400

TUNA OCEANOGRAPHY IN THE EASTERN TROPICAL PACIFIC

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By

Maurice Blackburn and associates
in the Tuna Oceanography Research Program
Scripps Institution of Oceanography
University of California
La Jolla, California

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CONTENTS

FIGURES

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ABSTRACT

A report on 3 years of oceanographic investigation in the eastern tropical Pacific Ocean, with the object of understanding environmental properties and processes responsible for changes in the abundance and distribution of yellowfin and skipjack tuna in a way that may lead to prediction of such changes, is presented. The program included field observations by means of cruises and statistical analysis of physical, chemical, and biological measurements obtained on cruises. It also included a laboratory-experimental program to give leads for developing field and statistical work programs, and it encompassed development and testing of moored unmanned instrumented ocean stations to collect and record ocean data.

INTRODUCTION

United States fishermen catch yellowfin tuna *(Neothunnus macropterus)* and skipjack tuna *(Katsuwonus pelamis)* by live-bait and purse seine fishing in the eastern tropical Pacific Ocean and adjacent waters. The annual catch was fairly stable in amount over the past decade at a level near that of the best year of the fishery, but it declined in value from about 1953 as a result of the increasing availability in the domestic market of lower-priced tuna from foreign fisheries (Power, 1959). It therefore became necessary to consider ways of cutting costs in the United States fishery, and reduction of time spent in searching for tuna seemed to offer attractive possibilities. Believing that such reduction of time could eventually be achieved if the effects of the ocean environment on the distribution and abundance of tuna were understood, the Bureau of Commercial Fisheries in 1957 contracted with the Scripps Institution of Oceanography for an "Investigation of oceanographic and climatic influences on the distribution and behavior of tunas in the eastern tropical Pacific." The period of the contract was from June 20, 1957 to June 30, 1960.

The investigation followed a proposal made in 1957 by the Scripps Institution of Oceanography, which read in part:

> The general question toward which investigations under this contract will be aimed is: "At what times and places in the eastern tropical Pacific can the tuna fleet find schools of tuna in a catchable condition?" Many places are already known at which good catches may be expected at certain times. However, in some years these expectations are not realized: fishing in a particular place at the right time does not yield good catches. It will be a primary aim of these studies to select one or more areas and try to reach an understanding of the chain of events--air circulation, water circulation, primary production, secondary production, catchable tuna. If the chain of events determining the presence or absence of catchable tuna at a particular time and place is understood, it should be possible to predict this and thus be of direct aid in advising the fishermen what areas at what times will be most productive. It should be emphasized that it is not predicted that a reliable, working forecasting service will be in existence at the end of three years. The accumulation of as much information toward that end as time and resources will allow will be a goal, however.

This paper is a short, simplified version of the report submitted to the Bureau on the research performed under the contract. The names of the investigators are given in the sections of the paper for which they were responsible.

The Bureau-financed research program has been known as Scripps Tuna Oceanography Research (STOR). Its work is continuing under another contract from the Bureau of Commercial Fisheries.

The following persons were paid from STOR funds for periods of at least one year:

Dr. M. Blackburn, Research Biologist (Program Director), September 1957-June 1960.
Dr. W. S. Wooster, Associate Research Oceanographer (half-time), July 1958-June 1960.
Dr. G. W. Groves, Assistant Research Oceanographer, January 1958-August 1959.
Mr. R. W. Holmes, Assistant Research Biologist, July 1957-June 1960.

Dr. W. H. Thomas, Assistant Research Biologist, July 1957-June 1960.
Mr. R. C. Griffiths, Graduate Research Biologist, July 1959-June 1960.
Mr. G. T. Barlow, Senior Electronics Technician (half-time), July 1958-June 1960.
Mr. R. J. Linn, Senior Marine Technician, July 1957-June 1960.
Mr. A. D. Reith, Senior Marine Technician, March 1958-June 1960.
Mr. M. L. Young, Electronics Technician, December 1957-February 1959.
Mr. R. V. Fidler, Laboratory Technician, April 1959-June 1960.
Mrs. M. A. Miller, Senior Draftsman (half-time), July 1958-June 1959.
Mrs. J. F. Scotten, Secretary-Stenographer, October 1957-June 1960.
Mrs. J. L. Connell, Engineering Aid, November 1958-June 1960.

The following investigators were supported from STOR funds in other ways:

Prof. W. H. Munk	Mr. J. M. Snodgrass
Prof. J. D. Isaacs	Dr. J. A. Knauss
Prof. C. S. Cox	Mr. G. I. Roden

Some of the above-mentioned persons were supported in part from other contract funds, especially from the Office of Naval Research and the Marine Research Committee of the State of California, as indicated specifically elsewhere in the paper.

The Scripps Institution provided a group of advisers called the Tuna Oceanography Advisory Panel of the Research Advisory Council, which had 12 meetings. Its membership on June 30, 1960, was as follows:

Dr. E. H. Ahlstrom (Bureau of Commercial Fisheries)
Prof. R. S. Arthur
Dr. M. Blackburn, Chairman
Prof. C. L. Hubbs
Prof. J. D. Isaacs
Mr. J. L. Reid
Dr. M. B. Schaefer (Inter-American Tropical Tuna Commission)
Prof. C. D. Wheelock
Dr. W. S. Wooster

The Bureau of Commercial Fisheries advised the Program Director from time to time through John C. Marr, formerly Director of the Bureau's Biological Laboratory at La Jolla, and subsequently through Gerald V. Howard, Director of the Biological Laboratory at San Diego. There were frequent meetings with these and other representatives of the Bureau.

The late Townsend Cromwell and Dr. Bell M. Shimada, of the Tuna Commission, were members of the Advisory Panel and gave valuable counsel in other ways.

There was close cooperation between STOR and the Inter-American Tropical Tuna Commission. The Commission assisted in many ways, especially by providing data on tuna catch per unit fishing effort and by helping to staff cruises.

The Bureau of Commercial Fisheries Biological Laboratories at La Jolla, San Diego, Stanford, and Honolulu assisted by providing information, and in other practical ways.

SCOPE AND PLAN OF THE INVESTIGATION

Figure 1 shows the main parts of the investigation by subject and area. It does not show the whole region of the fishery, which extends broadly from latitude 30° N. to 20° S. and up to about 700 miles from the mainland coast, or the whole region of the investigation, which included the waters off Peru.

The relationships of the items in figure 1, to each other and to the main purpose of the investigation, may be understood by reference to table 1, which shows schematically how the work was planned and carried out.

In explaining table 1 it is convenient to start at the bottom (Parts of energy chain studied). It was assumed that atmospheric conditions have effects on physical and chemical conditions in the upper ocean which in turn affect the availability of small biota (phytoplankton, zooplankton, and micronekton, all in the tuna food chain) and therefore the availability of tuna (see Introduction). Attempts to identify and study these effects, together with the associated methodological work, are discussed in the following sections of the paper:

Statistical analysis of ocean-atmosphere relationships
Physical features and processes in the ocean
Methods in physical oceanography: evaluation and development
Light, nutrients, and biota: methods and experiments
Light, nutrients, and biota: statistical analysis of ocean data
Tuna ecology (in part).

It was also considered that physico-chemical conditions of the ocean might affect availability of tuna directly, as well as indirectly through the small biota. This subject is dealt with in the following sections of the paper:

Recent changes in the ocean
Tuna ecology (in part).

It was seen that such researches would have their greatest practical value to the fishery if conducted in places already recognized, empirically, as good fishing areas (see Introduction). Therefore one such area, the Gulf of Tehuantepec, was selected for particularly intensive study, involving all the main parts of the energy chain; in two other areas, Baja California and Peru, the work was substantial in some parts only of the energy chain; in other areas, e.g., Panama Bight, Gulf of California, and certain oceanic islands, investigations were made in still smaller parts of the energy chain, as opportunity offered. It was realized that these studies of areas would be facilitated by similar investigations encompassing the eastern tropical Pacific at large, so as to provide a picture of average conditions for that region with which conditions in particular areas could be compared; therefore, such studies, which had been started earlier (e.g., Holmes et al., 1957; Holmes et al., 1958; Wooster and Cromwell, 1958), were continued. Finally, since long time series of measurements for statistical analysis of ocean-atmosphere relationships were not readily available from areas in the eastern tropical Pacific, it was decided to gain some insight into these relationships by using series that were available from the eastern north Pacific. These aspects of the investigational plan are shown in table 1 (Region investigated, and below).

The sources of data for the above-mentioned investigations in the various regions are indicated at the top of table 1. "Previous oceanography" means data from oceanographic cruises made before the STOR program started in mid-1957, together with measurements of surface temperature, sea level, and atmospheric conditions made on nonresearch ships and at tide gauge stations. "Further cruises" means oceanographic cruises made in the eastern tropical Pacific after mid-1957, by STOR and other groups of investigators, as explained in the next section. "Moored stations," explained in the next section, are devices that could be used to obtain oceanographic information from any part of the ocean, but primarily intended to supply it for the tuna fishing areas as far as the STOR program is concerned; the broken arrow indicates the experimental nature of this project. "Fishery records" means the records of catch, fishing effort, and catch per unit effort (apparent abundance) that are available for each species of tuna from the Inter-American Tropical Tuna Commission, as explained further in the section on "Tuna ecology."

SPECIAL OPERATIONS

This section describes the operations undertaken to obtain information, apart from that represented by "Previous oceanography" and "Fishery records," for the investigation.

Cruises

There were five STOR cruises, each distinguished by the initials TO (Tuna Oceanography):

TO-58-1 (Expedition SCOT).--This cruise was made in cooperation with the Tuna Commission, which paid about 30 percent of the expenses. The main purposes, so far as STOR was concerned, were (a) to obtain data for a study of interrelationships of light, nutrients, and biota for a wide range of eastern tropical Pacific waters, at a different season from previous cruises of the same kind (expeditions EASTROPIC, fall of 1955, and SCOPE, fall of 1956), and (b) to begin an oceanographic study of the Gulf of Tehuantepec. These matters are discussed elsewhere in this paper. The ship *Spencer F. Baird* was used; the cruise period was April 23-June 20, 1958; R. W. Holmes and M. Blackburn were scientific leaders before and after June 2, respectively. Figure 1 shows the expedition track.

TO-58-2.--The purposes of this cruise were (a) to make further oceanographic surveys in the Gulf of Tehuantepec and (b) to establish and tend moored instrumented stations. The results are mentioned elsewhere in the paper. The ship was again the *Spencer F. Baird*; the cruise period was October 31-December 8, 1958; G. W. Groves was scientific leader. The ship went to the Gulf of Tehuantepec (fig. 1) by the most direct route and returned in the same way.

TO-59-1.--This cruise was intended (a) to continue the work in the Gulf of Tehuantepec and (b) to gather further information about the interrelationships of light, nutrients, and biota over a range of eastern tropical Pacific waters. The results are mentioned elsewhere. The ship used was the *Stranger*; the cruise period was January 15-February 25, 1959; R. W. Holmes was scientific leader. The area covered was in the main like that of TO-58-2, but with an extension to the southeast of the Gulf of Tehuantepec, to the area of the Costa Rica thermal anticline or dome (fig. 1).

TO-59-2.--The purposes of the cruise were (a) to make another survey of the Gulf of Tehuantepec at yet another season of the year and (b) to cooperate with California Cooperative Oceanic Fisheries Investigations (CalCOFI) in making a detailed oceanographic survey of the Baja California region in summer, which is the tuna season there (fig. 1). The results of (a) are mentioned elsewhere, but those of (b) have not yet been analyzed. As regards (b) the cruise party took responsibility for traversing the regular CalCOFI station pattern in the southern half of the Baja California area. For CalCOFI purposes this part of TO-59-2 was known as cruise

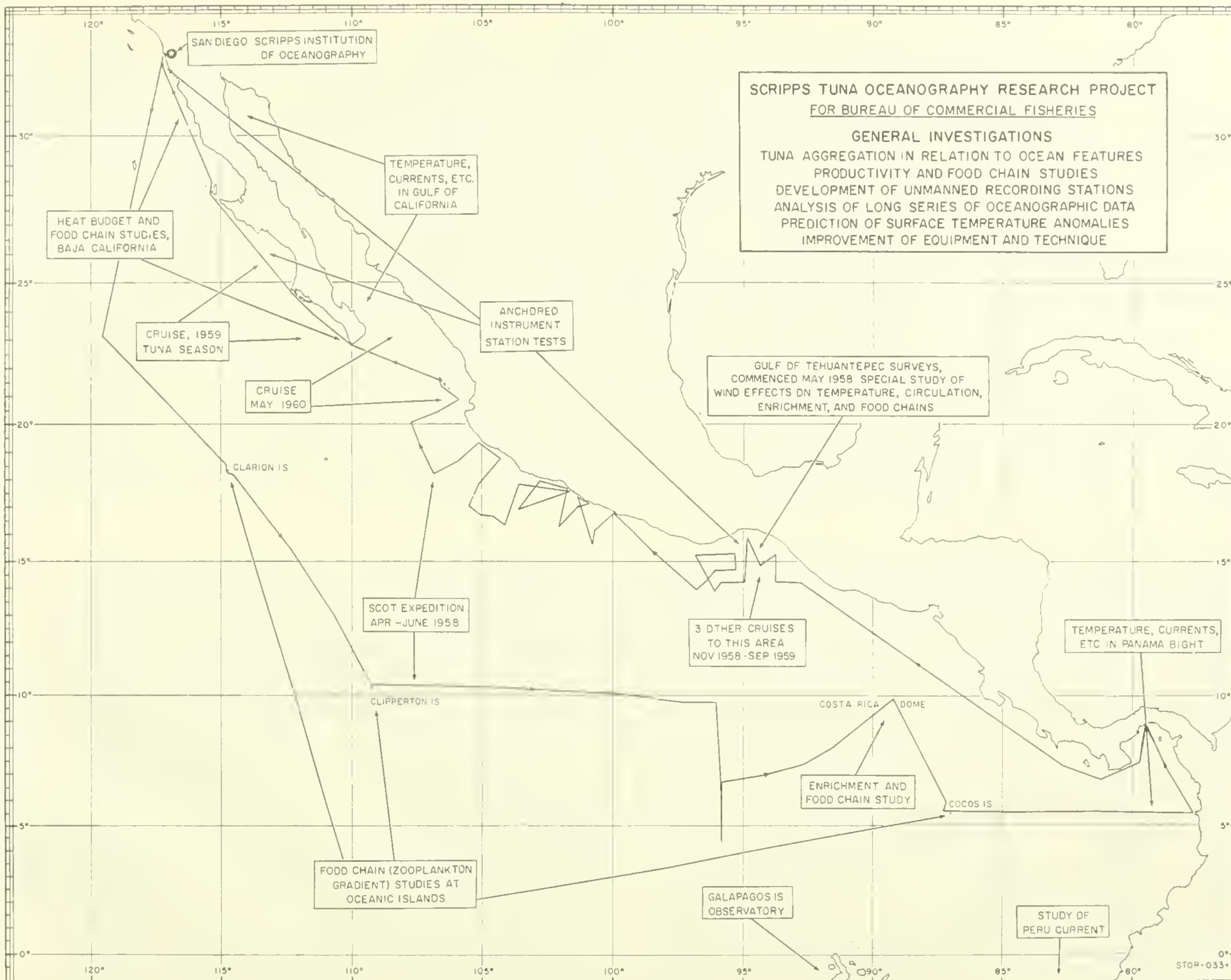
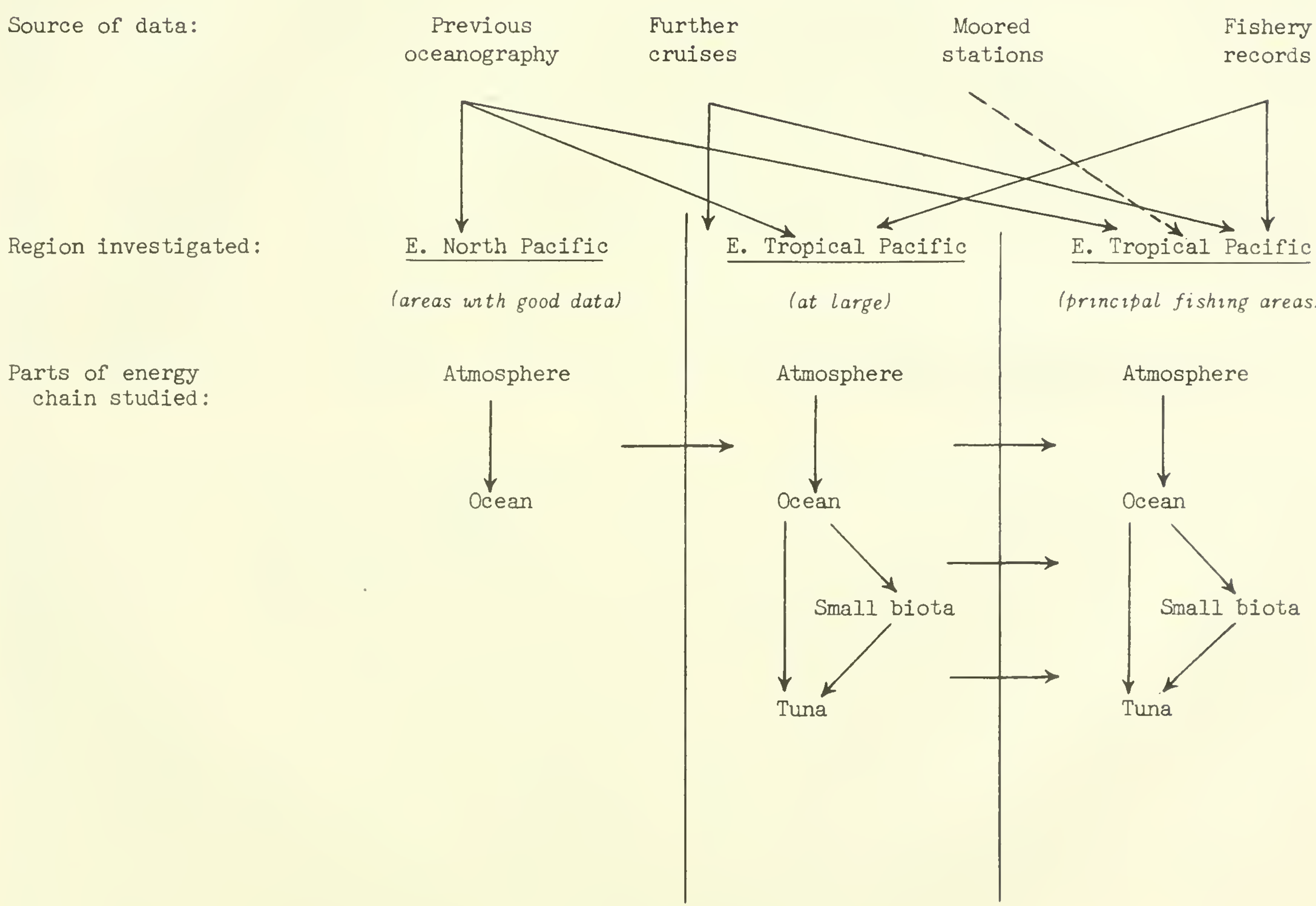


Figure 1.--Principal activities of the STOR program.

TABLE 1.--Schematic plan of the investigation. Arrows indicate connections which represent the actual research operations (collection or analysis of data). For further explanation, see text



5908-M. The ship *Hugh M. Smith* was used; the cruise period was August 13-September 22, 1959; M. Blackburn was scientific leader. After occupying the grid of stations off Baja California, the ship proceeded to the Gulf of Tehuantepec by the most direct route and returned in the same way at the conclusion of the Gulf survey.

TO-60-1.--The purposes of the cruise were (a) to make a detailed oceanographic study in the general area of the mouth of the Gulf of California, at the time of year when tuna normally move through this area to the Pacific coast of Baja California, and (b) to study, as opportunity offered, physical structure and distribution of physical, chemical, and biological properties at well-defined thermal fronts. Neither series of observations has yet been analyzed. The ship used was the *Hugh M. Smith*; the cruise period was April 30-May 27, 1960; R. C. Griffiths was scientific leader.

Figure 2 shows the track of TO-60-1. The density of observations between stations 1 and 38 was similar to that of the Baja California survey of TO-59-2; the density of stations further south was similar to that of the four surveys of the Gulf of Tehuantepec.

Table 2 summarizes the observations made on cruise TO-60-1, which are comparable in number and diversity with those of other STOR cruises.

Cruise of USCGSS *Explorer*.--By courtesy of the Director of the U.S. Coast and Geodetic Survey, a STOR staff member was able to participate in an oceanographic survey cruise between San Diego and Panama, from February 17 to March 1, 1960. He was responsible for adding phosphate and micronekton to the range of properties measured on the cruise.

STOR oceanographic survey methods.--Table 2 indicates the importance attached to measurements of light and various kinds of biota on STOR cruises. These properties vary according to time of day and therefore, as far as possible, certain observations were confined

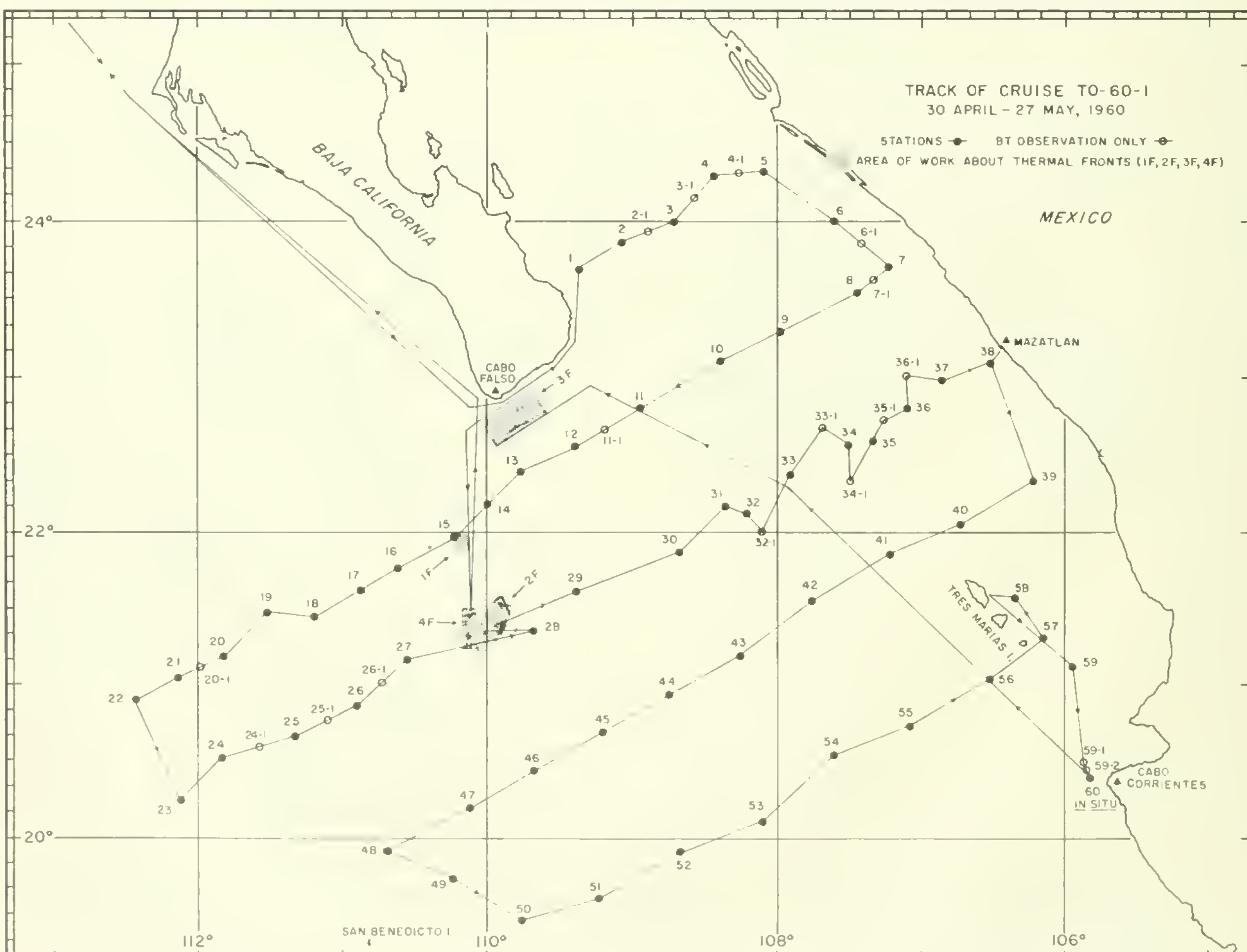


Figure 2.--Track chart, cruise TO-60-1.

