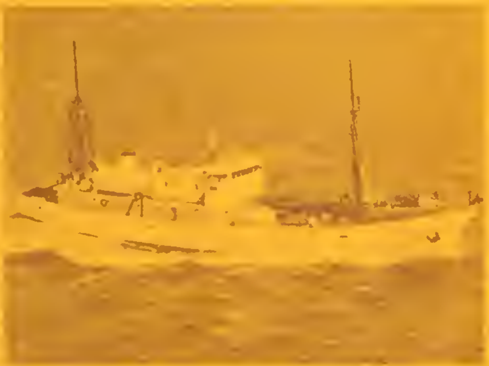
PROGRESS IN 1962-63

CIRCULAR 206

U.S. BUREAU OF COMMERCIAL FISHERIES
HAWAII AREA
BIOLOGICAL LABORATORY
HONOLULU, HAWAII

UNITED STATES DEPARTMENT OF THE INTERIOR
Stewart L. Udall, *Secretary*
Frank P. Briggs, *Assistant Secretary for Fish and Wildlife*
FISH AND WILDLIFE SERVICE, Clarence F. Pautzke, *Commissioner*
BUREAU OF COMMERCIAL FISHERIES, Donald L. McKernan, *Director*

VITAL STATISTICS OF TOWNSEND CROMWELL



Year built	1963
Length, overall	158 ft. 6 in.
Tonnage, gross	565
Speed, cruising	12.5 knots
Speed, maximum	13.5 knots
Vessel range	10,000 miles
Vessel endurance	60 days
Accommodations:	
Officers and crew	15
Scientific staff	10

Capabilities:
- Electronic telemetering
- Biological studies
- Oceanographic measurements
- Longlining
- Behavior studies
- Midwater trawling
- Fish scouting
- Gill net fishing

Ancillary equipment:
- Radar
- Loran
- 650-fathom Simrad echo sounder
- 2,500-fathom Furuno echo sounder
- 6,000-fathom Edo echo sounder
- Bathysonde
- Recording pyrheliometer
- Recording thermograph
- Gyroscopic compass and steering installation
- Electric deck log
- Radio direction finder
- Hydraulic controls for variable pitch propellers
- Single sideband radio set with special Fish and Wildlife frequencies and 250-watt radio telephone and CW

Underwater observation facilities:
- Inui bulb with viewing ports

VITAL STATISTICS OF CHARLES H. GILBERT

Year built	1952
Length, overall	119 ft. 9 in.
Tonnage, gross	196.5
Speed, cruising	9.0 knots
Speed, maximum	10.5 knots
Vessel range	8,500 miles
Vessel endurance	80 days
Accommodations:	
Officers and crew	12
Scientific staff	4

Capabilities:
- Oceanographic measurements
- Longlining
- Live-bait fishing
- Behavior studies
- Midwater trawling
- Fish scouting
- Gill net fishing

Ancillary equipment:
- Radar
- Loran
- Gyro compass
- 400-fathom Bendix recorder
- 6,000-fathom Edo echo sounder
- Single sideband radio set with special Fish and Wildlife frequencies and radio telephone
- Sperry automatic steering
- Radio direction finder

Underwater observation facilities:
- Stern underwater viewing chamber
- Modified bulbous bow with underwater viewing ports

Cover: The Laboratory's research ship Townsend Cromwell

FEBRUARY 1965

1962-63 HIGHLIGHTS

During 1962-63,[1] the Biological Laboratory, Honolulu, made significant new findings in the fields of tuna behavior, the oceanography of the trade-wind zone, the ecology of the skipjack and albacore, subpopulations of skipjack and bigeye tuna and Pacific-wide and Hawaiian Island oceanography--studies that are outgrowths of earlier exploratory investigations. In addition, the Laboratory participated in a survey of the fishery resources of the Indian Ocean. Our entire program was greatly facilitated by the completion of our new vessel, the *Townsend Cromwell*, one of the most modern ships in the Nation's oceanographic fleet.

Defining the sensory capabilities of the tunas received considerable effort in the studies of fish behavior at the Laboratory. Visual acuity curves were calculated for the little tunny and skipjack tuna and a study was started to determine the range of frequencies heard by the yellowfin. Direct underwater observations of behavioral and ecological interactions in animal communities that congregate under floating objects were made from a viewing chamber constructed beneath a raft. Studies that resulted in the description and classification of behavior patterns in the Pacific bonito also resulted in the first known observation of the courtship behavior of one of the scombrids, the family of fishes that includes bonito, tuna, and mackerel.

We have continued to take temperature and salinity readings at Koko Head and are attempting to correlate these, along with other information, with the presence or absence of skipjack in Hawaiian waters. This investigation is a part of a broader program in the oceanography of the trade-wind zone. Our present studies have led to hypotheses regarding the processes which determine the oceanographic climate in the tropical central Pacific. These hypotheses will be evaluated as our studies continue and expand into the field phase.

Studies were intensified on the skipjack and its relationship to the environment, and we think we are beginning to unravel some of the complexities associated with this species. Serological studies of skipjack blood samples collected from

[1] This report covers the period July 1962 to December 1963.

off the coast of Baja California indicated this population to be similar to one of the two genetic populations of skipjack found in the Hawaiian fishery. Recovery in the Hawaiian fishery of a skipjack that had been tagged off southern California provided substantiating evidence that skipjack of the eastern Pacific are intimately related to those appearing in the Hawaiian fishery.

A model on the origin of the exploited stocks of skipjack in the central and eastern Pacific was formulated. It incorporates the hypothesis that a large component of the species appearing in the eastern Pacific and Hawaiian skipjack fisheries originates in the central equatorial Pacific.

A summary of bird flock and fish school sightings collected over a 10-year period was completed. Since aggregations of sea birds in the open sea, especially when feeding, are generally associated with schools of fish, these data are useful indicators of the distribution of surface schools of pelagic fishes.

Ecological studies of albacore tuna were continued. Two cruises into the South Pacific Ocean indicated that the albacore spawning period in the South Pacific occurs in December and January. These spawning data and discovery of juvenile albacore in stomachs of predators captured at widely scattered points in the North and South Pacific were evidence that the albacore from the North and South Pacific constitute separate subpopulations, also that spawning occurs in a broad area in the North Pacific and in the South Pacific. The identification of juvenile albacore was simplified by the unique shape of the first elongate haemal spine of the species, a definitive character present in both the juvenile and adult albacore.

The critical question of the identification and location of subpopulations has been attacked by a variety of methods, one of these being the use of serological techniques. In this field, the Laboratory has made two important contributions to knowledge of tuna subpopulations--the discovery of a blood-group system in bigeye tuna similar to the familiar A-B-O system in man, and the definition of several skipjack subpopulations in the Pacific.

Research programs relating to the physical and chemical environment of the Pacific Ocean covered a wide array of problems. Compilation continued of Pacific-wide oceanographic station data, such as temperature, salinity, and oxygen. When completed, the data will provide information on the mean distribution of these parameters over broad areas of the Pacific, give a general view of the seasonal changes of these properties, and present some of the features of the currents throughout the Pacific. On a more limited areal scale, study began of the effects of the Hawaiian Islands on circulation patterns and on physical properties of the waters. The two-pronged approach to the problem included directly observing ocean currents by releasing drift cards at sea and using a topographic scale model of the Hawaiian Islands chain to evaluate some of the theoretical aspects of the circulation.

One of this Laboratory's special studies, the Indian Ocean Program--a part of the U. S. Program in Biology of the International Indian Ocean Expedition--was designed to study the biology of that area's large pelagic fishes and to explore the shelf areas of the Arabian Sea and the Bay of Bengal for benthic fishes and shellfishes. Objectives of these studies were to add to the scientific knowledge of these little-known waters and to indicate their potential protein resources for neighboring peoples. Our surveys revealed the presence of a variety of species of fish and shellfish, but we made few catches of pelagic fish in commercial quantities and encountered no new commercially important trawling ground.

It has been apparent for several years that the Laboratory's single research vessel, the *Charles H. Gilbert*, could not meet the increasing demands for more ship's time to collect data in the field. In 1962, the Congress appropriated funds for the construction of a new oceanographic research vessel for use in the Hawaiian area and the new ship, the *Townsend Cromwell*, was completed in November 1963. The *Cromwell* is one of the Nation's most modern oceanographic research vessels and is designed and outfitted to perform many types of oceanographic and biological work.

A significant innovation in the ship's design is a bulblike projection below the waterline on the bow. It significantly increases vessel efficiency by reducing the intensity of bow waves created by the ship's forward motion. It is called the Inui bulb after its inventor, Dr. T. Inui of Tokyo University.

The Inui bulb has a secondary, but most useful, function. Extending 10 feet forward, it makes an excellent chamber for underwater observation.

The use of the Cromwell will greatly facilitate many of the Laboratory's programs.

Behavior

Studies in the Behavior Program continued to be directed toward gaining fundamental knowledge on the responses of tunas and other pelagic fishes to their environment and to artificial stimuli. The studies included determining sensitivity ranges of vision and hearing in tunas, description and classification of behavior patterns in tunas and related fish, and observation of fish communities under objects adrift at sea.

