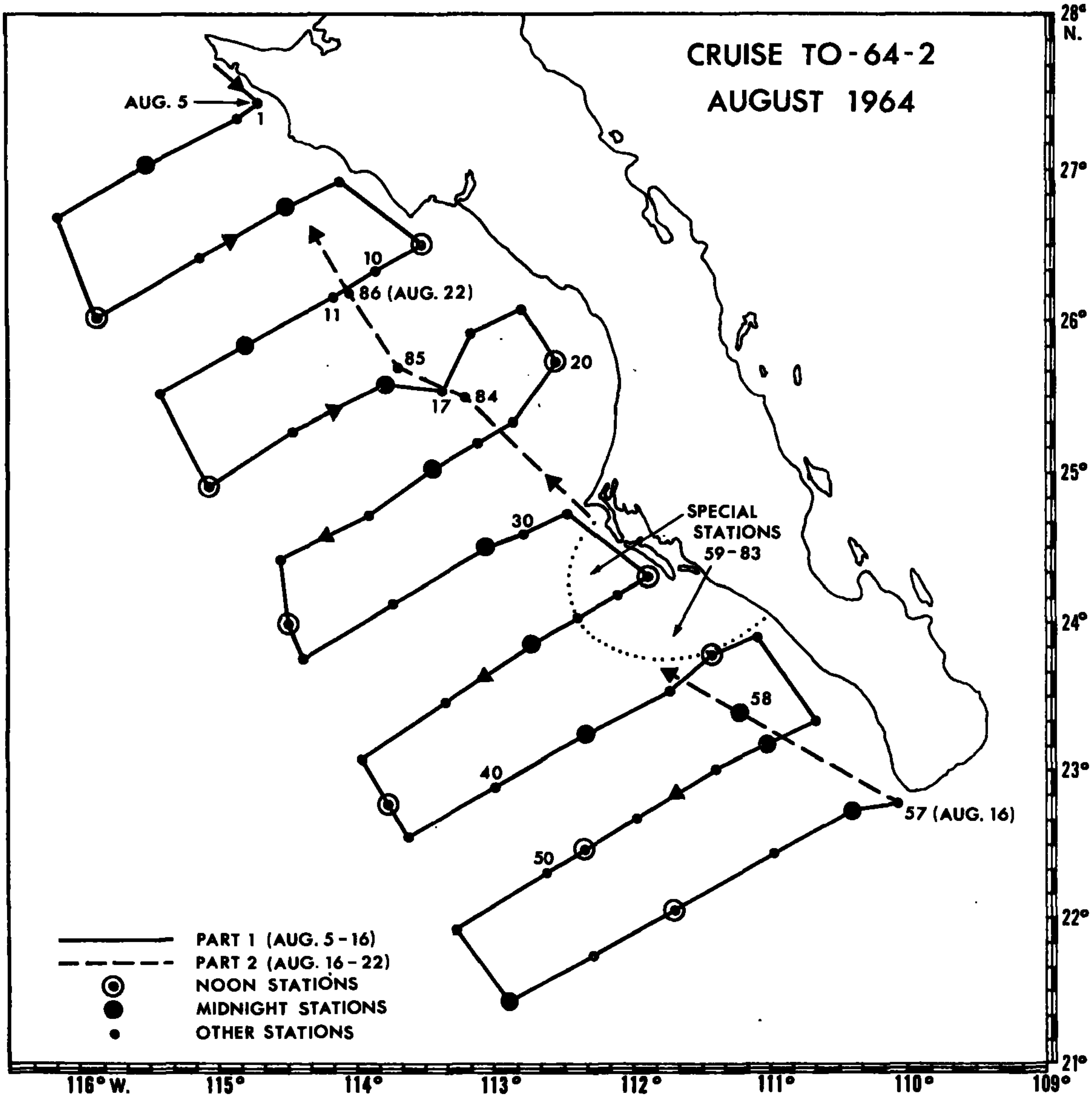

FIGURE 5.—Track and station positions for cruise TO–64–2.

occupied on part 2 of the cruise, temperatures were about the same as on part 1 except on August 21 and 22, when they were about 2° C. higher. Figure 6 includes only those tuna occurrences that were recorded for the period August 5–20. The red crab data are given in table 2.

Detailed surface temperature charts for the area in July and August show in most years a different configuration of isotherms from that found in June (Anonymous, 1963). Instead of lying more or less parallel to the coast, the isotherms become wavy; tongues of relatively cool water extend away from the coast, separated from each other by tongues of relatively warm water extending toward the coast. Figure 6 shows this situation very well; cold tongues run offshore from the two principal upwelling areas identified on cruise TO–64–1, and the northern area gives rise to at least two tongues. This distribution is probably caused by the eddies that characteristically appear about July and August (Wyllie, 1966). In figure 6 and later figures, the isotherms selected for charting always included those which showed the tongues, if present, in most detail. Temperatures under 20°

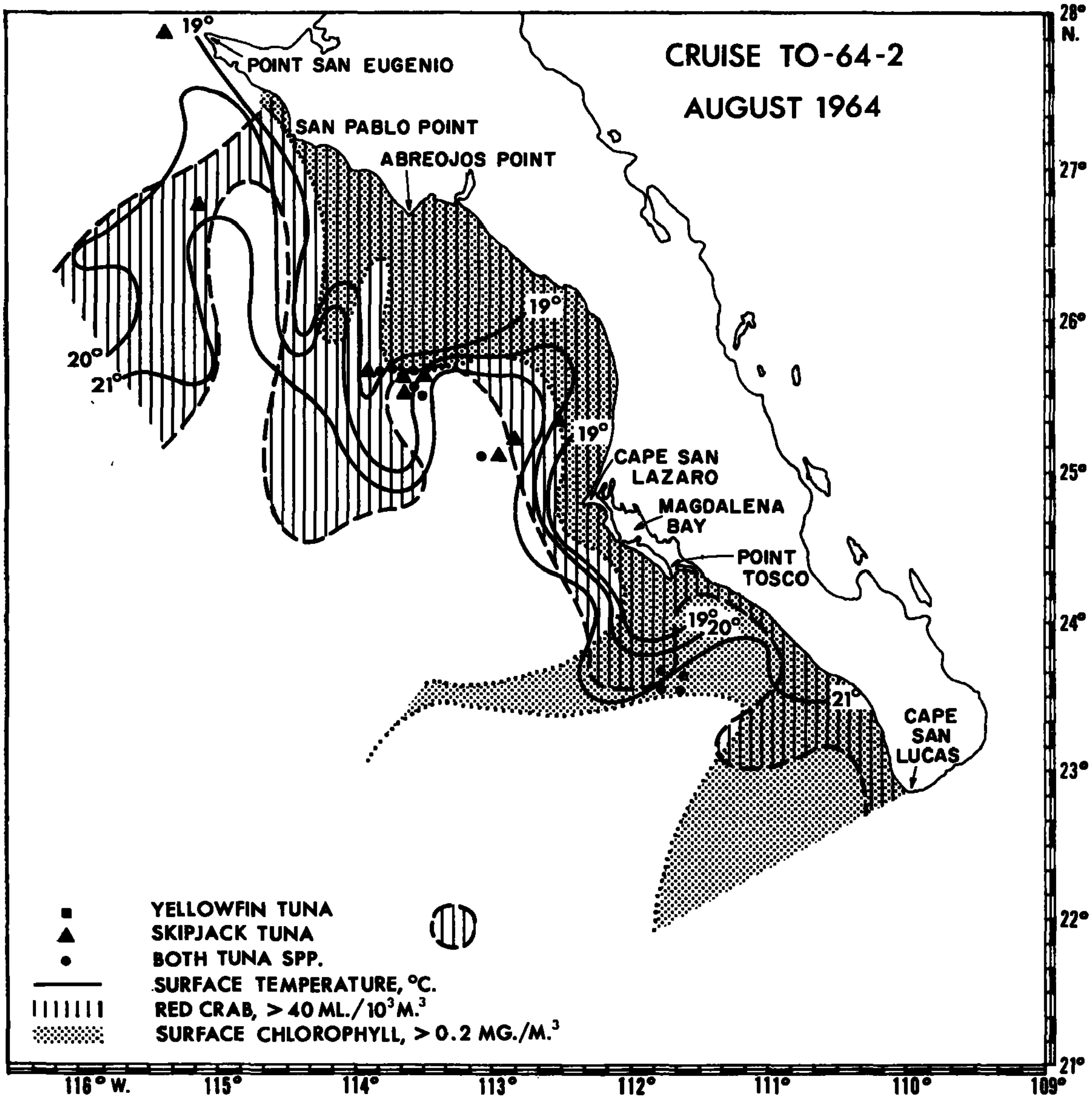

FIGURE 6.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–64–2 and locations of contemporaneous tuna catches.

occurred almost all along the coast on cruise TO–64–2; minima, at stations 1, 8, and 31, were between 15° and 16° C., and maxima, at stations 53 and 54, were between 26° and 27° C.