TABLE 2.--Observations on cruise TO-60-1

Kind of observation	Number on survey	Number at fronts	Total
Bathythermograph (BT)................	77	52	129
Hydrocast............................	60	4	64
Oblique zooplankton haul.............	58	4	62
Surface zooplankton haul.............	15	0	15
Oblique micronekton haul (half-speed).	15	0	15
Surface micronekton haul (full-speed).	66	0	66
Closing-net zooplankton haul series...	2	0	2
Plastic sampler cast (phytoplankton)..	33	4	37
Submarine photometer lowering........	14	0	14
Geomagnetic electrokinetograph (GEK)..	25	4	29

to stations occupied about local noon and others to stations occupied about local midnight.

Noon station work generally consisted of BT, hydrocast, plastic sampler casts for chlorophyll a and productivity work, submarine photometer lowering, and oblique zooplankton haul. Midnight stations generally had BT, hydrocast, oblique zooplankton haul, and oblique micronekton haul. The operations at other stations were generally confined to BT, hydrocast (sometimes abbreviated), and oblique haul (zooplankton).

Observations between stations consisted of BT lowerings, GEK fixes (certain areas only), and high-speed micronekton net tows. Continuous observations were made of surface temperature (Taylor or Foxboro thermograph) and incident solar radiation (Eppley pyrheliometer, signal recorded on Speedomax recorder).

Data lists.--R. W. Holmes and M. Blackburn compiled a data list for TO-58-1 (SCOT). It is entitled "Physical, chemical, and biological observations in the eastern tropical Pacific Ocean: SCOT Expedition, April-June 1958" and has been published as U. S. Fish and Wildlife Service Special Scientific Report--Fisheries No. 345, 1960.

Ready for submission, with a view to similar publication, is a similar data list for TO-58-2, TO-59-1, and TO-59-2. It is by M. Blackburn, R. C. Griffiths, R. W. Holmes, and W. H. Thomas, and is entitled "Physical, chemical, and biological observations in the eastern tropical Pacific: three cruises to the Gulf of Tehuantepec, 1958-1959."

Moored Ocean Stations

General remarks on the operations.--Although moored unattended instrumented ocean stations had been in intermittent use for 5 years prior to the STOR program (Bascom, 1956; Isaacs et al., 1957; Egeberg, 1959, for instance), their supposed capacity for routine long-term oceanographic work had not been adequately tested. Since it was obvious that the well-known limitations of research ships would affect the STOR program more than most oceanographic programs, because of the size and remoteness of the area and the fact that prediction as well as understanding was desired, it was proposed from the beginning that moored stations should be used in the investigation.

The investigators decided to start by testing the capacity of such stations to make and record comparatively simple yet desirable measurements (sea temperature at five levels down to 120 m., air temperature, wind direction, and wind velocity) under the following fairly rigorous conditions: hourly observations, various locations up to 2,000 miles from the Institution's headquarters and including rough weather situations, and surveillance and servicing only at 3-monthly intervals. The idea was to discover the limitations of the stations for simple kinds of observation with the minimum of delay, so that their use could be planned accordingly. If all went well we intended to make the stations capable of making further kinds of measurements, including chemical and biological measurements.

Four mooring sites were selected, one inshore and one offshore in the region of central Baja California and similarly in the Gulf of Tehuantepec. Preparatory work began in November 1957. The two sites in Baja California were occupied by moored instrumented stations in June 1958, and the sites in the Gulf of Tehuantepec were occupied in November 1958. By February 1959 it was known that all stations had come adrift and that the equipment therefore did not meet the needs of the program. The instrumentation had not proved satisfactory either. Fortunately most of the equipment was recovered by tuna fishing vessels.

It was then decided to redevelop the mooring assembly and much of the instrumentation. Because of reorganization of staff this work did not get underway until April 1959. Its status on June 30, 1960, to be described below, was that new equipment existed and was undergoing tests in southern California waters.

The foregoing observations refer to a type of station capable of measuring and recording conditions in the near-surface ocean and atmosphere, where we think that most of the information needed in tuna ecology can be obtained. Although the hopes of most of the program investigators are therefore centered upon this type, some attention has been paid to another type in which the interest is in measuring temperature throughout the water column for the purpose of investigating internal waves. This requires a special kind of mooring which could conceivably be useful in other situations, if it proves successful.

In the following sections these three types of moored stations will be discussed separately. They will be called A, B, and C respectively for the original general-purpose station, the redesigned general-purpose station, and the station for the investigation of internal waves.

No attention has yet been given to the telemetering of observations, although this will eventually be necessary to make the stations useful for routine forecasting work.

Because of the complexity of the equipment there is a vast amount of detail that could be given, but much of it is unnecessary for the purpose of this report. The following sections indicate the main features of the three types of equipment, with the main emphasis on the mooring system because this was the main area of difficulty, and the results of tests conducted with them.

Since this report was first written, the type B station was put into operation in California and Baja California waters in early November 1960, and worked very satisfactorily through December.

All of this work has been supported in part (75-80 percent) by the Office of Naval Research.

Moored station type A *(J. D. Isaacs, J. L. Faughn, A. L. Nelson, and C. D. Jennings)*.-- The essential features of the hull and mooring are available in publications cited above. The most detailed published figure of the mooring assembly is that of Egeberg (1959) although the hull he describes is not the one used in the work described here. Figure 3 includes a diagram of the station for comparison with those of types B and C.

A simple description of the instrumented station assembly as used on the STOR program is as follows:

Each station consisted of a 16-ft. fiberglass skiff, decked over and painted orange. A 300-ft. painter (sometimes nylon rope, sometimes plastic-coated stainless steel cable, bearing plastic line floats) attached the bow of the skiff to a submerged spherical float (about 3 ft. diameter) approximately 150 ft. below the sea surface. This float was anchored to the sea bottom with a steel cable of diameter 0.123 or 0.200 in. An electrical cable 390 ft. long, bearing thermistors at intervals and a pressure-sensing element at its free end, was suspended from the stern of the skiff.

Mounted on the skiff was a short mast carrying an anemometer rotor, an element for sensing air temperature, an orange flag, a lifeboat-type radar reflector and white flashing stroboscopic-type light intended to be visible at 50-sec. intervals at a distance of 4 miles in clear weather. A wind vane mechanism was mounted on the after deck.

Instrumentation inside the skiff consisted of a compass element (for identifying wind direction), batteries, and a Streeter-Amet print-out counter-recorder with 10 channels of information.

The thermistors were arranged to sense sea temperature at 0, 20, 40, 70, and 120 m. when the instrument string was vertically suspended. The pressure signal from the end of the string was intended to show deviation from vertical from which estimates of actual depth of the temperature observations could be made.

Magnesium-carbon sea-water batteries (6-12 volt) were used to power the stations moored in June 1958. Commercial lead-acid storage batteries were used on the stations moored in November 1958.

The sensing-recording system worked directly from the voltage. It consisted of a single vacuum tube blocking oscillator with pulse rate proportional to the resistance in the grid circuit. The pulses were fed into a counter-printer and counted over a fixed interval of time, and the total was printed on paper tape. The parameters being measured were caused to produce changes in resistance or to produce pulses directly. The timing

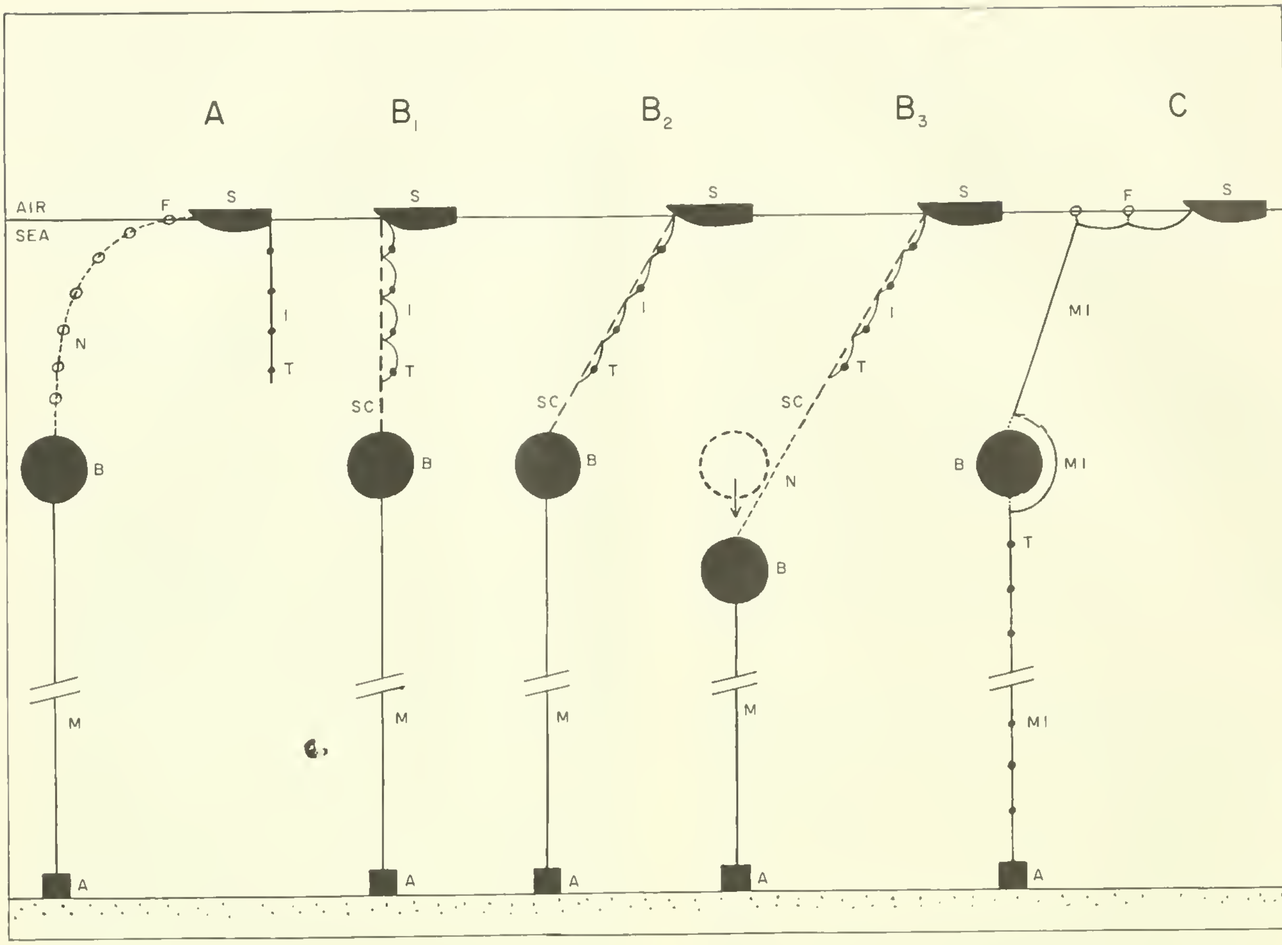


Figure 3.--Moored stations, types A, B, and C, diagrammatic, not to scale. B_1 shows type B under calm conditions, B_2 the same under windy conditions, B_3 the same as B_2 but incorporating the proposed self-reeling subsurface buoy. Skiff S, subsurface buoy B, anchor A, float F, thermometer T, lower mooring cable M, nylon upper mooring cable N, shock-cord upper mooring cable SC, instrument cable I, combined mooring-and-instrument cable MI. (See text)

system was mechanical, with an automatic clock-winding mechanism gear driven from the motor of the counter-printer and a positive camoperated contact on the second hand of the clock.

There were several tests of these stations and various components, but as far as the STOR program is concerned the main interest was in the following moorings which were made in the areas of the tropical tuna fishery (see fig. 1).

Skiff #21 was moored on June 27, 1958, in 153 fm. on the northwest edge of Uncle Sam Bank, Baja California, at 25°38.3' N., 113°30.0' W. It was seen in position and records were obtained by a research vessel on July 11. It was again reported in position on July 25, but not sighted there by a research vessel on August 3. On or about August 10, 1958, it was picked up by a fishing vessel at 25°29' N., 115°20' W., and returned to the Scripps Institution.

Skiff #5 was moored on June 28, 1958, in 1,968 fm. about 30 miles offshore of #21, at 25°23.0' N., 114°02.5' W. It was seen in position and records were obtained by a research vessel on July 11. It was again seen in position by a research vessel on August 3. It was reported far out of position by a naval vessel on November 14. A fishing vessel recovered the records and instruments on January 28, 1959, but could not get the hull aboard because of bad weather.

Skiff #6 was moored on November 2, 1958 (cruise TO-58-2), to replace #21, in 168 fm. at position 25°40.2' N., 113°30.0' W. It was retrieved, adrift, by the installing vessel in the neighborhood of the mooring position, on December 5, 1958.

Skiff #4 was moored on November 8, 1958, in 2,310 fm. in the Gulf of Tehuantepec, 14°31.0' N., 95°00.4' W., but was not found there by the installing vessel on November 25.

It was found adrift by a fishing vessel on December 23, 1958, position 13°57' N., 99°07' W., and returned to the Scripps Institution.

Skiff #8 was moored without instruments on November 9, 1958, in 122 fm. near the head of the Gulf of Tehuantepec, position 15°43.6' N., 95°04.6' W. It was revisited and instrumented on November 17. On November 27 it was again visited and the instrumentation (malfunctioning) was removed. It was not found when sought repeatedly during January and February 1959 (cruise TO-59-1) and remains unaccounted for.

In each case (except skiff #8, about which nothing is known) it was found that the painter had parted. The investigators concluded, from the condition of the painters and from other circumstances (including experience with other skiffs which had no thermistor strings and were under better surveillance, and performed much better), that some of the painters were probably cut accidentally by passing vessels, and some probably broken in bad weather after having become entangled with the thermistor strings.

The longest series of recorded data was an 11-day series from skiff #21, and even this was incomplete because the depth element and bottom thermistor did not work. Other series were likewise incomplete for some channels of information, some for most channels. This indicated failures in the instrumentation even before the skiffs went adrift.

Moored station type B *(J. D. Isaacs, E. E. Holt, G. B. Schick, and C. D. Jennings)*.-- Simple home-water mooring experiments were begun in July 1959 to find ways to improve the parts of the station assembly between the hull and the subsurface float, i.e., the painter and thermistor string. There are no grounds for dissatisfaction with the previously used hull or the taut-wire part of the mooring from the anchor up to the subsurface float.

The idea that seemed initially most attractive, and which has persisted in one form or another up to the present, is that the upper portion of the mooring should be a rubber shock-absorbent cord that would be almost vertical in the water in most kinds of weather in which other craft would be likely to approach the skiff, and that this cord should also support the thermistor string; we think that in this way the causes of past failures would be eliminated. The idea now is that there should be a single extensible shock-cord (Bungee) between the subsurface float and the skiff and that the thermistor string should be attached along it in a series of loops: an additional advantage of this combination is expected to be the maintenance of each thermistor at a constant depth. The system is shown in diagrammatic form in figure 3.

The first such mooring, made near the Scripps Institution on April 8, 1960, failed when the Bungee cord parted on May 30. Commencing June 23, further series of similar moorings were made with complete success, which has continued, as mentioned above, through December 1960.

During these tests the system was much improved by the use of a modified subsurface float, called the self-reeling subsurface float.

The self-reeling subsurface float was conceived to enable an instrument cable or a mooring line, between a subsurface point of attachment and a surface float, to be maintained free from slack with changing sea conditions. This system also allows the cable or wire to be retrieved and replaced without disturbing the remainder of the mooring. The self-reeling float consists of a spherical buoyant tank which is modified by the addition of three parallel reels having the same geometrical axis of rotation. Two of these reels are fixed to the sides of the sphere and a larger reel is fixed about the center. The ratio of the radii of these reels is designed to give the desired balance of forces and cause the float to wind itself up or down as the tension changes. When the tension on the surface line exceeds a predetermined value, the float winds itself down paying out a quantity of line. If the tension in the center line is less than a certain predetermined amount, the float will wind itself up, reeling in the excess center line. Its action may be compared to that of a "yo-yo," and the float is now known by that name.

The relatively large extensibility of the center line is affected mainly by the reeling action of the subsurface float and to a much smaller extent by the vertical motion of this float.

The two side reels wind and unwind two stainless steel cables leading down to a spreader bar and thence to the top of the lower (taut-wire) part of the mooring, and the center reel winds and unwinds a length of nylon leading up to the lower end of the shock-cord. The effect when used with Bungee is to add to the extensibility of the upper part of the mooring. The difference between this system and the previously mentioned one is shown diagrammatically in figure 3 (B3).

A photographic method of recording has been designed. The equipment consists of a watertight and light-tight box containing a camera, light source, timing motor, etc., and a panel on which are mounted the various instrument meters. The box together with storage batteries is then installed in a skiff and anchored at sea. The instrument meters are 0-1 microammeters calibrated in degrees Centigrade, wind velocity, etc. Thermistors are used as sensing elements in the instrument string. Electronic damping is utilized to minimize any tendency of the instrument needles to swing due to the rolling and pitching of the skiff. The camera is a 16 mm., magazine-loaded type, operated by a timing motor, and takes an exposure at half-hour intervals. The timing motor also operates a microswitch which turns on a bank of incandescent lights for a period of a few seconds every half hour. A simple transistorized flasher circuit is used to operate a beacon light mounted on the mast of the skiff.

At the present time the lead-acid storage battery is being used to power the anchored instrument stations. Research and development is being conducted on means of utilizing a thermoelectric generator for the purpose of charging batteries, the heat to be supplied by butane gas. Some work has also been conducted on a device that makes use of the rolling motion of the skiff in which it is installed, to produce sufficient electric current to keep a storage battery charged.

The hulls have been camouflaged to reduce the likelihood of interference with them. A radio-signalling device has been developed to aid location.

Moored station type C, for study of internal waves *(C. S. Cox)*.-- From January 1959 through June 1960 the following work was undertaken to develop methods of recording internal waves from unattended moored instrument stations and to analyze the measurements in order to find the mechanisms of generation, propagation, and decay of the waves.[1]

Internal waves in the sea exist because sea water is stratified. Displacement of internal layers from their equilibrium position results in the formation of waves within the body of the water which can propagate away from the generator. The internal waves are important to the economy of the sea for a variety of reasons:

1. Internal waves by their oscillatory nature introduce uncertainty into discrete measurements of dynamic heights.

2. Turbulence in the sea is intimately connected with internal waves: weak turbulent eddies in a vertical plane form internal waves, and conversely, breaking internal waves form vertical turbulence. Thus internal waves are connected with mixing processes in the sea.

3. Internal waves carry off energy from one place in the sea and distribute it elsewhere. For example, it has been calculated that tidal streams in the deep sea lose energy to internal waves when they pass over sea mountains of a suitable shape. The average energy transferred in this way probably is larger than the energy supplied by wind-induced stirring to water below 500 m. depth. It is part of the aim of this investigation to find the amount of energy made available to internal waves in this way, how far it can be transported and by what mechanism it becomes degraded to random motions.

4. Internal waves may influence sea life directly by subjecting organisms to vertical and horizontal motions of considerable extent. It is not uncommon to find internal tidal oscillations with a vertical amplitude of 70 m., somewhat below the euphotic zone. It seems likely that the associated vertical velocities of 1 cm. $sec.^{-1}$ will have a profound effect on slow moving animals which migrate below the euphotic zone.

In spite of their importance few observations have been made of internal waves in the deep sea. Recent observations by Reid (1956) show the existence of large internal tides off the California coast. Records of sea bottom temperatures at depths of 50 m. and 500 m. off Castle Harbor, Bermuda (Haurwitz, Stommel, and Munk, 1959) show the existence of irregular changes of remarkably large amplitude (about 1° C. at 500 m.) which these authors attribute to a continuous spectrum of internal waves. An alternate explanation in terms of the convection of turbulent eddies past the thermometers is possible, however. Many papers have dealt with observations and interpretation of internal tides (e.g., Defant, 1932, 1950) but Haurwitz (1954) pointed out that most of the periods of observation have been too short to give statistically reliable results. There is no question, however, that large amplitude oscillations of low frequency do occur in the ocean.

To measure internal waves in the deep sea and to resolve them into their component frequencies require observations of vertical motion (or, equally well, of temperature at fixed depths) for a sufficient time duration, preferably a few weeks. To separate the oscillations into normal modes in the vertical, one must observe from surface to bottom.

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[1] Peripheral to the main investigation, this study received about 25 percent of its support from the STOR program because of the need to encourage the design of other types of moored stations after the failure of type A. It was also seen that the study of internal waves per se could have some significance for the tuna oceanography program, e.g., as a mechanism for distributing biota. The bulk of the support, about 75 percent of the total, came from the Office of Naval Research.

These requirements have been met by using recording stations of type A modified by the installation of telemetering thermometers along the mooring wire (fig. 3,C). For these installations the mooring wire is insulated from the sea by a coating of polyethylene and by special fittings at each end of the wire so that the wire can carry electrical power and telemetered signals to and from the thermometers. That is to say, the mooring wire and instrument string are the same.