Visual acuity in tunas was tested by observing the response of the fish to patterns of alternating black and white horizontal and vertical bars. The experimental method, diagrammed in figure 1, involves training a fish to respond to a visual stimulus, which is an image of either vertical or horizontal stripes projected on an opal glass plate placed against a tank window. When the stripes are vertical, the fish is trained to swim down the tank to a food-drop area where it is rewarded; when the stripes are horizontal, it is trained to turn before reaching the food-drop area and return to the far end of the tank. If the fish fails to turn when horizontal stripes appear, it receives an electric shock. The projector is turned on when the fish is at the far end of the tank and turned off when it reaches a marked distance from the window. Filters are used to reduce the brightness of the image until the fish is no longer able to discriminate between vertical and horizontal stripes.

Visual acuity can be measured in fish that have been trained in this manner. Skipjack show a greater visual acuity than little tunny for bright targets (those with higher luminances), but the visual acuities of the two species are similar with targets of lower luminances.

A captive yellowfin tuna was taught to respond to underwater sound in a circular tank (fig. 2). The trained fish would swim by the loudspeaker placed against the tank wall and turn left into the open V (shown in the figure) whenever the sound was perceived. If there was no sound or the sound was too soft the tuna would swim straight by the speaker. Food reinforced this learned response. At any one pitch the loudness of the sound would be decreased until the tuna no longer made its trained response. Preliminary experiments showed the yellowfin to be capable of hearing sounds as high as 2,000 cycles per second with a maximum sensitivity near 500 cycles per second. For comparison, the highest pitch to which the yellowfin responded (2,000 cycles per second) was considerably lower than the maximum pitch of 15,000 to 20,000 cycles per second for normal human ears.

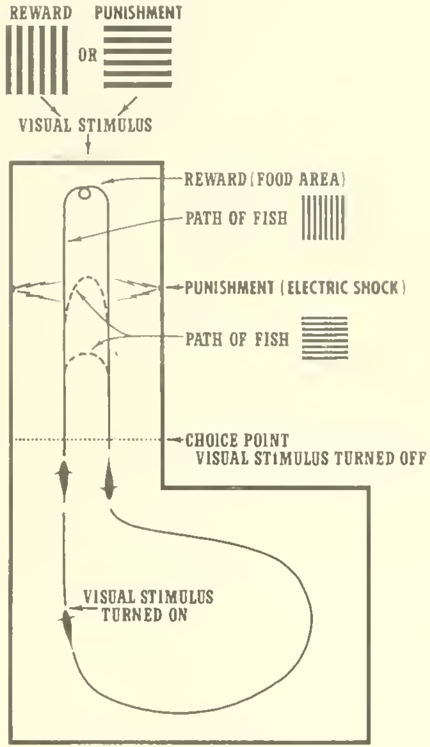


Figure 1.--Diagram of tank used in visual acuity tests, showing testing procedure and behavior of a trained fish.

FACILITIES FOR UNDERWATER SOUND EXPERIMENTS

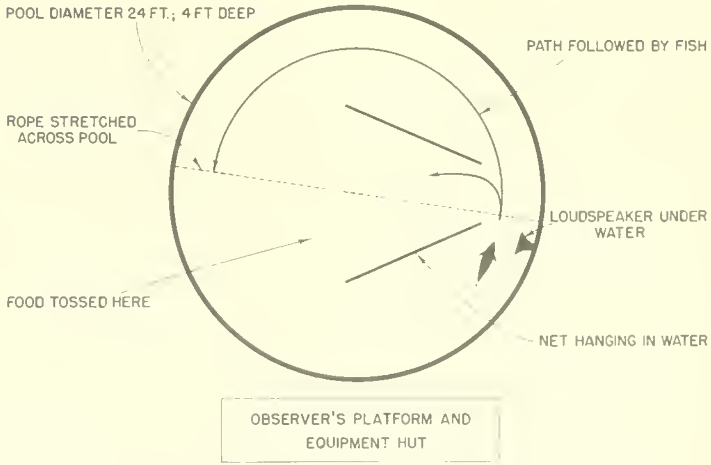


Figure 2.--Diagram of circular tank used to test underwater sound perception in yellowfin, showing testing procedure and behavior of a trained fish.

Since tunas swim constantly, knowledge of their swimming behavior is essential to understanding their reactions. By means of motion pictures, swimming speed and its relation to tail-beat rate have been calculated for skipjack tuna, yellowfin tuna, and Pacific bonito. All of the fish studied were about 1.2 feet in fork length. Relative to tail-beat frequency, yellowfin tuna moved the fastest and Pacific bonito the slowest (fig. 3). Maximum speeds observed in tunas that were feeding were 12 miles per hour for yellowfin, 15 for skipjack, and 8 for Pacific bonito. Although these data demonstrate that scombrids can swim fast, they usually swim slowly; for example, Pacific bonito slightly over a foot long usually swim about 2 miles per hour throughout the day.

We recently observed that, contrary to popular belief, scombrids do engage in highly specific courtship behavior. Observations made on the behavior of Pacific bonito in conjunction with Marineland of the Pacific at Palos Verdes, California,

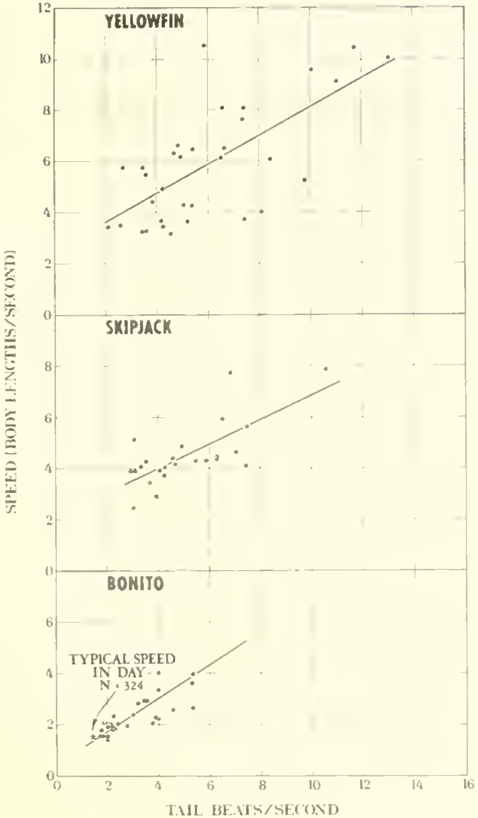


Figure 3.--Swimming speeds and their relation to tail-beat frequencies for yellowfin, skipjack, and bonito.

showed that these pelagic schooling fish have definite courtship rituals which include temporary pairing of the sexes, aggression between males, and adjacent release of eggs and milt. Bonito of both sexes have the same external appearance. Members of one sex identify members of the other by behavioral differences between the sexes rather than by physical differences in coloration or shape. During bouts of aggressive behavior, males were observed to display a transient vertically barred coloration pattern, apparently as a threat to other males. Similar color changes are known to occur in skipjack tuna, little tunny, and Pacific bonito while they are feeding (fig. 4) and these color changes also may serve as a threat to nearby fish.

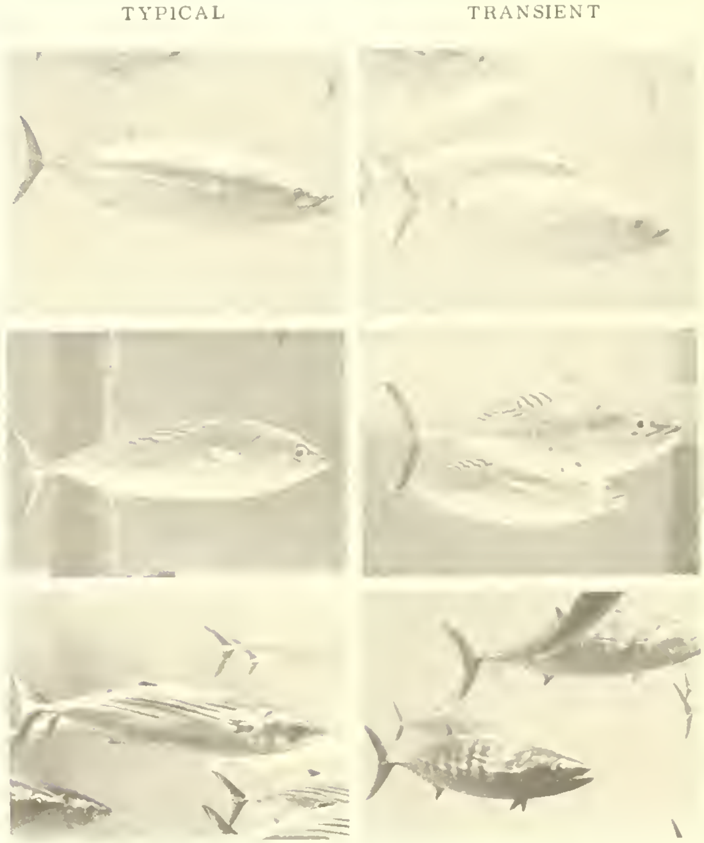


Figure 4.--Transient coloration patterns (right) observed in (top) skipjack, (middle) little tunny, and (bottom) Pacific bonito at feeding time. Typical patterns shown at left.

During these joint studies on Pacific bonito a variety of other behavior patterns was observed and classified. Some of these patterns were influenced by how recently the fish had eaten; e.g., one specific mouth movement was observed three times more often among fish which had not eaten recently than among those which had just fed. This mouth movement reduces the flow of water over the gills at times when the metabolic rate is low.