Concentrations of surface chlorophyll *a* ranged from 6.4 to 0.01 mg./m.³ Their generally much lower values than on cruise TO–64–1 reflect some decay in the upwelling regime. Only station 32 had a concentration above 1.0 mg./m.³ The isogram of 0.2 mg./m.³ in figure 6 follows rather closely the edge of the cool water, except in the extreme northwestern part of the area covered. It protrudes farther offshore between lat. 23° and 24° N. than the corresponding protrusion of the isotherms. The 0.1 mg./m.³ isogram (not shown) follows it closely in most areas.

The position of the isogram showing 40 ml./1,000 m.³ of red crabs is close to the 21° C. isotherm and the 0.2 isogram of chlorophyll *a*, except in the northwestern part of the area (fig. 6). In general, relatively high standing stocks of red crabs and

TABLE 2.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10 ³m.³ of water strained, on cruise TO–64–2*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³ m.³			*Ml./10³ m.³*			*Ml./10³ m.³*
4–5	H	520	30–31	H	143	58–59	H	165
7	Z,M	63	32	Z	531	60	S	>40
7–8	H	>40	34	Z	4	63	Z	103
12	Z,M	24	36	Z	13	64	Z	17
12–13	H	18	40	Z	11	65	Z	33
12–13	H	879	44	Z	9	69	Z	54
13	S	>40	45	S	>40	70	Z	9
16	M	1	46	M,Z	355	73	Z	9
16–17	H	190	50	Z	4	74	Z	7
17–18	H	333	51	Z	48	75	Z	13
17–18	H	18	51–52	H	3	76	Z	89
23	M	7	52	M,Z	37	77	Z	197
23–24	H	268	52–53	H	35	78	Z	28
23–24	H	>40	55	Z	6	79	Z	562
24	Z	11	56	M	1	80	Z	232
24–25	H	314	56–57	H	83	81	Z	101
27	Z	4	57	Z	13	(1)	M	>40
29	M	1	58	Z,M	5			

[1] Series of night surface hauls with the large micronekton net near Uncle Sam Bank.

chlorophyll *a* occurred together in the upwelling or in recently upwelled water.

The occurrences of tuna (both species) were on the edges of the area of high concentration of red crabs where surface temperatures were all between 22° and 18° C. No tuna were recorded in the large inshore areas where red crabs were equally or more abundant and temperatures were lower; the fish probably avoided these areas. One 1° square, bounded by lat. 26° and 27° N. and long. 114° and 115° W., had a significant amount of fishing effort (six boat-days) that yielded no tuna in the month of the cruise. According to figure 6, almost all of this area was either colder than 20° C. or had less than 40 ml./1,000 m.³ of red crabs; it is not surprising then that tuna were not found. Elsewhere, in areas where no occurrences are shown in figure 6, the distribution of yellowfin and skipjack tunas at the time of the cruise is not known. Tunas could have occurred along other parts of the edge of the cool, food-rich, water.

Figure 6 shows an isolated occurrence of abundant red crabs far offshore, where surface chlorophyll *a* was below 0.1 mg./m.³ and tuna distribution unknown. Such offshore distributions, which Boyd (1967) and Longhurst (1967) have reported previously, may represent individuals that the California Current has carried out of the coastal region.

CRUISE 6608

This CalCOFI cruise, made in August 1966, covered only part of the area of interest. The results represent conditions at a slightly later stage in the year than those for cruise TO–64–2. The CalCOFI stations have been given serial numbers as shown in figure 7. Figures 7 and 8 show cruise coverage and distributions of properties. The red crab data are given in table 3.

The surface isotherms (fig. 8), especially 23° C., show the same tonguelike distributions as before. Cool tongues ran offshore from areas which lie south of Point San Eugenio and Abreojos Point; here a small inshore belt of upwelling or upwelled water under 20° C. occurred. Warmer water lay on both sides of these tongues. Surface temperatures for the whole area were between 17° and 26° C.—very close to the range (16°–25° C.) in an average August (Anonymous, 1963).

Concentrations of surface chlorophyll *a* ranged from 2.0 to 0.03 mg./m.³, but those over 1.0 mg./m.³ were confined to a small inshore area between Point San Eugenio and San Pablo Point. It was not possible to draw an isogram for 0.1 mg./m.³ with confidence, because observations were not made in some parts of the area. In general, concentrations below 0.1 mg./m.³ were in water over 23° C., outside the main cool tongue shown in figure 8, but some of them were in the small (eastern) cool tongue as well. All concentrations above 0.2 were in the cooler water, as expected. They are charted in figure 8 to show two areas, which may, however, have been joined, because observations were not made between them.

The sampling of red crabs on this cruise was

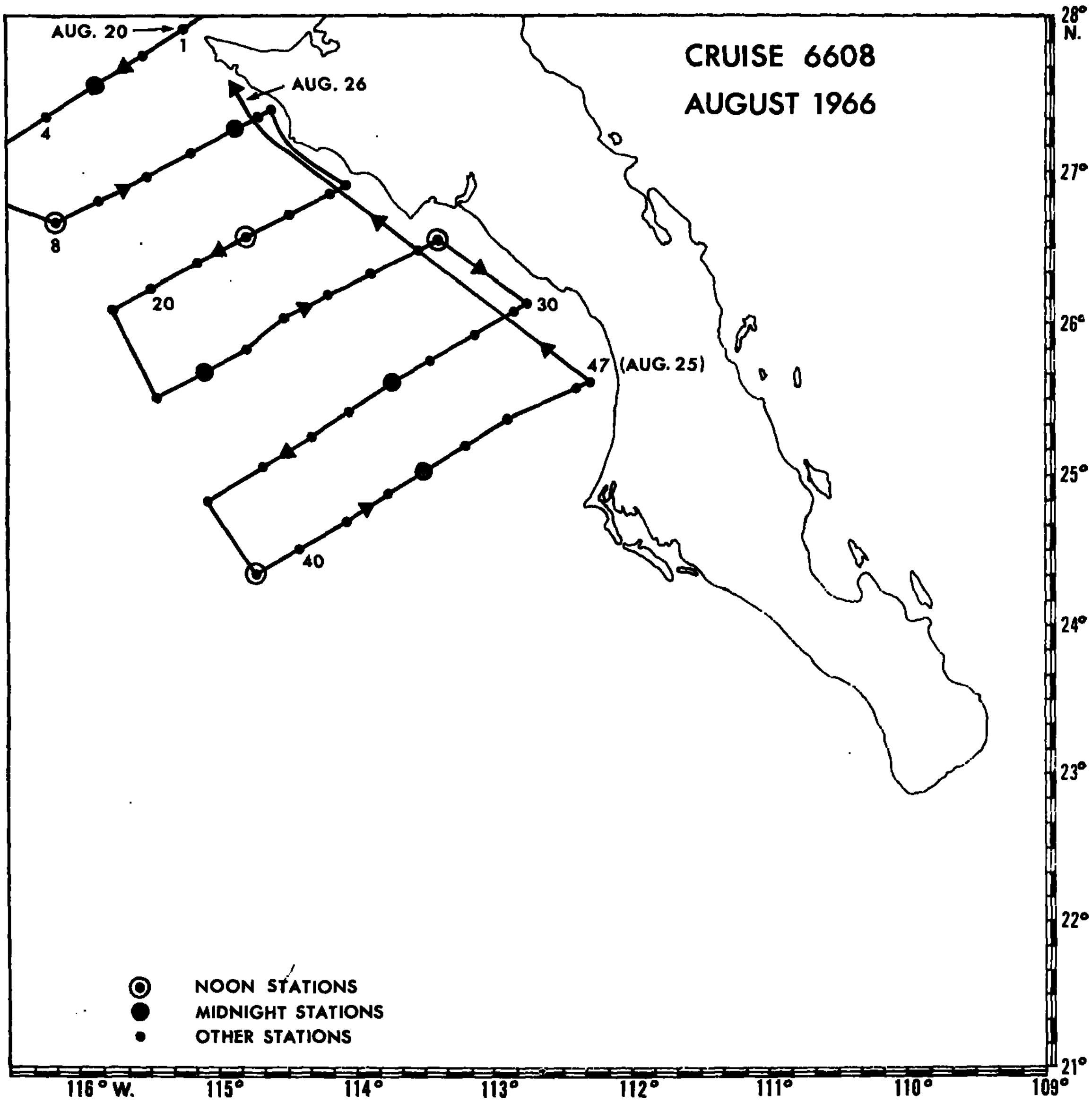

FIGURE 7.—Track and station positions for cruise 6608.

more restricted than on most of the other cruises because no standard micronekton hauls were made. Figure 8 shows four areas with concentrations over 40 ml./1,000 m.³ The northern area was in water which was cool and rich in chlorophyll *a* (over 0.2 mg./m.³); the eastern area was partly in and partly adjacent to the same kind of water; the southwestern area was in and adjacent to a tongue of cool water, with chlorophyll *a* concentrations about 0.1 mg./m.³; and the remaining small area was in warmer water where no chlorophyll data were obtained.