As many as 10 thermometers can be operated simultaneously without ambiguity of the telemetered signals. The ultimate accuracy appears to be of the order of 0.005° C. but practical difficulties have reduced this to 0.012° C. in the field.

A complete mooring was installed for test in 125 ft. of water, 3,000 ft. offshore from the Scripps Institution. Two thermometers were used and fastened 2 ft. apart at a depth of 80 ft. A pressure gauge was also installed, but developed various faults so that no record was obtained. Satisfactory temperature records were obtained from April 5-25 and May 12-20, 1960. During these periods, wind and sea conditions were gentle to moderate except for a period of 2 days during which there was a 20-knot onshore wind. The skiff rode at its mooring well but 11 hours of thermometer data were illegible, presumably because jerking of tape reels in the tape recorder spoiled the recording.

The short section of temperature record from one thermometer (fig. 4) shows a characteristic feature of the entire observation: the existence of two regimes. In one, sawtooth temperature fluctuations of semidiurnal tidal periodicity are prominent. At a later time the second regime, in which the fluctuations become more irregular, sets in. This behavior is in close accord with the nearshore observation of internal tides, reported by Arthur (1954).

Subsequently, a series of temperature readings was obtained over a 2-day period from each of nine thermometers along a 1,100-m. mooring cable in the San Diego Trough. Temperature oscillations were large and showed a roughly semidiurnal periodicity, at depths of 50 m. and 450 m. The records were analyzed to describe and measure the internal waves responsible for the oscillations.

Galapagos Islands Station *(P. Richardson)*

The STOR program during 1957-58 helped to establish a tide gauge station in the Galapagos Islands (fig. 1) as part of the Scripps Institution's IGY Island Observatories Program. It did this partly in the belief that it

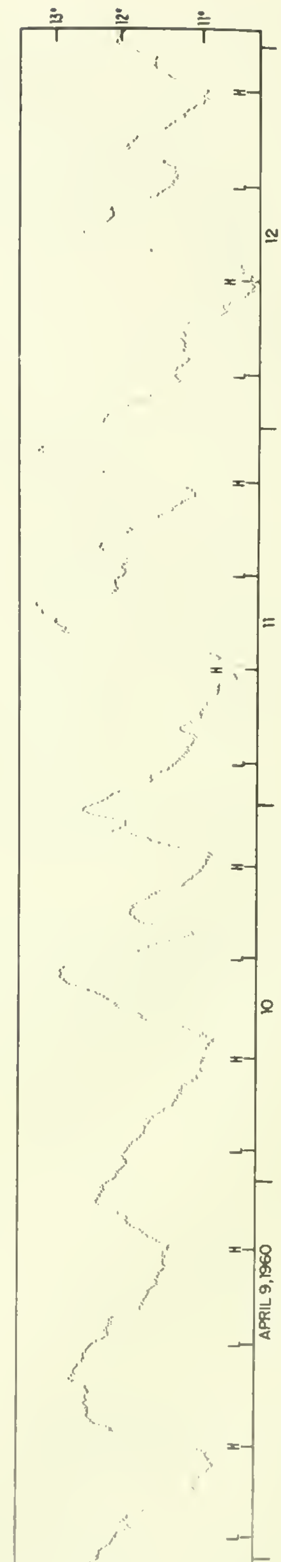


Figure. 4. --Temperature record from a moored station, 80 feet below surface at La Jolla. L and H are times of low and high tide.

might be able to use the facility for its own work, although the form later taken by the STOR program made it inappropriate to use the station.

Mr. Richardson was stationed in the Islands from January 20 to June 20, 1958. During this period he installed tide gauges at Wreck Bay, San Cristobal Island, and Darwin Bay, Genovesa (Tower) Island. The Wreck Bay station included a laboratory for salinity titrations. It was impossible to maintain the remote Darwin Bay station, and it was finally dismantled. The Wreck Bay station functioned well, with the help of Ecuadorian Navy personnel trained by Mr. Richardson, from its establishment in January 1958 through April 1959. It was renovated in October 1959 and is now being operated by the Inter-American Geodetic Survey for a further 2 years. Surface temperature, density, and sea level measurements become available to Scripps Institution from time to time.

STATISTICAL ANALYSIS OF OCEAN-ATMOSPHERE RELATIONSHIPS

As mentioned above, some of this work was concerned with areas adjacent to rather than in the area of the tropical tuna fishery, because of the ready availability of suitable records. It is thought that the experience gained in analyzing these records will be valuable when similar series of data are readily available for places in the eastern tropical Pacific; some such series already exist, but not in the most suitable form for analysis.

Statistical Prediction of Surface Temperature in the Northeastern Pacific

(G. I. Roden and G. W. Groves)

The 1921-38 series of monthly means of surface temperature, wind velocity, and incoming radiation, available for 5-degree rectangles off the coast of Washington and between California and Hawaii, were used. Autocorrelations, crosscorrelations, energy spectra, and coherence and phase relationships were used to show how surface temperature could best be predicted from wind velocity and radiation.

It was concluded: that useful forecasts could be made for only 1 or 2 months ahead; that they would be slightly improved by taking wind as well as temperature data into account, although radiation data were of very little use; that little would be gained by using data of more than one past month in addition to the present month, for making such predictions; and that optimum prediction by such statistical methods alone could account for only about 40 percent of the variance in the next month's average temperature.

A paper on this investigation, entitled "On the statistical prediction of ocean temperatures," was published in Journal of Geophysical Research, vol. 65, no. 1, p. 249-263, 1960.

The work was supported in part (about 30 percent) by the California Marine Research Committee.

Nonseasonal Variations in Sea Level Along the West Coast of North America *(G. I. Roden)*

Monthly sea level anomalies at 20 tide gauge stations, including 5 along the west coast of Mexico, were analyzed for persistence and relation to monthly anomalies in atmospheric pressure and sea surface temperature. The purpose of this investigation was to find out how well sea level responds to the inverted barometer effect, i.e., whether an increase in pressure is accompanied by a corresponding drop in sea level, and also whether there is any relation between the integrated thermodynamic processes represented by sea level and the sea surface temperature. The station records varied in length from 6 to 37 years.

The results of this investigation can be summarized as follows:

1. There is an immediate, inverse, and strong response of sea level anomalies to those in atmospheric pressure; the response is much more pronounced in high than in low latitudes.

2. There is a direct and moderate response between anomalies of sea level and sea surface temperature; the response is somewhat better in low than in high latitudes.

3. There is some agreement between anomalies in sea level and wind.

4. Sea level anomalies are much more persistent in low than in high latitudes.

5. The prediction of sea level is less successful than that of sea surface temperature.

A paper on this investigation, entitled "On the nonseasonal variations in sea level along the west coast of North America," was published in Journal of Geophysical Research, vol. 65, no. 9, p. 2809-2826, 1960.

The work was supported in part (about 65 percent) by the California Marine Research Committee.

Subdiem Oscillation in Sea Level and Associated Variables in the Eastern and Central Tropical Pacific

(W. H. Munk, G. W. Groves, and G. R. Miller)

In this work, which is not complete, the purpose is to use the very long series of hourly values of sea level, atmospheric pressure, and wind components that are available from Balboa, Canal Zone, and Honolulu and other stations in Hawaii, for an analysis of oscillations with subdiem frequencies, i.e., less than one cycle per day.

Compilation of data in suitable punchcard form for analysis has involved much labor even with the assistance of error-catching computer programs. The following time series are now in suitable form:

Balboa sea level	1907-57
Balboa pressure and wind components	1943-56
Honolulu sea level	1905-57
Honolulu pressure and wind components	1941-56
Hilo, Hawaii, sea level	June 1947-57
Kauai, Hawaii, sea level	Dec. 1954-56
Maui, Hawaii, sea level	1951-56

Processing of the data will involve cross spectral analyses between the oceanographic and meteorological series to derive information about the role of wind and pressure in setting up the oscillations in sea level. Differences between midocean (Hawaii) and the continental margin (Balboa), and between seasons, may have particular interest.

Relation Between Wind Velocity and Surface Temperature in the Gulf of Tehuantepec

(G. I. Roden)

In the Gulf of Tehuantepec, on the Pacific coast of southern Mexico, an area of cold surface water roughly coincides at certain seasons with a belt of high wind; this is discussed below. To study the statistical relation between sea temperature and wind velocity a spectral analysis was made of anomalies of 10-day means during the period January 1949 through June 1957, in four adjacent 2-degree rectangles. The results showed a good coherence of temperature anomalies and wind anomalies in adjacent rectangles. The coherence between wind and temperature anomalies was less good and significant only for frequencies between two and four cycles per year, approximately. The highest coherence was found near three cycles per year, with about 50 percent of temperature anomaly due to wind anomaly.

The study was incomplete in June 1960, but has since been completed and is in press, entitled "On the wind-driven circulation in the Gulf of Tehuantepec and its effect upon surface temperatures," in Geofisica Internacional. It has been supported in part (about 50 percent) by the California Marine Research Committee.

RECENT CHANGES IN THE OCEAN

It is now common knowledge that 1955 was a year of low surface temperatures in the eastern Pacific off the coasts of North America and Peru, and 1957-58 the beginning of a period of high temperatures in the same waters (e.g., Rodewald, 1957 and 1959). Several research agencies have been concerned with the investigation of the warming as far as it affected the waters off North America, which was the subject of a symposium held in 1958 on "The changing Pacific Ocean in 1957 and 1958" (Sette and Isaacs, 1960). The changes have been less well documented in the rest of the eastern Pacific, because of the smaller number of investigations and observational facilities, but some attention has been given to them by the STOR program, as shown below, and by the Inter-American Tropical Tuna Commission.

Surface Temperature Anomalies in Middle American Coastal Waters *(M. Blackburn)*

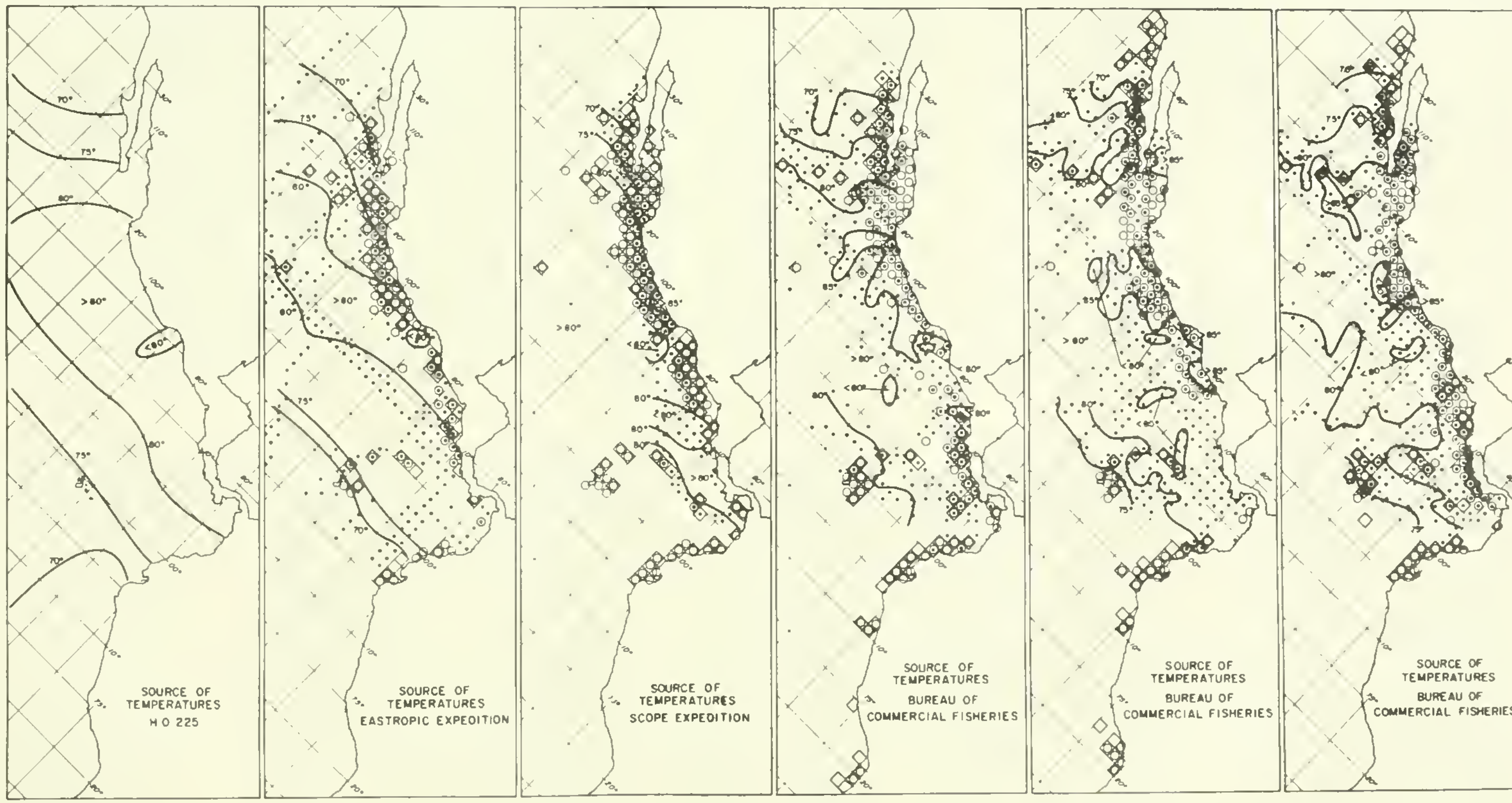
Figure 5 shows these changes as they appeared in the fourth quarter (October-December) of each year 1955 through 1959. The fourth quarter was chosen because of expeditions at that period in 1955 and 1956 (EASTROPIC and SCOPE, respectively) which, together with charts issued monthly since January 1957 by the Bureau of Commercial Fisheries, provided surface temperature data over a comparable period in the 5 successive years. The observations for each year, averaged for the available 1-degree rectangles which are indicated by points in figure 5, have been contoured in intervals of 5° F. Similar contours based on long-term average surface temperatures, adapted from published monthly charts (U.S. Navy Hydrographic Office, 1944), are shown for comparison in the left-hand panel.

The comparisons show that surface temperatures for the region as a whole were lower than average in 1955, about average in 1956, above average in 1957 and 1958, and reapproaching average off Central America, but not off southern Mexico, in 1959.

The information on tuna distribution in figure 5 is discussed later in this paper, under "Tuna ecology."

The above-mentioned monthly temperature charts of the Bureau of Commercial Fisheries,

DISTRIBUTION OF SURFACE TEMPERATURE (°F) AND TUNA



KEY — ○ YELLOWFIN TUNA CAUGHT □ SKIPJACK TUNA CAUGHT ⊡ YELLOWFIN AND SKIPJACK TUNA CAUGHT · TEMPERATURES OBSERVED

SOURCE OF TUNA INFORMATION TUNA COMMISSION

Figure 5.--Distribution of surface temperature, yellowfin, and skipjack in Middle American waters in the fourth quarter (October-December). Points indicate 1-degree rectangles for which temperature data were available.

based on ship weather reports, have been individually compared with the long-term average monthly charts to provide more information about the period 1957-59. Most 1-degree rectangles with data showed positive anomalies of about 2° to 6° F. from July 1957 through July 1959, but the anomalies were less consistent in the first half of 1957 and the last half of 1959. Central American temperatures were normal in most months after July 1959. In most months of 1960, temperatures were normal over the whole region.

Even during the warm period the anomalies were smaller in the Central American region than in the Mexican region. The observation of Austin (1960), that Equatorial Countercurrent waters showed a smaller anomaly than adjacent waters during 1955, may be enlarged into a hypothesis that the Countercurrent exercises a moderating influence on anomalous temperature regimes in general, both low and high, in the region between 5° and 10° N. where it approaches the coast.

Figure 5 shows also the rise in surface temperatures along the Baja California coast from 1955 to 1959, which is discussed elsewhere in the paper under "Tuna ecology."

Surface Temperature Anomalies and Associated Observations in Peruvian Waters *(W. S. Wooster)*

During the period 1939-56, ocean surface temperatures measured by Peruvian vessels were collected and published by the Compañia Administradora del Guano in a series known as Mapas Mensuales. From these data were selected the 1-degree squares for each degree of latitude from 4° to 17° S., for which data were most abundant. These were summarized in a long-term (18 years) average picture of the monthly change of surface temperature along the Peruvian coast. This showed the annual range of surface temperature varying from about 4° C. at 12° S. to nearly 6° C. at 4° S. Highest temperatures (up to more than 22° C.) occur farthest north in the summer and lowest temperatures (less than 15° C.) during winter at 13 to 15° S.

Detailed yearly charts were also prepared, which showed the character of year-to-year differences. During El Niño years, such as 1941, the summer warming showed a marked increase in southern penetration, duration, and intensity. During cold years, such as 1950-51, summer warming was notably reduced, and the winter cold regime more extensively developed than usual. Examination of these charts led to speculation about the cause of El Niño, discussed in the next section.

Since 1957 an active program of marine research has been carried out by the Peruvian Consejo de Investigaciones Hidrobiologicas. In part this program has consisted of periodic cruises off the Peruvian coast, from 4° to 17° S. and offshore a distance of 60 miles. Hydrographic observations included bathythermograph lowerings and surface salinity measurements. Data from three cruises in 1958 (February, April, and September) have been sent to Scripps Institution for analysis. These have been used in the preparation of temperature profiles and in an examination of the temperature-salinity relationship of surface waters.

The great value of these data is that they constitute an occasional three-dimensional check on the oceanic significance of coastal temperature being continuously monitored at Puerto Chicama and elsewhere. For instance, the cruise of February 1958 showed two intrusions of warm water from the ocean on to the Peru coast, separated by an area of cooler water; the salinity of the northern warm tongue of water was lower than that of the southern, which suggests a different origin for each tongue.

The temperature charts have been used as the basis of a paper entitled "Yearly changes in the Peru Current," which is in press in Limnology and Oceanography.

The work was supported in part (about 50 percent) by the Office of Naval Research, and assisted, as indicated above, by the Consejo de Investigaciones Hidrobiologicas.

El Niño *(W. S. Wooster)*

One of the most celebrated of oceanic disturbances is that known as El Niño, an occurrence of the first half of the year which is observed at irregular intervals (1891, 1925, 1941, 1953, 1957-58) from the coast of northern Peru. Symptoms of this phenomenon commonly reported include the presence of unusually high sea surface temperatures, southward coastal current, heavy rainfall, red tide (aguaje), invasion by tropical nekton, and mass mortality of marine organisms. Conditions during early 1958 are referred to above; off central Peru a shallow layer (less than 30 m.) of warm water (over 25° C.) of high salinity (greater than 35.2‰), underlain by a strong thermocline, lay offshore a distance of 20 to 60 miles, and only in a few places was evidence of upwelling present.

A hypothesis of El Niño has been developed, in which the phenomenon is defined as the set of conditions developing off an upwelling coast when reduction of the wind stress causing upwelling during an extended period of time leads to weakening or cessation of vertical mixing. The resulting conditions include an increase in surface temperatures, the development of a thin layer of light water offshore, a modification of the surface circulation depending on the nature of the variation in the wind stress, and the biological changes associated with the altered environment. At the same time, in a region such as the Peruvian offing, where a cold coastal current turns away from the coast at low latitudes (see below), the well-defined zone of transition to warmer waters may be at higher latitudes than usual. Testing of this hypothesis requires a better set of oceanographic and meteorological observations than is yet available from Peru. Analogous situations are undoubtedly present off other upwelling coasts, such as California, where data may be more abundant.

A paper on this subject, entitled "El Niño", was published in California Cooperative Oceanic Fisheries Investigations, Reports, vol. 7, p. 43-45, 1960.

PHYSICAL FEATURES AND PROCESSES IN THE OCEAN

This section of the paper deals with the physical oceanography of selected tuna fishing areas of the eastern tropical Pacific, with some reference to similar areas in other parts of the ocean. The work was done to improve our understanding of the distribution of tropical tunas in those areas; it is further discussed under "Tuna ecology."

Comparative Study of Eastern Boundary Currents *(W. S. Wooster and J. L. Reid)*

The Peru Current and California Current belong to a class of ocean currents known as eastern boundary currents. Other members of the class include the Canary and Benguela Currents off the west coast of Africa. A comparative study of these phenomena has been made to understand the causes of their similarities and differences.

The eastern boundary currents constitute the eastern limbs of the anticyclonic subtropical gyres. Flow is predominantly equatorward and is broad (about 1,000 km.), slow (less than half a knot) and shallow (usually above 500 m.). The difference in steric level across such currents is about one-third of a meter, and the average transport is of the order of $15 \times 10^6 m.^3/sec$.

Surface waters are of relatively low temperature, since flow is from high to low latitudes and since additional cold water is introduced seasonally along the coast by upwelling. Below the surface a general coastward rise of the thermocline is indicative of the distribution of mass associated with equatorward geostrophic flow. In all but the California Current, salinity decreases with depth to minimum values at depths of several hundred to a thousand meters, so the effect of coastal upwelling is to decrease surface salinity. The opposite is true in the California Current.

Isopleths of dissolved oxygen ascend toward the coast where the subsurface oxygen minimum is shoalest and has the lowest oxygen content. At times coastal upwelling is so intense that nearshore surface waters are significantly undersaturated. Coastal surface values of dissolved inorganic phosphorus may be as high as 1-2μg.-at./l. in contrast to the usual mid- and low-latitude oceanic surface concentrations of 0.2 μg.-at./l. or less. To these unusually high surface nutrient concentrations is attributed the extraordinary productive capacity of these regions.

The physical process of coastal upwelling which operates along the boundaries of these currents is of great biological importance. The model of the process involves the action of wind stress parallel to the coast transporting surface water away from the coast, with a compensatory replacement with deeper lying waters. This implies that time and space variations in the intensity of upwelling depend on variations in the magnitude of the wind stress component parallel to a given section of coast.

Values of average wind stress and the average orientation of coast lines in 5-degree squares along the eastern sides of oceans were used to compute seasonal values of Ekman transport of surface water away from the coast. These were then examined as possible crude indices of the seasonal and geographical variation of coastal upwelling.

Values of the index were plotted as functions of latitude and season (figure 6). The following tests of the index were made:

1. Estimates of the speed of vertical motion. For an offshore transport of 10 kg./cm./sec. and an upwelling zone 50 km. wide, the compensating vertical motion is about 50 m./month, a result comparable with previous estimates.

2. Annual range of surface temperature. At midlatitudes a summer maximum of upwelling will tend to increase this range, relative to comparable latitudes farther offshore. At low latitudes a pronounced seasonal change in the intensity of upwelling will tend to increase an otherwise small annual range of surface temperature. The observed annual range and the index are quite consistent in this respect.