Tunas, as well as many other pelagic fishes, tend to congregate in the vicinity of floating logs and other debris on the open ocean. Construction of a raft with an underwater viewing chamber permitted observation of the behavioral and ecological interactions of these fishes (fig. 5). During the first

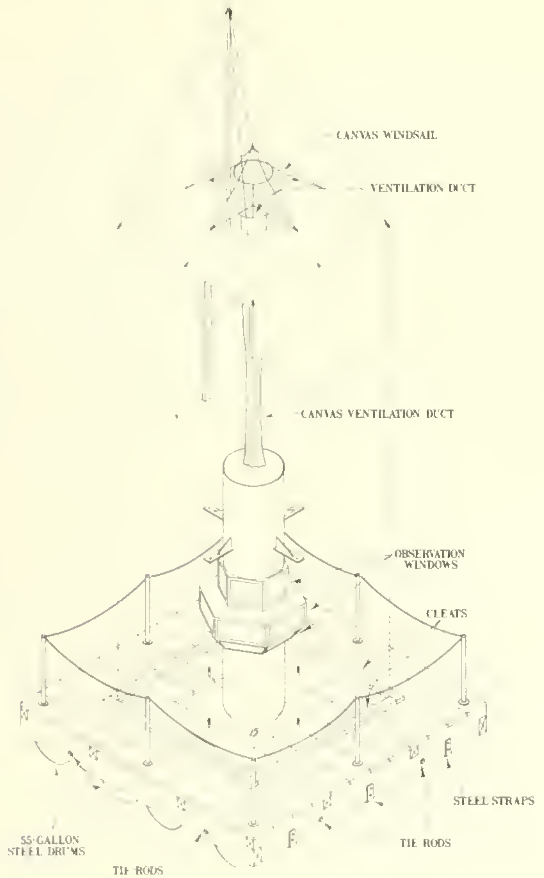


Figure 5.--Exploded view of the observation raft. In use, the observation chamber rides below the waterline.

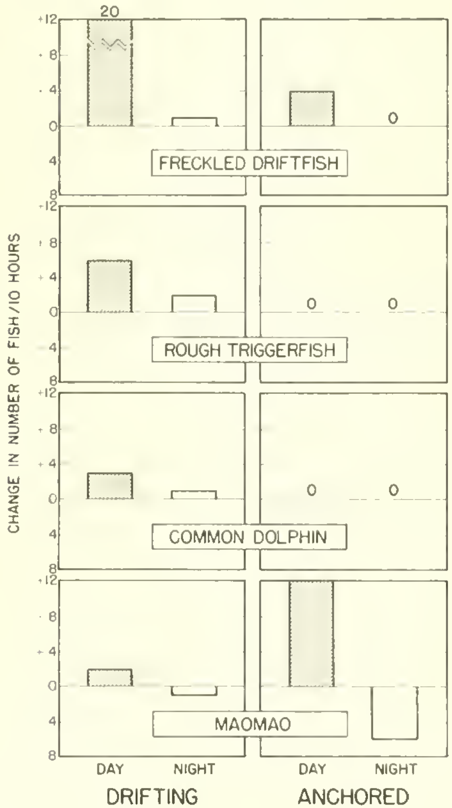


Figure 6.--Change in numbers of fishes at raft during day and night, and while it was drifting and anchored.

drifts of the raft near the island of Hawaii, fish accumulated more rapidly during daylight hours than at night and while the raft was drifting than when anchored (fig. 6). Apparently vision played an important role in the ability of fish to locate the raft. When the raft was anchored, the current flowing by it swept the small fish away. When the raft was adrift, a loose community of fishes and of other animals accumulated around it and formed a small area in the sea with associations and events similar to those of inshore environments with substrates.

Underwater observations emphasize the fact that although experiments carried out in shoreside facilities provide valuable information on the behavior of pelagic fishes, it is imperative that these fishes also be observed in their natural environment. Such observations need not be restricted by the limited capabilities of the human eye beneath the sea: sonar is a valuable research tool presently being used to study the behavior of some sea fishes. A survey was made to determine the characteristics required of a sonar gear specifically for tuna studies. The study indicated that existing instruments were not entirely satisfactory for field studies of tuna. The sound-reflecting qualities of these fish and their relatively fast speed, require very high resolution and information-rate characteristics. A frequency-modulated sonar is being designed that has these features and will permit a continual transmission of impulses that can trace such fast-moving fish as the tuna. This sonar gear will enable us to undertake studies on the form, movements, and social structure of tuna schools.

Trade-Wind Zone Oceanography

The Trade-Wind Zone Oceanography Program began at the Biological Laboratory in October 1962, as an outgrowth of a study of the Hawaiian oceanographic climate[2/] in which changes in the distribution of temperature and salinity were interpreted in terms of heat exchange across the sea surface and of water motion. Primary objective of this program is to investigate further the dynamic processes of surface waters in the Pacific trade-wind zone. The program encompasses an experiment consisting of a design and planning phase, which is described in this report; a 2-year, multiple-ship field phase; and an analytical and evaluation phase.

These studies will contribute to our understanding of the oceanographic climate in the trade-wind zone and may show that changes in distribution of water properties can be used to monitor changes in the oceanographic climate and to forecast favorable fishing conditions. The significance of these studies, however, extends beyond fishery problems. Studies of the dynamic processes of the trade-wind zone also will provide new knowledge on the Pacific heat engine which controls both continental and oceanographic climates. The trade-wind zone represents a region of net annual heat gain; therefore, the amount of heat gain and the rate at which heat is carried into higher latitudes affect long-term climatic trends.

While planning for future field activities, we have proceeded with the investigation itself and have begun preliminary studies. During this report period these studies have included the evaluation of Koko Head surface temperature and salinity data, the examination of parameters in the wind fields over the North Pacific, and the examination of thermocline structure.

In the studies of surface water processes, we have continued to measure surface temperatures and salinities each week at Koko Head, Oahu. Our purpose has been to learn more of the association between changes in the distribution of properties

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[2/] Seckel, 1962, Fishery Bulletin 193.

and the annually recurrent events and the relation of these changes in the environment to the success of the Hawaiian skipjack fishing season.

Our earlier studies have established that the Hawaiian Islands are located close to the boundary between the high-salinity North Pacific Central Water and the lower-salinity transition water of the California Current Extension (fig. 7). The boundary is usually located south of the islands during fall and winter and moves northward into the island region in spring and summer. The islands are then bathed by the lower-salinity California Current Extension Water. In late summer and fall the boundary retreats southward, and high-salinity North Pacific Central Water returns to bathe the islands.

An analysis of skipjack landings by the Hawaiian fishery showed changes with season: during fall and winter the monthly landings averaged approximately 200,000 pounds, while in spring and summer they increased to about 2 million pounds. The nature of this apparent relationship was investigated by studying the seasonal changes in water types bathing the islands. The weekly data on temperatures and salinities obtained from Koko Head indicate that two kinds of environmental conditions are associated with a good fishing season. The first condition is the presence of California Current Extension Water during the summer fishing season, the second, the simultaneous existence of yet unexplained dynamic factors that are empirically linked to the time when the Extension Water begins its northward movement and to the time when the sea surface temperature trend changes to the warming portion of the annual cycle. Initial warming in February means favorable dynamic conditions, whereas warming in March means unfavorable conditions.

Above-average catches are dependent on at least two variables (fig. 8). When only one environmental condition is favorable, catches tend to be average; when both conditions are unfavorable, catches are below average. One of these conditions, the time of initial warming, occurs well before the onset of the fishing season and has been used to forecast the avail-

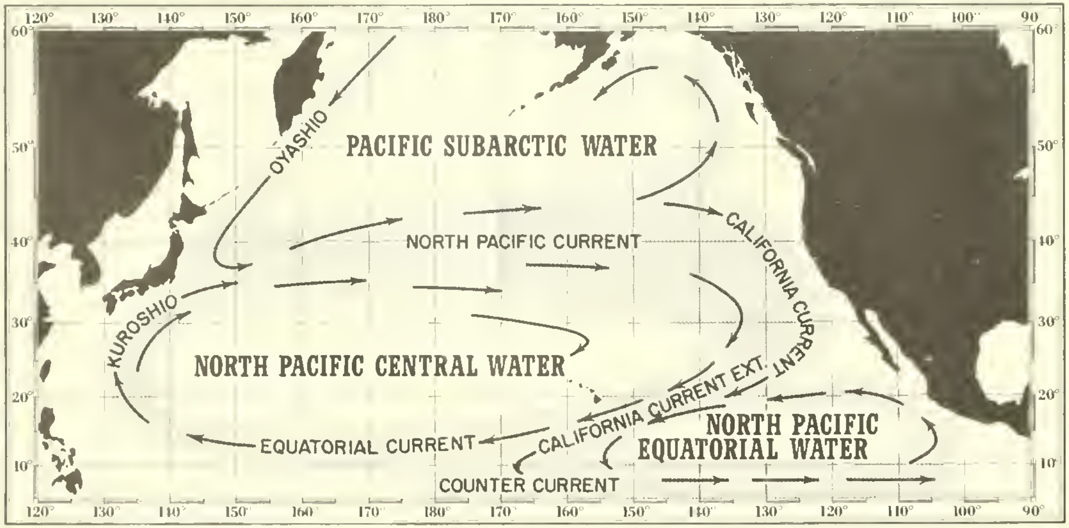

Figure 7.--Schematic diagram of North Pacific water types and currents.

ability of skipjack during the season. The other index has no predictive value because it occurs with the onset of fishing.

Although our predictions of relative catch level have proved useful so far, we cannot predict favorable fishing conditions and catch levels with assurance until we better understand the relation between skipjack and the environment. Two major oceanographic problems will be investigated by this program: (1) environmental conditions that attract the fish to the Hawaiian Islands and make them available to the fishermen, and (2) the nature of the physical processes causing changes in the environment. To understand these physical processes we need to understand the relation between the wind system and surface water motion in the Hawaiian region and to know the factors that determine changes in subsurface circulation.

