UNITED STATES DEPARTMENT OF THE INTERIOR

Progress in 1964-65 at the Bureau of Commercial Fisheries Biological Laboratory, Honolulu

Thomas A. Manar

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ABSTRACT

This report deals with research results achieved by the Bureau of Commercial Fisheries Biological Laboratory in Honolulu from January 1, 1964, to June 30, 1965. Described are developments in the following fields: the sensory capacities of tunas; tuna behavior; subpopulations research using genetic techniques; studies of the ecology of the skipjack tuna and the albacore tuna; biological surveys of the Indian Ocean; investigations of the oceanography of the Hawaiian Islands area and of the entire Pacific; and studies devoted to the evaluation of the use of a submarine for research in fisheries and oceanography. Publications issued or in press during the period are listed.

INTRODUCTION

This report deals with research results achieved by the Bureau of Commercial Fisheries (BCF) Biological Laboratory in Honolulu from January 1, 1964, to June 30, 1965.

Highlights of the reporting period include:

1. Successful employment of new methods to maintain living tunas in experimental tanks, a feat that has made possible the first visual acuity curves and hearing curves obtained from any of the several species of tunas; new measurements of swimming speeds of tunas; description of the fish community around and near a floating object at sea;

2. Discovery and use of a highly sensitive new blood group system for the identification of subpopulations of the skipjack tuna;

3. Publication of a set of hypotheses that analyzes all published material on the skipjack tuna to depict their migrations in the eastern half of the Pacific; these hypotheses suggest that the eastern Pacific and Hawaiian fisheries are in part drawing on the same stock, a subpopulation that is spawned in the equatorial waters south of Hawaii; they suggest also that the fishery reflects the passage of year-classes of varying strength;

4. Analysis of the emerging tuna fishery of the South Pacific; establishment of a cooperative agreement between this BCF Laboratory and the Nankai Laboratory in Japan to carry out common studies of the Pacific's tuna resources;

5. Representation of the interests of the United States in international organizations designed toward the better utilization of the marine resources of the Indo-Pacific region and the conduct of a multination survey of the Kuroshio, the rich, warm current that sweeps northward off the shores of Japan;

6. Surveys of the fishery resources of the world's third largest and least known body of water, the Indian Ocean;

7. Commissioning of one of the Nation's finest oceanographic research vessels, the *Townsend Cromwell*, and her employment;

8. Conclusion of 16 month-long cruises in the Hawaiian Islands as precursor to a larger investigation of the oceanography of the entire Trade Wind Zone, one of the most ambitious projects in American oceanography;

9. Completion of an oceanographic atlas of the Pacific Ocean, drawn from a massive amount of data collected during the past 58 years and offering definitive depictions of average seasonal conditions in the sea in layers of most concern to the fisheries, those between the surface and about 5,000 feet;

10. Research on a bold new concept in man's study of the sea, a nuclear-powered submarine dedicated to research.

Put more briefly, the period has seen significant research on the fishes, the fisheries, and the sea. This report deals with those topics in that order. To provide background for the general reader, material is touched upon that deals neither with the work of the past 18 months nor of this Laboratory. Detailed descriptions of research methods have been kept at a minimum, on the grounds that the person most likely to be interested in them, the specialist, will have ready access to such material elsewhere.

FIGURE 1. Living tunas for behavioral experiments are collected by expert fishermen of the BCF Laboratory's vessel *Charles H. Gilbert.* At the left, the struggling tuna is swung over the ship's rail as technician waits to guide it to the holding tank. In the other photograph, the fish is gently lowered into the fiber glass tank, where it will swim free. The men are standing on the lid of the tank. The Laboratory in Honolulu is the only one in the world where living tunas are regularly available for behavioral studies.

THE FISHES

The World of the Tunas

Fish and fish products, according to estimates of the Food and Agriculture Organization of the United Nations (FAO), provide man with 12 percent of the animal protein in his diet. The percentage is small, but the surprising thing may be not that men take so little of their food from the sea, but that they are able to take so much, for the fish are small and the ocean very large. Consider the catch of skipjack tuna, *Katsuwonus pelamis* (Linnaeus), in the Pacific Ocean: About 100 million fish (550 million pounds) are taken annually. These may represent one-tenth of the adult population, which would then be 1 billion fish. These 1 billion skipjack are found in an oceanic area covering some 23-million square miles. If they were spread out evenly, like checks in a plaid, then there would be one skipjack for each 0.023 square miles, or one for each 14.7 acres. To capture 3,000 of them, a relatively good catch, a boat would have to collect every skipjack tuna in an area 10 miles wide and 69 miles long.

But fishes are not distributed evenly. They seek out areas favorable for feeding or spawning, they gather in schools, they migrate from place to place with the seasons. Commercial fishing is possible only because over the millennia keen-eyed fishermen have noted and taken advantage of recurrent patterns in the behavior of fishes. Now these age-old observations are being extended and reinforced by the skills of modern science.

During the past few decades, scientists have learned a great deal about the sensory capacities of fish and how the animals behave. Much of that knowledge rests, however, on experiments with species that have little or no commercial value, with the notable exception of the salmon.

Hindering efforts to conduct systematic experimental studies of the food fishes of the open sea, such as the tunas, has been the difficulty of maintaining these relatively large and swift creatures in captivity. The Laboratory in Honolulu has conquered this obstacle in a way that has made possible several basic inquiries into the sensory capacities and behavior of tunas.

Several times a year, the *Charles H. Gilbert*, the smaller of the Laboratory's two research vessels, noses alongside the dock in Honolulu carrying on her deck a cargo of what look like oversized bathtubs with lids on them (fig. 1). A complex of water hoses runs to and from the tanks. Each container carries 5 to 10 live tunas caught only a few hours previously by the *Gilbert's* crew of expert pole-and-line fishermen.

FIGURE 2. Eyesight plays a significant role in the behavior of tunas. The "tear" in the eye of this skipjack is an artifact; it is a drop of water that remained when the fish was taken from the tank for photography.

The *Gilbert's* arrival is the signal for a crane operator to stand by. Fishery scientists fit a bridle to the "bathtub" tanks. One at a time, the tanks are lifted from the deck and taken to the 24-foot plastic swimming pools that are part of the Laboratory's complex for behavioral research. There the lids are unbolted. The crane lifts the containers and then lowers them into the sea water pools. Fishery scientists carefully tip the containers to let their living cargo swim free.

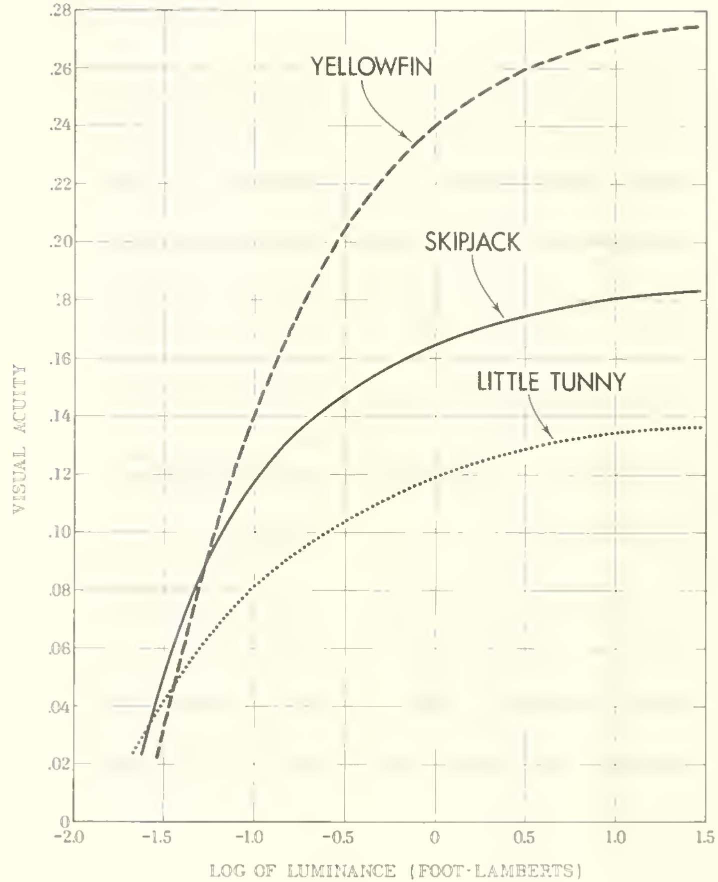
Such painstaking methods have had impressive results: the Kewalo Basin facility often has as many as 60 or more tunas waiting their turn for behavior studies. Thus this Laboratory has become the only one in the world where living tunas are regularly collected and held for study. The procedure for handling the fish was worked out by biologist Eugene L. Nakamura. One of the technological triumphs of the Laboratory has been its ability to keep skipjack tuna alive for several months. Prior to our improved handling methods, the skipjack usually dashed themselves to death. Now specimens have been kept alive as long as 6 months in the Laboratory's tanks.

Only since Nakamura perfected his methods of handling have he and other behavioral scientists in the Laboratory been able to conduct controlled experiments with tunas. Already several scientific papers have been prepared, each of them revealing previously unknown facets of behavior. Currently underway are studies of how well the fish see and hear and how they are able to maintain swimming depth. From the broad base of such information may come new and unconventional methods of catching tunas for commercial purposes.

How Well Do Tunas See?

How well tunas see has obvious implications for the fishery. Experiments in the lucent waters of the central Pacific a few years years ago proved it well-nigh impossible to catch skipjack tuna in any numbers with a monofilament

FIGURE 3. Visual acuity depends upon the brightness of an object. This figure compares the visual acuities of yellowfin, skipjack, and little tunny.



gill net; they dodged it easily. Observers stationed at the underwater ports of the *Charles H. Gilbert* and *Townsend Cromwell* have marked the apparent importance of vision in feeding behavior.

Eugene Nakamura has now measured the visual acuity of three species of tuna: skipjack, yellowfin, *Thunnus albacares* (Bonnaterre), and little tunny, *Euthynnus affinis* (Cantor). His experimental apparatus and methods were described in the Laboratory's last progress report. Briefly, the fish are taught to respond to a pattern of black-and-white stripes presented on a square of illuminated opal glass. Reward (food) follows one pattern, punishment (a mild electric shock) another.

The characteristic being measured is visual acuity, which is one of the several elements of visual perception. Technically, visual acuity is "the reciprocal of the minimum visible angle measured by minutes of arc." This measure of visual perception depends upon the brightness of an object. As the target becomes dimmer, details tend to blur.

The yellowfin "sees better," in this sense, than the skipjack, and the skipjack better than the little tunny (figs. 2, 3, and 4). Comparative size may have something to do with these results, a possibility Nakamura is now investigating.

It will be some time before these studies can be extended to the other elements that sum up the visual experience: the responses to color, form, size, number, position. Yet it is only in such a painstaking way that quantitative studies can be carried out.

A brightly lighted square of opal glass striped black and white is obviously nothing that a tuna is ever likely to encounter in its natural environment. Experiments of this nature represent only a first step toward an understanding of the role that sight plays in the life of the tuna. Nevertheless, it is a step that has needed taking. Equally desirable have been investigations of the responses of tunas to another stimulus that is also unknown in the sea—pure tones, the sort of tuneless "beep" with which television stations signal the passage of the hour.

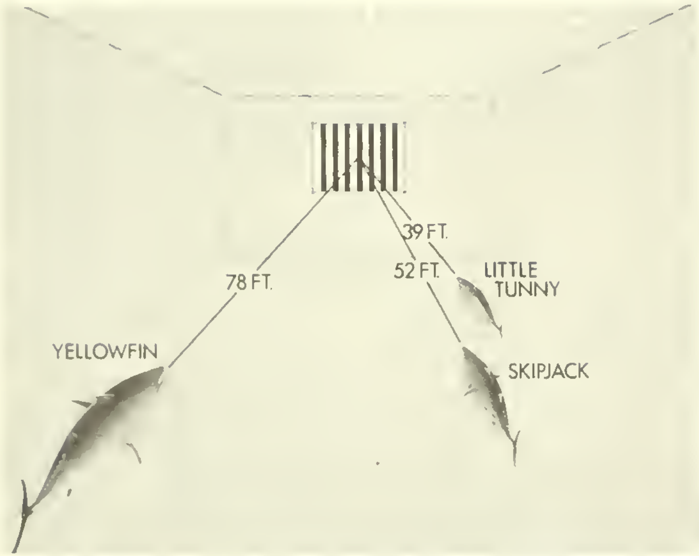


FIGURE 4. At a constant brightness, a yellowfin sees details of an object better than a skipjack and a skipjack better than a little tunny.

How Well Do Tunas Hear?

All man's ingenuity has failed to greatly improve his ability to see underwater, yet with the aid of relatively simple instruments, he can hear across oceans. Sound travels fast and far in the sea, obeying physical laws that are well defined. The explosion of a 1-pound charge of dynamite off the Hawaiian Islands has been picked up by hydrophones on the California coast.

The first quantitative measurements of the hearing capacity of a fish were made in the 1920's. The creature was a goldfish, and it responded to frequencies between 32 and 2,752 c.p.s. (cycles per second). That is, it could hear sounds so low that men could scarcely hear them but was unable to hear high-pitched sounds common in the human experience.

Despite the worldwide interest on the part of scientists and the fishing industry in the use of underwater sound to attract or repel food fishes, little quantitative research has been performed on the hearing abilities of the creatures. One reason may be that such knowledge is only slowly acquired because it is dependent on training the animals to respond to signals that offer punishment or reward. During the past months, Robert T. B. Iversen has recorded several hearing curves for yellowfin tuna. No such curves are available for any other member of the scombrids—the large and commercially important family to which the tunas belong.

Iversen has shown tnat the yellowfin tuna hears well at frequencies from about 100 to 2,000 c.p.s. Its hearing is most acute between 350 and 800 c.p.s. (fig. 5). Many sounds in the sea that might be expected to have biological significance for tunas are contained within that range. Examples are the sounds made by small fish swimming and by schools of squid. Iversen has been measuring auditory "thresholds," the minimum intensity at which the yellowfin tuna can hear a sound of a particular frequency. He has not yet ventured into other aspects of hearing, such as directional orientation, the ability to locate the source of a sound.

Although tunas respond to sound, there is only the slightest evidence that they themselves produce sound. That fish make sounds men can hear was demonstrated to science 101 years ago. (Fishermen had known it for untold millennia). Since the advent of sensitive hydrophones, scientists have learned that the sea is quite a noisy place. Many laboratories possess tape recordings of the hissings, grunts, squeaks, and moans that contribute to the totality of audible sound in the ocean. The living sources of some of these have been identified. The carangid *Trachurus trachurus* Linnaeus, for example, is known to make "sounds like those produced by running the fingers along the teeth of a comb."

Yet from the experimental work to date, one would think that the tuna, which is demonstrably far from deaf, is completely silent. A biological sound produced by its own kind might well be of importance in the behavior of tunas, but whether such a sound is produced is uncertain.

Maintaining Swimming Depth

Visitors to the Kewalo facility, watching the tunas continuously circling the tanks, are likely to ask two questions: "Do they always swim in the same direction?" and "Don't they ever stop swimming?" The answer to both questions is "No." The fish do change their direction of swimming. And never do they cease to swim, although normally they swim only slowly.

For swimming, to the tuna, is far more than a method of getting from one place to another. It is as vital to the fish as breathing is to a man. If the tuna stopped swimming, it would suffocate. And since the density of its firm body is slightly greater than that of sea water, the fish would also sink.