The data on tuna occurrence for the period of the cruise, August 20–26 (fig. 8) show a single record in the northern part of the area, located, like those on cruise TO–64–2, on the edge of an area that was rich in food but rather cold. The other records show a distribution of tuna right across one of the tongues of cool water, where temperatures were nevertheless high enough (over 20° C.) to permit the tuna to exploit the high concentration of red crabs; the tuna were located partly in and partly on the edge of this concentration of food. A significant amount of fishing

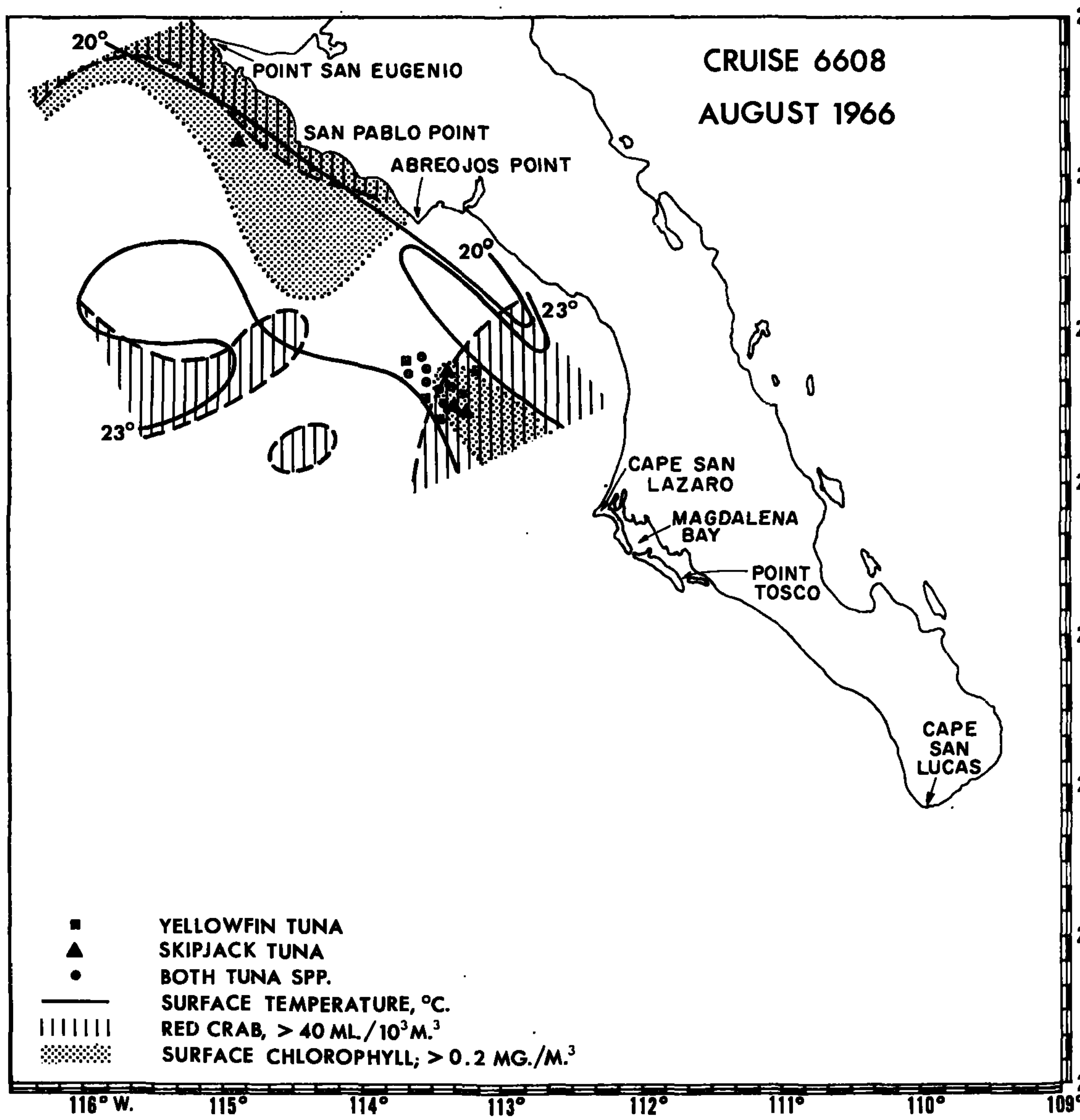

FIGURE 8.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise 6608 and locations of contemporaneous tuna catches.

effort (nine boat-days) in one 1° square, bounded by lat. 26° and 27° N. and long. 114° and 115° W., took no tuna in the month of the cruise. According to figure 8, nearly all of this area was either colder than 20° C. (the northeastern corner) or had less than 40 ml./1,000 m.³ of red crabs at the time of the cruise. It would not, therefore, be expected to contain many tuna. Elsewhere the distribution of tunas at the time of the cruise is not known. Fishing effort was not significant in the area of high concentration of red crabs in the southwestern part of the cruise area, where temperature and food were suitable for tunas.

CRUISE TO-59-2

This cruise, made August 16–29, 1959, was in a warm year (see fig. 1), and the results represent conditions at a later stage in the year than those for the previous cruise. The cruise started farther south than the others in this series; the area immediately to the north was covered at the same period by CalCOFI cruise 5908 which yielded

TABLE 3.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10 ³m.³ of water strained, on cruise 6608*

[Letters under kind of observation signify: Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³ m.³			*Ml./10³ m.³*			*Ml./10³ m.³*
1	Z	>40	23	Z	25	36	Z	113
1–2	H	>40	23–24	H	1,069	38	Z	6
2	Z	12	24	Z	7	41–42	H	17
5–6	H	392	24–25	H	334	43	Z	56
6	Z	13	25	S,Z	>40	43–44	H	426
7	Z	6	30	Z	28	44	S,Z	>40
14–15	H	1,353	31	S,Z	>40	45	Z	67
15	Z	13	31–32	H	818	45–46	H	468
16	Z	215	32	Z	20	46	Z	24
20	Z	7	32–33	H	12	(1)	H	5
21	Z	45	33–34	H	27	(1)	H	735
21–22	H	701	34	Z	14	(1)	H	1,762
22–23	H	1,044	35–36	H	58	(1)	H	14

[1] After station 47, on northbound track between lat. 26°30′ N. and 27°50′ N., at night.

temperature data (Scripps Institution of Oceanography, 1961), but no data on chlorophyll or red crabs. Cruise coverage and property distributions are shown in figures 9 and 10. Data on red crabs are given in table 4.

Surface temperatures were between 18° and 30° C. but the areas under 20° C. and over 28° C. were extremely restricted (fig. 10). The cold inshore region between Point San Eugenio and San Pablo Point probably represents upwelling at a very late stage. A large tongue or tongues of relatively cool water (less than 25° C.) ran offshore from the coastal upwelling area as shown for previous cruises. No such signs of relatively cool water were off Magdalena Bay, where upwelling probably ceases earlier than it does farther north.

Observations on surface chlorophyll *a* were fewer on this cruise than on the others. Concentrations were much lower than before—from 0.11 to 0.02 mg./m.³, which is consistent with the indications of a further weakening of upwelling. Concentrations were at or above 0.1 mg./m.³ only at stations 20, 30, 37, 38, 41, and 42. The isogram of 0.05 mg./m.³ follows the 25° C. isotherm fairly well (fig. 10), so the offshore tongue of relatively cool water generally had a higher concentration of chlorophyll than the surrounding warmer water.

The area in which concentrations of red crabs exceeded 40 ml./1,000 m.³ was broadly congruent with the area of cool water and the area of highest surface chlorophyll. The isograms of these three properties tend to be displaced a little from each other, but otherwise they agree in considerable detail. There was an isolated patch of red-crab-rich water off Magdalena Bay; it was not cool, and chlorophyll was not sampled in this particular area.

About half of the tuna catches that were made at the time of the cruise were north of Abreojos Point, where data on chlorophyll and red crabs are lacking; temperatures were mostly over 20° C. The catches to the south of Abreojos Point all were from water over 20° C. and show the kind of association with chlorophyll and red crabs that was mentioned for cruise 6608. The tuna were not only on the edges of the biologically rich areas but in the cores of these areas as well. The areas of abundant forage, which on cruise TO–64–2 were too cold for tunas except at the edges, were warm enough for the fish to penetrate on this cruise. As before, tuna distribution was not determined (insignificant amount of fishing) in certain large areas, including some in which temperature and food conditions appeared highly suitable.