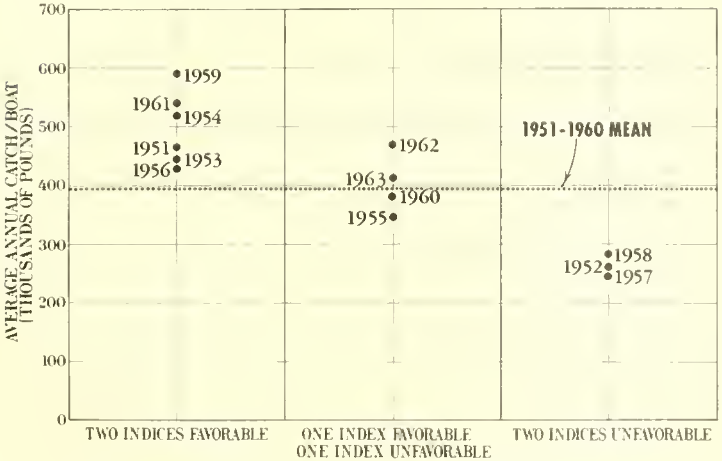

Figure 8.--Annual skipjack landings per boat in Hawaii related to environmental indices.

Over the North Pacific, there are three major types of wind systems: one is the trade-wind system associated with the pressure gradient between the North Pacific high and the Equatorial pressure trough, the second lies between the North Pacific high and the Aleutian low, the third between the Aleutian low and the Asiatic high. The last two are winter systems, the first present throughout the year. During the year, the trade-wind system changes in intensity, size, and location.

Figure 9 shows the locations about which the trade-wind system is centered. In the spring months the center moves from a location over the North Pacific Equatorial Water to one over the California Current Extension just east of the Hawaiian Islands. With the onset of fall, the movement is reversed. Although the center of wind action appears of importance in the seasonal changes in surface water movement, it does not appear to be associated with the time-of-initial-warming index used to predict the availability of skipjack in Hawaiian waters. However, indications are that the time of initial warming is related to the total winter atmospheric circulation pattern of the Northern Hemisphere. This relation is illustrated in the mean sea level pressure charts (fig. 10) for January 1963 and 1964. In 1963 the Asiatic high joined with the North American high, thereby creating a continuous ridge over the polar region and over the eastern Pacific. In 1964 the Asiatic, North American, and North Pacific highs appeared as isolated systems separated by pressure troughs. A pattern such as that of 1963 appears to be related to early initial warming of waters around the Hawaiian Islands, while the 1964 pattern appears to be related to late initial warming.

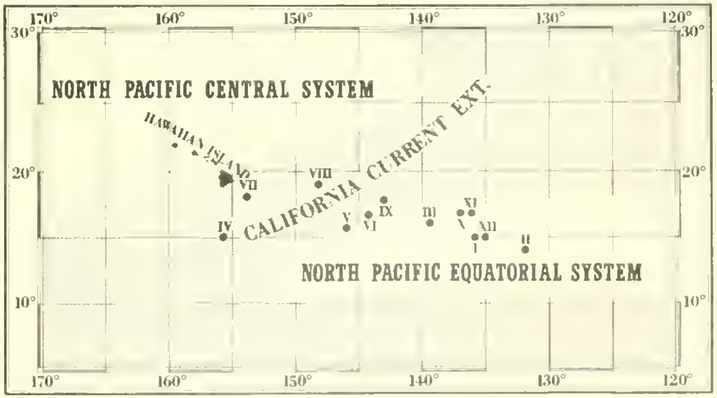

Figure 9.--Centers of the North Pacific trade-wind system during each month of the year.

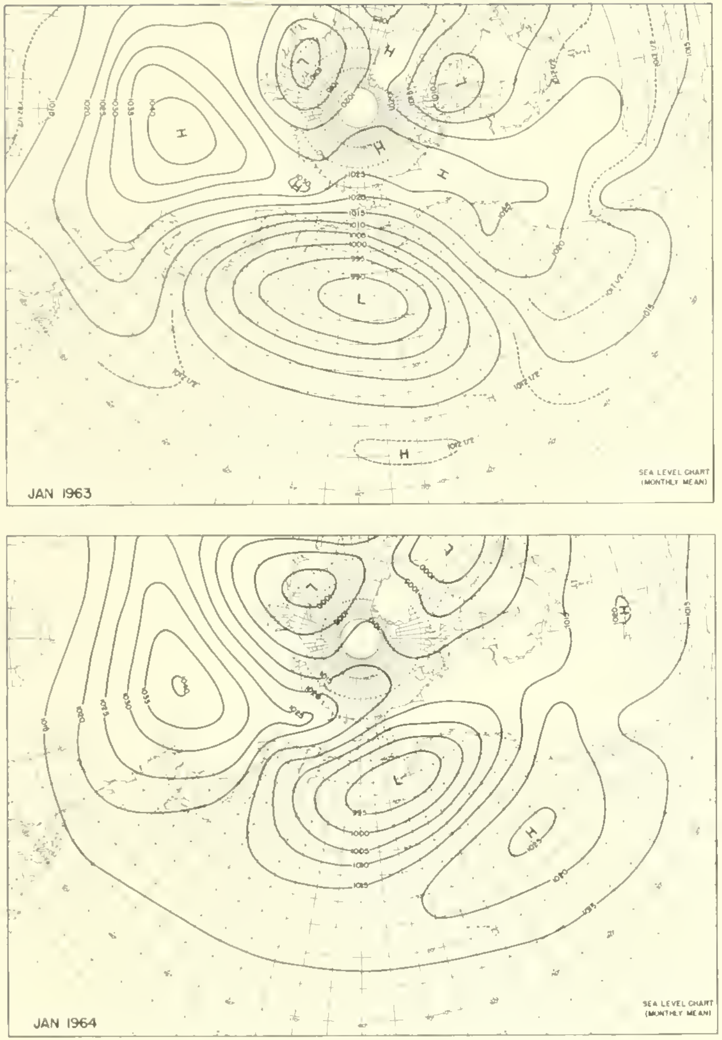

Figure 10.--Mean sea level atmospheric pressure charts, January 1963 and January 1964.

A study of the vertical temperature structure in the upper water column revealed that bathythermograph traces can be used to locate the depth of the high-salinity layer often found below the surface-water layer in tropical regions (fig. 11). The deviation of the temperature trace from the general trend lines was found to be associated with the high-salinity layer. This association appears to hold true throughout the tropical regions of all oceans where the high-salinity layer is present. This simple technique using the bathythermograph may be useful where traditional salinity determinations are either too slow or cannot be made, e.g., when taking current measurements or setting fishing gear in the high-salinity layer.

Our present studies have led to hypotheses regarding the processes which determine the oceanographic climate in the tropical central Pacific. These hypotheses will be evaluated as our studies continue and expand into the field phase.

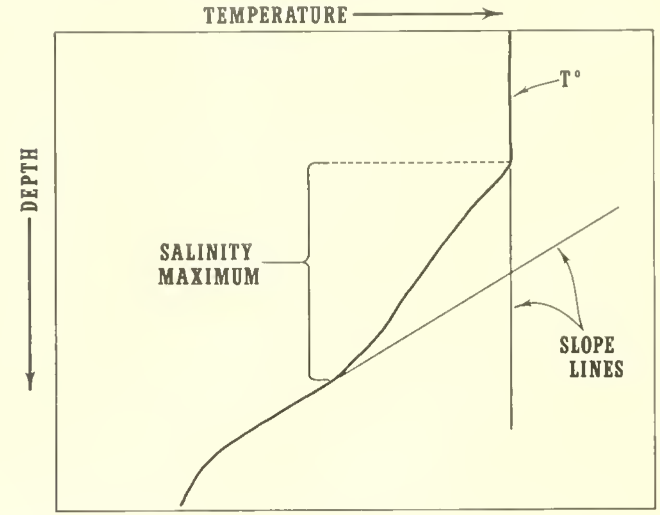

Figure 11.--A typical bathythermograph trace showing the high-salinity layer in Hawaiian waters.

Skipjack Ecology

Approximately 550 million pounds of skipjack tuna were taken from the Pacific Ocean in 1962, and there are indications that the intensity of fishing for this fish on a Pacific-wide basis is increasing. The skipjack is probably the most promising species which might be exploited to supplement the apparently limited yellowfin resources of the U.S. fisheries in the eastern Pacific. The possible increase in skipjack exploitation emphasizes the need to estimate the abundance of the resource and the effects of fishery activities on its long-term yield potentials.

Despite the present and potential importance of the skipjack fishery, little is known of the number of genetically separate skipjack populations, their spawning habits, movements, growth, and other dynamic parameters essential to the calculation of resource abundance and exploitation effects, as well as determination of the need for management and of appropriate management activities.

Significant progress in our understanding of skipjack ecology has been made recently. After a detailed review of previous studies, a model was designed that collates all pertinent information now known about the origin and distribution of exploited stocks of skipjack in the central and eastern Pacific Ocean. This model, now nearly completed, will enable us to assess our present knowledge of the skipjack tuna and to plan the future course of our research.

The model suggests that skipjack catches both in the eastern Pacific and the Hawaiian fishery contain large components that originated in the equatorial region of the central Pacific. When the model is completed, the testing of its hypotheses will begin.