The Kewalo facility allows exact studies of the swimming speed of tunas as it is related to the needs for ventilation of the gills and the maintenance of hydrostatic equilibrium. John J. Magnuson has found that the little tunny circles the tank at 0.75 meter second (about 1.5 m.p.h.) both day and night. When the fish were deprived of food for several days, their speed declined to 0.55 m. sec. (about 1.1 m.p.h.). The little tunny feeds by day. If the search for food played a predominant role in establishing swimming speed, one would expect the fish to swim slower by night; and certainly one would expect that the creature starved for several days and questing for food would swim faster than the satiated one. The little tunny, however, showed neither behavior. Whether the minimum speeds reached were chiefly related to a single function—gill ventilation or hydrodynamic lift—Magnuson is not yet sure. For some tunas, there is evidence that the requirements for gill ventilation are some-

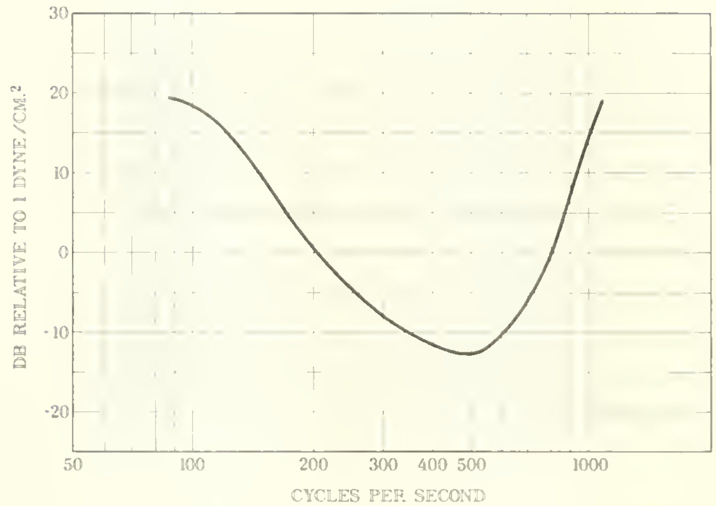


FIGURE 5. The yellowfin hears best sounds that are near 500 c.p.s., as is shown by the dip of the hearing curve at that frequency. Sounds of this frequency are common in the sea. An example is the sound produced by a school of small fish swimming.

what less than those for hydrodynamic lift, which means that the fish would sink before it would suffocate.

Magnuson's research, summarized very briefly here, has turned up one interesting if probably not too important bit of information: when he began to measure body density, he discovered that the little tunny in the laboratory tanks were slightly less dense than those fresh from the sea, most likely because of the presence of more lipids in their flesh—the creatures seemed to be getting fat on their shoreside diet.

The Fastest Fish

So far as this capability has been measured, the tuna seems to be one of the fastest fish. It ranks with the cheetah, the eagle, and the dragonfly as among the swiftest creatures of their kind on earth. Most of the time, however, in tanks at least, the tunas swim rather slowly. Rates reported from studies at sea vary widely.

The presence of underwater viewing ports on the *Charles H. Gilbert* has enabled our Laboratory scientist Heeny S. H. Yuen to make quantitative studies of the swimming speeds of yellowfin and skipjack tunas in the ocean. The procedure for finding these speeds is ingenious: the fish are photographed with a 16-mm. camera; from calculations that take into account the speed of the camera, the ship's forward movement, and its roll, Yuen is then able to measure successive images on the film in such a way as to arrive at a realistic estimate of the actual speed of a fish that may have appeared within the viewing range of the camera no more than half a second (fig. 6).

In this manner, he has made 510 measurements of the swimming speed of feeding skipjack tuna from four schools and 33 measurements of yellowfin from a single school. These results were then treated statistically to determine the validity of some of the relations suggested by the data.

The swimming speeds of the yellowfin tuna so measured were from 1.6 to 5.4 m. sec. (3.2 to 10.9 m.p.h.). These results fall between those reported for yellowfin swimming at a depth of about 350 feet (2 m.p.h.) and struggling at the end of a fishing line (40.8 m.p.h.).

The swimming speeds of the skipjack tuna (0.3 to 6.9 m. sec., or 0.6 to 13.9 m.p.h.) are much lower than those found by other researchers (about 10 m. sec., or 20.2 m.p.h.). The reason for this difference is unknown.

Both species swam faster (covered more body lengths) at the tailbeat rates measured than did the few other kinds of fish studied by earlier workers.

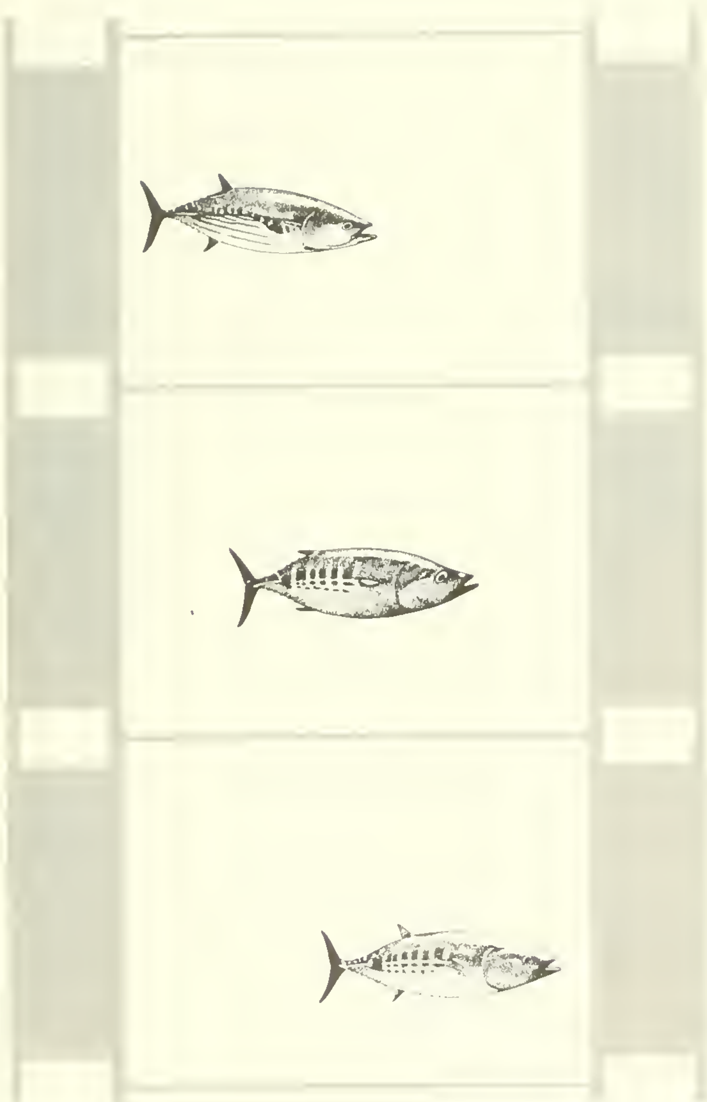


FIGURE 6. The swimming speeds of tunas at sea have been computed from the movement of the fish from frame to frame on motion picture film taken from the viewing chambers of the *Charles H. Gilbert*.

FIGURE 7. The new continuous-transmission, frequency-modulated sonar to be installed aboard the *Townsend Cromwell* will allow scientists to track individual fish and fish schools underwater. To locate tuna schools the commercial fleet now depends heavily on sighting bird flocks, which are associated with the schools (left). Conventional pulsed sonar (center) locates schools but cannot keep them under constant surveillance, as can the frequency-modulated sonar (right), which opens up wide areas of the sea to the scientists.

Although the observations just described tell us how fast individual fish swim, they say nothing about the speed of schools as units. What these speeds are, whether the fish school at night when visual contact may be lost, what depths they may prefer—these are unknown factors at present. They may not remain so. In spring 1966, the *Townsend Cromwell* will take to sea for the first tests of a new sonar system that is now being constructed in California for the Laboratory in Honolulu and that will be installed on the vessel early in 1966.

Unknown to the fish, long beams of unheard sound will play upon creatures almost a mile away from the ship and far below it. The echoes of these beams, received by sensitive electronic equipment aboard the vessel, will give scientists a new dimension to their picture of life in the open ocean.

The sonar will be a continuous-transmission, frequency-modulated equipment operating in two ranges of frequencies (fig. 7). This sophisticated gear was chosen instead of the more conventional pulsed sonar because it allows a target to be kept under constant surveillance. Its use lessens the probability of "losing" a target. The equipment will have a range of about 1,000 feet on individual tunas and perhaps 5,000 feet on a target of suitable strength—for example, a school. It will be capable of high resolution, distinguishing between fishes 7 inches apart at 300 feet.

And a still more exciting prospect looms ahead—the possibility of the construction of a nuclear submarine

FIGURE 8. The raft *Nenue* offers cramped quarters to the observer, who sits in a windowed caisson with a 360-degree view of the ocean around him. The raft has proved useful in studies of the fish communities of the upper layer of the ocean.

especially designed for fishery-oceanography research, the first nuclear submarine to be used for nonmilitary purposes. All the advance planning for this addition to the Nation's research capability has been done at our Laboratory and will be discussed later. Obviously, the submarine will have enormous possibilities for enlarging man's knowledge of the behavior of creatures in the sea.

The new sonar and the research submarine—these are exceedingly complex instruments for research. They make demands on many types of technical skills and cost a great deal of money. They are characteristic of much of the conduct of science of the latter half of the 20th century. But complexity and great cost are not necessarily the sole hallmarks of progress. The past months have seen some good science done at our Laboratory with a piece of equipment that was technologically feasible at least 2,000 years ago when Alexander the Great made his celebrated descent in a diving bell to the floor of the Mediterranean.

A Log With a View

Fishes collect around logs and other flotsam at sea. This habit is commonly exploited in sport fishing, and some small commercial fisheries have been based upon it. A few years ago, Reginald M. Gooding built what is essentially "a log with a view," a small raft equipped with a many-windowed caisson beneath the waterline. Tested first off the island of Hawaii, the raft *Nenue* proved seaworthy. The information she provided was found worth collecting. Early in 1964, the *Nenue* was shipped aboard the *Charles H. Gilbert* to equatorial waters. There she undertook two drifts, one of 8 days, the other 9. During daylight, she was manned at all times by two observers. Among them, Gooding, Magnuson, and Randolph K. C. Chang spent 276 hours observing the behavior of fishes under the dazzling canopy of the sea surface (fig. 8). The raft allowed them to obtain some striking photographs (fig. 9).

What did they find? When the raft was first put in the water, no fish were to be seen. Within 10 minutes the first of them arrived, little rudderfish that are cousins of the Hawaiian nenue for which the raft is named. Dolphin fish, known as mahimahi in Hawaii, appeared. They mingled with triggerfish, close relatives of the Hawaiian humuhumunukunukuapuaa, and many others. Within a short time, numerous fishes had been sighted. By the end of the longer drifts, almost a thousand fishes and some other creatures were swimming within sight. Many of the same species are present in both the Hawaiian and equatorial localities. The length of these creatures ranged from a few inches to several feet. The observations on these drifts constitute the most exhaustive study yet made on an underwater community in the open sea.

These raft studies and those described earlier have dealt with individual fish or at the most a few thousand, the school. Between the school and the millions of fish that make up the total population of a single species lies another natural unit of study, the subpopulation, a group of genetically related fishes. Its dimensions are as yet unknown, other than that they must stand somewhere between the few thousands of a school and the many millions of a species. The relatively recent application to fisheries of techniques of genetic research that have proved their value in agriculture and animal husbandry, as well as in the treatment of human illness, is now providing a powerful tool for understanding some of the fundamental problems of fishery utilization.

FIGURE 9. Whitetip sharks ***(Carcharhinus longimanus)*** photographed from the raft *Nenue*. The striped fishes are pilotfishes ***(Naucrates ductor)*** that accompany the sharks. Visibly attached to the sharks are suckerfish, ***Remora remora***. Sharks frequently approached the *Nenue*, as did a score of other fishes.

Blood Kin

The water that flows through a tap may have come from a single reservoir or from one fed by half a dozen streams. In a like manner, the reservoir of a species of fish that is sampled by a fishery may consist of groups from many sources. Such isolated, interbreeding stocks of fishes (or other animals) are called subpopulations. Many lines of evidence have strongly indicated that fished populations are not as a rule homogeneous, like water from a reservoir fed by a single stream, but consist of several subpopulations that breed separately in different places and perhaps at different times of the year.

Evidence for the existence of subpopulations has come from morphometrics, the study of the physical characteristics of the fish, from mathematical treatment of statistics on the catch, and from tagging studies. Morphometrics offer many interesting clues to the existence of subpopulations but have the shortcoming of dealing with characteristics that can be drastically modified by the environment; size is an example, for fishes of the same species can grow at different rates in waters of different temperatures, and these differential rates have not been shown to be linked to inheritance.

Catch statistics, again, provide inconclusive evidence. And tagging studies, which usually are made for estimates of population size and mortality rates, rather than for subpopulation research alone, are both slow and expensive.

Shortly after the discovery of human blood types at the turn of the century, Japanese scientists began to seek similar factors in fishes. These investigations were not aggressively pursued on an international scale, however, until the 1950's, when several U. S. investigators, including Lucian M. Sprague, now with the BCF Laboratory in Honolulu, took up this line of research.

Like men, like cattle, like most other creatures relatively high on the evolutionary scale, fishes of the same species may have different types of blood; this fact has given subpopulation research a new dimension. Here is a "tag" that is built in, that is inherited and unalterable.

Within the past decade, an entirely new and extremely active area of research has opened up, and the geneticist has entered the ranks of the marine professions. Recognizing the importance of the early findings, our Laboratory entered the field in 1960 and since then has become a world center for research on the blood groups of tunas (fig. 10). Its accomplishments have been described in several scientific papers and noted in previous progress reports. They are, briefly, (1) use of a number of systems, but mainly one called the B system, discovered by Sprague, in studies that showed that the Hawaiian fishery drew not on a single population of skipjack, but several; (2) determination, again largely by use of the B system, that as many as seven subpopulations of skipjack may exist in the central Pacific from Hawaii to Tahiti; (3) discovery of an A-B-O system in the bigeye tuna, a system named after that most familiar in humans and resembling it in that it is determined by the inheritance pattern of three related allelic genes; and (4) the finding of blood group systems in the yellowfin and bluefin tunas.

FIGURE 10. After they have been typed, some blood samples are frozen in a glycerin solution for later use in standardizing reagents. Here a technician syringes blood into solution that will be frozen.

In summer 1964, Kazuo Fujino, internationally known for his studies of the genetics of whales, joined the staff of the Laboratory in Honolulu to head the work on subpopulations. The discovery by Fujino and his colleagues of a highly sensitive new blood group system for distinguishing subpopulations of the commercially important skipjack tuna has highlighted recent blood group research at our Laboratory. This new system is called the Y blood group system. (As with most blood group designations, the name is arbitrary). What the Y system offers is an opportunity to examine any sizeable portion (100 or more fish) of the skipjack population and determine mathematically whether it represents a single subpopulation. It supplements earlier systems and, in recognizing several more and extremely subtle differences in blood types than the others, holds forth the promise of differentiating subpopulations that are closely related. To date, tests of the Y system have shown the existence of 15 kinds of "Y" individuals among skipjack.

It is the proportion of each of these kinds of "Y" types in a sample that allows scientists to delineate subpopulations. A single system is often not adequate, hence the merit of several. The Y system of skipjack blood will thus not replace the B and other systems already used but supplement and extend them.