CRUISE TO–65–1

This cruise (figs. 11 and 12), which was in September 1965, represents a still later stage in the year, when the distribution of surface temperature gives no indication of any coastal upwelling. The lowest temperatures, between 20° and 21° C., were offshore and probably indicate California Current water. The highest temperatures were slightly over 28° C. Temperatures on part 2 of the cruise were about the same as on part 1. On CalCOFI cruise 6509, which extended into the northern part of the area near the end of cruise TO–65–1, sur-

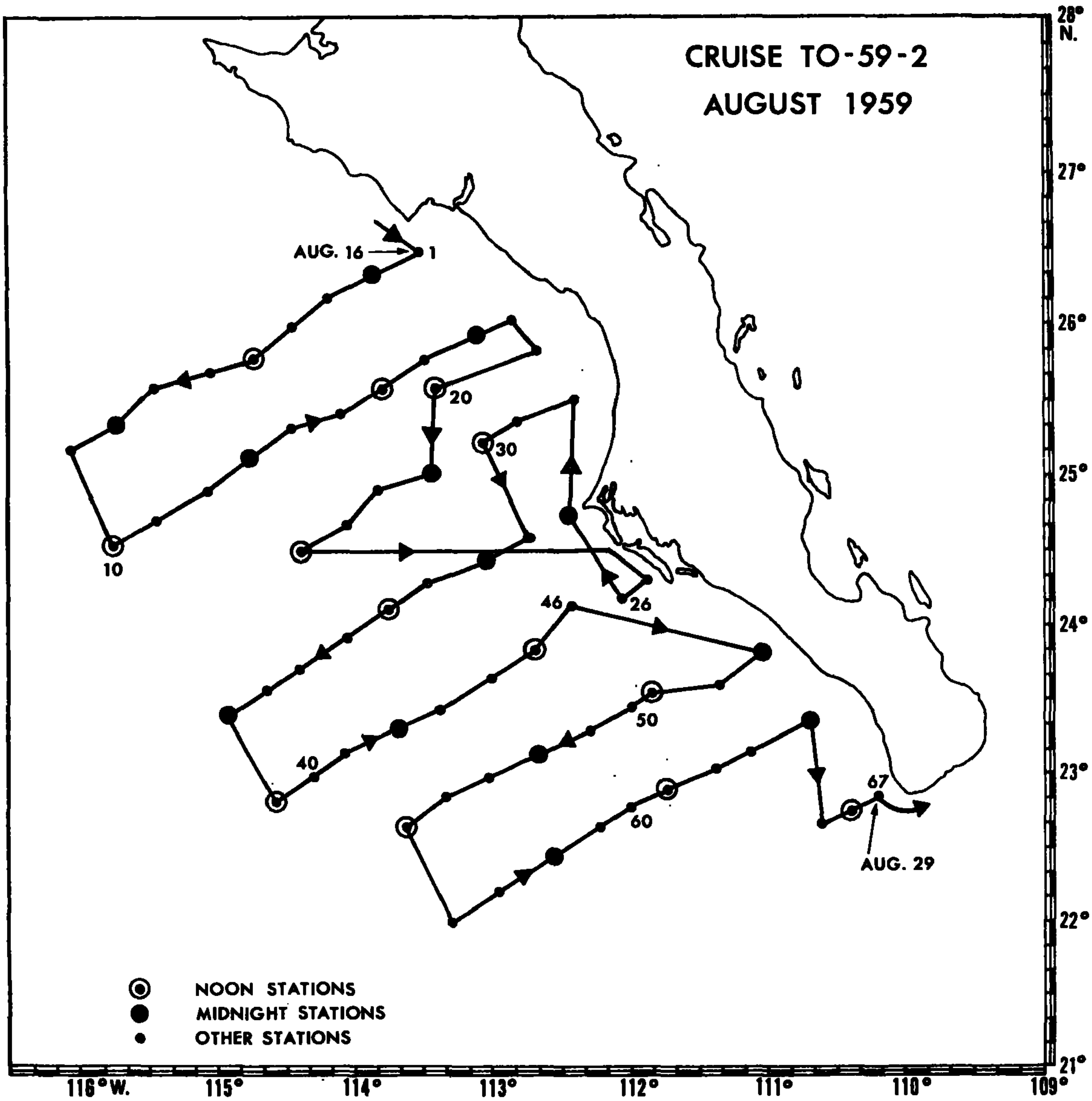

FIGURE 9.—Track and station positions for cruise TO–59–2.

face temperatures were about 1.5° C. lower in a few inshore localities, and elsewhere about the same as on TO–65–1 (Scripps Institution of Oceanography, 1967). Even these lower temperatures were over 20° C. and would not be expected to affect tuna distributions; therefore, all tuna occurrences for the whole period, September 8–25, 1965, have been given in figure 12. Data on red crab concentrations are given in table 5.

Surface chlorophyll *a* concentrations were all below 1.0 and ranged down to 0.02 mg./m.^{3}, although they were generally higher than on cruise TO–59–2. The 0.2 mg./m.^{3} isogram encloses the area of highest concentration, which is tonguelike and originates on the coast south of Point San Eugenio, as on previous cruises. It probably represents the biological result of a tongue of upwelled water which can no longer be distinguished from the surrounding water by its temperature. All stations inshore of this tongue and the following stations offshore had over 0.1 mg./m.^{3}: 4–6, 12, 13, 17, 23, 26–29, 32, and 36.

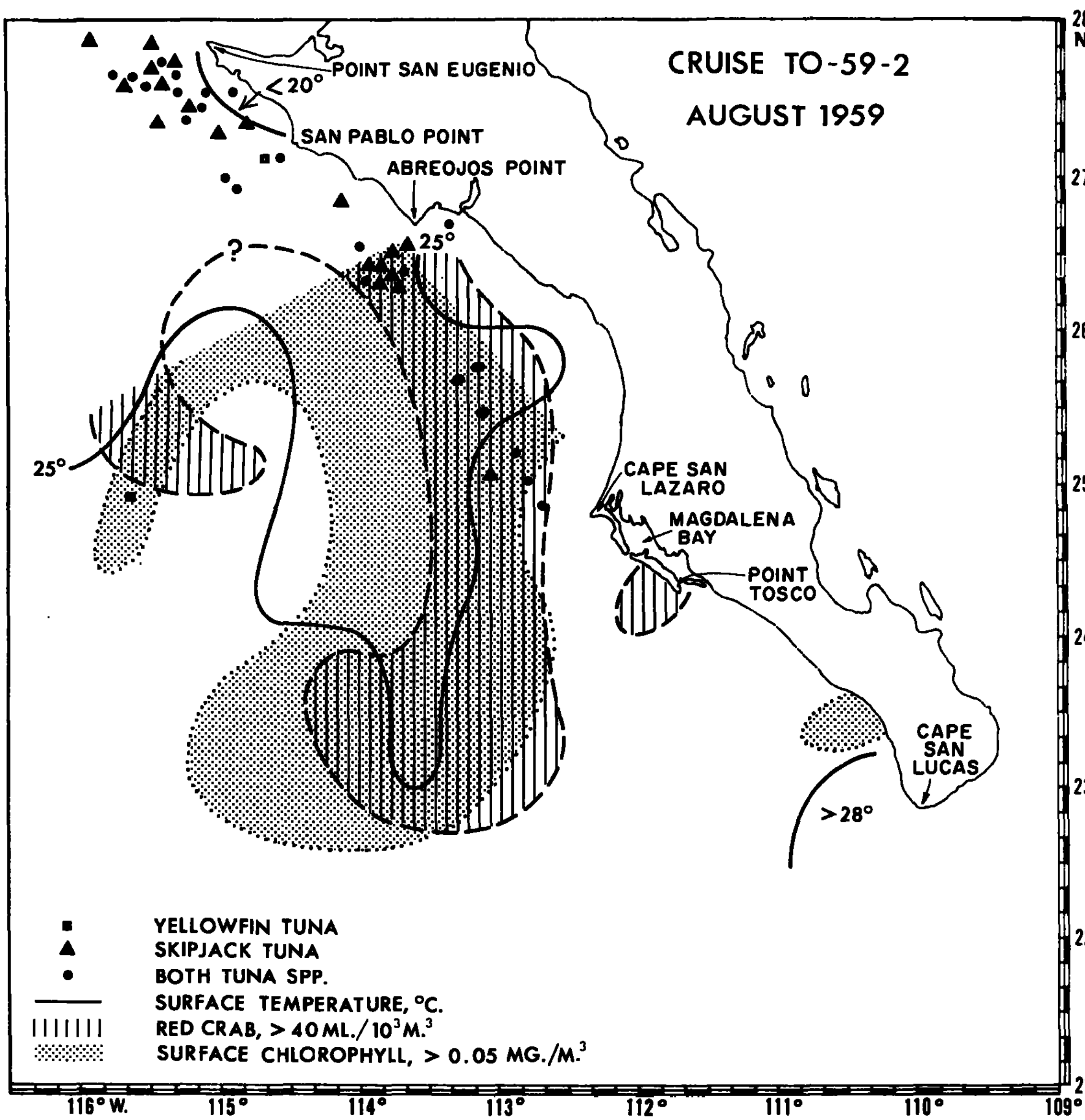

FIGURE 10.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO-59-2 and locations of contemporaneous tuna catches.