Another important step was the definition of a unit of effort for the Hawaiian fishery. This definition provides, for the first time, a basis for the study of tuna population dynamics in the Hawaiian fishery. The unit of effort was defined so that the varied fishing abilities of the vessels in the fishing fleet (fig. 12) could be converted into standard comparable units of effort.

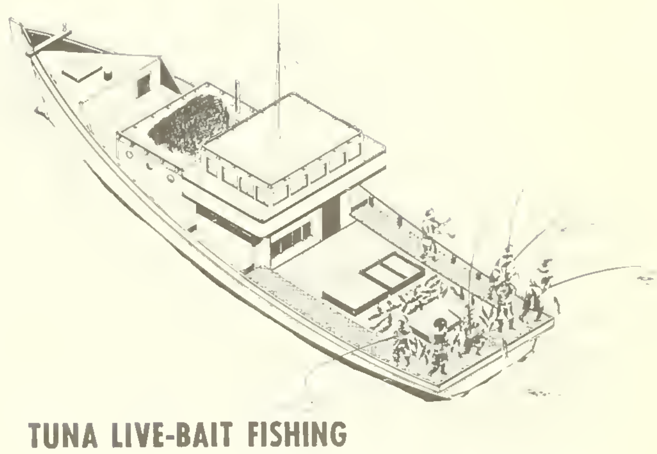

Figure 12.--Live-bait fishing in Hawaiian sampan skipjack fishery.

In the study of catch per unit of effort (fig. 13), we discovered that the catch per standard effective trip for the Hawaiian skipjack tuna fishery was not associated with fishing intensity. This observation suggests that annual fluctuations in catch for the Hawaiian fishery are largely associated with abundance and availability of skipjack and not with activities of the fishery, at least as they presently exist.

Noting that there was a steady decline in the number of men fishing per trip (fig. 14), we expected that boats with reduced crews would make smaller catches. On the contrary, catches did not show a decline. The fishermen increased their individual effectiveness by flipping the fish directly on the deck by allowing the barbless hooks to disengage themselves. Before crew reductions, the fishermen had grasped and unhooked each fish as it was lifted out of the water and swung toward the boat.

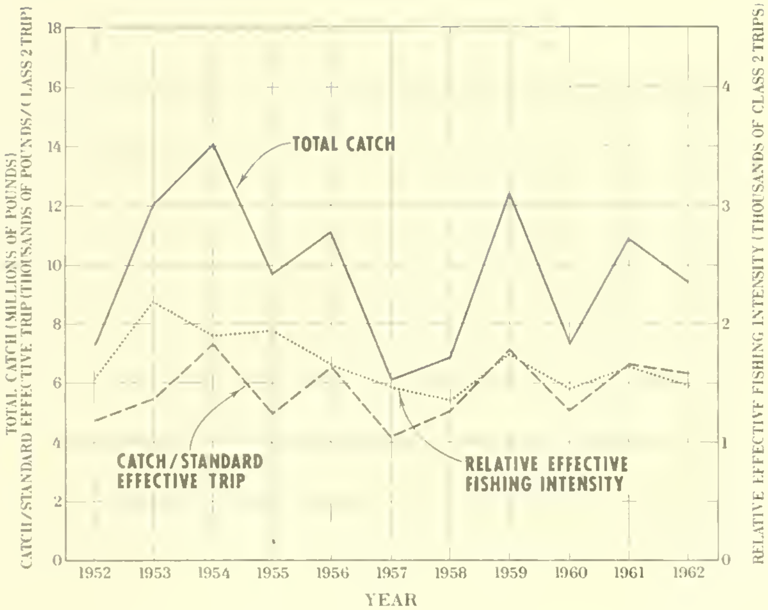

Figure 13.--Total annual catch, catch per standard effective trip, and relative effective fishing intensity, for skipjack in Hawaii, 1952-62.

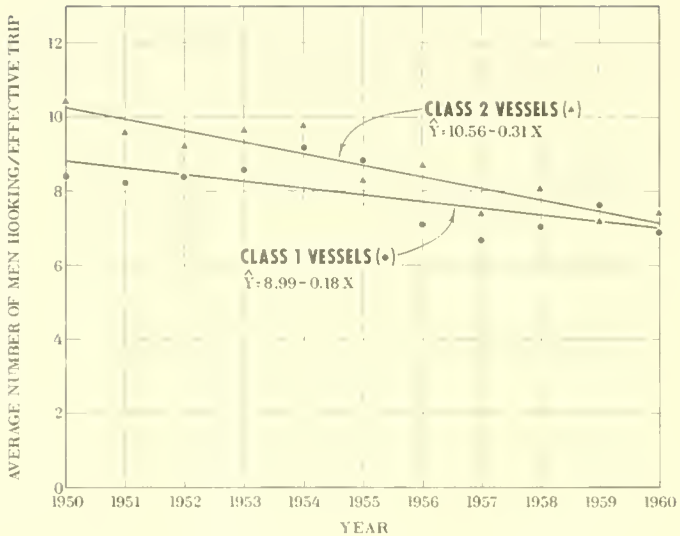

Figure 14.--Regression of average number of men hooking per effective trip on time (year), for class 1 and class 2 vessels, 1950-60. Class 2 vessels are larger than class 1.

Another aspect of the program concerned itself with the distribution of large fishes such as tunas, marlins, and sharks in the transition waters between the North Pacific Central Water and the North Pacific Equatorial Water was recently completed. These waters are characterized by moderately intense salinity and temperature gradients. On two cruises (January-February and July, 1963) longline sets were made in the transition zone area to the east of the Hawaiian Islands. Ten traverses were made at longitude 150° W. between latitudes 14° N. and 23° N. Catches of sharks and spearfishes tended to decrease as the longline stations progressed from the low-salinity waters of the North Pacific Equatorial Water through the transition zone and into the high-salinity water of the North Pacific Central Water. Catches of lancetfish (*Alepisaurus*), however, increased in the high-salinity water. During the first cruise the slender mola, *Ranzania laevis* (Pennant), seemed to be the only fish definitely associated with intermediate-salinity water. There was evidence that this species was spawning. Also, on this cruise skipjack tuna seemed to be associated with the predominantly North Equatorial Water while bigeye tuna catches were highest in the high-salinity water (fig. 15). During the summer cruise, however, catches of bigeye tuna were highest in the low-salinity North Pacific Equatorial Water.

During the first cruise from January to February we were fortunate enough to observe the annual northward movement of the salinity-temperature gradient (fig. 16). Heat-budget computations showed little net heat exchange across the sea surface during the cruise; therefore, the northward shift in temperature and salinity must have resulted largely from advective processes.

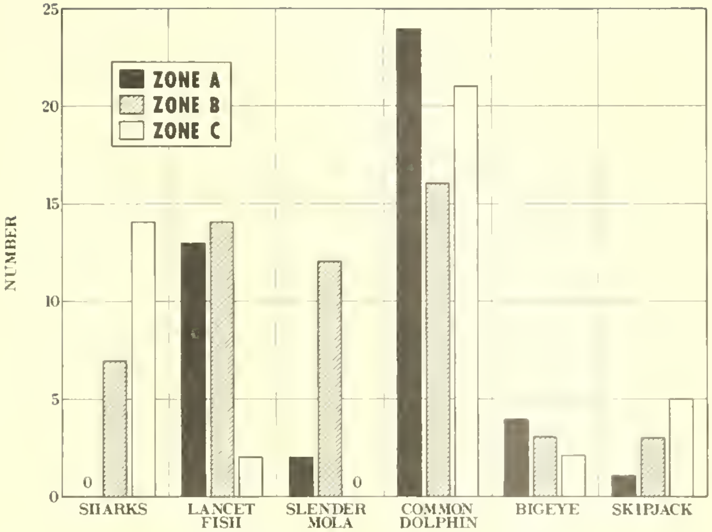

Figure 15.--Longline catches taken on Charles H. Gilbert cruise 63, by species and zone. (Zone A, North Pacific Central Water; Zone B, transition; Zone C, North Pacific Equatorial Water.)

Several studies were completed recently on the distribution of certain plankton organisms that could be used as indicators of water masses and water types. Studies of pontellid copepods indicated that some species have variable distributions within the South Pacific study area, some occur only in the proximity of land, and others are abundant only in areas characterized by particular water masses.

An analysis of bird flock and fish school sightings made by vessels of the Biological Laboratory, Honolulu, over a 10-year period clearly demonstrates a concentration of flocks and schools near the island groups encompassed in the study--the Hawaiian Islands, the Line Islands, and French Oceania. The analysis also shows seasonal changes in density for the entire area as well as variations in density between island groups. The density of sighted fish schools and bird flocks appeared to be greatest in French Oceania, followed by the Line Islands, then the Hawaiian Islands. Ocean regions between island groups had a much lower density of sightings than island areas.

During our continuing study of larval tunas we noted and described the unique shape of the elongate first haemal spine in albacore. The study showed conclusively that albacore is the only species of tuna having an enlarged, flattened haemal spine on the first caudal vertebra; this characteristic is definitive in differentiating both juvenile and adult albacore from other tuna species.