The geneticist drawing his samples from the commercial fisheries can distinguish subpopulations, but he cannot determine the place of their origin. To do that, he must have samples from far afield. For this reason, our Laboratory has collected samples of tuna bloods from throughout the Pacific.

The blood group studies represent the application to fishery problems of principles and techniques pioneered in other fields. Another technique of genetic research on human beings that has recently come into use in fishery work is the study of the sera of fish bloods. Certain inherited components of the clear fluid of bloods can be distinguished by a method called starch gel electrophoresis, which relies on the differential response of certain proteins in the serum to an electric current. Fujino and his associates have used this technique to locate two types of proteins in the sera of both skipjack and yellowfin tunas. They have found three phenotypes that allow the rigorous mathematical analysis upon which conclusions concerning subpopulations are based. An additional, very rare phenotype has been observed in the skipjack tuna.

Research on subpopulations deals with fish in units of x thousands to x millions These units in their totality constitute a species. And it is with the concept of species that both fishermen and fishery scientists are most familiar. At our Laboratory, two species are of special interest, the skipjack and the albacore tunas, both of which form the basis of large U. S. fisheries in the Pacific.

THE FISHERIES

The Catch of Tunas

Two hundred sixteen countries have commercial fisheries, but pickings are small for many of them. In 1963, the most recent year for which reliable statistics are available, two Pacific nations, Japan and Peru, took almost one-third of the world's 51.1 million ton harvest of the sea, according to FAO.

By weight, the tunas (or FAO's "tunas, bonitos, and skipjacks") do not bulk large in the world catch, accounting for only 3 percent of the total, or 1.4 million tons out of 51.1. They are among the most highly prized of fishes, so that in value to the fishermen they overshadow many others caught in greater quantities. In California in 1964, the four main species—albacore, bluefin, skipjack, and yellowfin—com-

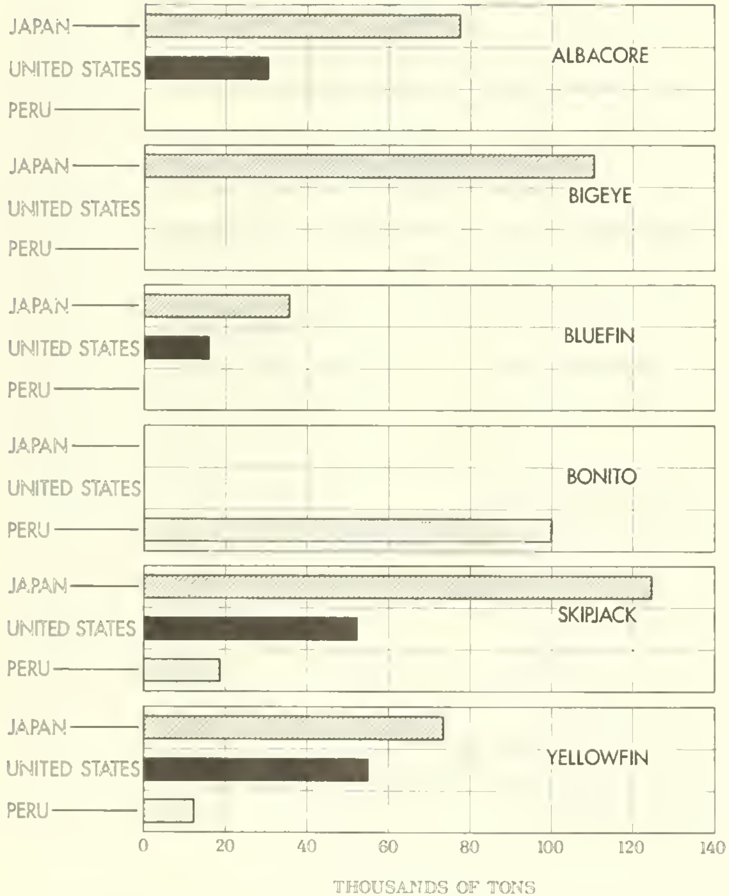


FIGURE 11. The catch of tunas and tunalike fishes in the Pacific Ocean accounts for about one-half of the world's total for these species. Here are shown catches of Peru, Japan, and the United States for 1963. Sources of the data are the FAO 1963 Yearbook of Fishery Statistics, Vol. 16, and material from the Nankai Regional Fisheries Research Laboratory, Japan.

TABLE 1. Catch (in thousands of metric tons) of major tuna and tunalike species by Japan, United States, and Peru in Pacific Ocean, 1963. Sources: FAO Yearbook, Vol. 16, and Nankai Regional Fisheries Research Laboratory, Japan.

	Japan	United States	Peru	Total
Albacore	77.4	30.3	...	107.7
Bigeye	110.2	......	....	110.2
Bluefin	35.3	15.8	....	51.1
Bonito	......	....	100.0	100.0
Skipjack	124.4	52.2	18.6	704.8
Yellowfin	73.3	55.0	12.3	195.2
Total	420.6	153.3	130.9	140.6

manded prices ranging between $200 per ton for skipjack and $350 per ton for albacore, against $47.50 for Pacific mackerel and jack mackerel. Similar disparities exist in other countries. In Peru, tunas in 1963 commanded a price per ton nine times that for the average of all other marine products and in Japan, about three times.

Although tunas are found all around the globe and are an important element of the French and Spanish landings, Japan, the United States, and Peru have the major fisheries. These three, in 1963, took 75 percent of the recorded world catch of tunas: Japan, 677,100 tons (half the world catch); the United States, 162,000 tons; Peru, 130,900 tons. The total value to the fishermen was: in Japan $209 million, in the United States $45 million, and in Peru $10 million. In dollar values, the tunas formed the base of the most important fishery in Japan, the second in Peru, and the third in the United States, where they were exceeded only by shrimp and salmon.

The Japanese fishing fleets range the Pacific, Atlantic, and Indian Oceans, so that the 1963 total of 677,100 tons represents a worldwide catch. Recently the Nankai Regional Fisheries Research Laboratory has made data available that allow the separation of statistics on fishes caught in the Pacific from those caught elsewhere. These figures show that in 1963, the total Japanese catch in the Pacific of the major tuna species was 420,600 tons, 64 percent of all Japanese tuna landings. The U. S. Pacific total was 153,300 tons, the Peruvian 130,900 tons. The Peruvian catches were dominated by the tunalike bonito, which are not taken in quantity by the United States and Japan. Thus about one-half (704,800 tons) of the world's catch of tunas comes from the Pacific Ocean (table 1 and fig. 11).

At the BCF Laboratory in Honolulu, investigations are now concentrated on two species, the skipjack and the albacore. Honolulu is located a little to the south of the North Pacific albacore fishery but within the spawning grounds of the species. With regard to the skipjack, Hawaii stands at what may be either the terminus of a migration of enormous dimensions or merely the center of a commuting web; or, like Grand Central Station, it may partake of the nature of both. Within a few miles of its shores lie the boundaries of two of the great water types of the Pacific Ocean, and the State itself is bathed in summer by one of the major oceanic currents, a circumstance that may have a profound significance in tuna studies. The local fishery affords scientists an opportunity excelled nowhere else in the world to collect living tunas and to observe the conduct of a year-round fishery. And near Hawaii lies a hidden tuna resource of immense potential value.

The Skipjack Tuna

The name "skipjack" has been applied to several species of fishes that jump above or play at the surface of the water. The tuna that is called "skipjack" is found and fished in all the world's oceans except the Arctic. There are names for it in at least 20 tongues.[1] In 1963, the skipjack tuna outranked in weight all other tunas caught in the Pacific (table 1). The skipjack is a short-lived fish and has a dark blue back and a silvery belly. It attains a length of about 30 inches. There are at least three cogent reasons for the study of the skipjack: the commercial importance of the present fishery; the much greater potential commercial importance of the species; and the growing possibility that elucidation of some of the mechanisms that link the skipjack and its environment in the central Pacific may give results that could be applicable to fishery problems throughout the world.

The Aku Fishery

The Hawaiians have a name for the skipjack tuna that is halfway between a cough and a sneeze—"aku." The aku catch is by far the State's largest, accounting for 69 percent of the total landings of 5,874 tons (about the average annual catch) in 1963, according to the Hawaii Division of Fish and Game. The skipjack are caught in Hawaiian waters every month in the year, but the fishery depends heavily upon the larger fish that are most often in evidence during the summer.

The Hawaiian aku fishery is conducted by the sampan fleet, the size of which has been dwindling with the years, although catches have not paralleled this trend. Fishing is done by pole and line. Usually schools are located by observing bird flocks. The schools are chummed with live bait, by preference the "nehu" or anchovy *(Stolephorus purpureus)*. Landings have varied from 29,000 pounds in January, traditionally one of the poorest months, to more than 3 million pounds at the height of the season in July, according to Richard N. Uchida, our Laboratory scientist who has made a definitive statistical study of the 1952-1962 catch.

[1] These include patois of the British West Indies (barriolet), Sinhalese (alagudura), Chinese (tow chung); English (skipjack tuna); Spanish (atun); Danish (bugstribet bonit), French (bonite à ventre rayé); German (bauchstreifiger); Greek (pelamys), Hawaiian (aku), Arabian (balanida); Japanese (katsuo), Indonesian (tjakalang), Norwegian and Swedish (bonit); Tagalog (galyasan), Portuguese (gayado), Tunisian (boussena), Yugoslavian (trup prugavac). The scientific name is almost equally various, there are 15 versions, of which *Katsuwonus pelamis* is most generally used (Rosa, Horacio, Jr 1950. Scientific and common names applied to tunas, mackerels, and spear fishes of the world, with notes on their geographic distribution. FAO, Washington, D. C.)

As predictably as tourists flock to the famous beaches of Waikiki in summer does the skipjack catch rise in the warmer months. Both tourists and tunas are a source of income to the State of Hawaii. (But tourism is a $200-million-a-year business; the fishing industry brings in about $1 million to the fishermen.) The arrival of both tourists and tunas in Hawaii is predictable. Unpredictable are the numbers in which either will turn up. May 1965 was a phenomenal month for the skipjack fleet. Official figures are not yet available, but it is no secret that in May the fishermen had a month such as normally occurs only at the peak of the season, July. In fact, this May's catch was estimated to exceed that of most July's. Fishing almost within sight of Waikiki, the sampans came home night after night heavily loaded with aku. And the captains of the Laboratory's research vessels reported that the fleet was only nibbling on the population; schools were abundant offshore for many miles to sea. In June the catch slackened, but Hawaii still appears to be headed for a record year.

The unusual catch in May could be attributed to two causes. First, it may have represented the passage through the fishery of a year-class of great strength. Year-classes of almost legendary abundance are well documented in many fisheries. Like comets and great men, they appear so briefly and infrequently as to be remembered long afterward. The much studied 1939 year-class of sardines off the west coast provides an instance, as does the classical 1904 year-class of Norwegian herring. Second, the May catch might have reflected the response of the skipjack to some change in the ocean environment. These two posibilities are not mutually exclusive, of course.

Aku Forecasts

As has been mentioned, the Hawaiian Islands lie near the boundary between two water types. It is a boundary that, like the front line in a stalemated war, shifts back and forth. Thus the islands are bathed by water of relatively high salinity during part of the year, by less saline water during the rest. Normally, but not always, the more saline water prevails during the fall and winter, the less saline during the late spring and summer.

Good fishing seasons for skipjack tuna are often characterized by a flow of less saline water about the islands. This circumstance is interesting but of little predictive value to the fishermen, for by the time the less saline waters arrive off Hawaii's shores, the fish are there too. Our Laboratory scientists have noted, however, what appears to be another characteristic of good fishing years: the seasonal warming of the sea surface starts early.

Using the time of initial warming, as measured at Koko Head, the southernmost point of the island of Oahu, and information on the changes in salinity near the islands, oceanographer Gunter Seckel for the past 6 years has issued an "aku forecast" in April. The season has usually borne out the forecast. The forecast for 1965 called for an "average or above average" catch, and the fishery is undeniably headed that way.

These forecasts are of more use to the scientists than to the fisherman. "Below average," for example, a term as exact as the scientists are yet prepared to use, could mean anything from rather poor to catastrophic, a big difference to a man trying to make his living from the fishery. To the scientists they provide clues to the natural processes that may account for the variations in the skipjack catch, and these clues are being followed up.

The phenomenal catch in May provided a dramatic illustration. The salinity value of 34.8 ‰ (parts per thousand) has been empirically selected as that separating "favorable" from "unfavorable" waters. Figure 12 shows that when the salinity at Koko Head dropped below this value, and stayed there, the estimated skipjack catch rose abruptly and although landings declined in June, they remained well above previous levels. The estimated monthly take of skipjack tuna from January through April was between 300,000 and 800,000 pounds per month. Then in May the catch increased to an estimated 3.5 million pounds and in June was 2.3 million pounds. For the first 4 months of the year average salinities at Koko Head were about 34.99 ‰, dropping to 34.65 ‰ in May and June.

On the basis of previously established criteria, the waters changed from what is designated as an unfavorable type in April to a favorable type in May. From the weekly landings and the biweekly salinity samples one can see that the change must have occurred about May 5. The salinity was 34.99 ‰ on May 4, dropped to 34.69 ‰ on May 7 and 34.53 ‰ on May 11. For the 7-day period ending on May 3, the estimated Oahu landings were 130,000 pounds, for the 7-day period ending May 10, they were 510,000 pounds.

This correlation supports the hypothesis that water type is important in the distribution of skipjack. It should be emphasized, however, that the correlation is between type of water, of which the salinity is merely an index, and skipjack catch—not between salinity itself and skipjack catch. The decline in the catch rate in June, when salinity remained low, shows that other factors also affect the availability of skipjack.

Skipjack Hypotheses

Theoretical studies of the origin of the skipjack caught by the Californian and Hawaiian fleets may seem remote from the immediate interests of the fishery. Yet until it is known where and when the fish are spawned and in what quantities it will be most difficult to arrive at valid suggestions for rational management of the resource. Since fishery scientists, dealing with matters that vitally affect major industries and international relations, only cautiously put forward general theories on the basis of evidence not wholly and repeatedly substantiated, there exists no generally accepted "skipjack theory." This reporting period, however, has seen the publication of a scientific paper by Brian J. Rothschild that considers all of the available data on the skipjack tuna and advances a set of interlinked hypotheses to explain some of the enigmas of the fluctuations of the skipjack catch. These hypotheses are not yet a theory, but constitute a bold and significant first step toward one, and almost all research on the skipjack in the next few years will need to take them into consideration.