3. Reported variations of upwelling. Examination of reports on upwelling along eastern

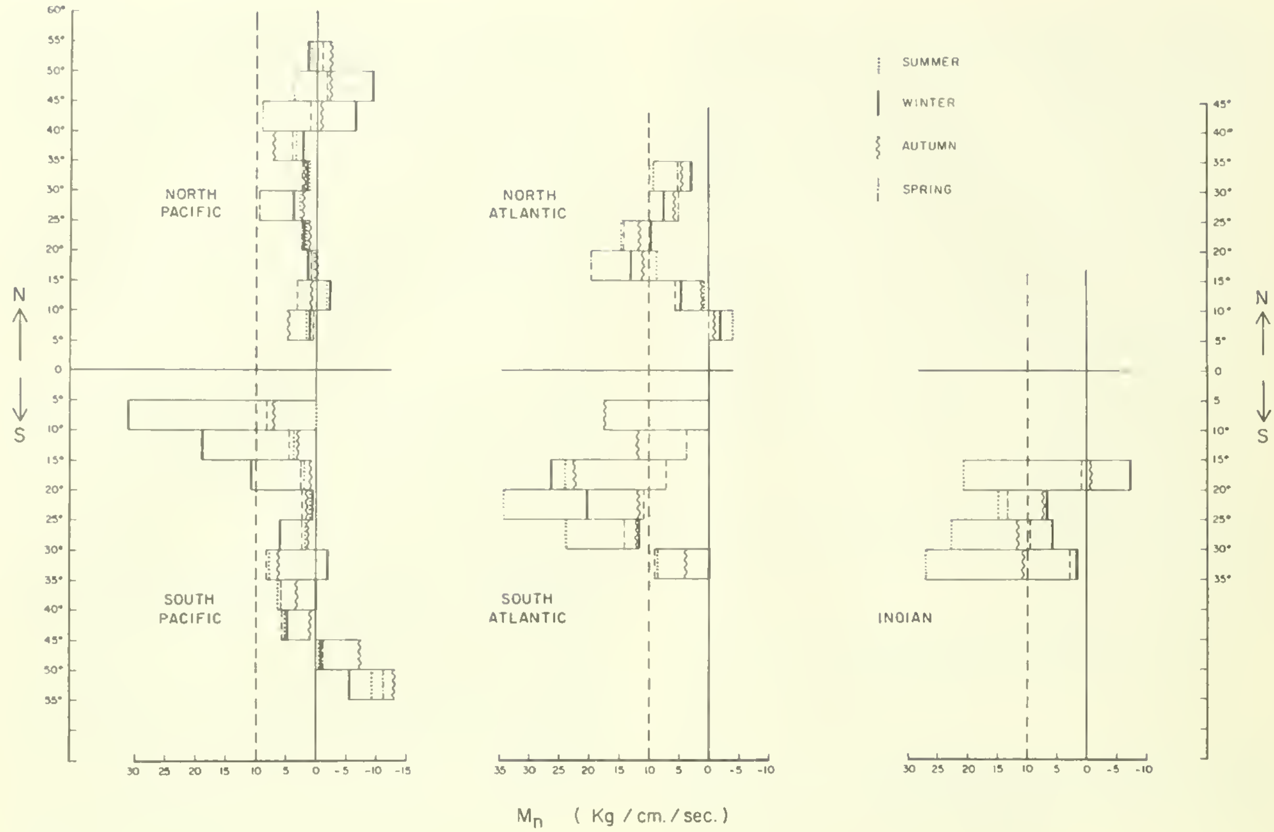


Figure 6.--Offshore Ekman transport of water, M_n, computed for each season from mean wind stress values and average coastline orientations for 5-degree rectangles along the eastern sides of oceans. Summer refers to the summer months in the northern or southern hemisphere as the case requires; similarly for winter, autumn, and spring.

boundary coasts showed that, with the exception of the Indian Ocean, behavior of the index is in qualitative agreement with what is known about seasonal and geographical variations of coastal upwelling.

These tests suggest that a simple model of dependence of vertical motion on the component of wind stress parallel to the coast and the resulting offshore Ekman transport is applicable. With better wind data it might be possible to make a more sophisticated analysis of the relationship, which might then have some predictive value for particular seasons and years. The reason for failure of the index in the Indian Ocean is not understood.

In regions of the better known eastern boundary currents there are occasional indications of surface poleward countercurrents close inshore. There are also indications that coastal undercurrents are a common feature of the circulation on the eastern sides of oceans. Indirect evidence for these is found in the frequent observations of near-shore weakening of the vertical density gradient with a deepening of the isopycnals below a few hundred meters. Such counterflows provide a mechanism for the retention of plankton populations in an area through which there is a predominant flow.

The eastern boundary current regions are well known for their high productivity. Standing crops of phytoplankton and zooplankton, rates of carbon fixation, and populations of fishes of commercial value are known to be large. In part, the upward transfer by upwelling of nutrients from the subsurface reservoir is considered responsible. High productivity is also favored by the shallow thermocline near such coasts, since the mixed layer is usually shallower than the "critical depth" (which depends on the amount of incoming radiation, transparency of the water, and the energy level at the compensation depth), a condition essential for maximal development of phytoplankton populations.

A paper entitled "Eastern boundary currents" is in press in The Sea: Ideas and Observations (Interscience Publishers).

The work was supported in part by the Office of Naval Research (about 25 percent) and California Marine Research Committee (about 50 percent).

Oceanography of the Gulf of Tehuantepec
(M. Blackburn)

The Gulf of Tehuantepec is a bight which forms the southern boundary of the Isthmus of Tehuantepec in southeastern Mexico, near Guatemala (fig. 1). The isthmus runs east and west, is only 120 miles in breadth between the Pacific and the Gulf of Mexico, and is only 735 ft. above sea level at its lowest point (the narrow Chivela Pass, oriented north and south along 95° W. through the Sierra Madre).

Because of this topography the Gulf of Tehuantepec is exposed to northerly winds from the Gulf of Mexico and the Plains States. The northerly is the predominant wind in frequency and strength throughout the year, especially from October through April when gales, called Tehuantepecers, are fairly common in the Gulf. Sea surface temperatures are lower in the affected area of the Gulf than elsewhere over most of this period, as shown for instance in figure 5. These facts have long been known: in conjunction with observations of average monthly surface current in the Gulf (Cromwell and Bennett, 1959), and observations made at a few oceanographic stations on Expedition EASTROPIC (Brandhorst, 1958), they suggested a pattern of wind-connected ocean phenomena leading to seasonal enrichment of near-surface waters and parallel changes in abundance of yellowfin tuna.

The area was selected for intensive study because it was thought to offer good prospects for explaining changes in tuna availability in terms of well-marked changes in sea and wind conditions, and so helping fishermen to minimize their scouting time. The intermittent windiness of the area limits the time that tuna boats can spend in it and makes it especially desirable that they locate fish without delay.

Six surveys of the Gulf were made on four cruises by STOR investigators. The cruises were TO-58-1 (Expedition SCOT) with one survey in May-June 1958; TO-58-2 with two surveys in November 1958; TO-59-1 with two surveys in January-February 1959; and TO-59-2 with one survey in September 1959.

Figures 7 and 8 exemplify the information obtained on these cruises. Figure 7 shows (above) vertical distributions of temperature along east-west and north-south sections in

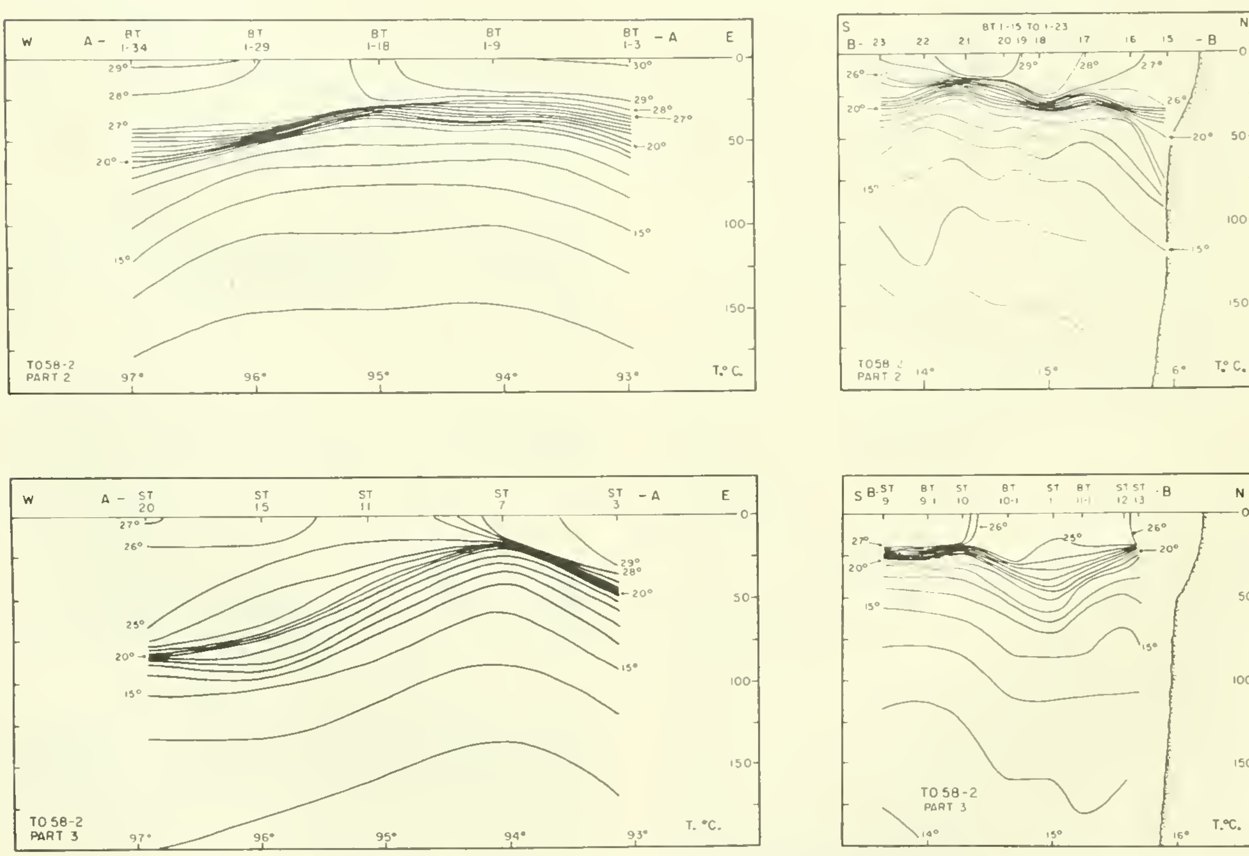


Figure 7.--(Above) Temperature profiles along east-west and north-south sections in the Gulf of Tehuantepec in November 1958, before a northerly gale. (Below) Profiles along the same sections after the gale. Depth scales in meters.

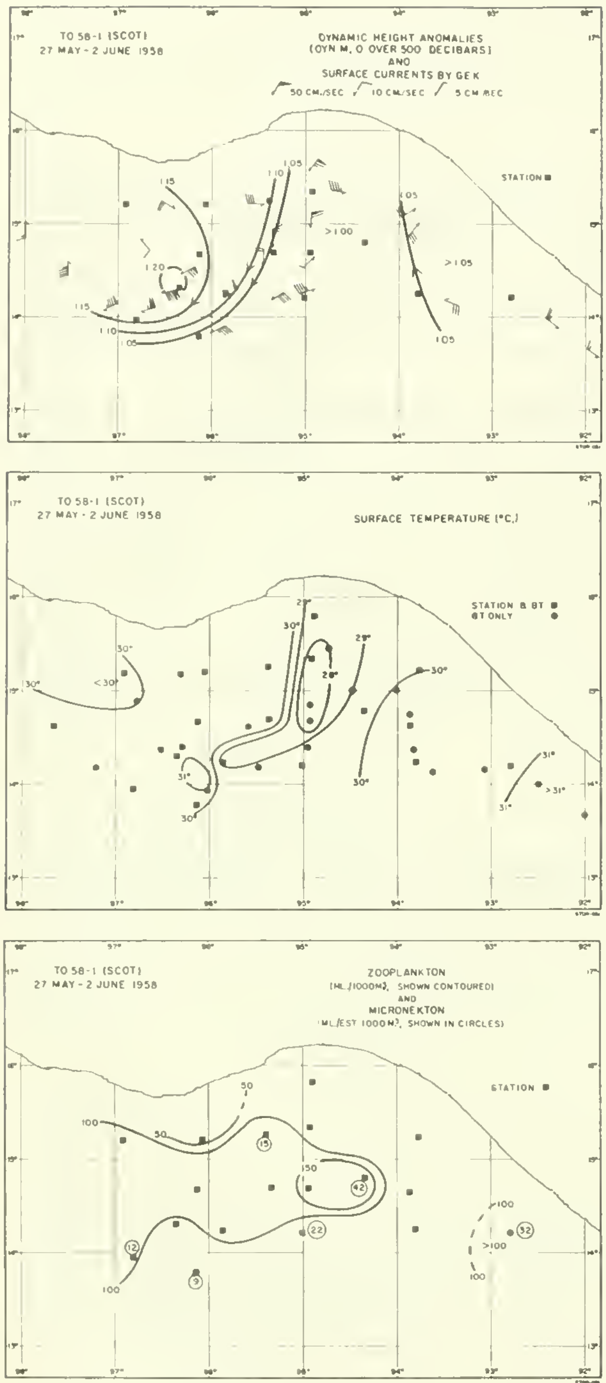


Figure 8.--Current, temperature, and zooplankton charts for the Gulf of Tehuantepec on SCOT Expedition.

November 1958 a few days before a northerly gale, and (below) similar information along the same sections a few days after the gale. The upper east-west section shows a gentle north-south ridge in the thermocline with its crest at about 94° W. where the thermocline top is about 20 m. below the surface, and the corresponding north-south section (along 95° W., the meridian of Chivela Pass) shows the thermocline top undulating at about the same level; a few isotherms from the thermocline top extend to the surface along the western shoulder of the ridge, especially near the coast. The lower sections show marked changes in the thermocline topography including the elevation of the top of the ridge to 12 m. below the sea surface; and additional isotherms reaching the surface along the western shoulder of the ridge, especially in midgulf at 15° N., where the thermocline almost breaks down. Isopleths of salinity, thermosteric anomaly, oxygen, and phosphate are distributed in almost the same way in the same sections.

Figure 8 presents horizontal distributions, from another cruise, of dynamic height anomaly and surface current by GEK, surface temperature, and zooplankton standing crop in the upper 300 m. (approximately), with some values for micronekton in the upper 90 m. (approximately). The western flank of the meridional ridge is seen to run south-southwest in the direction of the wind, and there is some clockwise circulation along this ridge and around the hollow to the west of it; surface current agrees well with geostrophic current. The coolest area is over the ridge but especially along its western flank at about 15° N. Zooplankton is most abundant in the cool area and south and west of it.

The following conclusions were drawn from the data of all cruises and from information in published average charts of wind, current, temperature, etc. They refer to the period September through May; the same processes may operate to a less extent from June through August, but no cruise observations have been made.

1. The prevailing northerly winds cause a current to flow from the head of the Gulf to the south and southwest. The effect of this, added to the effect of the normal flow northwestward along the Mexican coast, is to produce in the Gulf a more or less permanent flow pattern like that of a letter S rotated 90° clockwise, with its axis lying east and west after rotation. As a result the discontinuity layer (pycnocline, thermocline, etc.) forms a ridge in the eastern half of the Gulf and a hollow in the western half.

2. Stronger northerly winds (Tehuantepecers) increase the velocity of the southerly current and the slope of the western side of the ridge, and bring the top of the ridge closer to the sea surface. This process starts in October or November.

3. As the discontinuity layer approaches the windy sea surface, its top is stirred and

mixed layer temperature, salinity, phosphate concentration, etc. become locally more like those of the discontinuity layer. Production of biota, first phytoplankton and later zooplankton and micronekton, is stimulated in the near-surface waters. Surface productivity is up to 161 mg.C/m.^{3}/day. These phenomena are best developed in the region where the ridge top is most affected by the wind, i.e., along the western shoulder of the ridge. Within that meridional belt they tend to be best developed at about 15° N. instead of close to the coast, for reasons that are not entirely understood.

4. The biota tend to be carried downstream from the area of maximum production. If a strong clockwise eddy forms to the west of the ridge the effect is to concentrate some of the biota in the eddy region, but otherwise the effect is to transport them through the southwest waters of the Gulf. Average current charts suggest that the former event occurs more frequently in spring (February to April-May) than in winter. In any event the main concentration of zooplankton standing crop (the most ubiquitous biological measurement) is regularly in the southern, southwestern, or western parts of the Gulf. This concentration reaches about 600 ml./1,000 m.^{3}.

5. Toward the end of the Tehuantepecer season (May) the ridge and hollow flatten out, upward transfer of water properties diminishes, and productivity and standing crops of biota (except possibly micronekton, for which available measurements of standing crops are few) all decline.

6. There is no clear evidence of upwelling at any season. Enrichment is attributed to ridging, followed by vertical mixing and stirring of the ridge top by wind, as postulated by Cromwell (1958) for the offing of the Pacific coast of Costa Rica.

A paper entitled "An oceanographic study of the Gulf of Tehuantepec" has been submitted for publication as a Fishery Bulletin to Special Scientific Report--Fisheries.

Oceanography of Panama Bight

Observations on *Askoy* Expedition, 1941 (*W. S. Wooster*).--The Panama Bight lies between the Isthmus of Panama (about latitude 9° N.) and Punta Santa Elena (about latitude 2° S.) and extends westward from the coasts of Panama, Colombia, and Ecuador to about longitude 81° W. (fig. 1). Oceanographic observations were made in this region by the *Askoy* Expedition during the period February 9 to May 26, 1941.

Seasonal contrasts in weather within the Bight are related to movement of the Intertropical Convergence. In January-March the Intertropical Convergence is farthest south, offshore northerlies cause upwelling in the Gulf of Panama, and the Gulf experiences its dry season. In July-September the Intertropical Convergence is farthest north, and the region south of Cabo de San Francisco receives its least rain. The central part of the Bight receives heavy rainfall throughout the year. From June to November most of the Panama Bight is dominated by southwest winds.

These seasonal changes are reflected in the average surface distribution of temperature and salinity. In February surface temperatures of 26° to 28° C. and salinities of 34 to 35‰ are found in most parts of the Bight, with lower temperatures in the Gulf of Panama. By August low surface temperatures have disappeared in the Gulf, and the whole region is covered with surface waters of low salinity (less than 33‰. It is estimated that during the rainiest period the salinity of a 10-m. layer of water 300 miles long and 60 miles wide could be reduced by rainfall and runoff from 33 to 28‰ in a period of 2 to 3 months.

During the *Askoy* Expedition, surface temperatures of 26° to 28° C. and surface salinities of somewhat less than 34‰ were observed in most of the region. These high surface temperatures and relatively low surface salinities were characteristic of only a rather thin surface layer (reaching 25 m. or less) which was underlain by a shallow pycnocline. At 100 m. temperatures ranged from 15.8° to 19.5° C., salinities from 34.87 to 35.05‰.

In the Gulf of Panama high surface temperatures, low surface salinities, and the presence of a strong shallow pycnocline suggested that upwelling in early 1941 was less intense than usual. This was confirmed by comparison with ***Hannibal*** observations in March 1933, and by examination of long-term measurements of sea level and surface temperature at Balboa by the Panama Canal Company.

Correlation of a northerly wind-stress index for February-March with the average sea level for the same months over a 42-year period gave the significant correlation coefficient of -0.54. However, although the 1941 northerly wind-stress index was somewhat lower than average, it was not low enough to account for the unusually high sea level observed in 1941. Thus, it seems likely that some other large-scale process affecting sea temperatures over a large area was operating.

During the first half of 1941 El Niño was observed off the coast of northern Peru. Schott's explanation of this phenomenon, based on its characteristics in 1891 and 1925, calls for a cold tongue extending from the Gulf of Panama nearly to the equator. Although this cold tongue was not detected by the *Askoy*, unusually high temperature, low salinity, and a strong southward surface current measured west of Malpelo Island may be related to the influx of northern waters on the coast of Peru.

Examination of average surface current charts shows a northward coastal surface flow north of Cabo de San Francisco throughout the year, with a mean speed of about 25 cm./sec. (0.5 knot) and a width of less than 100 miles, along the Colombian coast. *Askoy* measurements in the northern part of Panama Bight show a subsurface distribution of mass consistent with such a current which appears to be the eastern limb of the general counterclockwise circulation in the Panama Bight. It is proposed that it be called the "Colombia Current."

A paper entitled "Oceanographic observations in the Panama Bight, *Askoy* Expedition 1941" was published in Bulletin of the American Museum of Natural History, vol. 118, no. 3, p. 113-152, 1959.

The work was supported in part (about 50 percent) by the Office of Naval Research.

Observations on TO-58-1 (Expedition SCOT), 1958 *(M. Blackburn)*.--Seven stations and 13 BT lowerings were made in the period May 16-19, 1958, along 5° 30' N. between Cocos Island and Cape Corrientes, Colombia (fig. 1). As a result the distribution of mass referred to above, namely a dome with a peak at about 80° 15' W., was found in about the same region as on *Askoy* Expedition, and is shown as a temperature profile in figure 9. The top of the dome was only 7 m. below the sea surface. Measurements of surface current by GEK agreed well with the thermocline topography, current direction being mainly south to the west of the dome and mainly north to the east of it.