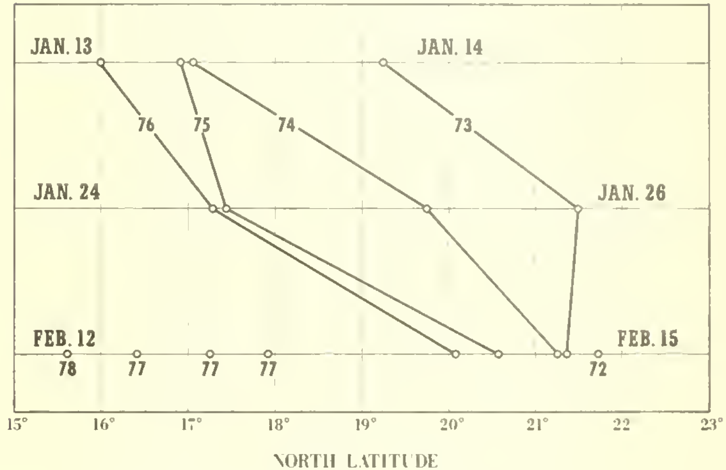

Figure 16.--Surface isotherm along longitude 150° W. during the period January 13 to February 15, 1963 (Charles H. Gilbert cruise 63).

Preliminary studies of skipjack stomach contents and ovaries showed that both the amount of food in the stomachs and the state of maturation (female gonad index) were inversely correlated with catch.

Other recent studies concerned size, distribution, and growth of skipjack; environmental factors related to catch of skipjack; and the continuing analysis of catch and effort statistics for the Hawaiian skipjack fishery.

Subpopulations

Identification of reproductively isolated groups, or subpopulations, within tuna species is the principal goal of the Subpopulations Program. While identifying these subpopulations, laboratory biologists also hope to gain new insight into the relationships between tuna subpopulations and their oceanic environment. Knowledge both of the identity of specific subpopulations and of their environmental boundaries is necessary to the calculation of abundance of populations as a whole and number of fish that can be taken annually without decreasing maximum long-term yields.

Serological techniques are used to identify tuna subpopulations. Serology, unlike other available methods, offers reasonable assurance that the characteristics studied are under genetic control and are not the result of environmental differences. Through these studies the Biological Laboratory has made two important contributions to knowledge of tuna subpopulations: (1) discovery of a blood-group system in bigeye tuna similar to the A-B-O system long known in man; (2) definition of several skipjack subpopulations in the Pacific.

Discovery of the A-B-O type blood-group system in the bigeye tuna was a significant contribution to the identification of tuna subpopulations. The study demonstrated that two reagents, when combined with individual blood samples from a large number of bigeye tuna individuals, showed four kinds of reaction patterns analogous to the A-B-O blood-type system of man (table 1). Hardy-Weinberg analyses of the relative proportions of these four blood types agree with a hypothesis that the blood-group system is determined by the inheritance pattern of three related allelic genes.

These serological findings in bigeye tuna are significant because it can be shown by an analysis of the expected and observed proportions of these four blood types in a representative population sample whether the sample has been drawn from a single subpopulation or from more than one subpopulation. Discovery of an A-B-O type of blood-group system in the bigeye tuna suggests the further possibility that future studies may uncover reagents capable of demonstrating similar or related systems in other tuna species.

Concurrent studies of skipjack tuna blood groups revealed the existence of subpopulations in widely divergent areas of the Pacific. Samples used in these studies were obtained from the waters around the Hawaiian Islands, Christmas Island, Marquesas Islands, Tuamotu Archipelago, Society Islands, western Carolines, and near Baja California. Further studies are expected to reveal the existence of still other skipjack subpopulations.

Table 1.--Agglutination reaction patterns of A-B-O blood groups in bigeye tuna and in man

	Specificity of reagents	Phenotype			
		AB	A	B	O
Human	anti-A	+	+	-	-
	anti-B	+	-	+	-
Bigeye	anti-A	+	+	-	-
	anti-B	+	-	+	-

Two skipjack subpopulations recently identified in the Hawaiian fishery have been the subject of intensive research at the Biological Laboratory to develop greater precision in our distinguishing of closely related subpopulations. Another aspect of the study concerns the association of these subpopulations with specific physical features of the major ocean currents. We have noted that certain changes in the dynamic features of the ocean near Hawaii appear to influence the movement of skipjack in Hawaiian waters.

Earlier oceanographic studies of the physical properties of the waters near the Hawaiian Islands showed that the boundary between the North Pacific Central Water and the California Current Extension Water moved northward in the spring and southward in the fall. The emigration of large skipjack into Hawaiian waters in the spring and out in the fall appears to be associated with the north-south movement of the California Current Extension Water. In 1963, laboratory biologists collected 360 skipjack blood samples from off the coast of Baja California, the analysis of which showed them to be indistinguishable from blood samples of one of the skipjack subpopulations found at the same time in the Hawaiian fishery. Since California Current Extension Water also is found off Baja California, this finding lends support to the hypothesis that skipjack subpopulations are uniquely associated with dynamic physical features of the major oceanic circulation systems.

In 1963, biologists seeking to identify tuna subpopulations had the opportunity to compare directly the reagents being used in their individual research programs. The need for this had long been recognized. Dr. Lucian M. Sprague visited Dr. Akimi Suzuki of the Nankai Regional Fisheries Research Laboratory in Japan to make direct comparisons of reagents of albacore tuna developed in the Biological Laboratory and those developed by Dr. Suzuki. Results of the tests demonstrated that some reagents developed by Dr. Suzuki were directly comparable with ours. Both research groups may expect to benefit from the pooling of knowledge that resulted from these and subsequent direct comparisons.

Some progress has been made in the studies of blood-group systems in yellowfin, albacore, and bluefin tunas, and these studies will continue. The rate of progress will depend to a large extent on the supply and quality of blood samples obtainable. To date, yellowfin samples have been available only during the summer and in limited numbers from the Hawaiian longline fishermen. Albacore samples are only sporadically available, and often they have been frozen for several months.

Bluefin samples are available but so far have proved the most difficult to work with; however, the new technique of starch-gel zone electropheresis shows some promise for this species. In this technique, electric current separates the protein components, which occur naturally in the serum of animals, into several well-defined chemical zones on a plate of potato starch gel (fig. 17). Because the presence or absence of certain proteins within these zones can--by application of the Hardy-Weinberg law--be demonstrated to be under genetic control, this technique is a potentially valuable tool for differentiating subpopulations. Tests of its adaptability to studies with tuna species have shown that this technique readily differentiates between albacore, bigeye, bluefin, and yellowfin tunas and appears also to differentiate between individuals within a species.

Figure 17.--Typical starch gel, showing hereditary protein components in fish serum.

Albacore Ecology

The Albacore Ecology Program was started at the Biological Laboratory in 1960 to inquire into all aspects of the life history of the Pacific albacore. Emphasis has been placed on investigations to determine whether albacore belong to more than one subpopulation and if so whether these groups intermingle, and to discover the nature of the albacore's migratory patterns. These investigations are based on studies of spawning habits, growth rates, differences in age and size composition of the catch in American and Japanese commercial fisheries, and other aspects of albacore biology. These fundamental studies, designed to determine the extent of the Pacific albacore resources and the effects of fishing on these resources, have been spurred by the increase in intensity of the commercial fishery during the past decade.

Since July 1962, the Albacore Ecology Program has established a field sampling station in American Samoa, continued the study of albacore spawning habits, estimated the age and size composition of the catch of the various Pacific albacore fisheries from 1955 to 1959, and continued the collection and study of juvenile albacore. These juveniles are found within the broad area where earlier studies showed that albacore spawned.

The field sampling station was established in American Samoa to document the rapid growth of the South Pacific albacore fishery. This is a longline fishery using vessels and gear similar to those shown in figure 18. Measured by the number of boats operating, fishing pressure for albacore in the South Pacific fishery based at American Samoa has increased approximately tenfold since inception in 1954. That year the fishery's fleet of nine boats fished an area of approximately 80,000 square miles, and caught 270 tons. By 1963, the fleet had increased to about 60 boats, the fishing grounds extended over an area of some 8 million square miles (fig. 19), and the catch was approximately 14,000 tons. The establishment or expansion of albacore fisheries based in New Hebrides, Fiji, and New Caledonia has further increased the rate at which these resources are being exploited in the South Pacific.

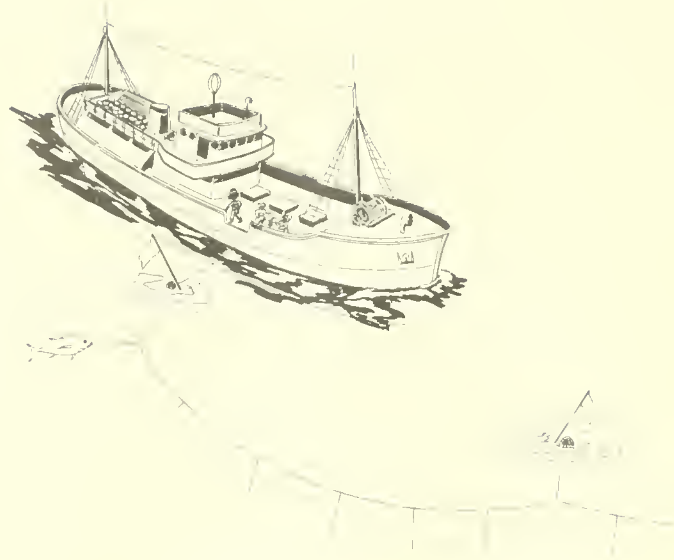

Figure 18.--The South Pacific albacore fishery uses longline gear similar to that shown above.

Laboratory personnel at the Samoan station have collected data on the length, weight, and sex of albacore from each catch landed by Japanese and Korean longline vessels at the island's canneries. These data, supplemented by information on fishing operations they obtained from the boat operators, will form the basis for a study of the population dynamics of the South Pacific albacore.