In brief, on the evidence of data on spawning, size distribution, movements, and gonad indices, Rothschild hypothesizes that the small skipjack that make up the bulk of the eastern Pacific catch are spawned not in those waters but somewhere in the central Pacific and that they immigrate to the shores of the Americas at an early age, stay

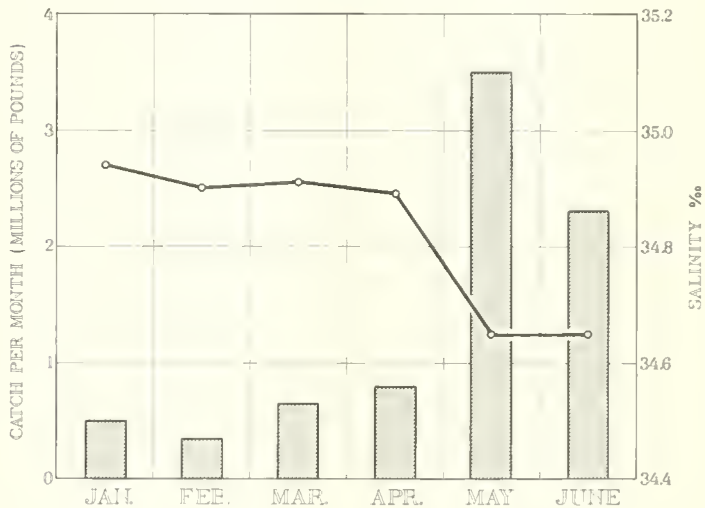


FIGURE 12. The arrival of water of lower salinity at Oahu can signal good skipjack catches. Here are shown the average monthly salinity values at Koko Head from January through June 1965 (the line) and estimated average skipjack catches (bars). Note that as salinity dropped, estimated skipjack catches increased.

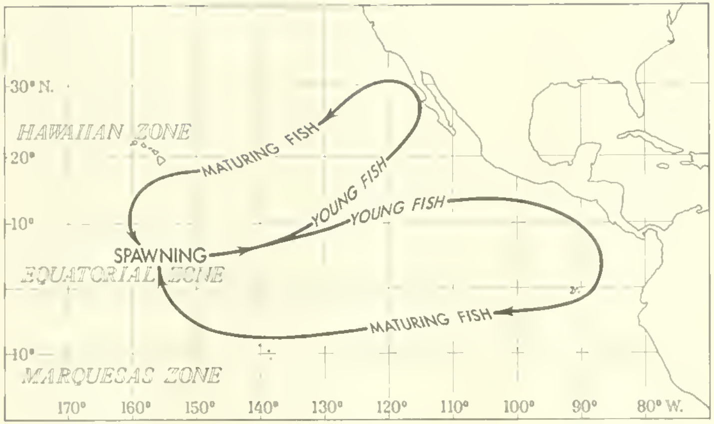


FIGURE 13. In a paper published during this reporting period, one of our scientists hypothesized that the large U. S. fishery for skipjack tuna in the eastern Pacific depends upon fish that are spawned in equatorial waters south of Hawaii. The skipjack remain in the fishery area only a short while, returning to the equatorial Pacific to spawn. The Hawaiian skipjack fishery may also depend to some extent on fish spawned in the Equatorial Zone.

there briefly (no more than a year), and then return to the central Pacific.

On the basis of subpopulation studies and other evidence, he suggests that the skipjack caught in Hawaiian waters do not comprise a single population unit. He postulates that the central Pacific spawing area can be divided into three adjacent zones, one lying near the latitude of Hawaii, another around the Equator, and the third south of the Equator near the Marquesas. The fish spawned in this last zone, he says, probably do not enter the eastern Pacific fishery. He seeks to determine whether the skipjack caught by the U. S. fishery in the eastern Pacific originate for the most part in the Hawaiian or the Equatorial Zone. Several lines of evidence suggest the conclusion that they come from the Equatorial Zone.

Some of the skipjack in the Hawaiian catch do not originate in Hawaiian waters; whether these come from the same equatorial stock as the eastern Pacific skipjack is not known. There is some direct evidence that the two fisheries are related: two skipjack tagged off Baja California in 1960 were caught in the Hawaiian fishery about 2 years later. Another skipjack from Baja California was caught at Christmas Island 16 months after tagging.

Other scientists have suggested that the skipjack of the eastern Pacific make long offshore-inshore migrations. What is new about Rothschild's hypotheses is that dimensions have now been postulated for these migrations: they reach from the coasts of the Americas 3,000 miles westward to the equatorial waters south of the Hawaiian Islands. New is the suggestion that the Hawaiian and eastern Pacific fisheries are to some extent drawing on the same population, with the implication that the "season" skipjack on which the Hawaiian pole-and-line fishery so heavily depends may be those which have escaped the nets of the eastern Pacific fishery earlier in their lives (fig. 13).

Rothschild offers evidence of fluctuations in year-class strength in the skipjack. This means that Hawaii could well serve as a base from which future eastern Pacific catches could be forecast as they could not be in the fishery area itself. The reasoning is this: Some of the skipjack taken in Hawaii originate in the same Equatorial Zone as do those caught in the eastern Pacific; the Hawaiian catch appears to reflect fluctuations in year-class strength; a knowledge of the mechanisms that affect year — class strength in the central Pacific would provide a lever toward understanding success of spawning in the Equatorial Zone and hence allow estimates of eastern Pacific catches.

Rothschild's paper is particularly important because he suggests critical tests of the hypotheses advanced. Because adult skipjack at the time of spawning have so far almost completely eluded capture, the next best indicators of recent spawning, the larval and juvenile skipjack, should be sought in an area of the Pacific reaching from the Hawaiian Islands 2,400 miles southeast to the Tuamotu Archipelago, and their genetic relationships determined. Equally important will be genetic studies of the skipjack of the eastern Pacific catch.

A few days before Rothschild's paper was scheduled to come off the press, the Laboratory received a copy of the *Bulletin of the Tohoku Regional Fisheries Research Laboratory* that contained an article by T. Kawasaki whose conclusions to some degree paralleled those of Rothschild. It is interesting that two men working independently should have arrived at somewhat similar conclusions from the sparse existing data on an exceedingly complex problem.

Kawasaki goes a step further than Rothschild is now prepared to do. He suggests that there are relations between the catch in Japan and that in the central Pacific. If he is right—and it is not known that he is wrong—he has introduced a new element into considerations of the fishery. The present controversy over the salmon of Bristol Bay illustrates vividly some of the difficulties that can arise when two nations draw upon a single stock. The possibility that his assumption may be valid underscores the pressing need for more detailed information about the skipjack resource.

Hawaiians, Californians, and Japanese are not the only fishers of skipjack tuna. It is one of the most widespread of the food species. Prior to World War II, the islands that now form the Trust Territory of the Pacific were mandated to the Japanese, and a skipjack tuna fishery flourished there, taking as much as 72.8 million pounds in a single year, seven times the average Hawaiian catch. Today this fishery is being revived under the auspices of the present trustee of the islands, the United States. A substantial fleet is building up at Palau in the Carolines and an American company

FIGURE 11. A new net 2 meters (about 6 feet) to the side was tested off Oahu in the summer of 1965. It was compared with the circular net 1 meter in diameter that is widely used to collect plankton.

has established a freezing plant there. In the spring of 1965, with the cooperation of the High Commissioner of the Trust Territory and the American firm there, the Bureau's Laboratory in Honolulu stationed an observer at Palau to document the resumption of the fishery at a commercial level. The data from the Trust Territory should offer an interesting supplement to those gained from the other U. S. skipjack fisheries and of Japan.

The Youngest Tunas

Our Laboratory has collected more than 3,000 samples of larval and juvenile tunas from the Pacific. Walter M. Matsumoto is identifying these fish and preparing charts of their distribution. He has also studied the larval phases of other fishes, recently completing a description of the larval and juvenile stages of the wahoo *(Acanthocybium solandri)*, one of the scombrids closely related to the tunas.

Towards the end of the reporting period, Matsumoto has been investigating improved methods of collecting juvenile tunas (fig. 14). Often found near the surface, they have proved to be the most elusive of fish, escaping capture so readily that much of the information on them comes not from nets operated by scientists but from the stomachs of those more experienced collectors—the larger fish.

About 550 million pounds of skipjack tuna are taken annually in the Pacific Ocean. The resource may be able to withstand a heavier rate of fishing. At present, however, skipjack remain (except in Hawaii) a secondary resource. They are taken in the eastern Pacific along with and as a supplement to or substitute for the more highly valued yellowfin. In Japan, skipjack supplement catches of the most prized of the tunas, the albacore, the other species upon which the Bureau's Laboratory in Honolulu is expending a considerable share of its research effort.

The Prized Albacore

Honolulu is one of the most cosmopolitan of American cities. Its cuisine reflects its various cultures. The diet ranges from poi to french fries to kasha, from taro leaves to spinach to bak choi. There is a particularly wide variety of sea foods, both locally caught and imported. The visitor to the fresh-fish market finds a profusion of fishes for sale, from the slender, silvery wahoo to the enameled splendor of the red and blue and green reef fishes.

Much of the product of the fresh-fish market is supplied by the Hawaiian longline fishery. Although Honolulu is located in a region fished successfully by the Japanese longliners, the Hawaiian longline fleet, composed of small vessels, stays close to shore, rarely losing sight of land. Only in recent years have some of the ships, with the encouragement of our Laboratory, ventured 200 or 300 miles to sea, where in some seasons they were rewarded by catches four and five times as great as those taken nearer shore.

Tunas make up the bulk of the Hawaiian longline catch: bigeye and yellowfin account for more than half. Only a few albacore are caught (about 8 tons in 1962), but these, it turns out, are uniquely important to science, for they provide key information on the history and habits of this valuable species.

Highly regarded as a food fish because of its flavor, texture, and color, the albacore is found in all the world's oceans except the Arctic. The Pacific catch is the world's largest. In 1963, Japan, fishing in three oceans, took 127,300 tons of albacore. Of these, 77,400 came from the Pacific. The United States, which has the only other large fishery, took 30,300 tons in an area that reached from Baja California to the Pacific Northwest and several hundred miles to sea.

Tagging studies have proved that the United States and Japanese albacore catches in the North Pacific are related. Working with data from these studies and the catch, Tamio Otsu of our Laboratory has depicted a complex pattern of migrations. Though many features are still obscure, in broad terms this investigation showed that the albacore are spawned in tropical and subtropical waters, migrate to temperate waters in their second year, and enter the eastern Pacific catch in large numbers in their third year. Many cross the Pacific to mingle in the catch off Japan, where they spend several years; eventually the older fish perform another migration, returning to subtropical and tropical waters to spawn. The albacore is a long-lived fish. It does not reach sexual maturity until its sixth year. The fish that migrate to the south are large and old.

The albacore taken in the Hawaiian longline fishery are unlike those caught anywhere else; they are on the average considerably larger than those in any other North Pacific fishery. They have reached record weights (93 pounds is the largest; albacore caught in the eastern Pacific fishery average about 14 pounds). These fish seem to represent the large, old segment of the population that has entered subtropical waters to spawn. That the albacore do spawn near Hawaii has been borne out by other studies. Although tuna eggs cannot be distinguished by species, many of the postlarvae can. Identification is especially simple for the albacore postlarva, which develops a flattened haemal spine on the first caudal vertebra. This unique characteristic appears in specimens as short as 2 centimeters, about three-fourths of an inch. Discovery of these small fish in Hawaiian waters has shown that the albacore spawn nearby.

Little Albacore

Very few of the juvenile albacore have been taken by the scientists' nets. More have been found in the stomachs of billfishes. During this reporting period, Howard O. Yoshida has studied juvenile albacore collected from the stomachs of billfishes from the Honolulu fresh-fish market. From 3,348 stomachs collected between June 1962 and December 1964, he took 23 juvenile albacore. (Stomachs contained far more skipjack—696; these form the basis of another study.) Most of the billfish, 2,791, were striped marlin *(Makaira audax)*, which weigh from 10 to 325 pounds.

By measuring the length of the vertebral column of his specimens, Yoshida was able to estimate the standard length of the intact fish. Using these lengths and his information on the date of the landing of the billfish, he estimated the growth rate of the very young fish, a matter upon which very little data exist. His estimate is that the young albacore grow about 3 centimeters (a little more than an inch) a month during most of their first year of life (fig. 15). He was able to estimate the date of spawning, which appears to begin late in May and to last several months.

It is only rarely that fish smaller than 40 centimeters (15.6 inches) enter the albacore fisheries. Hence Yoshida's work corroborates other information that would place the North Pacific albacore in subtropical or tropical waters during the first year of its life. Where its spawning grounds are centered and how extensive they are, is unknown. Some

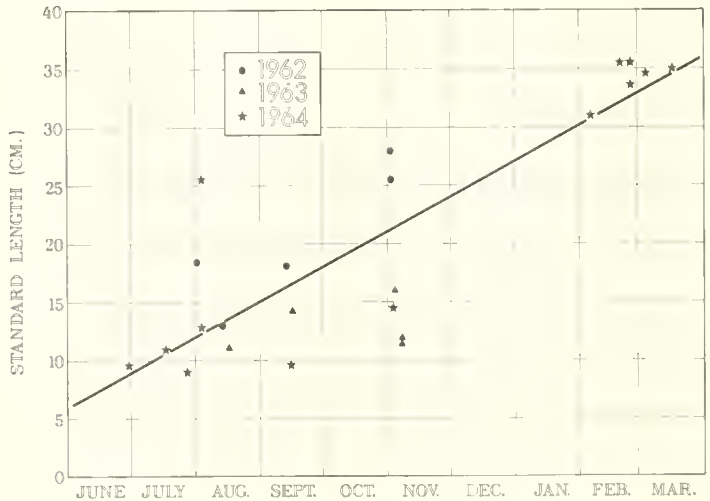


FIGURE 15. The juvenile albacore grows about 3 centimeters (a little more than an inch) a month in Hawaiian waters during the first year of its life.

evidence suggests the Hawaiian Islands may be only on the eastern fringe of them.

Yoshida's work also hints at varying seasonal and annual abundances of the juvenile albacore in Hawaiian waters.

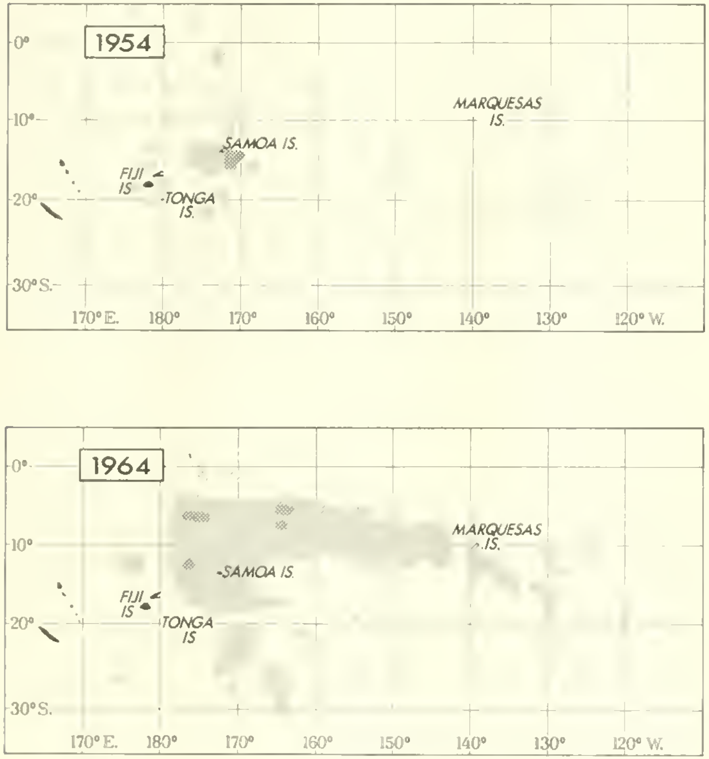


FIGURE 16. The area fished for tunas by vessels based in American Samoa has expanded greatly since operations began in 1954. It now reaches east of the Marquesas Islands. The BCF Laboratory in Honolulu maintains a field station there, as it also does at Palau in the Trust Territory of the Pacific Islands. Darker shading in the figures above depicts areas of heaviest catch.