Apart from temperature the most ubiquitous property measurement recorded along this track was standing crop of zooplankton. It was highest at station 59 (night station) and next highest at station 60 (noon station). Phosphate and salinity in near-surface waters were higher at station 60 than at stations 56, 58, or 62, and not measured elsewhere. Micronekton standing crop was higher in night hauls at station 59 than at stations 56, 57, or 61, and not measured elsewhere. All these observations suggest moderate enrichment and biological production in the neighborhood of the dome, possibly brought about by windstirring as suggested above. Standing crop of chlorophyll a, on the other hand, showed maxima at stations 58 and 62 (depending on the depth of observation)

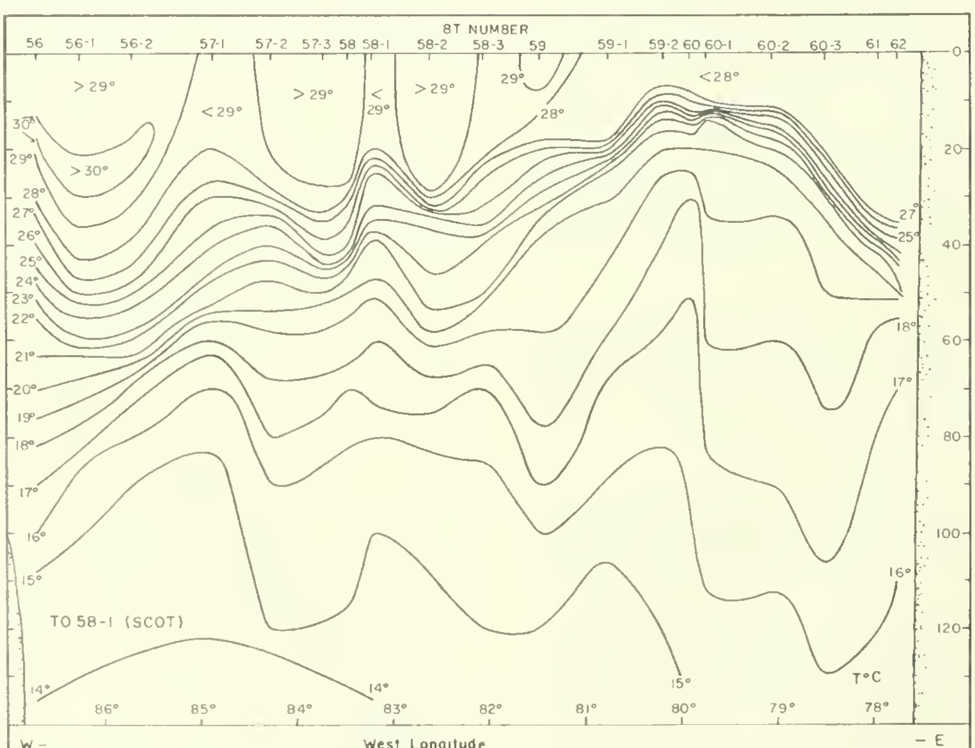


Figure 9.--Temperature profile along east-west section, Cape Corrientes to Cocos Island, SCOT Expedition in May 1958.

rather than at station 60, and was not measured elsewhere. Productivity was much higher at station 62 than at stations 56 and 58, but was not measured at station 60 or elsewhere.

Oceanography of the Gulf of California
(G. I. Roden and G. W. Groves)

Knowledge of the physical oceanography of this region (fig. 1), summarized originally by Roden (1958), was added to by analysis of data obtained on seven CalCOFI cruises during 1956 and 1957.

The seasonal variation of temperature, salinity, and oxygen at the surface and at subsurface depths was investigated. It was found that the annual temperature range in the surface layers is very large. Surface temperatures vary between 14° and 30° C. in the southern part of the region. In contrast to the pronounced seasonal temperature variations, the salinity does not change much from one season to another. In the south it varies between 34.9 and 35.2‰ and in the north between 35.4 and 35.7‰. Only in isolated bays does the salinity exceed 36‰ or fall below 34.5‰. During the rainy season (July to September) the salinities near the coast are influenced by runoff. With respect to oxygen, the surface waters are almost saturated, deviations of more than 15 percent from the saturation value occurring only rarely. The highest oxygen values occur in spring and are related to biological activities. The stability of the surface layers is very high, owing to the presence of a very well-developed thermocline. In the southern part of the Gulf the thermocline is pronounced throughout the year and in the northern part during the warm season. As a consequence of this the water below the thermocline in the southern part of the Gulf is so depleted of oxygen (between 200 and 500 m.) that its presence frequently cannot be detected by ordinary methods.

The area around Angel de la Guarda Island is of special interest. It is characterized at the surface by temperatures lower than anywhere else in the Gulf; at depths the temperature, salinity, and oxygen values are very much higher than observed elsewhere. This peculiar feature is due to two causes: (1) the presence of a deep and isolated trench (below 250 m.) between Angel de la Guarda and Baja California and (2) the intense tidal mixing.

The circulation in the Gulf is very complicated. At the surface there appears to be an outflow of water in winter and spring and an inflow in summer and fall. Below the surface, outflow takes place along the west coast and inflow along the east coast. In the northern part of the Gulf there are strong tidal currents, occasionally reaching velocities of several knots. In the vicinity of Cabo San Lucas or Cabo Falso intense temperature and salinity gradients are found at the boundary between the cold and low salinity California Current water and the relatively warm and high salinity Gulf water (cf. fig. 2). A similar but weaker phenomenon is observed in the vicinity of Cabo Corrientes where the Gulf water meets the water from the eastern tropical Pacific. All of these fronts are rather shallow phenomena and disappear below about 150 m. Below that depth the water is rather uniform and essentially the same as in the equatorial Pacific.

A paper entitled "Recent oceanographic investigations in the Gulf of California" was published in Journal of Marine Research, vol. 18, no. 1, p. 10-35, 1959.

The work was supported in part (about 50 percent) by the California Marine Research Committee.

Heat and Salt Budget of the California Current System *(G. I. Roden)*

The mean monthly variations in the heat and salt content of the upper 200 m. have been investigated for eight ocean areas off Baja California and California. These variations were related to monthly changes in the rates of incoming radiation, energy exchange with the atmosphere, and advection. With particular reference to the STOR program, we wanted to know whether advection of warm water occurs at any time of the year off the coast of southern Baja California, since this might facilitate the entry of tropical tuna from the south. The following results were obtained:

1. Significant northward flow off southern Baja California occurs only in late summer (September).

2. The rate of net incoming radiation off Baja California varies between about 200 cal. $cm.^{-2}$ day^{-1} in January and about 400 cal. $cm.^{-2}$ day^{-1} in July.

3. The rate of turbulent energy exchange with the atmosphere off Baja California varies between -70 cal. $cm.^{-2}$ day^{-1} in summer and -140 cal. $cm.^{-2}$ day^{-1} in winter.

4. The rate of heat advection by currents off Baja California varies between -200 to -400 cal. $cm.^{-2}$ day^{-1} in winter and spring to about -80 to +200 cal. $cm.^{-2}$ day^{-1} in late summer.

5. The rate of advection of salt off Baja California indicates that water of relatively high salinity enters the region between May

and September and again in December and January.

A paper entitled "On the heat and salt balance of the California Current region" was published in Journal of Marine Research, vol. 18, no. 1, p. 36-61, 1959.

The work was supported in part (about 50 percent) by the California Marine Research Committee.

METHODS IN PHYSICAL OCEANOGRAPHY: EVALUATION AND DEVELOPMENT

In the course of the STOR program, advantage was taken of some opportunities that presented themselves to improve or evaluate certain methods in physical oceanography.

Reliability of Ocean Measurements of Temperature and Salinity

(W. S. Wooster and B. A. Taft)

Although the validity of descriptive studies of the ocean depends on the quality of data employed, there have been few studies of the reliability of field measurements. Therefore a statistical study of such oceanographic data was carried out.

By following various pairs of thermometers through many reversals, and by examining the scatter of data on temperature-depth curves where observation points were closely spaced, estimates were made of the measurement errors in temperature data ($^{\circ}$C.) obtained in the field. These estimates, expressed as standard deviations for averages of two thermometer readings, are as follows:

total error	(upper limit 0.014°	- from temperature-depth curves
	(lower limit 0.011°	)
random error	0.009°	) from paired thermometer-analysis
systematic error	0.007°	)

An upper limit of measurement error in salinity data from the field, obtained from an analysis of salinity-depth curves, is 0.018‰ (standard deviation). Both temperature and salinity measurement errors as thus estimated are not significantly different from comparable estimates by earlier investigators.

In the upper layers of the ocean other errors may be significantly greater than those of measurement. This is particularly true in the upper few hundred meters where vertical gradients of temperature and salinity are usually large. Here sampling errors due to vertical oscillations, and errors resulting from uncertainty in depth determination, may be as large as 1 to 2° and 0.1‰. At greater depths, where vertical gradients are small, such errors are comparable to measurement errors.

The effect of salinity measurement errors on the determination of specific volume anomaly is much greater than that of temperature errors and amounts to a standard deviation of about 1.5 cl./ton. The resulting standard deviation of geopotential anomaly (0 over 1,000 db.) for a station on which standard depth intervals are used is 0.004 dyn. m. The measurement error of the difference between two such stations is $\pm$0.011 dyn. m. (two standard deviations), and at latitude 30° and 100 km. separation, the corresponding error in geostrophic current speed is $\pm$1.5 cm./sec.

A paper entitled "On the reliability of field measurements of temperature and salinity in the ocean," was published in Journal of Marine Research, vol. 17, p. 552-566, 1960.

The work was supported in part (about 75 percent) by the Office of Naval Research.

Modified Roberts Current Meter *(J. A. Knauss)*

The propeller-type current meter of Roberts (1952) was modified by:

1. The substitution of enlarged fiberglass propellers and tail fins.

2. The addition of a Vibrotron pressure element to measure depth.

3. The substitution of positive action wire wiping contacts for the original platinum contacts. Although this last modification increased the frictional resistance of the meter it was felt to be necessary in order to increase the reliability of the contacts.

4. The substitution of nylasint bearings for the original lignum vitae.

5. The use of a 24-volt a.c. power supply which allows one to distinguish between the velocity and direction contact. Power is fed down a single conductor wire through the electrical swivel into the meter. Two silicon diodes provide opposite phased currents to the direction and velocity contacts. Sea water is the return circuit and the electrical contact is recorded on one channel of a Brush recorder.

This instrument was designed to make subsurface measurements of current direction and velocity, and proved very satisfactory for this purpose on the Scripps Institution's IGY Expeditions Dolphin and Doldrums in 1958.

Dolphin was concerned with the Cromwell Current or Equatorial Undercurrent (Knauss and King, 1958) and Doldrums with the Equatorial Countercurrent (Knauss and Pepin, 1959). Currents were measured at intervals of 15-20 m. between the surface and 300 m. The usual technique was to make measurements from a drifting ship and measure the apparent velocity at different depths from the flow of water past the meter, while at the same time observing by radar the drift of the ship from an anchored taut wire buoy. Ship drift was subtracted vectorially from the meter reading to give the true velocity.

The work was supported in part (about 50 percent) by the Office of Naval Research.

Telerecording Bathythermograph
(J. M. Snodgrass)

Support was given to the improvement of the telerecording BT (Snodgrass and Cawley, 1957), which is not yet suitable for routine oceanographic work. This work is now being continued by a private manufacturer, who has outlined plans to correct the undue instability and hysteresis observed on field trials.

LIGHT, NUTRIENTS, AND BIOTA: METHODS AND EXPERIMENTS

It was shown under "Special Operations" that the STOR cruise program included a wide range of observations on submarine light and biota, and this was also the case with chemical nutrients as shown below. This part of the paper gives some information about what was done to obtain these data and process them, and it also gives particulars of the laboratory-experimental part of the research program. The next section, "Light, nutrients, and biota: statistical analysis of ocean data," shows more clearly the uses to which the data are being put.

Modified Submarine Photometer
(R. W. Holmes and J. M. Snodgrass)

The importance of submarine daylight in governing photosynthetic rates below the surface of the sea has led to the development of a versatile irradiance meter and associated depth sensing element.

This meter can be used with up to five detectors which may accommodate five different filters, or which may accommodate the same filters and measure horizontal and/or upwelling and downwelling irradiance. The depth sensing component enables depth measurements to be made at the same time as irradiance measurements are being made. The light collecting surface of each detector consists of translucent plexiglass which has been abraded with carborundum powder (#180 grit). This surface collects irradiance according to the Lambert or cosine law.

The sensitivity of this unit is adequate for photosynthetic studies, i.e., irradiance (downwelling) can be measured in the blue-green region of the spectrum (480 mμ) down to depths of 100 m. on bright clear days in clear ocean water. Increased sensitivity at low light levels may be obtained by amplifying the signal.

The circuitry is straightforward and permits the measurement of depth and submarine detector signals simultaneously. Each detector output is measured separately. The selection of the particular detector is made in the vessel's laboratory, and output of detector may be made at any depth in the 0-100, 0-120 m. range. Both the depth and detector signals are transmitted simultaneously over a two-wire system. A sea return is used in the detector switching circuitry.

A paper entitled "A multiple detector irradiance meter and electronic depth sensing unit for use in biological oceanography" is in press in Journal of Marine Research.

Measurement of Nutrient Concentrations
(W. H. Thomas)

This work arose out of the program of physiological experiments with oceanic phytoplankton (see below, Results with *Gymnodinium*), and the general feeling among Pacific oceanographers that inorganic phosphorus (phosphate) concentration is an imperfect measure of availability of plant nutrients in general. Phosphate concentration is routinely determined on STOR cruises, and it was decided that attention should be paid also to nitrate, nitrite, and silicate.

Cruise TO-59-2 provided an opportunity for testing measurement methods developed ashore (mainly those of Strickland, 1958) under seagoing conditions. It was found that nitrite and silicate could be measured at sea as satisfactorily as phosphate, although nitrate measurement was much more difficult. Vertical distributions of nitrate and silicate resembled those of phosphate; but quantitatively, phosphate appeared to be a poor index of other nutrients in and above the thermocline, since ratios of phosphate to nitrate and silicate were very variable.

The Inter-American Tropical Tuna Commission's cruise to the Costa Rica Dome in November 1959 provided 300 frozen water samples for nitrate, nitrite, and silicate measurements in the laboratory; phosphate concentrations were measured at sea. The summary of surface water data given in table 3 shows higher values at the Dome than off the coast of southern Mexico, off Cocos Island, or off San Diego (fig. 1). The high values at the Dome are consistent with previous information about the distribution of physical, chemical, and biological properties in this characteristically eutrophic area (e.g., Holmes et al., 1957; Wooster and Cromwell, 1958).

Culture and Physiology of Tropical Oceanic Phytoplankton *(W. H. Thomas)*

Oceanic tropical phytoplankton from the Costa Rica Dome and from the Gulf of Tehuantepec have been isolated into unialgal cultures. These cultures were used in laboratory experiments to establish the optimum chemical and physical conditions for growth. Optimum conditions were taken as those which supported a maximum rate of growth in the laboratory.

The optima were then compared with oceanographic conditions in the eastern tropical Pacific Ocean, as measured during STOR cruises. This comparison is intended to increase our understanding of the temporal and spatial distribution of phytoplankton in this region.

Most previous studies of this type have been done with more easily grown coastal species, and the results may not be completely applicable to the open sea. The present work is wholly concerned with species taken from open sea areas of particular interest to the STOR program.

The following algae have been cultured in this investigation: *Gymnodinium simplex* ? (two strains), *Nannochloris* (possibly *N. atomus*), *Chaetoceros* spp. (four strains), *Nitzschia* spp., and several unidentified forms.

Results with *Gymnodinium*.--Two isolates of *Gymnodinium* were obtained. One was from station 49 of Expedition SCOT (TO-58-1) ($9^{o}48.5'$ N., $89^{o}14.5'$ W.) in the area of the Central American Thermal Dome; the other was from station 19 of cruise TO-58-2 ($14^{o}40.3'$ N., $96^{o}58.6'$ W.) in the Gulf of Tehuantepec.

Morphologically, these isolates are identical. The cells are about 17 μ in length and 7 μ wide. The sulcus is not well developed. The cells are motile with the typical whirling motion of dinoflagellates. Dr. J. B. Lackey has tentatively identified this organism as *G. simplex*.

Logarithmic growth rates have been measured at different temperatures in various experiments. For both isolates the optimum range is 21-29° C. Maximum growth of the Dome isolate occurred at 29° C., and at 26° C. for the Tehuantepec isolate. A comparison of the optimum range with sea surface temperature charts of the eastern Pacific Ocean shows that this organism would grow most successfully, if supplied with other requirements, as far north as 27° N. in the summer months and south of 23° N. in the winter. This conclusion is based on the position of the 21° C. surface isotherm. *Gymnodinium* might occur in waters having a lower temperature, but would not grow at an optimum rate. Thus, it appears to be a tropical organism. The growth rates of the Tehuantepec isolate are slightly less than those of the Dome isolate at most temperatures. This difference has not yet been explained.

The growth rate of the Tehuantepec isolate was measured at several light intensities. Saturation occurred at about 700 foot-candles; the half-saturation value is 200 ft.-c., and compensation is about 30 ft.-c. For the Dome isolate similar figures are 800, 250, and 30 ft.-c., respectively. No inhibition of either isolate was observed at illuminances from 800 to 2,000 ft.-c. Growth at higher intensities was not measured; fluorescent lights were

Table 3.--Mean surface nutrient concentrations, Tuna Commission cruise to Costa Rica Dome and Cocos Island, November 1959

[Concentrations in μg.-at./l., numbers of observations in parentheses]

Areas	NO_3	NO_2	SiO_3	PO_4
Dome	6.1 (15)	0.10 (18)	2.5 (20)	0.76 (16)
Near the Gulf of Tehuantepec	2.8 (4)	0.12 (4)	0.3 (4)	-
Tehuantepec north to Baja California	0.6 (14)	0.01 (14)	0.5 (14)	-
Near Cocos Island	0.3 (9)	0.00 (9)	0.3 (8)	0.37 (8)
Off San Diego (October 1959)	1.0 (1)	0.03 (1)	0.5 (1)	-

used. Similar figures were obtained for the dinoflagellate *Prorocentrum micans* by Kain and Fogg (1960) with fluorescent light, but saturation occurred at only 300 ft.-c. with tungsten illumination. Our values for saturation of *Gymnodinium* growth are much less than those observed for dinoflagellate photosynthesis by Ryther (1956). He observed saturation at 2,500 ft.-c. There may be a difference between optimum light requirements for growth, and those for photosynthesis.

The remaining work on *Gymnodinium* concerned its chemical nutrient requirements. Various artificial sea waters have been tried as substitutes for sea-water media. The basic medium tried with *Gymnodinium* was Provasoli's (1957) ASP-2, which contains all the major salts and minor nutrients present in sea water, plus vitamin B_{12} and other vitamins known to stimulate growth. This medium was also modified by substituting nitrilotriacetic acid for EDTA as a chelating agent, changing the trace metal content, and by adding soil extract. Some growth in ASP-2 occurred when soil extract was added, but this was much less than in enriched sea-water controls; otherwise, no growth occurred in ASP-2 or various modifications thereof. Toxicity of artificial sea water was shown by the loss of cellular motility, cell enlargement, and cell wall thickening. Some growth occurred in another artificial medium, ASP-6. However, none of the various modifications resulted in any increase of growth over a sea-water medium. These experiments indicate that some unknown component in sea water is necessary for maximum growth of *Gymnodinium*.

The nitrate requirements of the Dome isolate were studied in separate cultures containing sea-water media prepared with concentrations of added nitrate ranging from 0-2,000 µ g.-at./l. These were incubated at 800 foot-candles and 25° C. The growth rate was identical in all cultures. This suggested that *Gymnodinium* could effectively utilize concentrations of nitrate as low as those supplied by the sea water and soil extract in these media.

This was confirmed by growing the alga (Dome isolate) in a mass culture containing sea water enriched with phosphate, EDTA, soil extract and 50 µ g.-at./l. of added nitrate. Samples were taken at intervals of 12-16 hours for cell counting and for analyses of the nitrate concentration of the medium. In two such experiments, the growth rate decreased when a concentration of 3 to 7 µ g.-at./l. of nitrate remained. Nitrate was shown to be a limiting factor by adding nitrate to separate portions of the cell suspension after the rate had decreased. The original rate was nearly restored by this addition. When growth in the mass culture ceased, the nitrate concentration in the medium was 1 µ g.-at./l.

Calculations of the amount of nitrogen required per *Gymnodinium* cell were made on a rate basis by dividing the increments of change of cell numbers by the increments of change of nitrate between sampling times. They were also made by dividing the final population by the amount supplied. The mean of these determinations, with both methods, was 1.1 µg.-at.N/cell; on a cell volume basis it was 0.49 µ g.-at.N/mm^3. Kain and Fogg (1960) give values for various phytoplankton which range from 0.19 to 1.6 µ g.-at.N/$mm.^3$

Comparison of the nitrate concentration in surface water of the eastern tropical Pacific Ocean with the rate-limiting concentration of 3 to 7 µ g.-at./l. shows that the latter is fivefold to tenfold greater than the surface concentration except at Dome stations where the two are equal (table 3). Thus the *Gymnodinium* should grow at its maximum rate in the Dome area, where it was originally obtained, provided that factors other than nitrate are also not limiting.

Experiments on other nitrogenous nutrients and on phosphate requirements are planned.

Results with *Nannochloris*.--This alga was obtained from station 19 of cruise TO-58-2, off the Gulf of Tehuantepec. It is a tiny green rod, about 2-3 µ in length and 1 µ wide. Dr. J. B. Lackey tentatively identified it as a species of *Chlorella*. However, it reproduces without the release of autospores, and therefore is probably a species of *Nannochloris*.

The light and temperature requirements of this alga have not yet been studied in detail. However, stock and experimental cultures have been grown at 500 ft.-c. and 21° C.

Nannochloris grows just as well in ASP-2 (artificial sea water) as in the enriched sea-water medium. However, if vitamin B_{12} is omitted from ASP-2, the alga grows poorly and does not survive a second transfer. If this result can be obtained consistently the organism could serve as a useful bioassay organism for B_{12} in sea water: it has a short generation time (8-10 hours), its growth could be measured easily by turbidimetric methods, and internal stores of B_{12} could be reduced by growing it in ASP-2 without B_{12} before the assay.

Nitrate and phosphate requirements of this alga have been not yet established with any precision. Batch cultures in ASP-2 medium containing 0 to 100 µ g.-at./l. of nitrogen and 0-100 µ g.-at./l. of phosphorus showed that enough nutrients could be carried over in the inoculum to allow at least 2 days' growth. This suggests that requirements are low and probably comparable to those of *Gymnodinium*.

Results with *Chaetoceros*.--Two isolates of the diatom, *Chaetoceros*, have been obtained, one from the Dome, another from off Tehuantepec. They grow as single cells rather than in the chains of cells generally characteristic of this genus. Their taxonomy and morphology have not been studied.

The Dome isolate grows well in ASP-2 even when vitamins are omitted. The saturation light intensity for growth is about 500 ft.-c. and the maximum generation time is about 12 hours. Studies of the temperature requirements of both isolates are underway, and further nutritional work is planned.

Results with Other Cultures.--A culture of a green alga from near Guadalupe Island has been maintained since 1957, but no experiments have yet been made with it. A culture of a flagellate from San Diego Bay is likewise available. Several algae are present in transfers from the original cultures taken from the Dome and Tehuantepec, but they have so far defied isolation from contaminating microflagellates.

Results with Natural Populations.--During Expedition SCOT (TO-58-1) cultures were established aboard ship of the mixed natural populations available at the oligotrophic station 4 (west of Baja California) and the eutrophic station 49 (Costa Rica Dome), and experiments were made by offering suspected nutrients in various combinations (a total of 14 treatments) to culture aliquots (three per treatment) which were then incubated at 25° C. and 600-900 ft.-c. The nutrients were N, P, Si, trace elements, soil extract, purines and pyrimidines, and amino acids. The results were broadly as follows: most components of the phytoplankton at station 4 did not grow under any treatment; and most components at station 49 behaved under the various treatments in a way that suggested that N and P were not growth-limiting and that Si, trace elements, and the components of soil extract were limiting.