In a study of albacore spawning habits in the South Pacific, the Charles H. Gilbert made two surveys of the waters around New Hebrides, New Caledonia, Fiji, Ellice Islands, Tonga, and Samoa. During the second survey (fig. 20), between October 7 and December 13, 1963, and designated Ahipalaha II,[3] plankton nets and midwater trawls were towed to sample larval and juvenile albacore, longline fishing was used to sample adults, 204 of which were caught. Female albacore taken on the

[3] "Ahipalaha" is the Hawaiian name for albacore tuna.

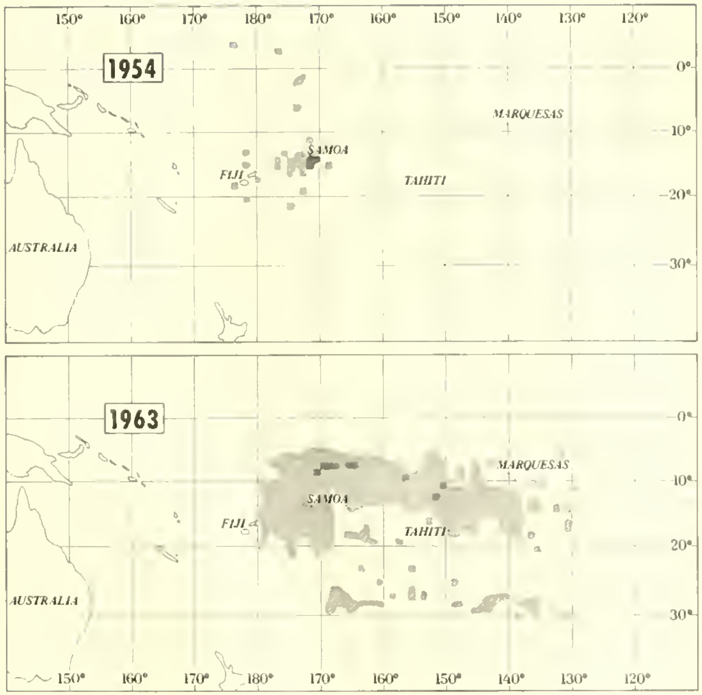

Figure 19.--Fishing grounds of South Pacific albacore fishery based at American Samoa in 1954 and 1963.

cruise were not quite ready to spawn. The earlier survey, Ahipalaha 1, conducted between January 15 and April 5, 1963, was too late in the year to demonstrate the peak of the South Pacific albacore spawning season. Therefore, it appears that the peak of the spawning season in this area occurs in December-January.

In conjunction with a recently completed investigation of the size and estimated age composition of albacore taken in the various Pacific fisheries, estimates were made of the total number of albacore taken from 1955 to 1959. For these years, the annual catch in the North Pacific varied from 5.1 to 8.5

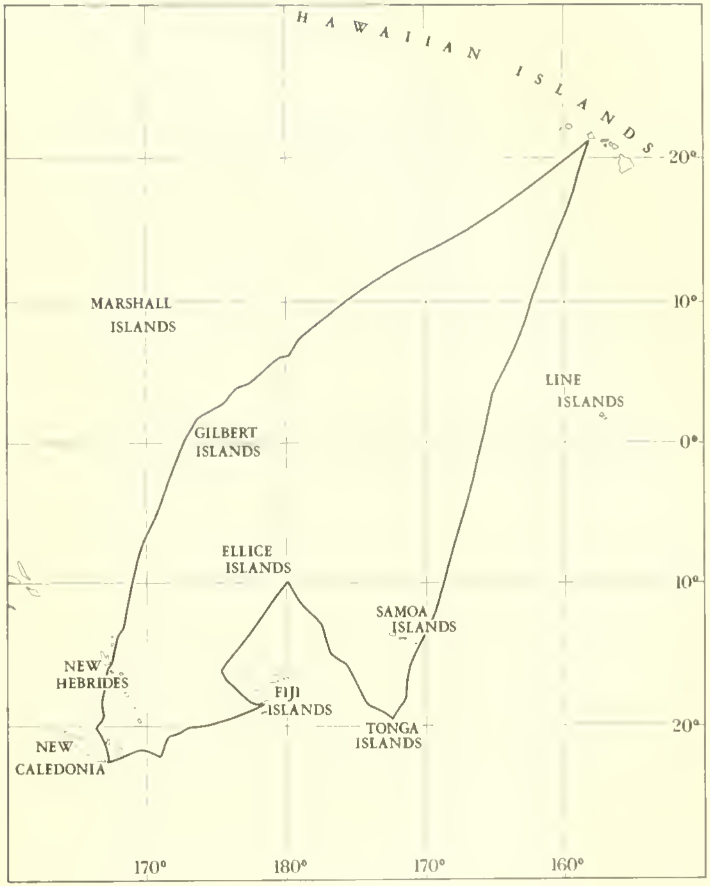

Figure 20.--Track of the Charles H. Gilbert on cruise 69 (Ahipalaha II), October 7-December 13, 1963.

million fish; in the South Pacific, from 0.5 to 1.0 million fish. To the North Pacific total annual landings the U.S. west coast fishery contributed an estimated 2.0 to 3.1 million fish; the Japanese spring live-bait fishery, 1.2 to 4.0 million fish; and the Japanese winter longline fishery, 1.2 to 2.4 million fish.

In the South Pacific, annual landings varied from 0.4 to 1.0 million fish for the Japanese tropical longline fishery and from 1,300 to 93,000 fish for the Chilean fishery.

Four age groups were represented in the U.S. west coast albacore catch with the 3-year-olds constituting roughly 68 percent of the landings by weight.

For the small Chilean fishery the catch was estimated to be composed of about seven age groups with the 3-year-olds contributing about 80 percent of the total.

In the Japanese spring live-bait fishery, seven age groups were represented, and, though the dominant age group differed from year to year, the 4- and 5-year-olds usually dominated and contributed nearly 85 percent to the catches. The Japanese winter longline catches were comprised of 10 age groups, among which the 4-year-olds and the 5-year-olds were the most important groups, accounting for 29 and 27 percent of the catches. Seven age groups made up the catches of the South Pacific Japanese tropical longline fishery where the dominant group of 6-year-olds constituted 40 percent of the total landings.

To learn more about the early life history of albacore, we have continued to collect and examine juveniles from the stomachs of large predatory fishes. Although only a few specimens have been obtained in this way it has been by far the most successful collection method we have found to date. Between June 1960 and November 1962, a total of 12 juvenile albacore, ranging from 61 mm. to 283 mm. in standard length, was found in the stomachs of predators taken between the Hawaiian Islands and longitude 170° E. in the North Pacific and between longitude 163° W. and 179° E. in the South Pacific. The fact that these juveniles were taken at such widely scattered points of the Pacific strongly supports the findings of our earlier studies on albacore spawning habits, which had indicated spawning in a broad area of the North and South Pacific.

Juvenile albacore were identified by the presence of the unique laterally flattened shape of the haemal spine of the first caudal vertebra (fig. 21). This character, which is definitive

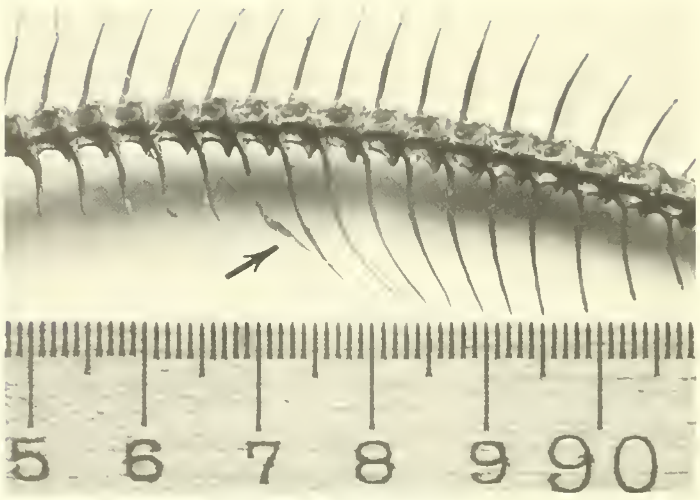

Figure 21.--Portion of axial skeleton of juvenile albacore showing laterally flattened haemal spine.

early in the life of the albacore, was found to be useful for differentiating this species from other tuna. Its presence was recognized in a specimen as small as 61 mm. in standard length.

As is to be expected, we also found that some other characters which distinguish adult albacore were not definitive in the juveniles in our collection because these characters change with growth. The configuration of the first haemal arch appears to be such a character.

The information accumulated from albacore studies made to date at the Biological Laboratory suggests strongly that all North Pacific albacore belong to a single intermingling population; also that the South Pacific albacore population is confined to the Southern Hemisphere and is discrete from that of the Northern Hemisphere. Tagging studies have been of prime importance in reaching these conclusions.

Indian Ocean

The Indian Ocean Program was organized in 1962 following assignment to the Laboratory of responsibilities for the fisheries phase of the United States Program in Biology of the International Indian Ocean Expedition. Biologists of the Exploratory Fishing Base at Seattle, Washington, cooperated with those at the Biological Laboratory in planning four of the nine cruises of the United States Program that were carried out by the National Science Foundation research vessel, the Anton Bruun.