The area where red crabs were over 40 ml./1,000 m.[3] shows the same close but not exact correspondence with the chlorophyll-rich area that was found on previous cruises, and all the tuna catches were made in or very close to this area. The highest concentrations of carnivores (tuna), herbivores (red crabs), and plants (chlorophyll *a*) all were in the same restricted area. Because all temperatures were suitable for tunas, the tunas occurred, as before, not only around but through the food-rich areas.

CRUISE TO-66-1

The cruise period in the area of interest was November 4–21, 1966. The cruise (figs. 13 and 14) included stations with numbers below 15 and above 70, which were occupied on behalf of another investigator and were all north of lat. 28° N.

As I expected, conditions were much more uniform throughout the area on this cruise than on any of the others, because coastal upwelling had ceased. The only inshore pocket of cool water,

TABLE 4.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10^3 m.^{3} of water strained, on cruise TO–59–2*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10^3 m.^{3}			*Ml./10^3 m.^{3}*			*Ml./10^3 m.^{3}*
1	S	>40	20	S,Z	>40	36	Z	6
2	Z,M	>40	21	M	64	38	M,Z	34
5–6	H	2	21–22	H	36	38–39	H	2
6–7	H	4	22–23	H	20	40–41	H	93
7	Z	>40	26	Z	158	41–42	H	5
8	M	176	26–27	H	15	42	M	132
8–9	H	35	26–27	H	16	42–43	H	5
9–10	H	3	27–28	H	8	43–44	H	8
11–12	H	1	28–29	H	6	46–47	H	6
13	M	42	30–31	H	8	46–47	H	27
13–14	H	26	30–31	H	1,158	52	M	108
15	Z	6	31	Z	7	53	Z	128
15–16	H	2	32	Z,M	229	53–54	H	495
17–18	H	225	32–33	H	158	54	Z	9
18	Z	>40	33	Z	58	55	Z	8
18–19	H	24	34	Z	9	57	Z	15
19–20	H	43	35	Z	13	57–58	H	2
19–20	H	213	35–36	H	59	58	M,Z	20

which might have indicated upwelling, was a very small one off Point Tosco (21°–22° C.). Temperatures for the whole area were between 18° and 26° C. on part 1 of the cruise; on part 2, temperatures at reoccupied stations were only slightly (less than 1° C.) lower.

The range of chlorophyll *a* concentrations was about the same as on cruise TO–65–1, but their distribution was more uniform. Concentrations were over 0.1 mg./m.^{3} in most of the area as shown in figure 14. Concentrations were over 0.2 mg./m.^{3} at all stations north of lat. 26° 20′ N., and there only. Similarly, concentrations of red crabs were 40 ml./1,000 m.^{3} or higher in most parts of the cruise area (see table 6 for data). Finally, the recorded catches of tuna (all those for the period November 4–21) were scattered through the large area of suitable temperatures and abundant red crabs.

There was no opportunity to make a similar cruise closer to the end of the season for yellowfin and skipjack tunas off western Baja California, say in December or January. Such a cruise would probably have shown that the area available for the tunas had contracted because of the southward movement of isotherms, and a rather featureless distribution of the tunas—similar to that on cruise TO–66–1, associated with relatively uniform distributions of red crabs and chlorophyll *a*—in the area of suitable temperature.

OCEANIC PROPERTIES AND THE DISTRIBUTION OF TUNAS

The results of cruises TO–64–1, TO–64–2, 6608, and TO–59–2 all show the expected close agreement in detail between areas of relatively cool water that are attributable to upwelling and areas of relatively high surface chlorophyll *a*. The poor agreement between isograms of temperature and chlorophyll *a* in the northwestern portion of the cruise area shown in figure 6 is not necessarily an exception to the preceding statement, because the cool water may not represent upwelling there. The results of cruise TO–65–1 show a region of relatively high surface chlorophyll *a* in a locality and with a shape, which suggest an origin in upwelled water. No signs of upwelling appeared on cruise TO–66–1. The distributions of surface isotherms in space and time are consistent with previous information about upwelling off southern Baja California. Temperatures rise and chlorophyll *a* concentrations fall in the upwelling areas as the upwelling becomes weaker.

The results of all the cruises show rather close agreement in detail between the areas of relatively high surface chlorophyll *a* and the areas in which the concentration of red crabs is more than 40 ml./1,000 m^3. The concentration of chlorophyll *a* which shows this agreement varies; on most of the cruises it was 0.2 or 0.1 mg./m^3., but it was higher on cruise TO–64–1 and lower on cruise TO–59–2. The only complete lack of agreement appears in

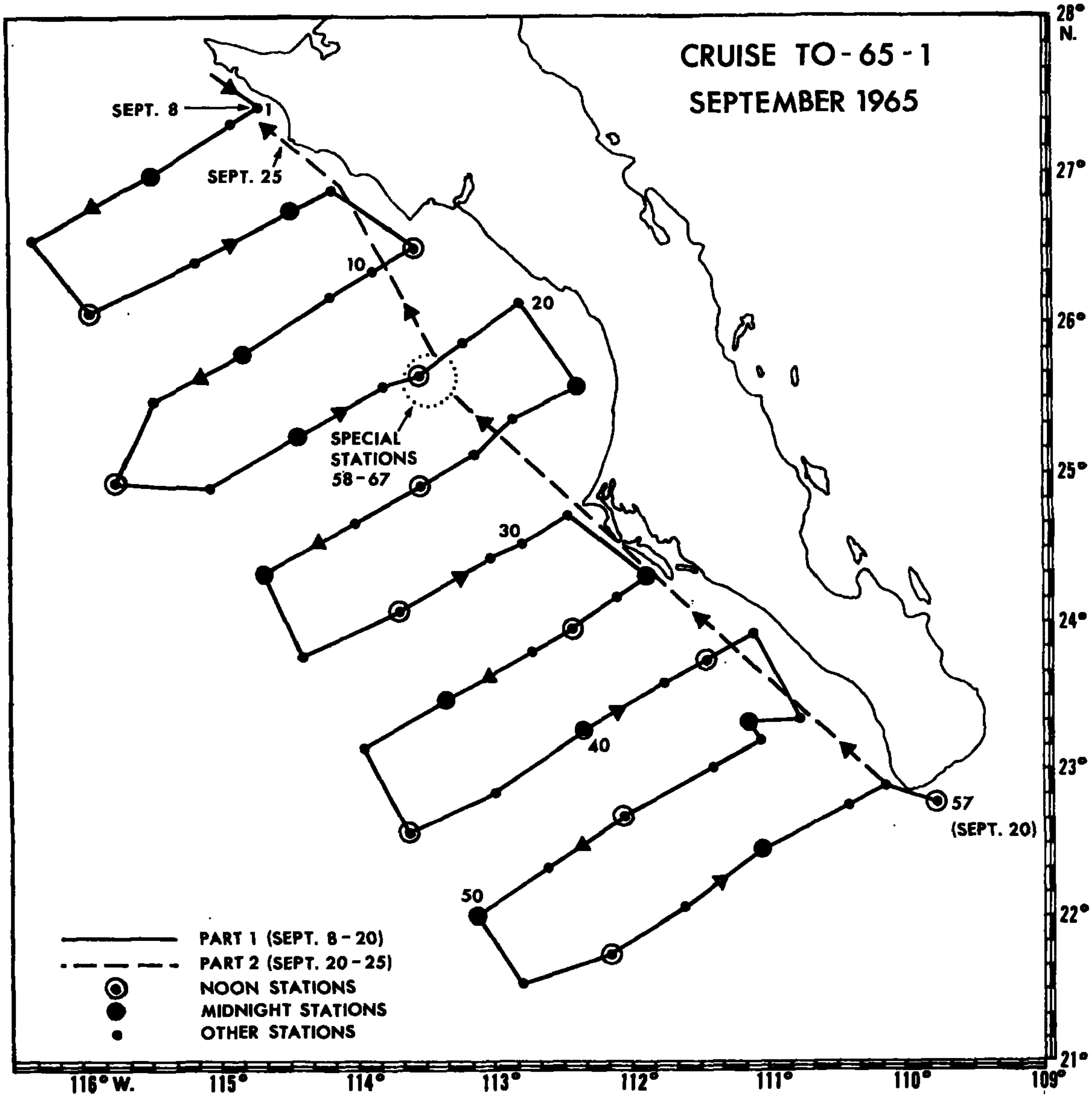

FIGURE 11.—Track and station positions for cruise TO-65-1.

the northwestern part of the cruise area shown in figure 6. Elsewhere in all the charts, agreement is fair to good. The area boundaries for the two properties seldom coincide, but they tend to lie close together and to have the same shape. Where the isograms of chlorophyll *a* follow those of temperature, all three properties—temperature, chlorophyll *a*, and red crabs—have a closely similar distribution (e.g., fig. 10).