A paper entitled "The culture of tropical oceanic phytoplankton" was published in abstract form in the Preprints of the International Oceanographic Congress, New York, 1959.

Experimental Evaluation of the C^{14} Method of Measuring Productivity *(W. H. Thomas)*

The carbon-isotope method of measuring productivity (phytoplankton production rate) has become widespread in oceanography since its introduction by Steeman Nielsen (1952). It has had considerable use in the eastern tropical Pacific (Holmes et al., 1957; Holmes, 1958; and later sections of this paper). The question of what actually is measured (e.g., gross or net production or neither) is constantly raised and has been investigated by several workers. It has been investigated in the STOR laboratory by experiments with cultures of *Dunaliella primolecta* Butcher.

The Steeman Nielsen C^{14} method for the measurement of synthesis of organic matter (production) by phytoplankton has been compared with the increase in organic matter and generation rates in *Dunaliella* cultures. The C^{14} measurements were also compared with contemporaneous measurements of photosynthesis made by the oxygen and pH methods. Satisfactory agreement between all these measurements was observed during the logarithmic growth phase of well-nourished cultures. At moderately high light intensities (200-1,500 ft.-c.), production as measured by the C^{14} method accounted for 60-80 percent of the net production as measured by the oxygen method. Measurable C^{14} assimilation (corrected for dark assimilation) persisted at light intensities below the compensation point for oxygen production. The ratio of dark- to light-saturated C^{14} assimilation increased under nitrogen-deficient, but not under phosphorus-deficient conditions. Under severely nitrogen-deficient conditions, production measured by the C^{14} method exceeded the net oxygen production, but approximated oxygen production corrected for respiration. In an extremely phosphorus-deficient bacterized mass culture, production measured by the C^{14} method approximated the gross oxygen production rate; in a bacteria-free phosphorus-deficient culture, production by the C^{14} method was less than the net oxygen production rate.

It is concluded that the Steeman Nielsen C^{14} method provides adequate measurements of organic matter synthesis by actively growing *Dunaliella primolecta*. Under conditions of extreme deficiency of nutrients or at low light intensities, the C^{14} method provides data which agree more closely with O_2 production uncorrected for respiration than with net O_2 production. These results are discussed in relation to the findings of other workers and in relation to applications of the method in the field.

Measurements were considered to be accurate to within 15 percent. Modifications of the method to increase precision included the preparation of uniform $BaC^{14}O_3$ precipitates for standardization and the addition of a mylar window to the counting chamber.

A paper entitled "An experimental evaluation of the C^{14} method for measuring phytoplankton production, using cultures of *Dunaliella primolecta* Butcher" was completed to a first draft and circulated for comment.

Improved Methods of Measuring Chlorophyll A
(R. W. Holmes and R. J. Linn)

Standing crop of chlorophyll a is determined routinely at noon stations on STOR cruises, by measuring optical densities of acetone extracts of material filtered from sea water. To facilitate the optical density measurements a number of modifications have been made in the Beckman Model DU spectrophotometer. They expedite the determination of chlorophyll a and simplify the maintenance of the spectrophotometer aboard ship. To hasten the measurement of the optical density of the chlorophyll extracts the conventional 10-cm. cell compartment cell holder has been replaced with one which accommodates four rather than two 10-cm. semimicro cells (volume about 5.2 ml.).

Maintenance of the DU has been simplified by the construction of new desiccant holders which may be easily inspected and changed; by the transference of the C batteries to a box located next to the cell compartment which also contains an external switch for the adjustment of screen voltage and plugs for the rapid determination of battery condition with a special test meter; and by the location of the 6-volt storage battery chargers adjacent to the transmittance dial on the DU. The DU is covered with a wooden lid when not in use and the heat generated by the chargers helps to reduce difficulties caused by salt air.

The need for a more sensitive method of estimating chlorophyll a has been evident for some time. A fluorimeter was constructed to increase the sensitivity about eightfold over the optical density method and this instrument performed well in the laboratory. It failed to operate on the first sea trial, possibly because of moist conditions in the vessel's laboratory, and awaits modification.

A paper entitled "A modified Beckman Model DU spectrophotometer for seagoing use" has been submitted for publication as a Special Scientific Report--Fisheries of the Fish and Wildlife Service.

Enumeration of Phytoplankton *(R. W. Holmes)*

The use of the molecular filter in the preparation of marine phytoplankton for microscopic examination and enumeration has received attention, and certain modifications in the method of Goldberg, Baker, and Fox (1952) are recommended.

The proposed method involves the microfiltration of a fixed and preserved sea-water sample. The organisms are retained on the upper surface of the filter where they are washed with successively diluted volumes of sea water, dehydrated with ethanol, stained with alcoholic Fast Green, and finally rinsed with absolute thanol. The filter disc is then cleared with beechwood-creosote, xylene, or anisole, and mounted directly on a microscope slide with xylene or toluene balsam under a thin cover glass.

Many nannoplankton species may be readily identified and counted on the filter disc. The keeping properties of the preparations appear to be excellent; no signs of deterioration are visible in preparations over 5 years old.

Using this technique half of the Expedition SCOT fine net (32μ mesh) samples have been identified and counted. This work, when completed, will form the basis of a floristic study of the larger species of phytoplankton in the area.

Electron microscope technique for identification of phytoplankton (especially coccolithophorids) has been improved.

A paper entitled "The preparation of marine phytoplankton for microscopic examination and enumeration on molecular filters" has been completed.

The work was supported in part (about 50 percent) by the California Marine Research Committee.

Standing Crop Measurements of Major Zooplankton Components *(R. C. Griffiths)*

The standard measurements of zooplankton standing crop in eastern tropical Pacific investigations have been the displacement volume, per 1,000 $m.^3$ of water strained, of (a) the total catch and (b) the total catch minus any organisms longer than 5 cm. The latter volume has been used in quantitative studies such as those reported below, e.g., in investigating statistical relationships with standing crops of other biota, but there was some inconsistency in these results for which it was thought the varying composition of the zooplankton might be responsible. Therefore, the problem of measuring the volumes of the major components of plankton catches was attacked.

The displacement volume is obtained by separating plankton from its preserving fluid by filtration and placing the drained plankton in a graduated cylinder with a known volume of fluid. Another method of measuring the volume of the plankton is to make the original suspension up to a standard volume, filter, and measure the volume of the fluid removed from the plankton by the filtering process. Of these two the former appears preferable: for example, a sample of zooplankton was measured 10 times by the first method, and the statistics were range 52-69 ml., mean 69 ml., and standard deviation 6 ml.; statistics for 10 measurements of the same sample by the second method were 36-80 ml., mean 60 ml., and standard deviation 15 ml.

Replicate measurements of this plankton sample were made also by the colorimetric method of Sutcliffe (1957). They were highly inconsistent, and several tests were made to determine possible causes. The method depends upon the absorption of the supernatant liquid of the plankton sample, before and after the addition of India ink. The factor that apparently contributed mainly to the inconsistency of the results was the minute invisible debris that remained in the supernatant liquid after visible plankton and debris had settled: readings of transmittance taken after the sample had stood overnight were always several units higher than readings taken after the sample had stood, say, half an hour, till visible debris had settled. In one test a difference of 1.1 units of percent transmittance changed the computed plankton volume by 28 ml. The method is probably too sensitive for plankton work.

From previous experience it is known that the dominant types of small eastern tropical Pacific plankton (i.e., excluding large salps and medusae) are copepods, euphausiids, chaetognaths, pteropods, and siphonophores, though other forms may predominate occasionally. To pick these organisms from a plankton sample is tedious and difficult. Work has been done on several selected Expedition SCOT stations, but to reduce time taken only very small aliquots (2-3 ml.) have been picked.

Copepods, for example, are segregated from an aliquot, being counted at the same time. A method of determining the volume of such a small quantity of plankton is given by Tranter (1960). The equipment consists of: a piece of burette tube about 25 cm. long, graduated in intervals of 0.05 ml., with a stopper at one end; a tube of gauze (monel metal, 80 meshes per inch, strengthened with strips of solder, plugged at one end by a brass disc) that fits inside the burette; and a funnel through which the plankton is introduced into the gauze tube. The plankton is put inside the tube and washed with alcohol. The tube is dried by tapping and rolling on filter paper. The tube, with the plankton inside, is dropped into the burette tubing which contains alcohol to a known level. The change in level is measured and, given the displacement of the empty gauze tube, the volume of the plankton is found.

In practice certain difficulties were encountered. In an aliquot of about 3 ml. of plankton usually more than 1,000 copepods are found. It proved difficult to get them into the gauze tube, because they plugged the funnel and their bristles caught in the mesh.

A modification of Tranter's method was developed. A glass tube, with a removable filter at each end, was used instead of the gauze one. The plankton was introduced into the tube (with or without a funnel). It still occasionally plugged the glass tube, but much depended on the way it was put in. When all the plankton was in the tube the liquid was allowed to drain through either end as desired. The filters occasionally became clogged. Later the tube with the dried plankton was dropped into a burette containing a known level of isopropyl alcohol. This part of the process had to be done carefully and slowly, to ensure that no air bubbles were retained by the plankton.

The method used is not entirely satisfactory, but it has been used to produce some results that were in urgent demand. With either Tranter's method or the above-mentioned modification of it, the problem of leaching by the alcohol may make replication of results difficult. An investigation of the replicability of results is proposed.

Estimates of copepod number and volume, per 1,000 $m.^3$ of water strained by the net, are now available for 20 Expedition SCOT stations, together with estimates of mean volume per copepod for each station. The latter range from 0.0004 to 0.0018 ml. and are more or less normally distributed.

It was surprising to find that the copepod volumes were generally less than half the previously measured total volumes. Possible explanations are (a) that draining of liquid from the plankters is more efficient with a homogeneous part of the sample than with the whole, especially where alcohol is used as an aid to drainage; and (b) that the plankton becomes shrunken with time, the elapsed time in this case being about 2 years. However, the measurements within each series can probably be properly compared with each other even if between-series measurements are suspect.

Collection and Measurement of Micronekton

(M. Blackburn and A. D. Reith)

Examinations of tuna stomach contents, in the eastern tropical Pacific (F. G. Alverson, Tuna Commission, unpublished data) and elsewhere, show that tuna feed much less on zooplankton than they do on micronekton, i.e., active animals ranging in length from about 0.5 to 10.0 cm.

Because of this, and the fact that attempts to correlate standing crops of tunas with contemporaneous standing crops of zooplankton were mainly unsuccessful, we decided that routine measurements of micronekton standing crop should be made on STOR cruises for analysis in relation to contemporaneous tuna standing crops (see below). It was also thought that the results could be used as part of a more general study of interrelationships of biota in the eastern tropical Pacific (see below).

Since STOR schedules of station work were already very long, it was not possible to devote more than 1 hour per diel (24-hour period) to collecting micronekton. This meant that the work had to be done at night when nets do not have to be lowered so far to capture the diurnally migrating organisms; it was also thought that fewer animals would escape the net at night.

A net was built for TO-58-1 (SCOT) and used on that and subsequent STOR cruises in essentially the same way throughout, so that all results (except on TO-58-2, when the work was mainly experimental) are comparable.

This net is shown in figure 10. It is made of Marion Textiles 467 pattern nylon netting throughout, the meshes being approximately rectangular and about 5.5 mm. x 2.5 mm., and it measures 19 ft. along the vertical axis from the mouth to (but not including) the detachable cod end. The cod end, made of 56xxx nylon grit gauze, is the one routinely used with zooplankton nets. The mouth of the net is square (for simpler attachment of bridles and depressors, and simpler handling and stowing aboard ship), 5 ft. x 5 ft.

The arrangement of towing bridles and 45-lb. depressors is shown in figure 10. The ratio, filtering area/aperture area, is approximately 7.6. A BT is attached to the frame to show the maximum depth of the net during the haul.

As now used the net is paid out on 350 m. of 3/8-in. wire at 25 m./min. and hauled back at 10 m./min., all with the ship steaming at 5 kn. This oblique haul takes 49 min., and the maximum depth averages 90 m.

The equipment is not ordinarily used with a flowmeter, since this might cause some organisms to be lost. An experiment was made in which the complete net was towed with a flowmeter and a tow was then made with the net removed (i.e., second tow with frame, flowmeter, and depressors only). It indicated a filtration coefficient of 0.757, which has been used to convert all actual micronekton volumes into volumes per estimated 1,000 $m.^3$ (see figs. 12, p. 36, and 13, p. 37).

After preservation of the catch in buffered formalin all nonnektonic watery organisms over 1 cm. in length (salps, medusae, siphonophores, and heteropods) are removed and total displacement volume is measured. The catch is then sorted into the following components whose volumes are separately measured: fishes, cephalopods, adult crustacea longer than 3 cm. (galatheid and portunid crabs, adult stomatopods, adult shrimps), and remainder (mainly euphausiids, stomatopod larvae, amphipods, phyllosomas, pteropods, and very small watery organisms).

Experimentally throughout the cruises, and routinely commencing with TO-59-2, a high-speed micronekton net was used when the ship was steaming at ordinary cruising speed (9-11 kt.). This net, which is also shown in figure 10, is of the same material throughout as the other and used with the same detachable cod end, but it is only 8.5 ft. long and mounted on a circular frame of 70 cm. diameter. The ratio, filtering area/aperture area, is 7.5. The net is paid out on 50 m. of 3/8-in. wire, with one 45-lb. depressor attached so as to swim 10 ft. below it, and is towed horizontally on that length of wire for as long as necessary (normally from 2 to 3 hours). It can be brought aboard for change of cod end and restreamed within 5 min., without slowing the ship. Records from attached BTs show that the normal depth of towing under these conditions is about 10 m. There is no routine use of a flowmeter, but a test similar to the above-mentioned one indicated a filtration coefficient of 0.938, which is used to standardize all catch volumes in terms of an estimated 1,000 $m.^3$ of water strained. The catches are sorted and measured as described above.

Such nets eventually wear out, but have been found to be good for about 1,000-1,500 miles of trouble-free towing and represent a valuable source of information.

Experiments with Cultures of Red Crabs
(Pleuroncodes planipes) (C. M. Boyd)

Predominant in the micronekton of the Baja California region, and in stomachs of yellowfin and skipjack caught in that region, is the galatheid crab *Pleuroncodes planipes* (red crab).

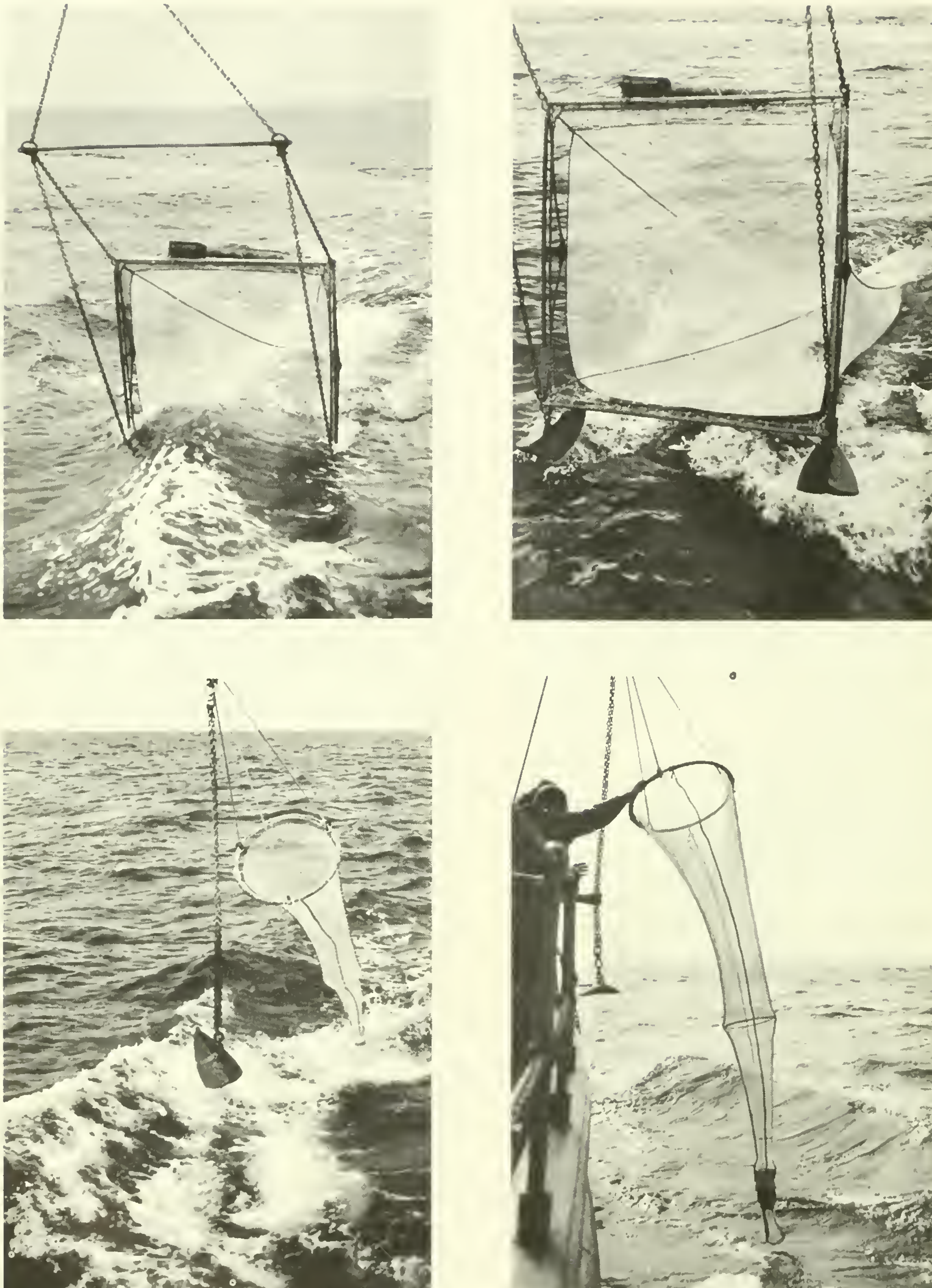


Figure 10.--(Above) Net for collecting micronekton at 5 knots. (Below) Net for collecting micronekton at 10 knots.

Various studies on its life history and ecology are in preparation. The following is a summary of work recently performed with live animals in the laboratory.

Adults

1. Adult crabs have been maintained in the laboratory under controlled conditions for several months.

2. Crabs kept isolated in 2-quart containers molt about every 56 days; when kept in groups in circulating sea water they molt about every 38 days.

3. Females bear eggs during winter and spring. The egg-carrying season ended on April 12, 1960, in the laboratory.

4. Eggs require from 6 to 22 days to ripen and hatch.

5. Females may produce more than one brood of larvae a breeding season; association with males is a prerequisite to egg-laying.

Larvae

1. The larval stages have been reared from eggs in the laboratory, and some individuals are still alive as juveniles. With streptomycin and no penicillin in the medium, 56 out of 100 newly hatched larvae survived to the megalops stage. Ten larval stages have been recognized in these cultures; only five were thought to exist when a previous study, based on plankton samples, was made.

2. Durations of larval stages have been established. Development from egg to megalops took 56 days in one case and 66 days in another.

3. The larvae were fed on *Artemia* nauplii, and may therefore be carnivorous in nature.

LIGHT, NUTRIENTS, AND BIOTA: STATISTICAL ANALYSIS OF OCEAN DATA

This section of the program is comparable to that on "Statistical analysis of ocean-atmosphere relationships," which was reported above, in that it attempts to show predictive quantitative relationships. In this case, the variables being predicted are biotic, relating to links in the food chain of tuna. Ultimately it is hoped to demonstrate relationships predictive for tuna from variables further back along the energy chain, as indicated in the introductory sections. At present, for lack of good quantitative data all along the chain for any part of the eastern tropical Pacific, such comprehensive relationships can only be indicated in a qualitative way, e.g., the work in the Gulf of Tehuantepec reported in this paper; these studies are valuable, however, in giving leads as to relationships that might later be investigated by statistical methods.

Relationships in the Energy Chain up to Zooplankton *(R. W. Holmes)*

General remarks.--The purpose of this section of the work is to understand and predict changes in primary production (productivity) and zooplankton standing crop in terms of variables on which they are probably dependent.

In selecting variables for measurement and analysis the investigator has been guided by his previous experience in the eastern tropical Pacific and by the work of G. Riley (e.g., Riley, 1946) at Yale. The large number of oceanographic variables measured at noon stations on STOR cruises, and on Expeditions EASTROPIC and (particularly) SCOPE in 1955 and 1956, is indicated below sufficiently for the present purpose. Further details are available elsewhere (Holmes et al., 1957; Holmes et al., 1958; Holmes and Blackburn, 1960).

Analysis of these data is still in its preliminary stages. A large number of simple two-variable correlation coefficients were first determined as an aid to later work. Multiple linear regression is now being used, and the existence of a suitable program (by R. C. Sprowls and J. Tauchi, University of California, Los Angeles) has enabled effective use to be made of the IBM No. 709 digital computer at Western Data Processing Center, University of California, Los Angeles. This program has made it possible to consolidate the data in a form in which they can easily be inspected for relationships. It is realized that this may not be the most appropriate method of analysis, because of possible non-linearity and non-normality; however, both zooplankton and chlorophyll a measurements were log-transformed before use. In the results presented below, * and ** indicate coefficients, etc. significant at the 5 percent and 1 percent level of probability, respectively, and R^2 is the fraction of the sum of squares of the dependent variable Y that is attributable to the regression.

All the measurements were made at noon stations, and n for each regression indicates the number of stations available. It is emphasized that the values of all variables at each station were obtained nearly simultaneously, i.e., within 4 hours. Thus the regressions represent attempts to relate contemporaneous measurements of successive links in the energy chain. This is justified: (a) because no better data exist, nor can they be obtained without prohibitive expense until moored stations are very highly developed; and (b) because we may at present assume a steady state in the tropical ocean, as other investigators have done, rejecting only data from the Gulf of Tehuantepec where it is probable that such a state does not exist (see above).

Throughout this investigation it has been realized that noon station data show rather consistently a significant positive linear relationship between phytoplankton standing crop, as measured by chlorophyll a, and each of the following simultaneously measured variables: primary production (fig. 11) and standing crop of zooplankton (see fig. 13, p. 37; also Holmes, 1958). This has strengthened the belief in the existence of an approximately steady state.