A New Fishery

The North Pacific albacore fishery is relatively old, dating back to the turn of the century at least. The albacore fishery of the South Pacific was established only 11 years ago. The most important operations are based in American Samoa, where one American firm established a cannery in 1954, another in 1963.

Starting modestly with 7 Japanese tuna boats in 1954, the fishery grew to a total of about 100 vessels in 1963. In December 1964, 68 vessels from three nations were operating; 40 vessels were from Japan, 17 from South Korea, 11 from Taiwan.

The growth of the South Pacific fishery has been a matter of extreme interest to the Bureau's Laboratory in Honolulu. Samoa provides a rare opportunity to study the early history of a considerable commercial fishery. As a result, the Laboratory, through the cooperation of the Governor of American Samoa and the American firm there, established a field station at Pago Pago in 1963. Manned by observers from our Laboratory, the field station is effective not only in obtaining biological samples of the catches, but also in collecting catch and operational data from the vessel operators who deliver their catches to the canneries. These data are transmitted to Honolulu, where Otsu is preparing a comprehensive report on the Samoan fishery.

The fishery has expanded rapidly. Figure 16 shows the fishing area in 1954, and in 1964, when the vessels were fishing in an area from the Equator to as far south as 30°, the latitude of mid-Australia, and from slightly east of the international date line to long. 120° W., south of San Francisco. The area covers about 8 million square miles and takes the vessels as far as 3,000 nautical miles from their base.

The fishermen gear their efforts toward capturing the profitable albacore. The albacore catch increased from about 360 tons in 1954 to 14,900 in 1963, but dropped to 11,700 in 1964. Figure 17 shows the total annual landings of albacore, the total number of fishing trips made each year, and the average catch per fishing trip. The rather sharp decline in landings in 1964 appeared to be caused by a decrease in fishing effort, compounded by the effects of a decreased average catch per fishing trip.

Cooperative Effort

It is obvious that American and Japanese interests are linked in both the North Pacific, where the fishing fleets draw on a common resource, and in the South, where mutually dependent commercial efforts are involved. Fishery scientists of neither nation can speak with full authority on albacore problems without access to all available information on the Pacific, and much of it has not been published.

Under these circumstances, the Laboratory in Honolulu in 1964 entered into an informal agreement with the Nankai Regional Fisheries Research Laboratory, where much of the Japanese tuna research is conducted, to cooperate in studies of the albacore. Tamio Otsu left Honolulu in September and spent the next 6 months at Kochi, Japan. Unpublished data from the North Pacific fishery, some going back to the years before World War II, were made freely available to him. In return, our Laboratory has provided its Japanese sister laboratory data from its cruises, from the eastern Pacific, and from Samoa. Although this project was launched before the formal beginning of the International Cooperation Year, it is fully in the spirit of that enterprise.

Otsu returned to Honolulu in March 1965, bringing with him transcriptions of the Japanese data to be coded, checked, and key punched so that they can be analyzed by computers. This work is scheduled to be finished by the end of 1965. The wealth of information in the data should provide the basis of many new studies of the prized albacore.

The Hidden Resource

The central Pacific is fished by the Hawaiian fleet and the Japanese. The Hawaiian fleet is rarely out of sight of land. It takes about 7,000 tons of tuna a year. The Japanese fleet ignores the islands to reap a harvest overwhelmingly larger than that taken by the Hawaiians.

Several lines of evidence suggest that the Japanese fleet is not exhausting the protein riches of the central Pacific: there are still far less potentially harvestable fish caught than uncaught. The most plentiful tuna larvae in the area are those of the skipjack tuna. Because the skipjack apparently spawn no more frequently or plentifully than the other tunas, the presence of these larvae point to the existence in the central Pacific of an immense population essentially untouched by the Japanese longline fleet and only sampled by the Hawaiian vessels. The bigeye and yellowfin tunas taken on the Japanese longlines are large and old; somewhere in the area there must be not only more of these fishes but

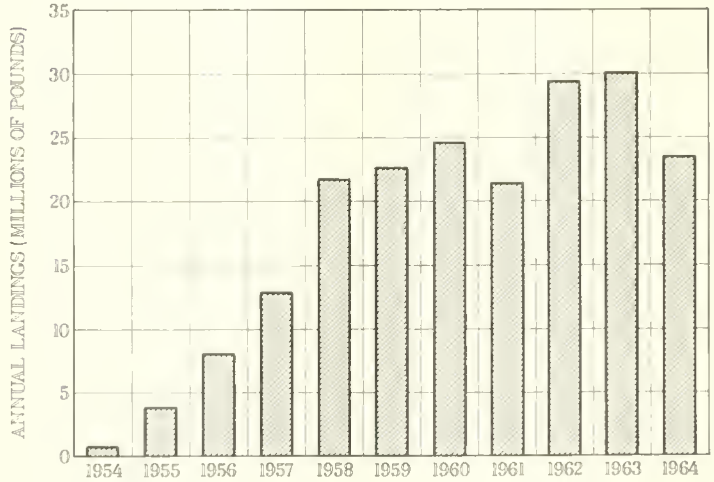


FIGURE 17. Until 1963, the history of landings at American Samoa was one of almost steady increase. Two factors account for the slump in 1964: fewer vessels were fishing and the average catch per trip decreased.

also larger populations of the smaller and younger fish, that now are not taken at all.

Speaking at the Governor's Conference on Science and Technology, State of Hawaii, in January 1965, John C. Marr, BCF Area Director, Hawaii, said, "It has been estimated that these resources could yield an annual catch of perhaps 200,000 tons. We know that the resources exist, we know the general—but not the specific—details of their geographical distribution, we know that they generally occur beneath the surface, and we suspect that they occur in schools. We do not know where major concentrations occur, if such exist, we do not know their depth distribution and how this may vary, and we do not know certainly that the fish occur in schools."

As this report has shown, much of the work of our Laboratory is shaped toward solving the problems in measuring, locating, and harvesting this great hidden resource.

Tunas in the Indian Ocean

Although it covers one-seventh of the globe, until recently the Indian Ocean has been one of the least explored areas on earth. Our Laboratory has planned and implemented that portion of the U.S. contribution to the great International Indian Ocean Expedition that is concerned with fishery biology. Scientists, technicians, and crew members from the Laboratory participated in several of the cruises of the U.S. biological research vessel *Anton Bruun*. In the course of these cruises, our Laboratory collected information on the distribution and abundance of tunas; when examined in conjunction with data from the Japanese tuna catches there, this information should bring a new understanding of the food resources of the Indian Ocean, which is bordered by teeming nations whose need of new supplies of animal protein is pressing.

Effort in the Indian Ocean was devoted to carrying out a wide north-south survey to determine the distributional limits of the various species and to gather environmental data.

Richard S. Shomura, who is analyzing the information on the high-sea resources of the Indian Ocean, found a most distinct separation of water types along the transect at long. 70° E. (fig. 18). Arabian Sea Water with high temperatures and high salinities in the surface layers extended south to about lat. 10° N. In the central Indian Ocean, equatorial water was found from lat. 10° N. to about lat. 11° S. From there to lat. 37° S., the southernmost station, South Indian Ocean Central Water prevailed. The other three transects showed more complex relations.

All of the catches of albacore tuna were made south of lat. 8° S. in waters that seem to be of the South Indian Ocean Central type. The albacore were mostly large.

The yellowfin tuna were taken widely in the central and western Indian Ocean. In the central portion, they were taken from about lat. 10° N. to about lat. 30° S. They appeared to be associated with both the equatorial water and South Indian Ocean Central Water. They averaged 76 pounds.

Bigeye tuna were caught from lat. 10° N. to the southernmost station, but a gap appeared to exist between lat. 12° S. and 40° S. They averaged 100 pounds.

The data from the Indian Ocean cruises will be added to the tremendous store from the Japanese fisheries in a cooperative study that will be carried out with scientists from the Nankai Regional Fisheries Research Laboratory. The study will examine the relation of distribution and abundance to oceanographic features.

One of the aims of the biological program in the Indian Ocean was to gather information on creatures of the sea other than food fishes. Included were the zooplankton—those little drifting marine animals that make up much of the food of fishes. These data are still being studied. From the preliminary studies have come some interesting results.

Bulking large in the economy of the sea and the food chains of most oceanic fishes are the copepods, small animals much less than an inch long that resemble shrimp. Biologist E. C. Jones of our Laboratory has found that in the central Pacific the occurrence of some members of the copepod family Candaciidae provides clues to the history of the waters in which they are collected.

Preliminary results suggest that members of the same copepod family can be used in the Indian Ocean in the same way—that certain species are associated with waters of certain temperature and salinity. The distribution of some is associated with water found primarily in the Arabian Sea, that of others with equatorial water or the South Indian Ocean Central Water.

In another Indian Ocean study, biologist Thomas S. Hida has examined the fishes collected by bottom-trawling in the Bay of Bengal and the Arabian Sea and is making a study of the polynemids (threadfins) of the Bay of Bengal. Some species of this group are commonly used for food.

International Studies

As has been pointed out, the skipjack tuna populations of the eastern Pacific, the Hawaiian area, and Japan may well be linked; certainly Japan and the United States are drawing on a common albacore resource in the North Pacific; they are competing, most unequally, for the fishes of the central Pacific; in the Indian Ocean, Japan takes many more tons of tunas than does India. Fishery problems, when they deal with the creatures of the high seas, are not local. They are at least oceanwide in scale.

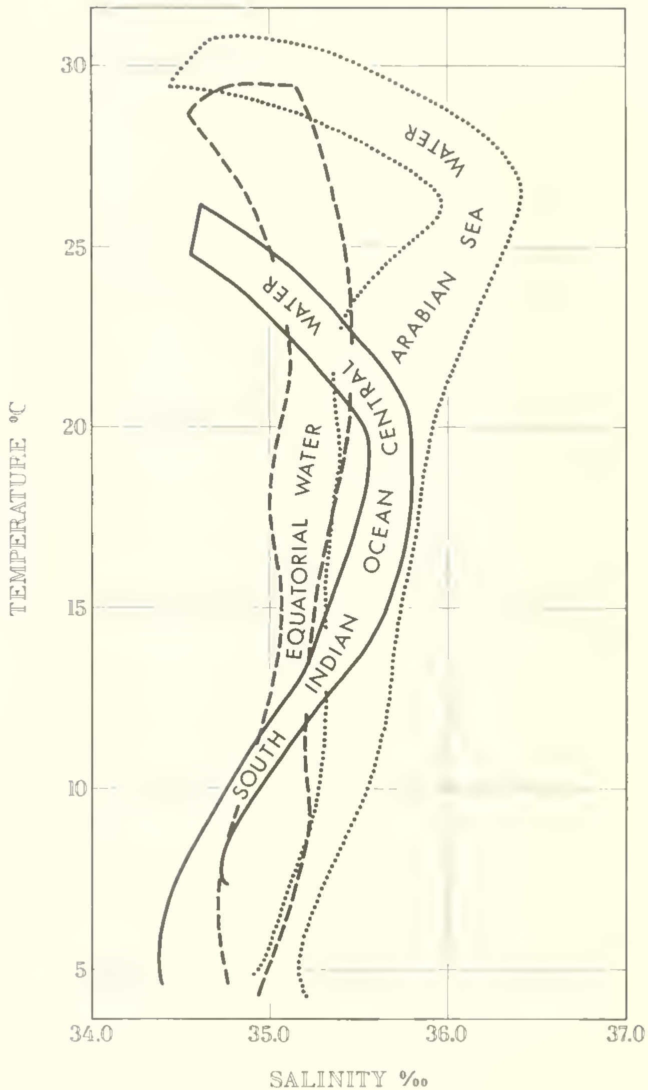


FIGURE 18. Water types along long. 70° E. transect in the Indian Ocean, based on temperature-salinity distribution. Arabian Sea Water is very warm, highly saline. Equatorial water is cooler and less saline. The waters of the south central Indian Ocean partake of some of the characteristics of both the others.

The Pacific and Indian Oceans provide about one-half of the world fish catch, although together they constitute three-fourths of the oceanic waters in the world. Their shores are bordered by some of the most populous nations on earth. In these coastal areas alone live about a billion people, one-third of the world's population.

To develop and properly use the living aquatic resources of the Indo-Pacific area and further to attain these ends through international cooperation, an Indo-Pacific Fisheries Council was established in 1948 under the auspices of the United Nations. The Council has 17 members, comprising most of the nations of the region with the notable exceptions of mainland China and the U.S.S.R. The Council has met 11 times, most recently in October 1964 at Kuala Lumpur, Malaysia. There the United States was represented by John C. Marr, Area Director, BCF, Hawaii.

The 12th Session of the Council is now scheduled for Honolulu in October 1966. It will mark the first time the group has met on American soil.

One of the most productive fishery regions on earth is the Kuroshio Current off Japan. Originating in tropical waters, the warm "Black Current" sweeps northeastward off the coast of Japan, follows a great arc beneath the Aleutian Islands, and eventually contributes to the sluggish south-moving California Current that influences the climate of our western States.

A major international survey of this Pacific counterpart of the Gulf Stream is now underway. Participating nations include: Japan, Hong Kong, Korea, the Philippines, the Republic of China, the United States, and the U.S.S.R. At the request of the Department of State, Marr serves as U. S. National Coordinator of the Coöperative Study of the Kuroshio and Adjacent Regions (CSK).

Object of the CSK is an intensive effort to understand the oceanography, and secondarily, the fisheries of this fruitful region of the sea.

The need for international studies of fishery resources, and particularly tuna resources, figured in the deliberations of the American Fisheries Advisory Committee when it met in Honolulu in January 1964. The Committee placed special emphasis on the fishery resources of Hawaii and the central Pacific Ocean. Organized under the Saltonstall-Kennedy Act of 1954, the Committee is responsible for advising the Secretary of the Interior on general fishery matters. One of the earliest conclusions reached at the meeting was that in view of the fact that the tuna fisheries are becoming more international in nature and world tuna consumption has increased, the "United States must make every effort to increase its catch of tuna."

In its proceedings the Committee emphasized the need for further studies of the oceanography of the Pacific Ocean as it relates to the fisheries, and it is in that field that for several years our Laboratory has poured much of its effort, becoming the acknowledged center of oceanographic research in the central Pacific.

THE SEA

The Cruises of the *Townsend Cromwell*

Townsend Cromwell was a modest, cheerful, and able oceanographer who lost his life in a plane crash in 1958. He was 36. Bearing his name today are a son, a major ocean current, and one of the Nation's finest vessels for oceanographic research, a ship much better equipped than any Townsend Cromwell ever had a chance to use.

The subsurface Cromwell Current which Townsend Cromwell discovered while on the staff of the Bureau's Laboratory in Honolulu, is one of the principal features of the

Pacific Ocean. Shallow and swift, it runs eastward beneath the Equator for about 5,000 miles, carrying as much water as 10,000 Mississippi rivers.

The ship, *Townsend Cromwell*, especially designed for oceanographic and fishery research, was commissioned in January 1964. By July 1965, she had made 17 oceanographic cruises. A vessel 158 feet long, she has a cruising speed of 12.5 knots and can carry 10 scientists and 15 officers and crew. She can travel anywhere in the Pacific. Her equipment includes radar, Loran, echo sounders, recording pyranometer, and such new and specialized scientific instruments as a salinity-temperature-depth recorder.