The occurrence of red crab maxima with chlorophyll *a* maxima is not surprising because red crabs feed on phytoplankton, but the circumstances whereby they maintain aggregations in chlorophyll-rich areas are not altogether clear. On the one hand, the distribution data of Boyd (1967) and Longhurst (1967) indicate that the red crab can be swept away from the coast by the California Current during its pelagic phase. On the other hand, substantial numbers of this species occur in the benthos along the Continental Shelf and Slope (Boyd, 1967), and these individuals probably help to maintain pelagic concentrations in coastal areas by generating larvae and by ascending into the upper waters from time to time. Larvae are most

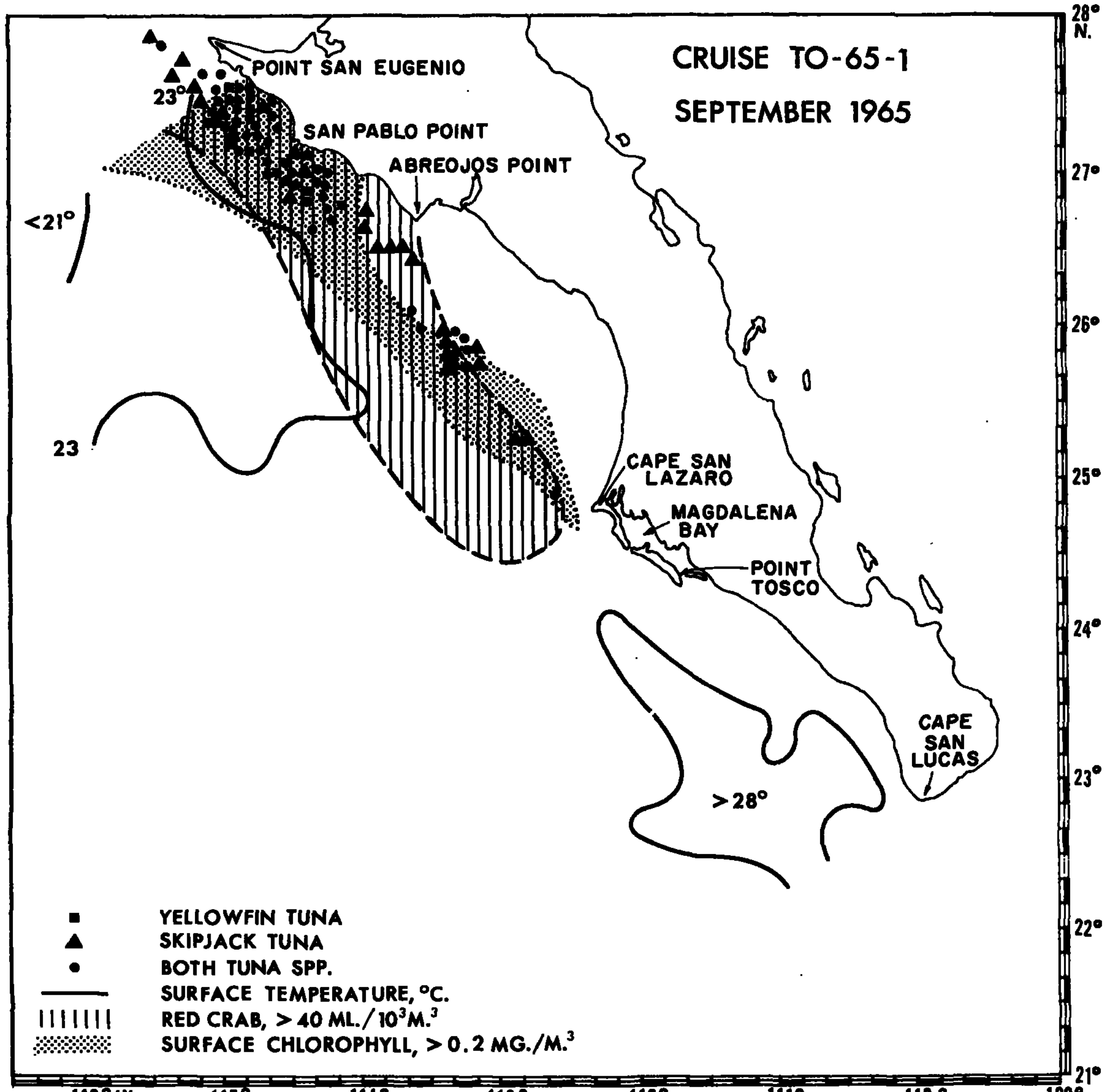

FIGURE 12.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO–65–1 and locations of contemporaneous tuna catches.

numerous in inshore waters off the west coast of southern Baja California before and during the upwelling season, and benthic adults probably produce many of them (Longhurst, 1968a). The maintenance of pelagic aggregations is probably served also by the formation of inshore eddies after June (Wyllie, 1966). I assume that these processes, together with the animal's own appreciable mobility, maintain high concentrations in inshore areas where food (phytoplankton) is abundant; when food is scarce inshore red crabs presumably sink, disperse, or die.

The presence of red crab concentrations in cool water on some of the cruises results from the relation between chlorophyll *a* and upwelling, and is, therefore, not apparent on cruises TO–65–1 and TO–66–1. Longhurst (1967) showed that red crabs are practically eurythermal between about 9° and 28° C.

The data on tuna occurrence are all consistent with the hypothesized association with surface temperature (about 20° C. or more) and food sup-

TABLE 5.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in* $ml./10^3 m.^3$ *of water strained, on cruise TO–65–1*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water; P, found in predator stomachs. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10³ m.³			*Ml./10³ m.³*			*Ml./10³ m.³*
2	Z	64	21–22	H	9	54	Z,M	3
3	M	1	22–23	H	15	(1)	P	>40
6	Z	32	26	M	22	60	Z	5
7	M	1	29	S,Z	>40	61	Z	55
7–8	H	500	36	Z	21	62	Z	3
8	Z	6	37	Z,M	12	63	Z	32
10	S,Z	>40				64	Z	3
11	Z	4	39	Z	5	65	Z	10
11–12	H	5	40	M,Z	4	66–4	Z	2
12	M,Z	3	41	Z	4	(2)	M	>40
12–13	H	5	42	Z	6	(3)	H	20
12–13	H	20	44	Z	2	(3)	H	158
15–16	H	5	45	M	<1	(3)	H	550
16	M,Z	5	49	Z	18	(3)	H	>40
16–17	H	342	49–50	H	15	(3)	H	2,500
18	Z	2	50	M,Z	24	(2)	H	100
20–21	H	18	51	Z	2	(3)	H	30

[1] Stomach contents of 3 yellowfin tuna (*Thunnus albacares*) at Thetis Bank.
[2] Series of night surface hauls with the large micronekton net near Uncle Sam Bank.
[3] After station 67, on northbound track between lat. 25°50′ N. and 26°40′ N., at night.

ply (40 ml./1,000 m.³ or more of red crabs), for all cruises except TO–64–1. On that cruise the tunas showed a tolerance of temperatures down to 17° C., but no lower in the presence of a larger food supply than that available to them at or over 20° C. Only one small area of abundant food (over 40 ml./1,000 m.³) and no area in which it was highly abundant (over 100 ml./1,000 m.³) had temperatures at and over 20° C.; food was highly abundant only at temperatures below 17° C. This difficulty (for the tunas) did not arise on any of the other cruises. On cruise TO–64–2 the edges of the areas of abundant food were warm enough for the tunas, which were found there and nowhere else. On cruises TO–59–2, TO–65–1, and TO–66–1 all parts of the food-rich areas were warm enough for tunas, which were, accordingly, widespread in them; they might have been found in still other places in the food-rich areas if the fishermen had searched there. On cruise 6608 the situation was partly like cruise TO–64–2 and partly like the other cruises. Except on cruise TO–64–1, no tuna were ever found more than 20 nautical miles (37 km.) from the charted boundaries of the food-rich areas.

From these results I may conclude that yellowfin and skipjack tunas aggregate in the areas of most abundant food where surface temperatures are about 20° (±1°) C. or over in waters west of Baja California, except at the beginning of their seasonal entry into those waters when they may occur at temperatures down to 17° C. Temperature determines range limits (penetration northward and toward the coast), and food supply determines distribution within the range limits. Because the principal food in this area is the red crab which occurs in areas rich in phytoplankton, tunas generally aggregate in or near the areas of highest surface chlorophyll *a*, provided that temperatures are suitable.