Variables related to primary production (productivity).--With all available stations (n = 40) for the following variables:

X_6 log 1000 chlorophyll a (mg./m.^{3})
X_5 incident radiation (g.cal./cm.^{2}/day)
X_4 mean mixed layer phosphate (μg.-at./l.)
X_3 mixed layer depth (m.)
X_2 mean mixed layer oxygen (ml./l.)
X_1 mean mixed layer temperature ($^\circ$ C.)
Y surface in situ productivity (mg.C/m.^{3}/day)

the multiple linear regression equation is

$$Y = -36.5 + 36.3^{**} X_6 - 0.0388 X_5 - 22.4 X_4 - 0.143 X_3 + 15.16 X_2 - 2.40 X_1$$

This is significant ($F = 5.79^{**}$) with $R^2 = 0.513$. With only X_6 and X_5 it is still significant but with R^2 lower (0.357) and standard error of estimate slightly higher. The only variable with a significant coefficient in either case is X_6, but correlations between the "independent" variables probably obscure the effects of some of them in the equation. For instance there are significant correlations between X_1 and X_4, X_3 and X_6, and X_5 and X_6.

The 40 stations may be divided into a "winter" group (October-February, various cruises, within 200 miles of the coast) and a "summer" group (April-June, TO-58-1 (SCOT), up to 500 miles off the coast). For the winter stations (n = 21) the corresponding equation is

$$Y = -115.8 + 82.3^{**} X_6 + 0.001 X_5 - 26.5 X_4 - 0.331 X_3 + 10.5 X_2 - 2.98 X_1$$

with $F = 6.48^{**}$, and $R^2 = 0.735$. For the summer stations (n = 19) we have

$$Y = -70.55 + 7.56^{*} X_6 + 0.005 X_5 + 46.0^{**} X_4 + 0.015 X_3 + 3.03 X_2 + 0.888 X_1$$

with $F = 3.51^{*}$ and $R^2 = 0.637$. These results suggest a stronger relationship between productivity and phosphate in summer (when both are, on the average, low) than in winter (when they are higher). Phosphate may be limiting for plant growth in summer and not in winter. There is a close relationship between productivity and chlorophyll a in both seasons.

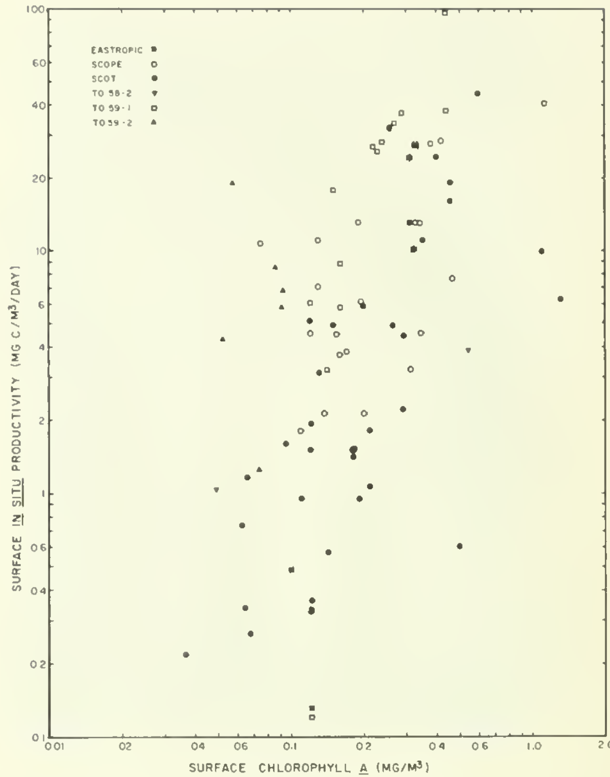


Figure 11.--Surface chlorophyll a and productivity, plotted for noon stations of six cruises.

Variables related to zooplankton standing crop.--Special interest attaches to the understanding and predictability of zooplankton standing crop because it is close to tuna in the energy chain.

The purpose of the first series of analyses was to seek relationships predictive for zooplankton from nonbiological variables that might be measured without too much trouble from anchored stations.

With the following variables:

X_5 mean mixed layer light attenuation coefficient (k)
X_4 mean mixed layer oxygen
X_3 mean mixed layer depth
X_2 mean mixed layer temperature
X_1 incident radiation
Y log 10 zooplankton in upper 250 or 300 m. (ml./1,000 m.^{3})

the equations, for all stations (n = 40), winter stations (n = 18), and summer stations (n = 22), respectively, are

$$Y = 2.92 + 4.10^{**} X_5 - 0.0208 X_4 - 0.00590^{*} X_3 - 0.00305 X_2 - 0.00018 X_1$$

$$Y = 3.83 + 2.49 X_5 - 0.0600 X_4 - 0.0128^{**} X_3 - 0.0427 X_2 - 0.00042 X_1$$

$$Y = 1.16 - 3.51 X_5 - 0.234 X_4 + 0.00117 X_3 + 0.0447 X_2 + 0.00030 X_1$$

These are all significant, and the values of R^2 are respectively 0.431, 0.638, and 0.638. Similar equations disregarding X_2 and X_1 are

$$Y = 2.77 + 4.26^{**} X_5 - 0.218^{*} X_4 - 0.00561^{*} X_3$$

$$Y = 2.73 + 2.36 X_5 - 0.117 X_4 - 0.0115^{**} X_3$$

$$Y = 3.16 + 4.93^{**} X_5 - 0.372^{**} X_4 + 0.00004 X_3$$

These are all significant, with R^2 slightly lower than before (respectively, 0.424, 0.558, and 0.558) and the respective standard errors of estimate slightly higher than before, and they are more informative as to the dependence of zooplankton upon different physico-chemical properties at the two seasons. The light attentuation coefficient is considered a substitute for a measurement of phytoplankton standing crop, in this context, and shows the expected relation to zooplankton in the summer only.

The standard error of estimate for the first of these six equations, applied to the mean zooplankton volume of the series which was 74 ml./1,000 m.^{3}, yields upper and lower 95 percent confidence limits of 129 and 42 ml./1,000 m.^{3}. Most planktologists, from a knowledge of variability in zooplankton catches from nonvertical hauls (e.g., Silliman, 1946), would set limits as wide as these or wider, around a similar value. Thus it is possible that zooplankton standing crop could be estimated at least as well from the above-mentioned physico-chemical measurements as from measurement of a sample of the zooplankton itself.

With a different set of independent variables ($X_5 \ldots X_1$, for chlorophyll a, mixed layer temperature, mixed layer depth, surface *in situ* production, and mixed layer oxygen, respectively) significant regressions were again obtained for all stations, winter stations, and summer stations, but standard errors of estimate were slightly higher than before. Thus this combination, which includes two variables that it would be extremely difficult to measure on an unmanned moored station, would probably be less efficient than the other as far as estimating zooplankton is concerned. Of the individual coefficients only those for chlorophyll a (both seasons) and mixed layer depth (winter only) were significant.

The interpretation of these results in respect to cause-and-effect relations is obviously difficult. They suggest hypotheses that can be more rigorously checked by statistical studies of smaller groups of the data (station groups more homogeneous in time and space, fewer variables in different combinations, etc.), and this is expected to be the next step in the investigation.

The relationships for summer stations seem to confirm the expectation better than those for winter stations, e.g., more obvious dependence of productivity on phosphate and of zooplankton on k (considered as a measure of phytoplankton standing crop). This suggests that the steady-state assumption is more nearly valid for summer than winter (cf. fig. 13). However, the differences may merely reflect the fact that the summer stations are the more homogeneous as to time (all data from one cruise).

Zooplankton-Micronekton Relationships

(M. Blackburn)

The measurement of micronekton volumes is complete only for catches by the large 5-kn. net (fig. 10) on cruises TO-58-1 (SCOT) and TO-59-1.

Figure 12 shows the distribution of standing crop of total micronekton on TO-58-1. It resembles published charts of distribution of standing crop of zooplankton (Brandhorst, 1958) and tuna (Griffiths, 1960; Alverson, 1960) in the way values diminish from coastal to offshore waters, and to some extent in the location of richer and poorer areas along the coast. A statistical consideration of this resemblance to tuna standing crop appears below. In this section only the connection with zooplankton, which was measured at most night stations when micronekton hauls were made, is discussed. It is obviously impossible to connect these night observations directly with the longer series of noon observations discussed above, which were made at different stations, but ways can probably be found to combine the two series when the occasion demands it.

The right-hand panels of figure 13 show the significant relationship between total micronekton and zooplankton for Expedition SCOT stations (April-June 1958), and the corresponding nonsignificant relationship for stations on TO-59-1 (January-February 1959). The geographical distribution of stations was different on each cruise. For SCOT stations significant correlations were found also between zooplankton and each component of the micronekton except large crustacea. Data for stations north of 23° N. (Baja California region) have been excluded, since there were only a few stations and the plotted data did not agree well with those from tropical areas.

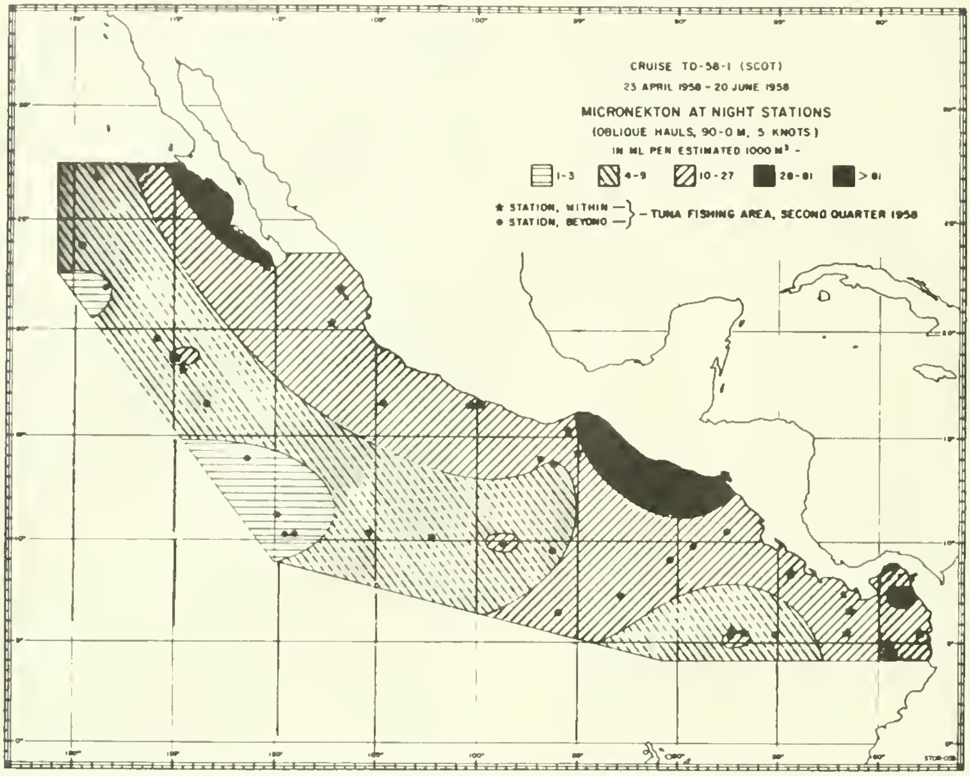


Figure 12.--Distribution of total micronekton on SCOT Expedition.

It is of interest to compare these plots with chlorophyll-zooplankton plots for the same cruise, which are shown on the left in figure 13. For Expedition SCOT this relationship is significant but for TO-59-1 it is not. There is thus no evidence of a steady state in the biotic part of the energy chain for TO-59-1, but the data indicate the possibility of such a state in the area and period of TO-58-1 (SCOT).

This may be examined further. The lines in the SCOT plots in figure 13 indicate functional or structural relationships obtained by the method of Bartlett (1949), not least-squares regressions. It is obvious that the slope coefficients are not 1.0 and that chlorophyll a and micronekton increase more than zooplankton does between any two points on each line. This, on the face of it, is no steady state, but there are considerations that do not exclude such a state. For instance, some components of the micronekton might feed directly on plant material in living or detrital form (e.g., copepod faeces). Euphausiids, which are commoner in night micronekton than in day zooplankton catches, are known to do this, and so possibly do the large crustacea (pelagic crabs, etc.) that sometimes bulk very large in the micronekton although they are seldom taken in the zooplankton. (Large crustacea and zooplankton crops are not correlated, as mentioned above.) One way to test this possibility is to study the relationship between micronekton and chlorophyll a at the same (night) stations; some data were collected for this purpose on cruise TO-59-2 and more on TO-60-1, but they have not yet been analyzed. At present it appears possible that a steady state is approximated in certain regions and seasons.

The question of the steady state has practical significance for the STOR program, because its existence would warrant the use of simpler models and methods for analysis and prediction of, say, standing crop of tuna food. For instance it would justify the belief that the size of a given standing crop of tuna food depended upon events in the same area and not in some other, which would simplify understanding and prediction. In investigations by the Bureau of Commercial Fisheries in the central tropical Pacific there was evidence of progressive poleward displacement of organisms at higher trophic levels (King, 1958; Murphy and Shomura, 1958), which complicated the investigation.

TUNA ECOLOGY

(M. Blackburn)

In this section the dependence of yellowfin and skipjack tuna upon temperature and food

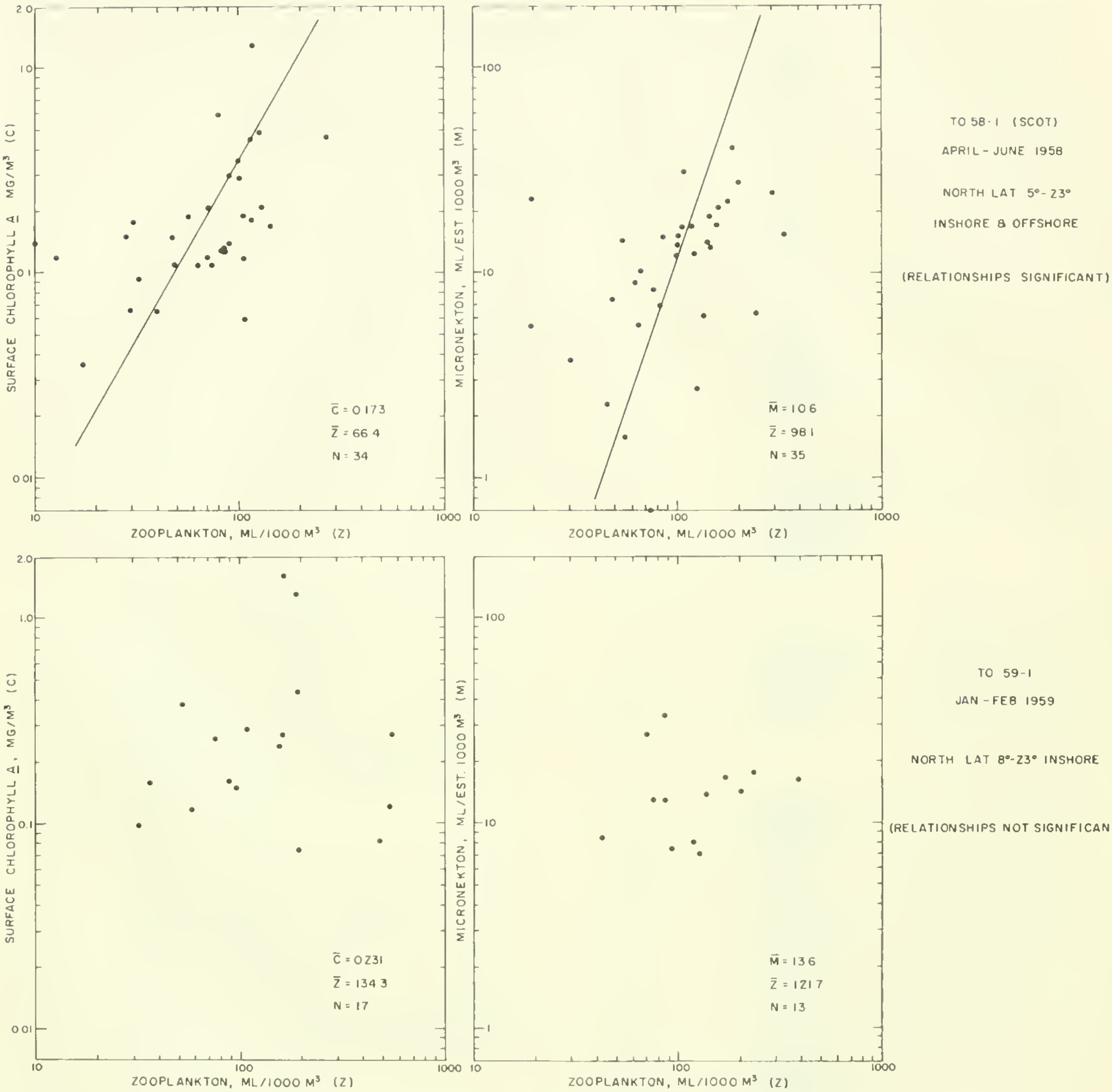


Figure 13.--Chlorophyll a and zooplankton at noon stations, and zooplankton and micronekton at night stations: TO-58-1 (SCOT) and TO-59-1. The lines in the upper panels indicate functional or structural relationships, not least-squares regressions.

supply is considered. The data on tuna abundance are on abundance as apparent from the records of the baitboat fishery. The Inter-American Tropical Tuna Commission has compiled such data in terms of mean catch per standardized day's fishing for each 1-degree rectangle for each quarter-year in the period 1951-59 (Shimada and Schaefer, 1956; Griffiths, 1960; Alverson, 1960). More recently the data were made available by 1-degree rectangles and months and have been particularly useful in this form.

Baja California

Occurrence of yellowfin and skipjack in Pacific coast waters of Baja California is normally confined to the warmer months. This is well-known, and dependence of distribution upon temperature in near-surface waters has been generally surmised.

This belief appears fully justified as far as the limit of distribution is concerned, for reasons evident in figure 14. The lower part of this figure shows (a) the northern limit of

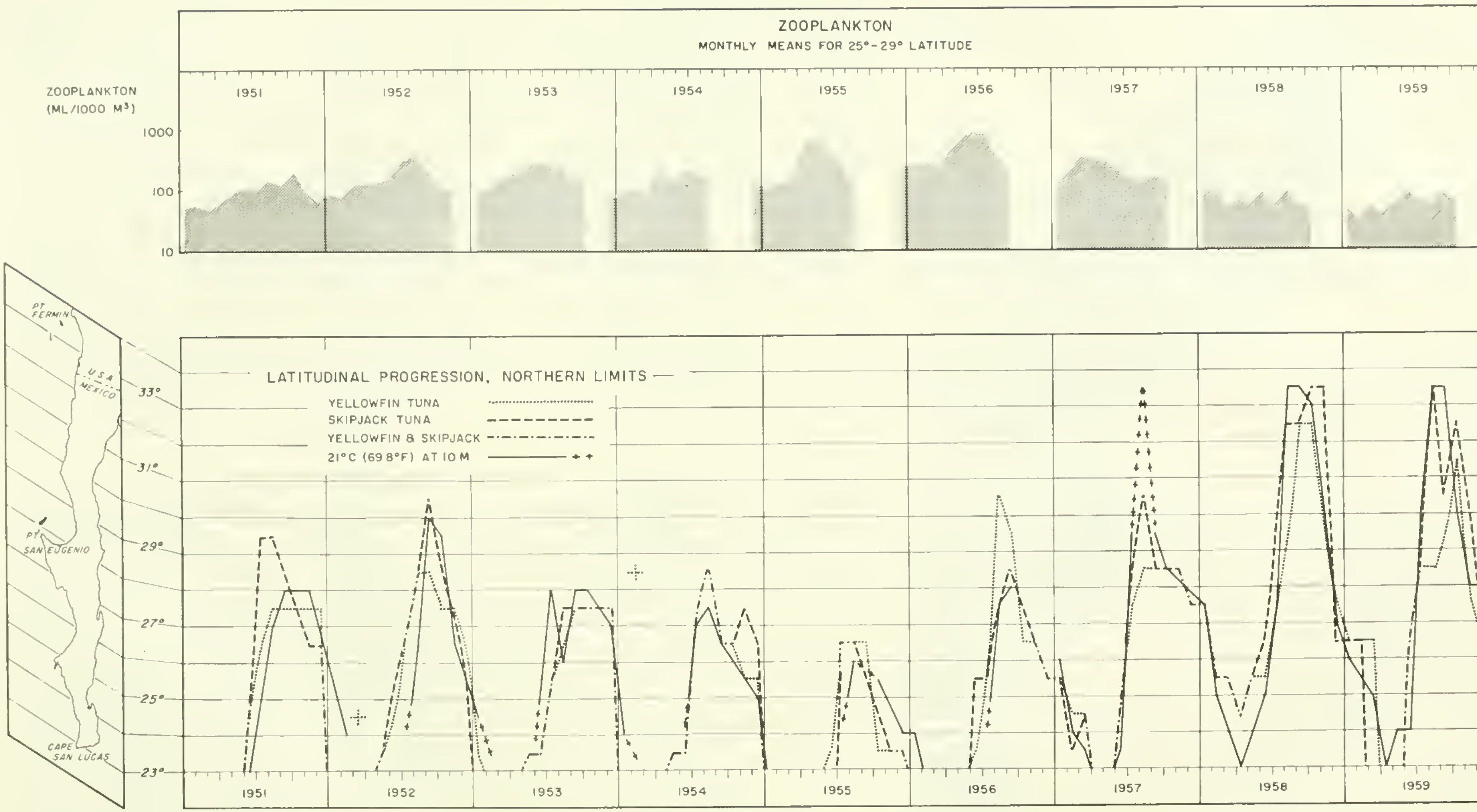


Figure 14. --(Above) Mean zooplankton volume, Baja California coast between lat. 25° and 29° N., by month and year. (Below) Northern limits of yellowfin, skipjack, and 21° C. water, by month and year.

occurrence of yellowfin and skipjack in each month of the period 1951-59 in waters between 23° and 34° N., regardless of the quantity of tuna taken, and (b) the northern limit of the isotherm 21° C. at a depth of 10 m. as obtained from records of CalCOFI cruises, except in 1959 where it shows the surface 21° C. isotherm as obtained from monthly mean sea surface temperature charts of the Bureau of Commercial Fisheries. The temperature record is incomplete between 23° and 25° N. because most CalCOFI cruises did not extend so far south and the information was not readily available otherwise. It is incomplete or ambiguous to a much smaller extent in waters farther north, as indicated in figure 14.

The 21° C. isotherm was chosen because its distribution was found to correspond more closely than that of any other with the distribution of tuna, although the 20° C. isotherm corresponded nearly as well. The agreement is actually very good; there are exceptions which could be explained by the fact that there are generally more observations on tuna, per 1-degree rectangle and month, than on temperature. The northern limit of the isotherm in August 1957 is doubtful and could have agreed much more closely with the skipjack limit than appears in the figure. There is one completely anomalous record of yellowfin in February 1954. The negative temperature anomaly of 1955 and positive anomaly of 1957-59, and the ways in which they respectively restricted and extended the range of the tunas at the northern limit of their distribution, are evident.