In February 1964 the newly commissioned vessel sailed from Honolulu on a 20-day oceanographic cruise that took her 960 miles south, 550 miles east, and 240 miles north of Oahu. For the next 16 months, except in August 1964, she set forth on a voyage that followed the same unaltering course. When the last cruise of the series was completed on July 2, 1965, she had sailed 72,000 miles, spent 320 days at sea, collected many thousands of items of data, and proved a significant point: that the work had been well worth doing.

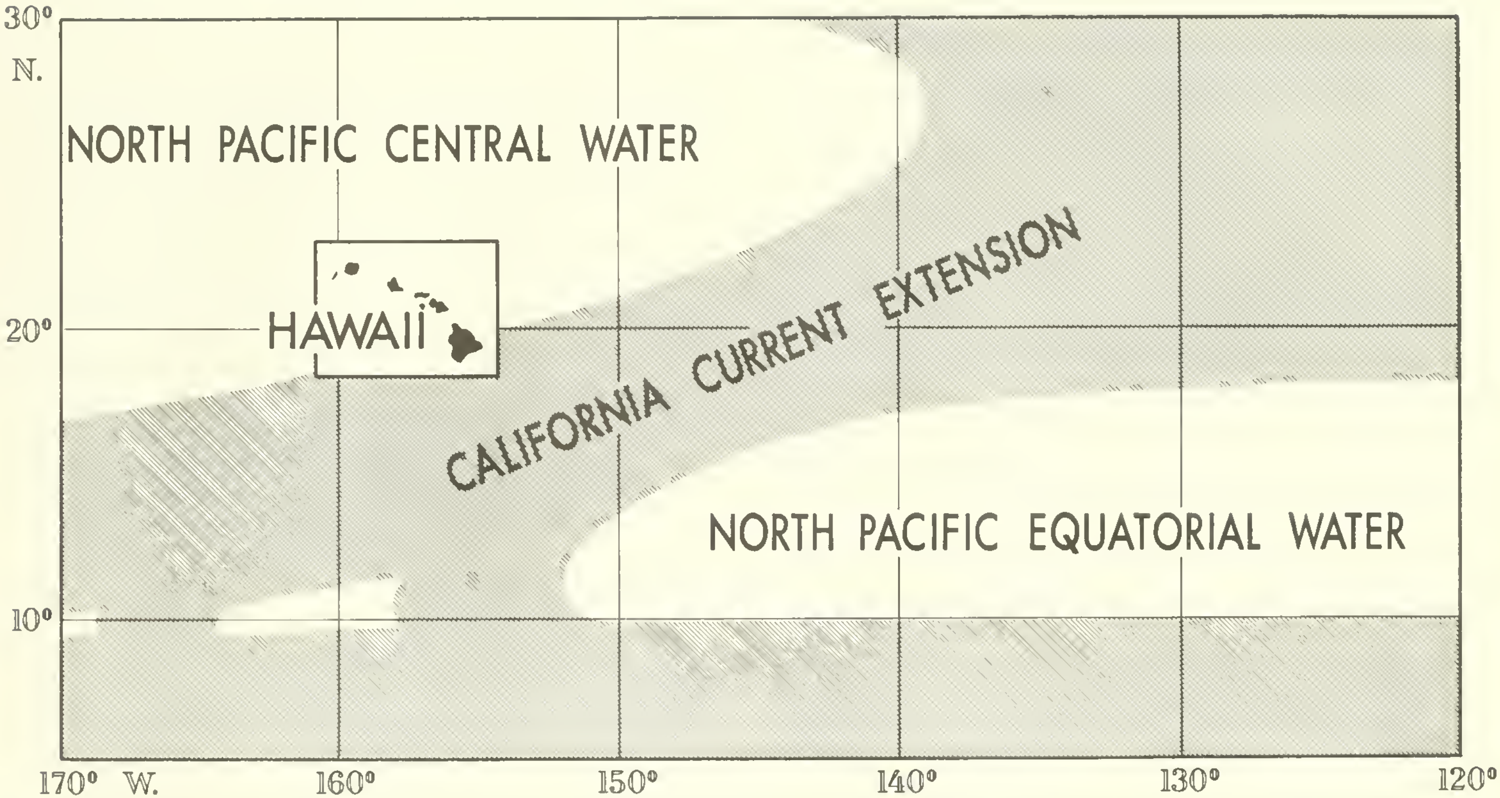
The waters of the Hawaiian region rank among the most intensively studied in the world. More oceanographic cruises have put forth from Hawaii than any of the other 49 states, except California and Massachusetts (the sites of the Nation's largest and oldest oceanographic institutions) and perhaps Washington. The Hawaiian waters are so well known, in fact, that oceanographers are now in a position to progress beyond a broad, essentially static description of average conditions in seasonal and annual terms to analyses of the dynamic processes these conditions reflect. This difference is approximately that between a still photograph and a motion picture. It was the *Townsend Cromwell's* mission to gather the sequential data on which such studies must be based, and to survey the distribution of physical and chemical properties of the ocean with area, depth, and time.

Although the numbers and distribution of fish must be intimately related to changes in the environment, not until a few decades ago did scientists feel confident enough of their knowledge of the fisheries and the ocean to begin attempts to link the two. But with the prodigious growth of oceanography and fishery biology during the past few years, such efforts have been made in several fisheries located in many areas of the world ocean. In Japan, for example, oceanographers have used their investigations to locate promising areas for the tuna fleet. As another instance, our Laboratory in the 1950's found rich accumulations of tuna in the equatorial region south of the Hawaiian Islands. The *Townsend Cromwell's* cruises were undertaken in support of an enterprise of somewhat more sophistication than these pioneering ventures; they were part of an effort to depict the whole environment as it changes through the year.

The central Pacific affords a particularly convenient laboratory for such investigations. As has been said, seasonal and annual conditions in the surface waters are well known. The climate is equable, so that field studies can be carried on throughout the year and thus comprehensive winter data, so rare in studies of the temperate Pacific, can be readily obtained. The pronounced seasonality and sharp annual fluctuations in the Hawaiian skipjack catch suggest that if the availability of the fish directly reflects changes in their immediate environment, then that availability can be readily monitored from catch statistics. And the partial success of the "aku forecasts" hints that skipjack availability is related to observable dynamic processes in the ocean.

The Hawaiian Oceanographic Climate

In 1962, after analysis of all the data available at that time, oceanographer Gunter R. Seckel of our Laboratory



published a description of the oceanographic climate of the Hawaiian region. Describing the mixed layer, that warm upper skin of the ocean that extends from the surface to the thermocline a few score feet below and which is characterized by temperature and salinity values that change only negligibly with depth, he found that the central Pacific can be thought of as two adjacent lakes whose waters have differing properties. The banks of these lakes are not solid earth but those immensely wide streams in the ocean we call currents. These currents follow irregular, meandering courses in time and space, now squeezing an adjacent lake, now allowing it room to expand. And the currents themselves contract and dilate with the different seasonal wind regimes.

The current in the central Pacific, which is called the California Current Extension, generally runs south of the

FIGURE 19. In winter and fall, the Hawaiian Islands are usually bathed by the highly saline waters of the North Pacific Central type. In summer their shores are washed by less saline waters from the California Current Extension.

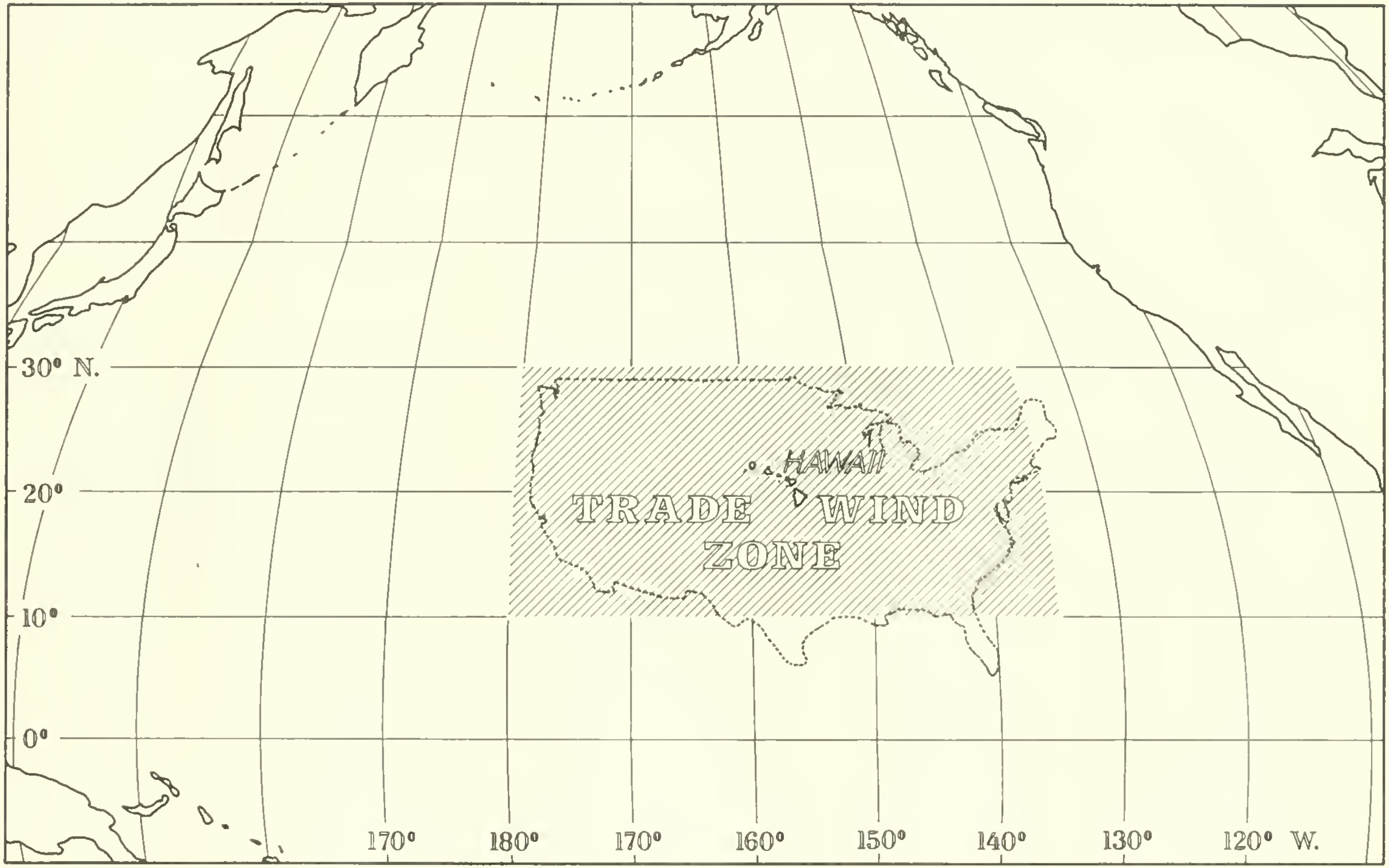
Hawaiian Islands in the fall and winter and shifts northward to bathe the archipelago in the spring and summer. It separates the highly saline water of the North Pacific Central water type on the northwest from the less saline water of the North Pacific Equatorial water type on the southeast (fig. 19). To interpret seasonal changes in the positions of these three bodies of water, Seckel formulated a simplified heat budget for the region. This budget indicated that warm water was flowing into the region during the early spring, and cold water at times in other seasons. Thus sea surface temperatures responded not only to the amount of solar radiation in the region itself, but reflected processes that had their origin far out in the Pacific. The sea surface temperatures, however, described massive water movements far less clearly than did salinity values. Because the Hawaiian region is neither one of extreme evaporation nor precipitation, surface salinity is less affected by seasonal changes than is surface temperature, which is primarily responsive to the seasonal march of the sun. For this reason, the movement of isohalines, lines of equal salinity value, within the region can be interpreted to depict the movement of the boundaries of the water types in the area. He found that these movements could be predicted to some degree from temperature and salinity data gathered twice weekly at Koko Head, Oahu, Hawaii.

The movements of the upper layers of the water are largely determined by the winds, and the dominant wind system of the lower latitudes of the North Pacific is that of the trade winds. On the basis of the studies briefly summarized above, Seckel proposed that the Bureau's Laboratory in Honolulu begin a long-term investigation of the oceanography of the Trade Wind Zone, an area larger than the continental United States and reaching from long. 135° W. to 180°, and from lat. 10° N. to 30° N. (fig. 20). The proposal called for a three-phase study: design and planning, field work, and evaluation of the results.

When the *Townsend Cromwell* sailed on the June 1965 cruise, she was concluding the initial part of the first phase, which has been called the Trade Wind Zone Oceanography Pilot Study. Although about twice the size of Texas, the area covered by the *Townsend Cromwell* in the Pilot Study is small in comparison with the entire Trade Wind Zone (fig. 21). It is only as large as one ship, even as swift and well-equipped for scientific work as the *Townsend Cromwell*, can cover in a single month. The pattern for the scientific observations (fig. 22) was established early in the series of cruises and did not vary significantly throughout. This unchanging routine, in fact, was the heart of the study, whose object was to document month-to-month changes in the oceanographic and meteorological properties in the area, with the ultimate aim of understanding the relation of winds and weather to the oceanographic properties at the surface and to a depth of more than a quarter of a mile, particularly as they affect the commercial fisheries.

The plan for the investigations included 43 oceanographic stations 90 miles apart. Samples were obtained at 20 levels to about 4,500 feet. After July 1964, casts to about 12,000 feet were made on three stations each cruise. Bathythermographs, which record temperature in the upper layers of the ocean, were taken at 30-mile intervals along the cruise tracks, except at three locations on each cruise, where they were made at 10-mile intervals. In addition, meteorological observations were made and the radiation from sun and sky was recorded.

Seven persons are now engaged full time in processing the data gathered on the cruises. The data are being transferred to cards for analysis by computers at the University of Hawaii. The data are scheduled to be published in 1966.



They will be followed by a series of descriptive and analytical reports in 1966 and 1967. Preliminary analyses have shown that the monthly cruises have gathered information that does indeed provide new insights into processes in the ocean.

Beneath The Surface

Man lives in a sea of air, the most immediately perceptible characteristics of which are temperature—is it hot or cold? —and humidity—is it wet or dry? Taken together, these properties define climate. Neither alone will do so. In July

FIGURE 20. Trade Wind Zone of the North Pacific Ocean. Oceanography of the zone is to be investigated by the BCF Laboratory in Honolulu.

the weather is equally warm in New Orleans and Tucson, but a man who flies from the one city to the other will have no difficulty in distinguishing between the languorous breath of the South and the crisp air of the West. Conversely, the air in warm Miami in summer can be as humid as that in cool San Francisco.

The creatures of the ocean live in an environment whose climate and weather can likewise be described to some degree in terms of two properties—temperature and salinity. Is it hot or cold? Is it very saline or less so?

Neither temperature nor salinity values vary widely in the central Pacific, but these variations might define oceanographic climates as distinguishable as those of New Orleans and Tucson, Miami and San Francisco. And variations exist not only at the surface, but beneath it, so that a man might fish at the same depth in the same spot in two successive months but be taking his catch from waters of sharply contrasting climates.

The detailed description of the subsurface layers of the ocean in the Hawaiian region is one of the fruits of the Trade Wind Zone Oceanography Pilot Study. As a result of their preliminary analyses, Seckel and his colleague, Robert L. Charnell, are able to say that south of the Hawaiian Islands are locations where the upper 300 meters (about 1,000 feet) contain as many as four distinguishable layers of water whose salinity values suggest they originated in surface water types formed many miles away (figs. 23 and 24). This finding emphasizes the importance of the Hawaiian region as a monitoring station, for here in one easily accessible location are reflected the effects of energy input in the Pacific wind systems from lat. 40° S. to above 40° N.