Because the distributions of temperature, chlorophyll *a*, and red crabs are all partly controlled by the seasonal coastal upwelling, at least through September, the same is true of the distribution of the tunas. Concentrations of tuna prey are much higher off western Baja California than anywhere else in the eastern tropical Pacific, where they are generally less than 10 ml./1,000 m.³ (Blackburn, 1968). These high values are a consequence of the upwelling and of the unusually short tuna food chain. The upwelling, however, furnishes an environment that tends to be too cold for yellowfin and skipjack tunas in spite of its biological richness, and this physical feature is decisive. The tunas do not enter the area and exploit the rich food supply until temperatures begin to rise. They then aggregate around the edges of the large tongues or patches of food and gradually penetrate into the cores of those areas as they become warm. Later the distribution of both the food and the tunas

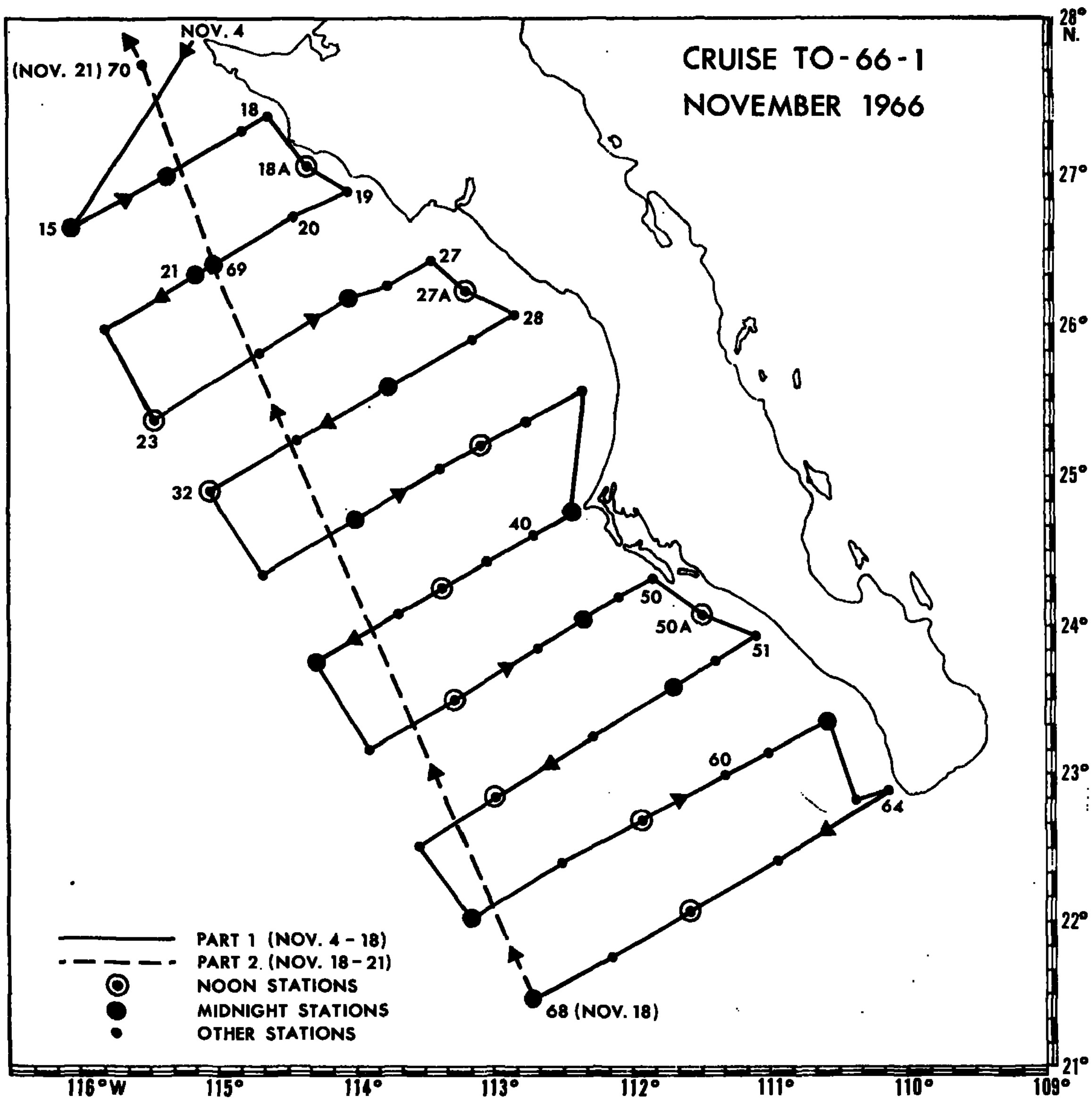

FIGURE 13.—Track and station positions for cruise TO-66-1.

becomes rather uniform in areas of suitable temperature, and finally the physical environment again becomes unsuitable with the start of winter cooling. The supply of pelagic red crabs remains fairly high throughout the year (Longhurst, 1967; Blackburn, 1968; and this paper).

The foregoing interpretation of the tuna distribution data might be criticized on two grounds. One is that nearly all the tuna catches shown in the charts were within 100 nautical miles (185 km.) of the coast, although suitable environmental conditions occurred much farther offshore on some of the cruises (see figs. 8 and 10), as well as in the inshore areas where the catches were made. Charts of IATTC data from the commercial fishery for many years, compiled by Joseph and Calkins (1969), show clearly that most of the fishing effort in the Baja California area is expended and most of the catch of both species taken within about 100 nautical miles of the coast. This situation is understandable because the tuna are associated with upwelling, which is a coastal process, and fishermen generally do not operate farther offshore than is necessary to make good catches. On

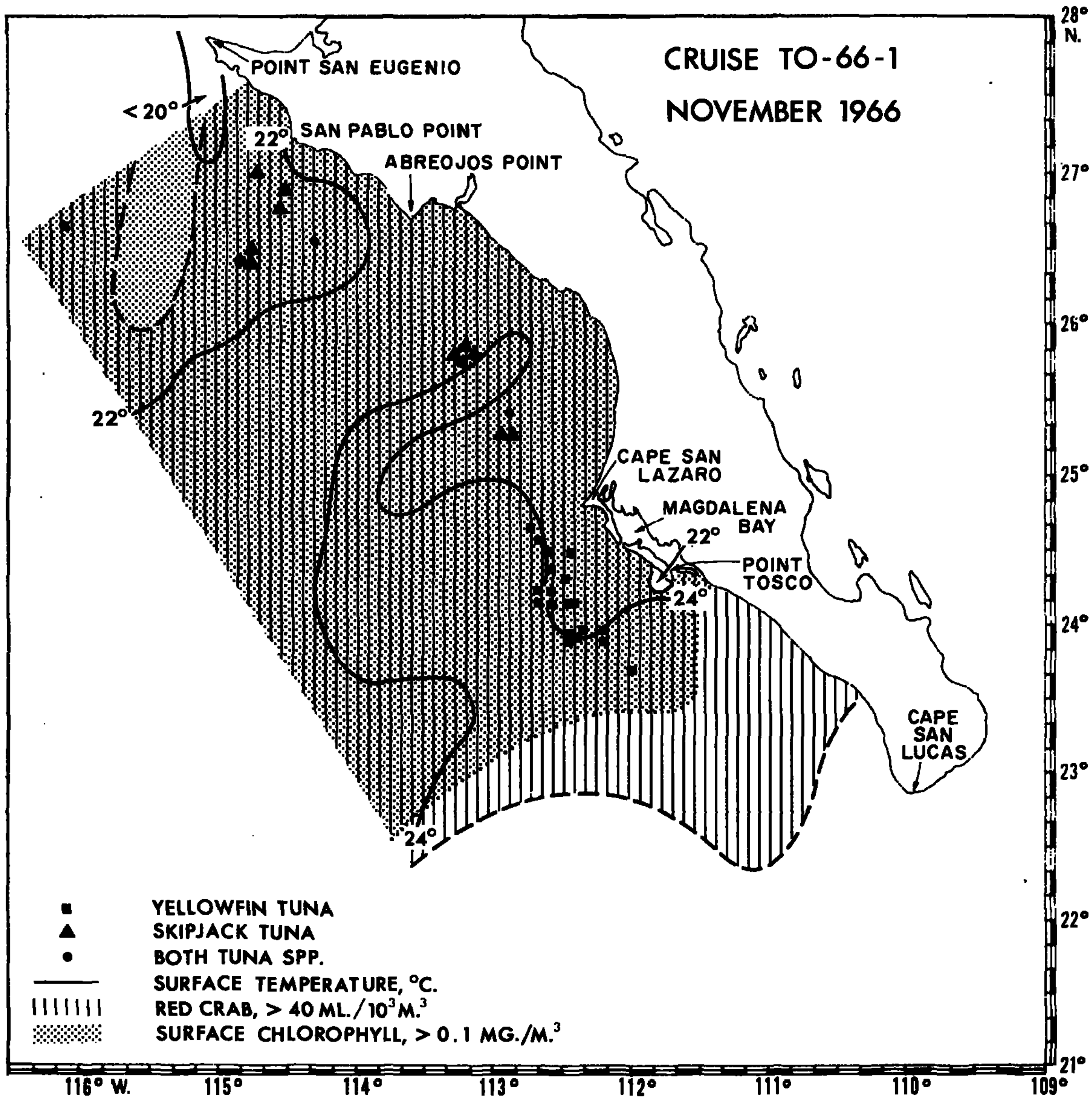

FIGURE 14.—Distributions of surface temperature, surface chlorophyll *a*, and red crabs for cruise TO-66-1 and locations of contemporaneous catches.