The upper part of figure 14 shows monthly mean zooplankton volumes, averaged for all available stations between 25° and 29° N. (CalCOFI data: Thrailkill, 1959, and unpublished). The seasonal peak of zooplankton sometimes precedes and sometimes coincides with the entry of tuna into the area; zooplankton volumes tend to be lower in warm than in cool years and are therefore not positively related to northward penetration of tuna.

The more important question--what determines changes in abundance of tuna within the area of its occurrence at a given time?--cannot yet be answered. Table 4 summarizes attempts to correlate mean yellowfin and skipjack abundance in 1-degree rectangles with surface temperature and zooplankton standing crop in the same rectangles in the same months. The only months worth considering were July, August, and September, because CalCOFI cruises (the main source of oceanographic data for the area) are seldom made during the later part of the tropical tuna season; even in the above-mentioned months such cruises usually only cover the area north of 25° N. No meaning can be read into table 4. For the months considered it is probable that the tuna data are much more representative of the sampled 1-degree rectangles than are the oceanographic data. There are not many rectangles available in any month, and it must be borne in mind that 5 percent of such an array of correlation coefficients are expected to be misleading.

Cruise TO-59-2 included a detailed oceanographic survey of waters south of 26° N., with a great variety of physical, chemical, and biological measurements made at many stations for comparison with contemporaneous data on tuna abundance. This was in August when the fishery would normally have been active, but in the outcome it was inactive because of a dispute about prices. Similarly, cruise TO-60-1 was intended to throw light on the abundance and distribution of tuna in the season and area in which they occur before they arrive in Baja California (fig. 2). Neither set of cruise results has been fully analyzed.

Middle America

The region considered is the offing of the Pacific coast of southern Mexico (Mexico excluding Baja California) and Central America. Recent surface temperature anomalies in this region were discussed above and shown in figure 5.

Figure 5 compares the known distribution but not abundance of yellowfin and skipjack tuna in the years 1955-59 in the fourth quarter. In the cold year 1955 and the average year 1956 skipjack together with yellowfin occurred along the whole coast; as temperatures rose in 1957 and 1958 skipjack were no longer found in the thermal-equatorial region, although yellowfin were; when temperatures dropped slightly in 1959 the range of the skipjack extended slightly farther into the thermal-equatorial region than in the 2 former years, although not nearly as much as in 1955 and 1956, and the range of the yellowfin still remained about the same as in all former years.

From this and similar distribution charts for other quarters of the years 1955-59, the conclusion is drawn that skipjack probably avoid surface waters of very high temperature; the data have not been sufficiently analyzed to show the limiting surface temperature but it is probably about 83° F. or 28° C. Yellowfin may also be affected by high temperatures, not in their area of distribution but in their abundance within that area; an incomplete study of records of abundance by 1-degree rectangles and quarters over the period 1955-59 suggests that yellowfin were

TABLE 4.--Baja California, third quarter, summary of correlation tests: tuna, mean baitboat catch per standardized day, with mean surface temperatures and zooplankton volumes from CalCOFI cruises.

(YF) Yellowfin
(SK) Skipjack
(*) Coefficient significant ($P \leq 0.05$)
(**) Coefficient highly significant ($P \leq 0.01$)
(+) Coefficient positive
(-) Coefficient negative

[Months with data in less than 9 1-degree squares are not listed; none of these coefficients were significant.]

Year and month	Number of 1-degree squares	Tuna-temperature correlation	Tuna-zooplankton correlation
1951			
August	16	YF and SK, nonsig.	YF and SK, nonsig.
September	11	YF and SK, nonsig.	YF and SK, nonsig.
1952			
August	11	YF*(+), SK nonsig.	YF**(+), SK nonsig.
September	16	YF and SK, nonsig.	YF and SK, nonsig.
1954			
August	12	YF*(-), SK nonsig.	YF and SK, nonsig.
1956			
August	10	YF nonsig., SK**(+)	YF nonsig., SK*(+)
September	9	YF nonsig., SK**(+)	YF and SK, nonsig.
1957			
July	17	YF*(+), SK nonsig.	YF and SK, nonsig.
August	9	YF nonsig., SK*(+)	YF and SK, nonsig.
1958			
July	18	YF and SK, nonsig.	YF and SK, nonsig.
August	10	YF and SK, nonsig.	YF*(+), SK nonsig.
September	11	YF nonsig., SK*(-)	YF and SK, nonsig.

scarcest during the warmest years in the thermal-equatorial region, season for season, although figure 5 has not been constructed to show this.

From this and the information for Baja California, it is apparent that the northern area of the skipjack fishery was enlarged and the middle area reduced in 1957 and 1958. For yellowfin, the northern area was likewise enlarged; the middle area was not reduced but fish were possibly scarcer in it. The southern area (South America) was also enlarged for both species by extension toward the south, as shown in figure 5; according to workers in the Inter-American Tropical Tuna Commission, this change also was temperature-connected. The fishery was therefore concentrated at the northern and southern ends of its normal area, and the middle region (southern Mexico-Central America) received less attention than usual. This redistribution of fish and fishing effort affected the investigation in the Middle America region, where, in the outcome, it was impossible to get information on abundance of tuna for some areas in which oceanographic work was done on STOR cruises.

Brandhorst (1958) drew attention to the partial similarity between charts of distribution of zooplankton standing crop and thermocline topography on the one hand, and tuna abundance on the other. Therefore all available zooplankton measurements for the Middle America region were assembled and compared with the mean abundance of yellowfin and skipjack in the same 1-degree rectangles and months. The zooplankton data were scanty because of the small number of oceanographic cruises. There were respectively 15, 14, 33, and 24 1-degree rectangles, with both kinds of information for the same month, for the following cruises: SHELLBACK Expedition (May-August 1952), EASTROPIC (October-December 1955), SCOT or TO-58-1 (April-June 1958), and TO-59-1 (January-February 1959). Zooplankton data have not yet been fully analyzed for cruises after TO-59-1; for other cruises (e.g., Tuna Longline Expedition 1953, Expedition SCOPE 1956) the numbers of 1-degree rectangles with both zooplankton and tuna information were much lower than those above.

For the above-mentioned four cruises only one zooplankton-tuna correlation (TO-59-1, zooplankton-yellowfin) was significant at P = 0.05, positive.

The next step was to introduce surface temperature data into the study. At present four regressions of tuna abundance on surface temperature and zooplankton, in the same 1-degree rectangles and months, are available: EASTROPIC, both tunas, n = 14; SCOT, yellowfin only (not enough skipjack data), n = 33; TO-59-1, yellowfin only (not enough skipjack data), n = 24. None is significant, hence for TO-59-1 the combination, temperature-zooplankton, is less closely related to yellowfin than zooplankton alone.

For SCOT (n = 20) and TO-59-1 (n = 14) total micronekton and its four components were tested for correlation with yellowfin. No correlation coefficient was significant. The largest of them was obtained with the large crustacea component for Expedition SCOT, and this was significant and positive when used with abundance of total tuna (i.e., including skipjack in the few 1-degree rectangles where this species was taken).

The regression of yellowfin on temperature and large crustacea was investigated for SCOT and TO-59-1 but in neither case was it significant. The regression of total tuna on the same two variables was not significant either for SCOT stations (for TO-59-1, total tuna and yellowfin were identical); that is to say, the relationship between total tuna and large crustacea lost its statistical significance when temperature was introduced.

These results are scanty, as are the data, but more consistent than those in table 4. There are indications of a positive relationship between standing crop of yellowfin and that of animals in its food chain, as would occur if yellowfin aggregated upon supplies of food. The independent effect of surface temperature on yellowfin aggregation is comparatively slight. For skipjack, in view of the situation shown in figure 5, it could be expected that temperature would sometimes have a significant direct effect.

Observations from a few Baja California stations, those at which zooplankton and micronekton measurements were available and comparable with those from Middle America stations, were included in the material discussed above.

Gulf of Tehuantepec

Inspection of tuna abundance data by 1-degree rectangles and months showed that yellowfin are most abundant in the winter and spring and least abundant in summer, and skipjack generally scarce in all seasons. The seasonal cycle of abundance of yellowfin agrees broadly with that of zooplankton as inferred from STOR cruise data (higher standing crops in November and January-February than in May-June or September; see above).

Further, the area of maximum concentration of zooplankton is regularly in the southern, southwestern, or western parts of the Gulf, and the same is broadly true of yellowfin in the winter and spring months. In the quarter November-January the average yellowfin catch per day's fishing is greater in the extreme southwest of the area, and in February-April (the height of the fishing season) it is greatest to the west of the thermal ridge. It is probable that the zooplankton is generally distributed in about the same way at the same seasons, for reasons given elsewhere in the paper. These observations support the idea of aggregation of yellowfin on biota in their food chain.

The matter is discussed in the paper "An oceanographic study of the Gulf of Tehuantepec," referred to under "Physical features and processes in the ocean."

Oceanic Islands

One weakness of the hypothesis that tuna aggregate in times and places of abundant food has been the observation that tuna are generally more abundant around ocean islands than in the neighboring ocean, whereas this is not always true of zooplankton. Such a situation was found by Tuna Commission workers at Clarion Island in May and June 1957 (Bennett and Schaefer, 1960). Zooplankton standing crop was uniformly low from the offshore ocean through the fishing area to the shore of the island.

On Expedition SCOT zooplankton hauls were made around each of three ocean islands in the following way: about half a mile from the island and about 11 miles from it on opposite sides, one such series in daylight and an identical one in the dark. The three islands (Clarion, Clipperton, Cocos) are shown in figure 1. The zooplankton distribution at each island was the same in the night as in the day series of hauls. At Clarion Island both offshore stations yielded more zooplankton than the inshore station; at the other two islands the inshore station yielded more than either offshore station.

The results obtained at Clarion Island agreed with those previously obtained in denying zooplankton the role of a tuna-attracting property. It is possible that tuna are attracted by micronekton which subsist on phytoplankton or plant detritus. Pelagic crabs *(Pleuroncodes planipes)*, an important item of tuna food in Baja California waters, were very abundant in the micronekton at one of the offshore Clarion Island stations on SCOT Expedition, and might enter the area of the fishery. Figure 12 shows the high standing crops of micronekton that were encountered locally near Clarion and Cocos Islands, although not at Clipperton Island.

It would therefore be premature to conclude that oceanic island aggregations of tuna do not depend on the presence of some kind of food.

SUMMARY AND EVALUATION

The material presented above may be appraised in various ways, of which the most rigorous is to list the scientific conclusions most clearly pertinent to the problem of understanding and forecasting abundance and distribution of tuna in the eastern tropical Pacific. These conclusions (1-9), together with brief explanatory comments, are as follows:

1. Yellowfin and skipjack tuna at the northern end of their range are generally scarce in waters where the temperature in the upper 10 m. is less than 20° or 21° C. According to other workers the southern end of the range of each species is likewise associated with certain temperatures, although perhaps not with the same temperatures as at the northern end. Skipjack are scarce in waters where temperatures in the upper 10 m. exceed 28° C. The effect of these apparent temperature-limitations in a year of high temperature in the entire eastern Pacific, such as 1958, is to permit each species to extend its distribution a few degrees of latitude polewards in each hemisphere (e.g., Baja California to California, Peru to Chile), while causing skipjack to vacate the thermal-equatorial region off southern Mexico and Central America. In a year of low temperatures such as 1955, the distribution of each species is more or less continuous over a narrower band of latitude along the coast of the American continent, with the thermal equator near its center.

2. The correspondence between the northern limits of tuna and of 21° C. surface water is always so close that the effect of the temperature on the tuna may be assumed to be almost immediate, and direct. Because the main effect in a normal year is to permit tuna to enter the Pacific coast waters of Baja California in summer only, it was considered that the tuna might enter those waters in a current of warm water flowing from the south at that season. However, a study of the average annual heat budget of those waters virtually removed this possibility, by showing that little advection of warm waters occurred in the upper 200 m. at any season.

3. The possibility of predicting 30-day or 10-day changes of mean surface temperature, from previous averages of surface temperature and wind velocity in the same area, was investigated statistically both in the eastern tropical Pacific (Gulf of Tehuantepec) and adjacent to it (northeastern Pacific, where longer series of data were available). This empirical approach was not highly successful; the best combination of variables for prediction accounted for about 40 percent of the variance of the next month's temperature. It was thus important to identify and understand more adequately the relationships between wind and surface temperature in different areas (4, 5, and 9 below).

4. Within-year changes in relationships between wind and sea temperature were investigated for the California Current and Peru Current regions as part of a comparative study of eastern boundary currents of the world. Seasonal values of Ekman transport of surface water away from the coast, computed for different latitudes from values of average wind stress and orientation of coastlines, agreed qualitatively with known seasonal and geographical variations in upwelling on four out of the five eastern boundary coasts (west coasts of North America, South America, North Africa, and South Africa, but not Australia).

5. Major changes in surface temperature regime between years are also considered to be wind-connected, as a result of investigations of oceanic disturbances called Niños in Peru (and the more detailed studies by others on similar but better-measured disturbances in the northeast Pacific). Niños result in warming of the sea surface such as occurred between 1957 and 1959 (1 above). A hypothesis has been developed which defines the Niño as the set of conditions developing off any upwelling coast when reduction of the wind stress causing upwelling, during an extended period of time, leads to weakening or cessation of vertical mixing.

6. Abundance of yellowfin tuna, from place to place within the temperature-controlled limits of its distribution, is probably determined mainly by the abundance of zooplanktonic or micronektonic organisms in its food chain, with surface temperature playing a

less important role, in the region between Baja California and the Equator and offshore to the limits of the fishery. The statistical evidence for this is not strong, but it does exist for the two periods for which most data are available for yellowfin and food chain animals in the same localities. The relationship to environmental factors of abundance of yellowfin in other regions (including Baja California itself), and abundance of skipjack in any region, is still obscure.

7. Observations made in summer between Baja California and the Equator were consistent with an approximately steady state in the biotic part of the tuna food chain, with abundance of phytoplankton positively correlated with abundance of zooplankton and a similar relationship between zooplankton and micronekton, from place to place; abundance (standing crop) of phytoplankton was also positively correlated with rate of primary production. It would therefore be possible to estimate abundance of tuna prey from contemporaneous data on phytoplankton and this might lead to estimates of abundance of yellowfin (6 above).

8. Abundance of zooplankton can also be estimated within reasonable confidence limits from contemporaneous measurements of certain physico-chemical variables (e.g., mean light attentuation coefficient and mean dissolved oxygen concentration in the mixed layer, and the depth of the mixed layer itself), both in summer and winter, in the region between Baja California and the Equator. This offers greater practical possibilities for estimating abundance of tuna food and tuna than does the method of measuring phytoplankton (7 above), because the physico-chemical ocean properties would probably be more easily measured on unmanned moored stations (16 below).

9. Four cruises were made to the Gulf of Tehuantepec, an important fishing area for yellowfin, to learn by repetitive observation the particular form of the assumed connection between yellowfin, its food, physico-chemical properties of the water including temperature, and local wind (cf. 3, 4, 6, 7, and 8 above). It was found that cooling, chemical enrichment, and biological production in near-surface waters result from the seasonal effect of local wind in (a) setting up a circulation which results in a domed or ridged discontinuity layer, and (b) stirring the upper part of the layer in the region where it is closest to the sea surface. This process is different from upwelling (4 above). The wind-induced circulation also appears to act on the biota produced, distributing them in a way that is spatially and temporally consistent with the major features of yellowfin distribution if the latter is considered to be related to the distribution of tuna food.

The following additional scientific accomplishments of the program (10-15) are less directly related to the study of tropical tuna ecology at present, either because the investigations are incomplete or because there has been insufficient opportunity to integrate them with other work, but they are all considered to be pertinent to the main investigation.

10. Unialgal cultures of several tropical oceanic species of phytoplankton were successfully maintained in the laboratory and used there to study algal growth in response to various conditions of light, temperature, and chemical nutrients; some of the artificial environments simulated those of the ocean. Similar work was done at sea on cultures of mixed natural populations. This work is required to improve the understanding (and therefore the practical efficiency) of some of the more empirical parts of the investigation, such as the attempts to substitute physico-chemical variables for phytoplankton in statistical relationships predictive for tuna food (7 and 8 above). For example, some experiments showed that nitrate is limiting for the growth of *Gymnodinium*, which suggested that this variable should receive attention in further work; efforts were then made to make measurement of nitrate concentration a part of the shipboard oceanographic routine in the eastern tropical Pacific.

11. An experimental evaluation of the C^{14} method of measuring productivity, or plant production rate, was made with laboratory cultures of *Dunaliella*. It was concluded that the method gives adequate estimates of synthesis of plant material except under extremely nutrient-deficient or light-deficient conditions.

12. Studies were made of the distribution of physical properties and ocean structure and circulation in the Panama Bight and Gulf of California, which are tuna fishing areas. In Panama Bight there is a doming of the discontinuity layer, like that in the Gulf of Tehuantepec (9 above), which is probably connected with the abundance of tuna in the area. The mouth of the Gulf of California is a region where sharp horizontal gradients of temperature (fronts) are frequent; since it is widely supposed that these fronts play an important role in the seasonal aggregations and migrations of tuna, perhaps by causing concentrations of animals on which tuna feed, a program of oceanographic observations in this area was begun.

13. Statistical studies of interrelationships of anomalies of sea level and associated variables (atmospheric pressure, wind components, and surface temperature) were made, and in part completed, in areas in and adjacent to the eastern tropical Pacific where suitable time series of data were available. This represents an effort to utilize data from shore (tide gauge) stations in further studies of the reaction of the ocean to atmospheric changes (cf. 3, 4, 5, and 9 above).

14. A statistical study of the reliability of ocean measurements of temperature and salinity was made.

15. Work was begun on the life-history of the red crab, *Pleuroncodes planipes*, which is the predominant organism in the micronekton of Baja California waters and the main item in the diet of tropical tuna in that area.

Finally, much attention was given to development and improvement of oceanographic techniques (16-18), as follows:

16. Deep-moored unmanned ocean stations, capable of making frequent observations of several properties of ocean and atmosphere in the same locality over periods of at least 3 months, are desirable for understanding and necessary for forecasting in the kind of fisheries oceanography exemplified by the present program. Such a station, developed to measure wind velocity, wind direction, and sea temperature at various depths in the upper 120 m., each hour, was tested in Baja California and the Gulf of Tehuantepec in 1958, but was unsuccessful. Some of its features were redesigned, and it performed satisfactorily in ocean tests during 1960. Another type of moored station, designed specifically for measuring temperatures at various levels throughout the whole water column, was used with some success in 1960. All these types recorded, but did not transmit, their measurements.

17. Work was done to develop, improve, or test methods of measuring submarine daylight extinction, standing crops of chlorophyll a and micronekton, and concentrations of various chemical nutrients; and methods of making enumeration or biomass measurements of components of the phytoplankton, zooplankton, and micronekton, some of which might be more useful in statistical relationships than measurements of the unsorted material.

18. The Roberts current meter was successfully modified for subsurface current measurements.

RECOMMENDATIONS FOR FUTURE WORK

Further work is recommended along the following broad lines, mainly in continuation of investigations reported above. The items are not necessarily in order of importance. It should be borne in mind that unforeseen circumstances such as new developments in oceanographic technique, or changes in the ocean or the fishery, might dictate major changes in the program.

1. Further statistical analysis is needed to show which combinations of variables have the greatest value for predicting abundance of tuna in various areas and seasons. This would involve linking up the results presently being sought in different parts of the energy chain. In particular, the connections between tuna and environmental factors directly affecting them need more study; this would be greatly facilitated if some information about tuna abundance could be obtained at precisely the same time and place as ocean properties are being measured on research ships, and for this reason the Bureau of Commercial Fisheries' own study of the use of sonar for detecting tuna is of great potential importance. Another special need is for more statistical work on interrelationships of atmospheric and oceanic properties in the eastern tropical Pacific.

2. Basic research is required in most parts of the tuna energy chain in order to understand the forms that empirically determined statistical relationships have and the limits within which they are likely to be satisfactorily predictive; to suggest combinations of variables with a view to finding new or improved relationships; and to assist in making certain kinds of observations quantitative. In particular, more information is needed about the relationship of phytoplankton to its physico-chemical environment, especially the chemical nutrients limiting its growth.

3. Useful relationships will differ from area to area depending, fundamentally, on the particular physical features and processes of atmosphere and ocean in those localities. In some areas, it is even possible that nonquantitative relationships could be of value. For this reason the detailed oceanographic survey work being done in special fishing areas should be expanded to cover more physically distinct types of ocean environment, such as dome areas, upwelling areas, island and bank areas, and front areas. It seems logical and necessary that the greater part of this work be carried out north of the Equator, as hitherto, as long as funds restrict cruise time to less than 3 months per year.

4. More work is needed to improve and evaluate certain types of measurements and to provide some not presently available, especially in biological, chemical, and optical oceanography. It seems particularly desirable to find better means than volumetric for measuring standing crops of zooplankton and micronekton, or alternatively to find means of making volumetric measurements on major components of the zooplankton and micronekton without undue expenditure of time.

5. Some type of moored unmanned station, capable of making and telemetering frequent measurements of a wide range of physicochemical properties at levels between 1 m. above and 100 m. below the sea surface, at moderate cost, is a necessity. It is recommended that the work to develop and test a sea temperature-and-wind recording station type be continued until one is available for dependable routine use. Efforts should then be put into: (a) devising procedures for servicing and maintaining stations, and listing and analyzing records; (b) developing instruments to measure additional properties dictated by the statistical-ecological part of the program; (c) increasing the number of stations operative in the eastern tropical Pacific; and (d) making it possible for the stations to telemeter observations so that forecasts could be made.

PUBLICATIONS AND MANUSCRIPTS

By March 1, 1961, the date of submission of this paper, the following papers had been *published* from the STOR program:

Holmes, Robert W., and Maurice Blackburn.
1960. Physical, chemical, and biological observations in the eastern tropical Pacific Ocean: SCOT Expedition, April-June 1958. U. S. Fish and Wildlife Service, Special Scientific Report-Fisheries No. 345, 106 p.

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Wooster, Warren S., and Townsend Cromwell.
1958. An oceanographic description of the eastern tropical Pacific. Bulletin of the Scripps Institution of Oceanography, vol. 7, no. 3, p. 169-282. (Publication was assisted financially by the program but was not the outcome of its own research.)

Wooster, Warren S., and Bruce A. Taft.
1960. On the reliability of field measurements of temperature and salinity in the ocean. Journal of Marine Research, vol. 17, p. 552-556.

By March 1, 1961, the following papers were *in press* or had been *submitted for publication:*

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An oceanographic study of the Gulf of Tehuantepec. U. S. Fish and Wildlife Service, Special Scientific Report--Fisheries.

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