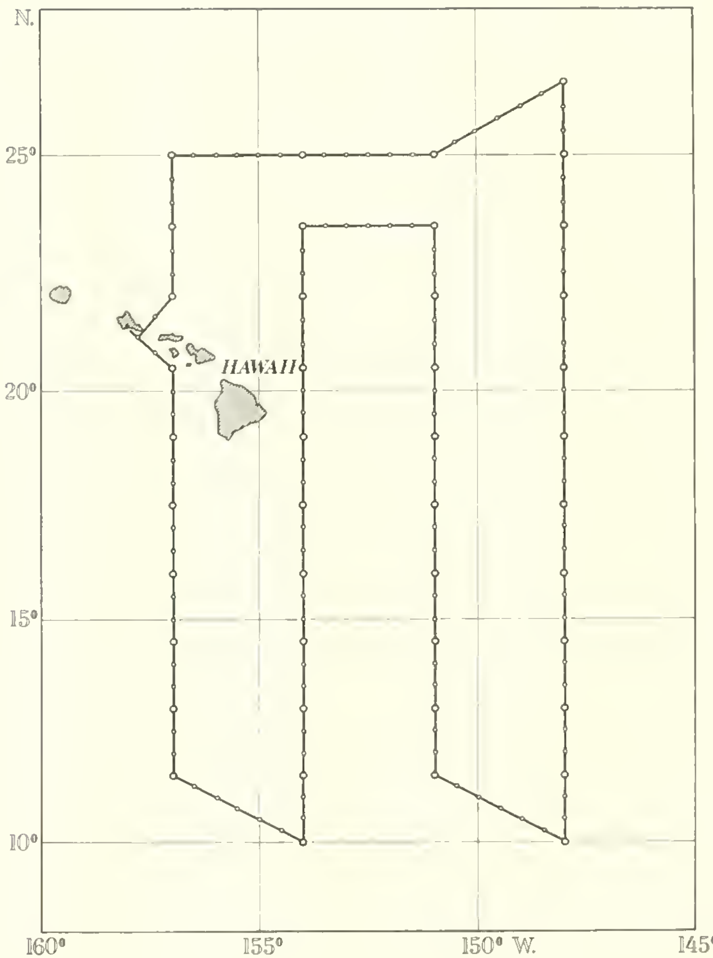


FIGURE 21. In the Pilot Study for the Trade Wind Zone investigation, the *Townsend Cromwell* covered the track shown above each month for 16 months.

These layers of water change in size and position, and sometimes most rapidly; along a meridian, displacements by as much as 300 miles in a month have been observed. The movement of each of the various layers appears independent, yet the distribution of properties is dependent upon occurrences in each of the layers.

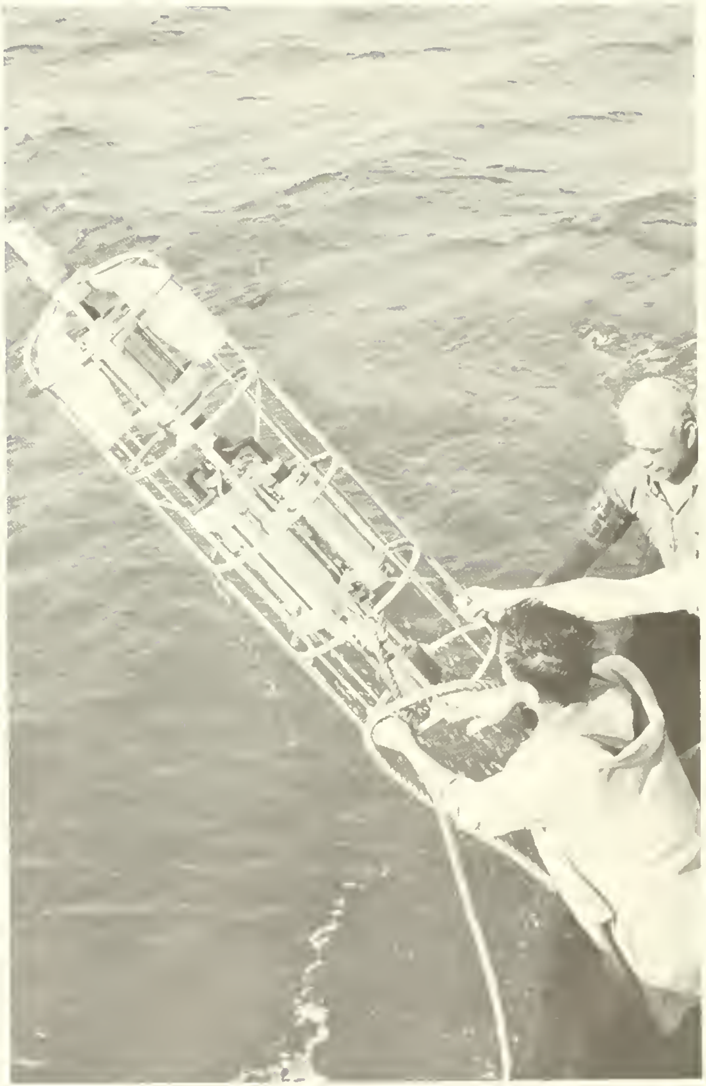
These initial results of the Pilot Study support the feasibility of the full-scale investigation. This research will require the use of three ships over a period of 18 months to 2 years. It will start in 1967.

Nothing exactly like the Trade Wind Zone Oceanography investigation, both in nature and scope, has been attempted before. Although it springs from an interest in fishery problems and the compelling need to understand better the relation of the fish to the sea, the study will bear importantly on the fields of meteorology and naval operations. It might also provide information that would make this type of investigation no longer necessary, for it could point to those sites in the ocean where such observation platforms as anchored buoys might most appropriately be located, thus making it possible to obtain truly synoptic data on oceanographic and meteorological conditions in midocean without the use of surface ships.

The First Mile Down

In the preceding section it has been shown that to understand the nature of the water column in the vicinity of the

FIGURE 22. The heart of the Pilot Study of the Trade Wind Zone was an unvarying pattern of observations of oceanographic properties month by month. At the left a technician reads temperature registered by thermometer in Nansen bottle. In the center a technician operates the bathythermograph winch. She is Barbara Boldt, the first woman to serve as a sea-going technician at this Laboratory. At the right the "fish" of the salinity-temperature-depth recorder is brought aboard the *Townsend Cromwell*.

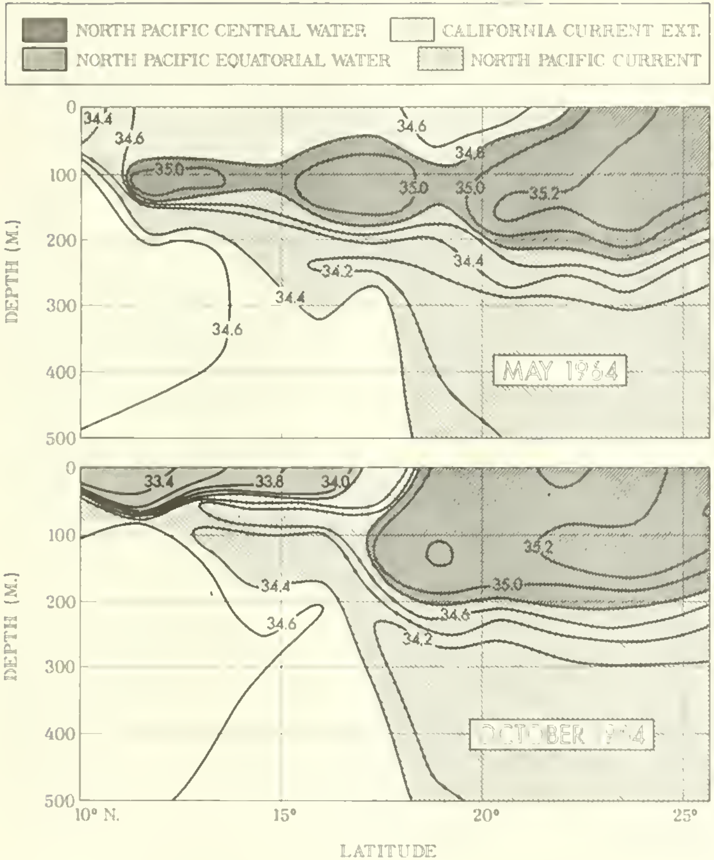


FIGURE 23. Salinity values along long. 148° W. in May and October 1964. The sections extend to a depth of 500 meters, about 1,500 feet. The shading delineates bodies of water whose salinities are characteristic of surface values in other parts of the ocean. Note that at lat. 15° N. there are four layers of waters of different types in the first 300 meters (1,000 feet).

Hawaiian Islands, one must take into account the climate and weather of areas thousands of miles away. The face of the earth is essentially a single ocean interrupted by islands that range in size from a single lonely volcanic peak thrusting up from the floor of the deep sea to the vast bulk of Eurasia. This ocean occupies more than 70 percent of the surface of the earth. For many reasons, however, the chief being that each occupies an identifiable basin and thus forms a convenient unit of study, it is conventional to regard this world ocean as being comprised of four smaller oceans, the Pacific, the Atlantic, the Indian, and the Arctic. These bodies are still very large entities; the Pacific Ocean alone occupies about one-third the surface of the earth.

A Pacific-wide Study

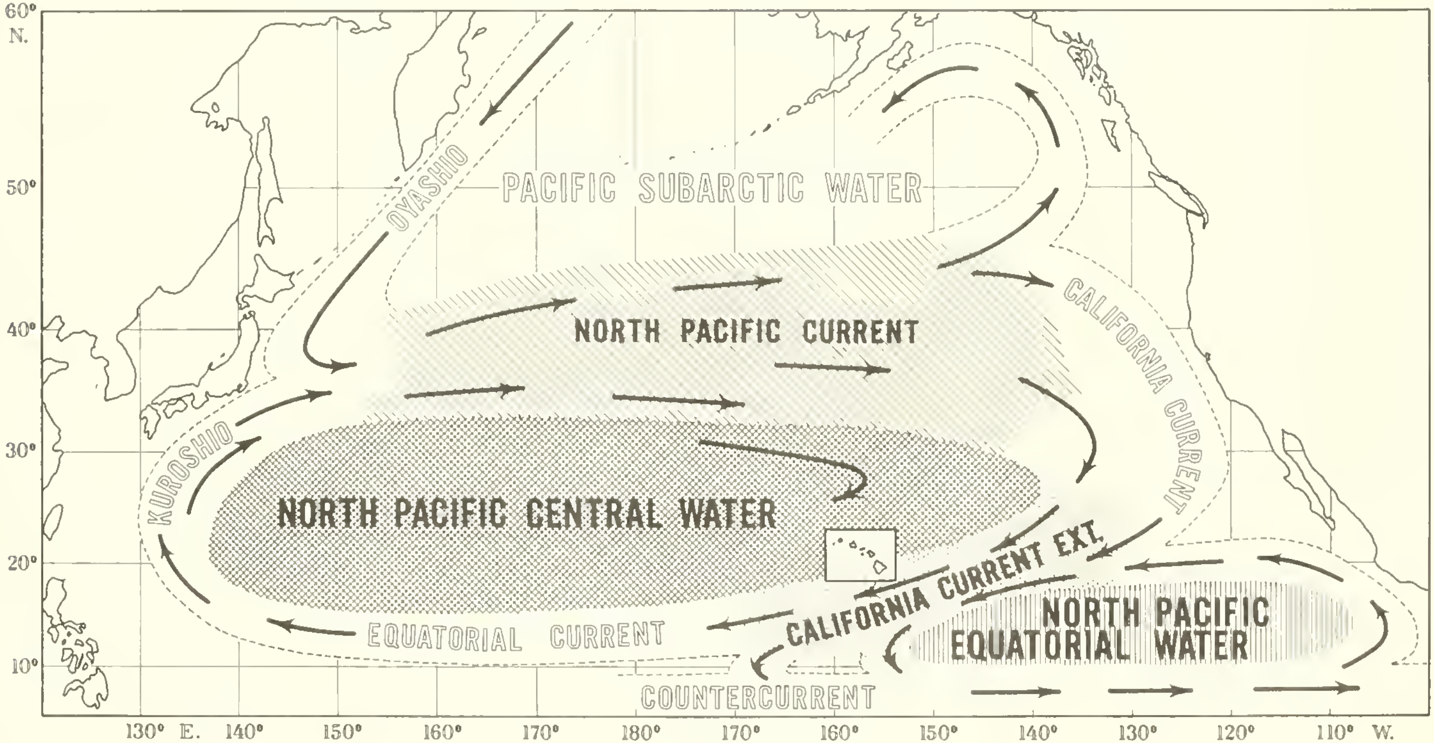
Although conditions within one part of the Pacific influence those in all others to some degree, studies of the Pacific Ocean in its enormous entirety are relatively rare. At least two reasons account for this circumstance. The first is that some studies can be made in a relatively small region with acceptable precision even if one neglects the influence of the remainder of the ocean. The second reason is simply that it is a tremendous task to study the ocean as a whole. Oceanographic research has been conducted in the world ocean for almost a century now. An immense fund of information has been collected, particularly within the past few decades. Until the development of computers, it was impossible to handle these data without undue expenditures of money and time. Today analysis of all temperature and salinity data now available from the Pacific Ocean by manual methods would run to some 200 man-years and an expenditure of $1.5 million.

FIGURE 24. Surface origin of water types shown in figure 23. By sampling the water column near Hawaii, oceanographers can see the results of events that have happened hundreds or even thousands of miles away.

Yet critical fields of study exist in which one does need to examine the entire Pacific Ocean, or large sections of it. Some of these fields lie within the range of fishery research. An example might be the investigation of albacore catches of the North Pacific. Here is a fishery that reaches from the shores of North America to those of Japan. If one hopes to investigate the response of albacore to oceanographic conditions, one must consider this entire 6,000-mile-wide sweep of water.

Faced with a problem such as this, the biologist recognizes that he has neither the time nor the professional competence to analyze the scores of separate studies of an area of this extent. What he needs is a single publication in which all the available information has been evaluated and summarized by an expert in oceanography.

Adequate publications exist for the surface layer of the Pacific Ocean and for the layers below about 1,000 meters. Yet the chances are great that the biologist's primary



interest will focus on the intervening layers, from those just below the surface to 1,000 meters, for these hold the world's substantial stocks of marine creatures, including the tunas. Existing atlases of this marine domain are based on limited amounts of data (less than half the total, at the best) and rest upon methods of analysis relatively insensitive to some of the subtle changes in oceanographic properties.

Recognizing these needs, Richard A. Barkley of our Laboratory started 5 years ago to prepare such a publication. It has now been completed and is ready for submission to the publishers, so that by 1967, or if all goes well, late 1966, there will be available an atlas of the oceanographic properties of the top 5,000 to 6,000 feet of the entire Pacific Ocean, based upon 50,000 oceanographic stations.

The 3 million observations upon which the atlas draws come from cruises as early as 1906, and as late as December 1964. The data have been supplied on punched cards by the National Oceanographic Data Center. They have been analyzed at our Laboratory, by use of the facilities of the University of Hawaii Statistical and Computing Center for most of the automatic data processing.