the other hand, the IATTC charts show that yellowfin and skipjack tunas are sometimes sought and captured offshore, for instance at Alijos Rocks, about 150 nautical miles (278 km.) from the coast (fig. 2), and even about 1° of longitude to the west of that locality. Nothing suggests that these offshore tuna are not aggregated in food-rich areas of suitable temperature in the same way as the inshore tuna. Furthermore, one definite record of an offshore commercial tuna catch appears to be associated with a tongue of food-rich water (fig. 10). This catch was at Alijos Rocks on cruise TO-59-2. The only other cruise in the present series which yielded information about properties at Alijos Rocks was TO-65-1 (see fig. 11, station 14). On that occasion, no tongue of biologically rich water reached the Rocks area, concentrations of chlorophyll *a* and red crabs were low, no tuna were seen or caught while the scientific party was fishing at the Rocks, and no commercial catches were recorded there during the cruise period.

The other possible objection to the model of

TABLE 6.—*Concentrations of* Pleuroncodes planipes, *adults and juveniles (not larvae), in ml./10^3m.^{3} of water strained, on cruise TO–66–1*

[Letters under kind of observation signify: M, micronekton haul; Z, zooplankton haul; H, high-speed net haul between stations; S, seen in the water. Where concentrations were measured or estimated by more than one method, the highest concentration, corresponding to the first letter, is listed]

Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration	Station No.	Kind of observation	Concentration
		Ml./10^3 m.^{3}			*Ml./10^3 m.^{3}*			*Ml./10^3 m.^{3}*
15	S	>40	33–34	H	5,238	50	S,Z	>40
16	M	<1	34	S,Z,M	>40	52–53	H	43
17	Z	6	34–35	H	720	53	S, Z,M	>40
18A	Z	12	35	Z	7	53–54	H	25
20	S,Z	>40	36	Z	35	53–54	H	87
20–21	H	23	37	Z	7	56	Z	>40
21	S,Z,M	>40	38–39	H	20	57	M	<1
21–22	H	2	39	Z	41	59	Z	7
23–24	S	>40	39–40	H	13	60	S	>40
24	Z	7	40	M,Z	67	61	Z	57
24–25	H	20	41	Z	7	62	Z	50
25	M,Z	>40	42	Z	7	63	Z	7
25–26	H	53	43	S,Z	>40	65	S	>40
26	Z	27	43–44	H	73	68	Z	>40
27	Z	18	44	Z,M	19	(1)	H	233
29	Z	26	45	S,Z	>40	(1)	H	70
29–30	H	37	46	Z	13	(1)	H	150
30	S,Z,M	>40	47	Z,S	>40	(1)	H	82
30–31	H	704	48	M,Z	144	69	S,Z	>40
30–31	H	792	48–49	H	87	(2)	H	>40
33	S,Z	>40	49	Z	205			
33–34	H	>40	49–50	H	260			

[1] After station 68, on northbound track between lat. 23°40′ N. and 25°30′ N., at night.
[2] Immediately after station 69, on northbound track, at night.

tuna distribution offered in this paper is that many people who are acquainted with the Baja California fishery consider that yellowfin and skipjack tunas are distributed in relation to the banks shown in figure 2 and that abundance is higher at the banks than elsewhere, except when temperatures are low. No publications clearly demonstrate this relation as far as Baja California is concerned, and no studies off Baja California or elsewhere show conclusively the nature of any "bank effect" which might be attractive to tunas. In fact, only one such study has been attempted and the results were inconclusive (Bennett and Schaefer, 1960, at Shimada Bank in the eastern tropical Pacific). Nevertheless, belief in some kind of favorable bank effect upon tunas is so widespread that it must be considered here.

The tuna catches charted in figures 4, 6, 8, 10, 12, and 14 may be compared with the bank positions in figure 2. Many of the catches were made at or very near banks; they can be classified into two groups. All of those for the periods of cruises TO–64–2, 6608, TO–59–2, and TO–65–1 were in or close to tongues or patches of upwelled water, which either enveloped or touched the banks. None of the catches in the periods of cruises TO–64–1 and TO–66–1 were associated with upwelled water. On TO–64–1 no such water was warm enough for the tunas to enter, and on TO–66–1 there was none at all. The charts show also that many catches were in areas of upwelled water which were not close to banks, except on cruises TO–64–1 and TO–66–1.

When upwelled water of coastal origin extends over banks, it provides a ready explanation not only for the catches of tuna on banks (and at Alijos Rocks, as noted above) but also for the catches made between the banks. The unspecified bank effect may exist independently of the upwelling effect, but it is not required to explain the tuna distributions. If a bank effect exists, it is probably small in relation to the upwelling effect, and the banks are probably more suitable for tuna when upwelled water reaches them (providing it is not too cold) than when it does not. An observation from Uncle Sam Bank, which is very frequently visited by fishermen during the tuna season, is pertinent. Surface temperature charts for CalCOFI cruises 6007–8 (July 26 to Aug. 13, 1960, in the area of interest) and 6008 (Aug. 20–22, 1960) both show tongues of cool water (but over 20° C.) protruding offshore from the northern upwelling area. On the earlier cruise the tongue lay considerably west of Uncle Sam Bank, but on the later cruise it had changed its position and enveloped the bank (Scripps Institution of Oceanography, 1962a, 1962b). No tuna catches were recorded near the bank during the first cruise period.

but some were recorded there during the second period.

On the other hand, tuna aggregations upon banks which are not affected by upwelled water might be primarily attributable to a bank effect. Further work is needed to establish the reality of the bank effect and to explain it if it does exist. Obviously, this research should be attempted in a situation where upwelling is not likely to interfere with the bank environment, such as one of the offshore southern banks toward the end of the tuna season. In the meantime, it is reasonable to assume that some feature of banks makes them slightly more attractive to tunas than other areas when temperatures are suitable, and that this feature affects tuna distributions in situations where upwelled water does not interfere. Off Baja California these situations are probably most common in the southern part of the area, where upwelled water does not seem to reach far offshore; at the beginning of a tuna season when tuna are unable to enter upwelled water; and after all upwelling has ceased.

Fishermen often make an additional observation that tunas aggregate near boundaries between blue and green water. Some of the results of this study, especially for cruise TO–64–2, are consistent with that opinion. Blue water would frequently have suitable temperature but not much food; green water may contain suitable food but be too cold. Tuna would be expected to aggregate at the boundary under those circumstances.

The relation of tuna to the Cape San Lucas front was discussed under cruise TO–64–1. Evidence is lacking that this particular front has any effect upon tunas independent of the tuna-limiting temperatures that may occur in it. Low temperature tends to be limiting, whether located in the front or not, and no other feature of the front seems to have any effect upon the tunas.

If the area west of Baja California could be thoroughly and frequently monitored for surface temperature and surface chlorophyll *a* during a tuna season, it would be possible to specify areas in which aggregations of yellowfin and skipjack tunas would be expected—including offshore areas which fishermen might not otherwise visit—and those in which tuna would not be expected. This work could perhaps be done from ships, which already yield much data on surface temperature and could be equipped to yield data on surface chlorophyll *a* (Lorenzen, 1966). The chlorophyll equipment would be costly, however (about $2,000 per ship), and require careful maintenance aboard ship. Overflying aircraft or satellites offer another possibility. They would probably yield much more useful data than ships except in cloudy situations. Methods of measuring surface temperature from sensors above the ocean already exist, and measurement of surface chlorophyll is said to be feasible (Duntley, 1965). Obviously, the chlorophyll information could assist in mapping distributions of other useful organisms besides tuna—for example, the red crab itself, a possible human resource (Longhurst, 1968b), and other herbivores. Temperature data alone would be insufficient to specify distributions of tuna or red crab.

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