The atlas emphasizes the density structure of the Pacific. This structure is closely related to processes of advection, mixing, and water-mass formation. The atlas contains a series of 135 charts showing properties along the various sigma-t (density) surfaces, with the deepest at about 2,000 meters average depth. These charts are arranged by quarter years. In addition, the atlas contains a set of vertical sections that extend across the Pacific from Asia to the Americas, and from about 30° S. to the northern boundaries of the Pacific. Other charts show temperature, salinity, and sigma-t at 10 meters by months and the density of observations at several levels by quarter.

Examples of the charts are shown in figures 25 and 26. In figure 25 is shown the 25.40 sigma-t surface averaged for January, February, and March throughout the Pacific. The lighter lines at the top and bottom of the chart show that this layer reaches the surface level of the water at mid-latitudes (it sinks to more than 1,000 feet off Japan). The surface layer north and south of these lines has water of higher density. Plotted on the chart are the salinity values, which also reflect temperature distributions, since density is a function of temperature and salinity. It is easy to see on this chart the effect of the large rivers of the Pacific Northwest as they pour into the ocean and decrease the average salinity. Their influence is felt over a good part of the eastern half of the North Pacific Ocean.

Figure 26 is a vertical section showing average values of salinity and depth reaching from 30° S. to 53° N., from Chile to Canada, along long. 139° W., which runs near the Marquesas Islands. The vertical scale is density, and this accounts for the irregularity of the top line. As the lower panel makes apparent, the density of water above 1,000 meters varies considerably; it is least dense (lightest), depth for depth, at about 10° N.

The atlas will provide the basis for a number of analytical studies. Two already underway include work on the three-dimensional distribution of mass transport by currents and rates of water-mass formation and dissipation. These and a variety of other related research projects are intended to lead towards a realistic conceptual model of the Pacific Ocean that can be used in computer-simulation experiments to study such factors as diffusion and biological consumption of dissolved oxygen, as well as the response of the ocean currents to changes in the atmosphere. Thus the atlas will have a bearing on a host of studies in fishery biology, as well as constituting a definitive document in the oceanography of the Pacific.

Drift Cards and Collecting Nets

In addition to the completion of the atlas, which has occupied much of the energies of Barkley and his associates during the reporting period, two other projects in oceanog-

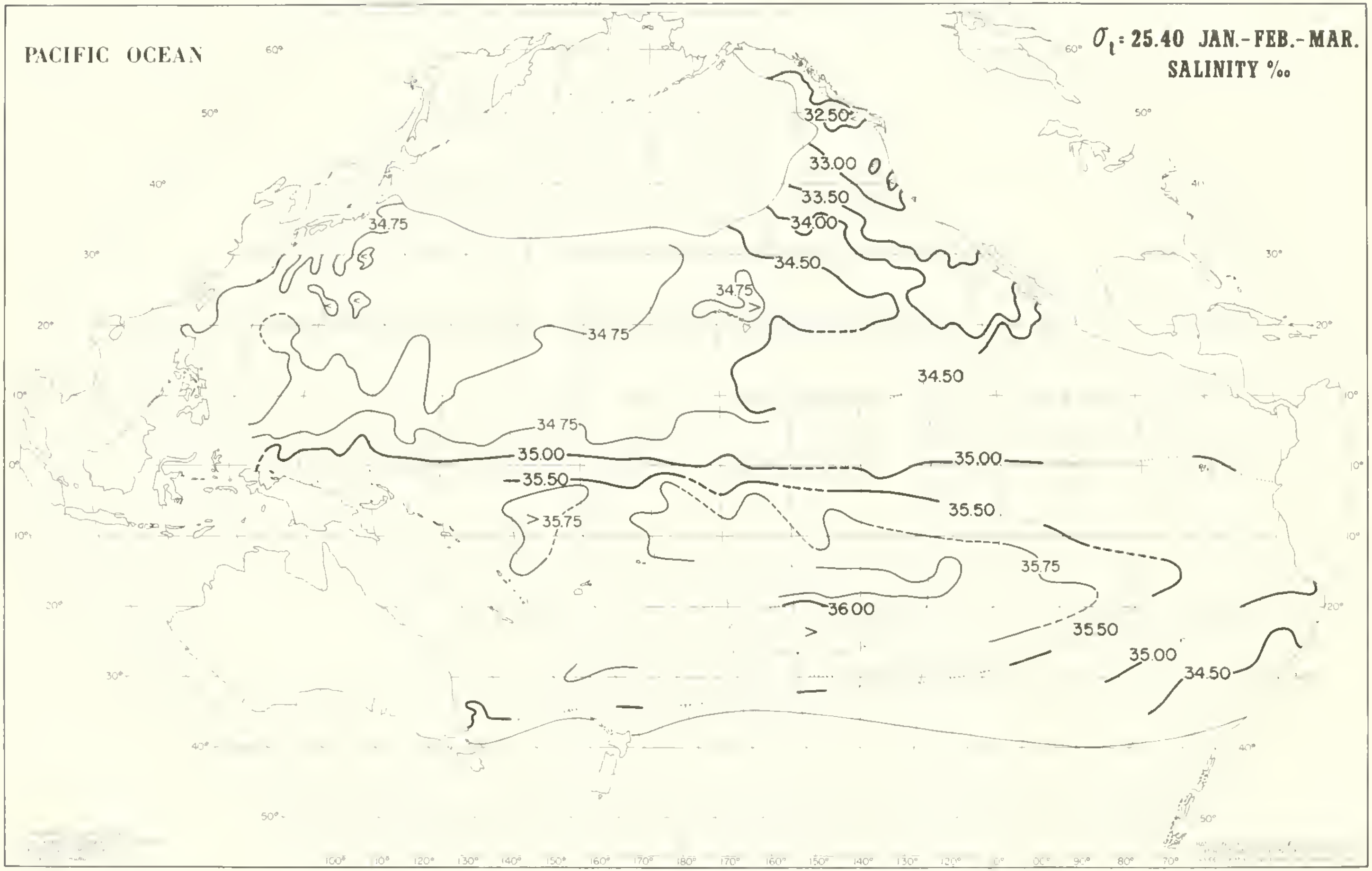


FIGURE 25. Chart from the oceanographic atlas of the Pacific Ocean, showing a sigma-t (density) surface that extends from the surface (northern and southern extremes) to a depth of about 1,000 feet off Japan. The period is January through March. The values marked by numbers are those for salinity, which is given in parts per thousand. The effect of the large rivers of the Pacific Northwest is very clear from the salinity distributions. The discharge of fresh water into the sea is evident for hundreds of miles offshore.

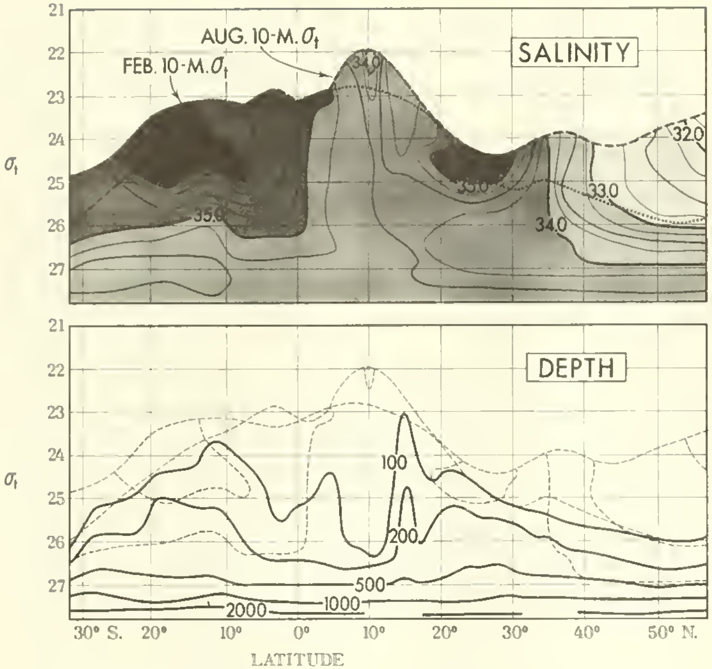


FIGURE 26. Vertical section showing average values of salinity and depth from lat. 30° S. to 53° N. along long. 139° W.

raphy have been conducted. One, now nearing completion, is a continuation of the study of surface ocean currents around the Hawaiian Islands by the use of drift cards. For a year or more, drift cards have been dropped from an airplane flying a fixed pattern near the island of Oahu each month. The results of the drift-card returns are now being analyzed. The second study ventures far afield from physical oceanography and concerns itself with the mathematics involved in the problem of trapping the small creatures of the sea in nets.

Fishermen are not the only persons who deplore the fish that got away. Scientists are equally concerned. As has been mentioned, the standard collecting device for plankton is the 1-meter net. Barkley has published a short paper with a long title, "The theoretical effectiveness of towed-net samplers as related to sampler size and to swimming speed of organisms," in which he explores the relation of the mouth opening of the collector, the towing speed, and the estimated swimming speeds of the animals captured. One of the interesting things that has come out of the paper is a set of estimates as to how fast the creatures would have to swim to escape nets, both standard and unconventional, towed at various speeds. The data collected by Walter Matsumoto and mentioned earlier may be of value in testing the soundness of this theoretical treatment.

A Submarine for Research

On June 17, 1965, Secretary of the Interior Stewart L. Udall announced that a study sponsored by the Bureau of Commercial Fisheries shows that it is feasible to build a specially designed nuclear-powered submarine for fishery and oceanography research.

The study was conducted by Electric Boat Division of General Dynamics Corporation, Groton, Conn., the pioneer submarine designer and builder that developed the *Nautilus*, *Skipjack*, *George Washington*, and other submarines.

Much of the preliminary research on this project was conducted at the Honolulu Laboratory by Donald W. Strasburg. It has become increasingly apparent to the Laboratory that neither the tuna resource nor the oceanic environment can be fully understood on the basis of observations from surface vessels. A submarine would make a better platform for tuna research. The known behavior and distribution of tunas indicated that such a vehicle should have a 20-knot speed, a 1,000-foot operation depth, and a submerged endurance of 6 weeks. Provisions for direct viewing of fish, con-

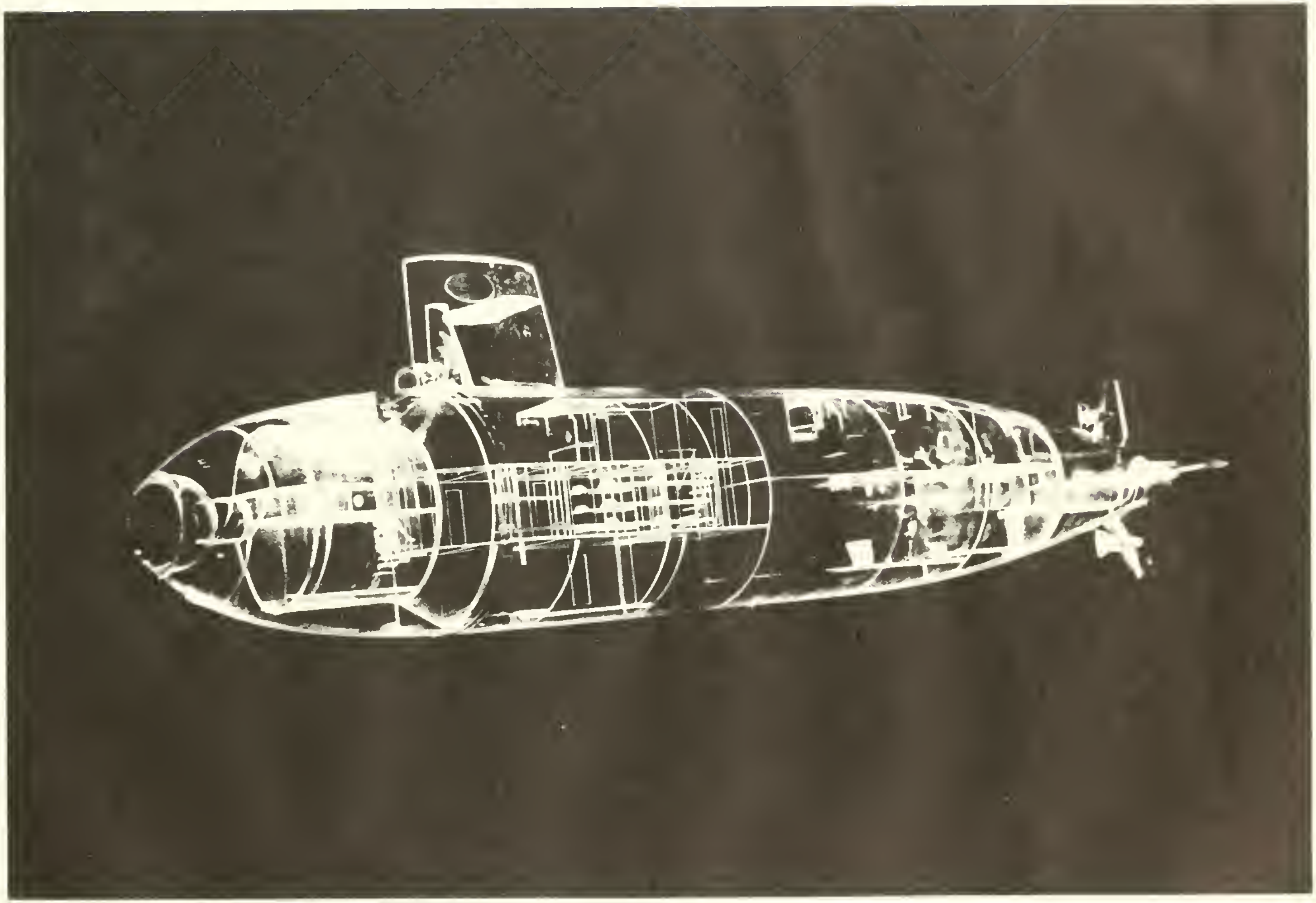


FIGURE 27. Plastic model of nuclear-powered submarine proposed by this Laboratory for fishery-oceanography research. The craft would be 163.5 feet long and carry a scientific party of 7, a crew of 24. It would be able to make a host of studies impossible to carry out from surface ships.

tinuous environmental sampling, and quiet operation are also essential.

With these criteria, Electric Boat has made preliminary designs for a submarine (fig. 27) that would be 163.5 feet long (a few feet longer than the *Townsend Cromwell*), have a maximum submerged speed of 20 knots, a surface speed of 11 knots, an operating depth of 1,000 feet. The craft would carry 7 scientists in addition to the crew of 24. The vehicle would be unique in almost all respects. There would be an 8-foot observation sphere in the bow with five windows for direct observation. The scientific laboratories would equal or excel those of surface craft. Equipment would include: water sampler capable of delivering 15 water samples simultaneously, hull-mounted instruments for recording temperature, salinity, and depth; a continuous-transmission, frequency-modulated sonar; two inverted echo sounders. Seven television cameras would be mounted on the hull. In the stern laboratory would be placed a tube from which trawls, plankton nets, fishing lines, bottom samplers, and other instruments could be launched while the craft is submerged.

The object of the submarine is to place the scientist in the environment which he is studying. With it, he would be less dependent on weather (most oceanographic operations are necessarily conducted in equable climes, although the fish are less radically affected). The submarine could study such oceanic features as thermoclines, fronts, currents, turbulence, and waves, where precise control and the ability to hover or maneuver in three dimensions are needed to define the features of the environment or determine the relations among variables. A neutrally buoyant submarine could accompany a particular water mass and measure its changing physical and biological properties. There is little, in fact, in observational oceanography that the submarine could not undertake, and further uses will undoubtedly present themselves when the craft is available for operation.

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