Two longline and two trawling cruises were organized to investigate the fish and shellfish of potential commercial value in the little-known waters of the Indian Ocean. Three of the cruises were completed in 1963. Information and specimens obtained by U.S. Fish and Wildlife biologists and oceanographers on these cruises will supply much of the material needed for the various facets of the United States Program, though other participating organizations, such as the U.S. Coast and Geodetic Survey and the Lamont Geological Observatory, will contribute supplemental material.

The Bureau's Indian Ocean Program was designed to fulfill two primary and two secondary missions. The primary missions were (1) to study the biology of the large pelagic fishes such as tunas, billfishes, and sharks in the central and western Indian Ocean, and (2) to explore the shelf areas of the Arabian Sea and the Bay of Bengal for benthic fishes and shellfishes. The secondary objectives were (1) to learn the indentity and distribution of larval and juvenile tunas and (2) to study the zoogeography, ecology, and systematics of planktonic copepods of the family Candaciidae in these waters. All of these studies were planned to provide scientific information about these little-known areas of the sea and to indicate their potential value as sources of protein foods for nearby nations.

The track of the Anton Bruun on the three cruises made in 1963 is shown in figure 22. Two trawling cruises (1 and 4B) were made to collect data on the benthic fishes and invertebrates of the Bay of Bengal and the Arabian Sea, while a longline cruise (2) sought data on the pelagic fishes of the Indian Ocean.

A 42-foot Gulf of Mexico shrimp trawl (fig. 23) was used to sample the benthic fauna. During cruise 1, in March and April, 1963, a total of 27 successful hauls was made in depths

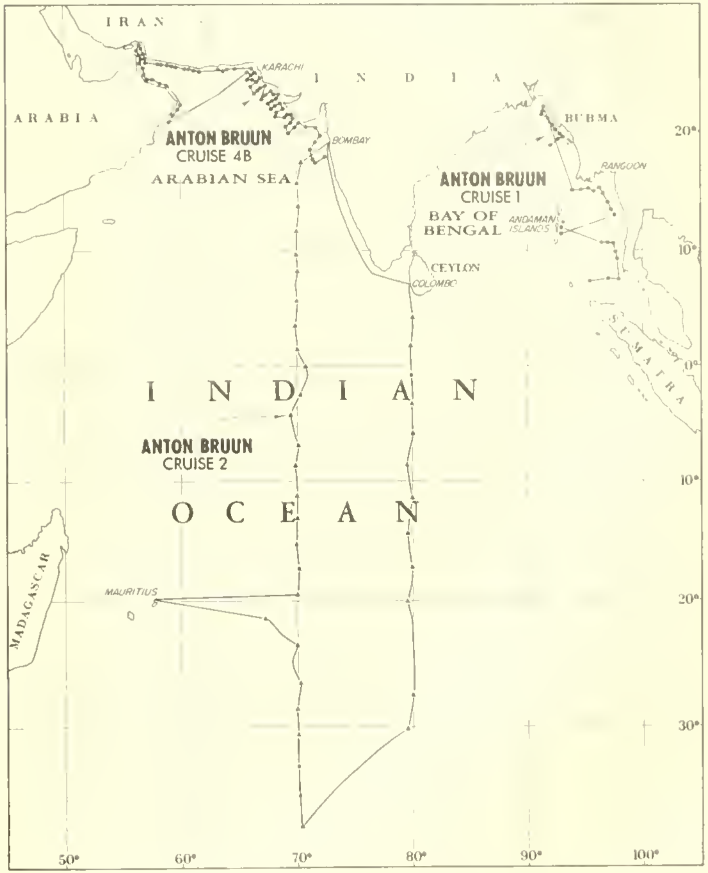

Figure 22.--Track of the Anton Bruun in Bay of Bengal (cruise 1); central Indian Ocean (cruise 2); and Arabian Sea (cruise 4B).

ranging from 8 fathoms to more than 1,000 fathoms along the coasts of Thailand, Burma, East Pakistan, and the Andaman Islands. In general, most of the catches exceeding 100 pounds per hour of trawling were made in depths of 8 to 30 fathoms, approximately 100 miles south-southeast of Chittagong, East Pakistan, and about 100 miles southwest of Rangoon, Burma. Stingrays, guitarfishes, croakers, lizardfishes, and catfishes dominated the catches in weight. Most of the fishes caught on the survey weighed less than 1 pound and were considered to be of little market value. None of the hauls produced shrimps in commercial quantities. The best catches of 56 and 34 pounds per hour of trawling were made in depths ranging from 165 to 205 fathoms.

On a trawling cruise (4B) conducted in November and December 1963, along the Continental Shelf from Bombay, India, to the eastern coast of Arabia, 77 successful hauls were made in depths ranging from 8 to 200 fathoms. The best catches came from off the Arabian coast south of Al Masirah in 21 to 40 fathoms of water. There one haul accounted for 11,200 pounds per hour of trawling. This catch was predominantly rays. Another haul resulted in 4,738 pounds of portunid crabs and fishes per hour of trawling. Good catches were also made in depths of 8 to 20 fathoms between Bombay, India, and Karachi, West Pakistan, and consisted mostly of stingrays, threadfin breams, croakers, grunts, and threadfins.

The longline cruise for pelagic fishes in the central Indian Ocean was carried out in May, June, and July, 1963. On this second cruise of the Anton Bruun, from 30 to 40 baskets[4] of Japanese longline gear were fished at each of 33 stations along longitude 70° E. from Bombay south to latitude 37° S. and along longitude 80° E. from latitude 30° S. north to Ceylon. Each fish caught was identified and its length, weight, and sex were recorded. Stomach contents, ovaries, and blood samples were also collected from these fishes.

A preliminary examination of the data collected on the longline cruise showed several interesting patterns in the distribution of pelagic fishes and some differences in their availability in the different areas covered. Tunas were virtually absent in the samples from the central Arabian Sea. Of the commercially important tunas, yellowfin (fig. 24) were widely distributed in the central and western Indian Ocean, ranging from about latitude 10° N. to approximately latitude 30° S. Areas of maximum abundance appeared to be in the vicinity of the Equator where catch rates of 2 to 18 yellowfin per hundred hooks fished were encountered. The highest single day's catch of tunas was 44 yellowfin taken at a station west of

[4] The so-called "basket" consists of a line about 200 fathoms long and bearing six hooks. The name is derived from the former custom of storing each unit in a basket.

Figure 23.--Lowering the cod end of the Gulf of Mexico shrimp trawl onto the deck of the Anton Bruun after a successful haul.

the Maldive Islands chain. Albacore were taken only in waters south of approximately latitude 15° S. but its distribution extended to the southern limit of the area surveyed, approximately latitude 37° S.

The total catch from cruise 2 was 185 tunas, 35 billfishes, 87 sharks, and 70 miscellaneous fishes, including the uncommon pelagic ray and the moonfish.

Zooplankton samples also were collected on the three cruises of the Anton Bruun for use in studies related to our secondary missions on the Indian Ocean Expedition. Although the tuna larva distribution studies have not begun, some preliminary results are available from the study of copepods. Some interesting distribution patterns have been noted in several species of copepods of the family Candaciidae from cruises 1 and 2. The presence or absence of these species indicated that on the first transect of cruise 1, along longitude 70° E., three types of water were encountered. Moving from north to south along the transect, Arabian Sea Water extended from Bombay to latitude 9° N., Equatorial Water from latitude 9° N. to approximately latitude 11° S., and South Indian Ocean Central Water from latitude 11° S. to the southern end of the transect at approximately 37° S. The second transect (cruise 2) along 80° E. did not present as clear a picture of the water masses as the first, but the distribution of species of Candaciidae indicated that there was much mixing of all three water types.

Figure 24.--Landing a large yellowfin tuna taken by longline on the Anton Bruun (cruise 2).

The examination of zooplankton samples collected by the Lamont Geological Observatory on a cruise around the tip of South Africa resulted in some new discoveries on the distribution of certain species of copepods. Comparisons of the morphology of the Atlantic and Indo-Pacific specimens of *Candacia pachydactyla* indicated marked differences, suggesting that these specimens represent two genetically separate populations. The existence of two reproductively isolated populations would suggest that equatorial species of Candaciidae from the Indo-Pacific are not transported into the Atlantic.

In 1964 the data-collecting phase of the United States Program in Biology will continue with the collection of biological material and physical and chemical data on cruises 5 to 9 of the Anton Bruun. On cruise 5 longline fishing will be carried out along longitudes 55° E. and 75° E. Upon the completion of cruise 5 we will analyze the data and samples from this and from our earlier cruises and will then publish our findings.

Oceanography

For some years the oceanographic research program of the Biological Laboratory has been concerned with two long-term study projects: summarizing and analyzing oceanographic data from the entire Pacific and investigating the effect of the Hawaiian Islands on circulation patterns near the islands and on circulation systems and water properties of the North Pacific. These projects will be continued in the future. Both are designed to contribute to a comprehensive description and analysis of the Pacific Ocean's physical features and dynamic processes. Such studies of static physical characteristics, of changing oceanographic weather, and of oceanographic climate are fundamental to the progress of the science of oceanography and essential to understanding the ecology of the wide-ranging tuna.

Studies include a summary and analysis of all oceanographic station data of the Pacific obtained from the National Oceanographic Data Center; these data are being analyzed in several ways with the principal objective of determining seasonal changes in water properties and currents at various levels within the sea.

Studies of the characteristics of water layers of a given density (isopycnic surfaces) have been helpful in analyzing seasonal changes in water properties and currents. Figure 25 presents an analysis of seasonal changes for water of a given density. It shows the winter and summer values of depth, temperature, salinity, and dissolved oxygen in a water layer

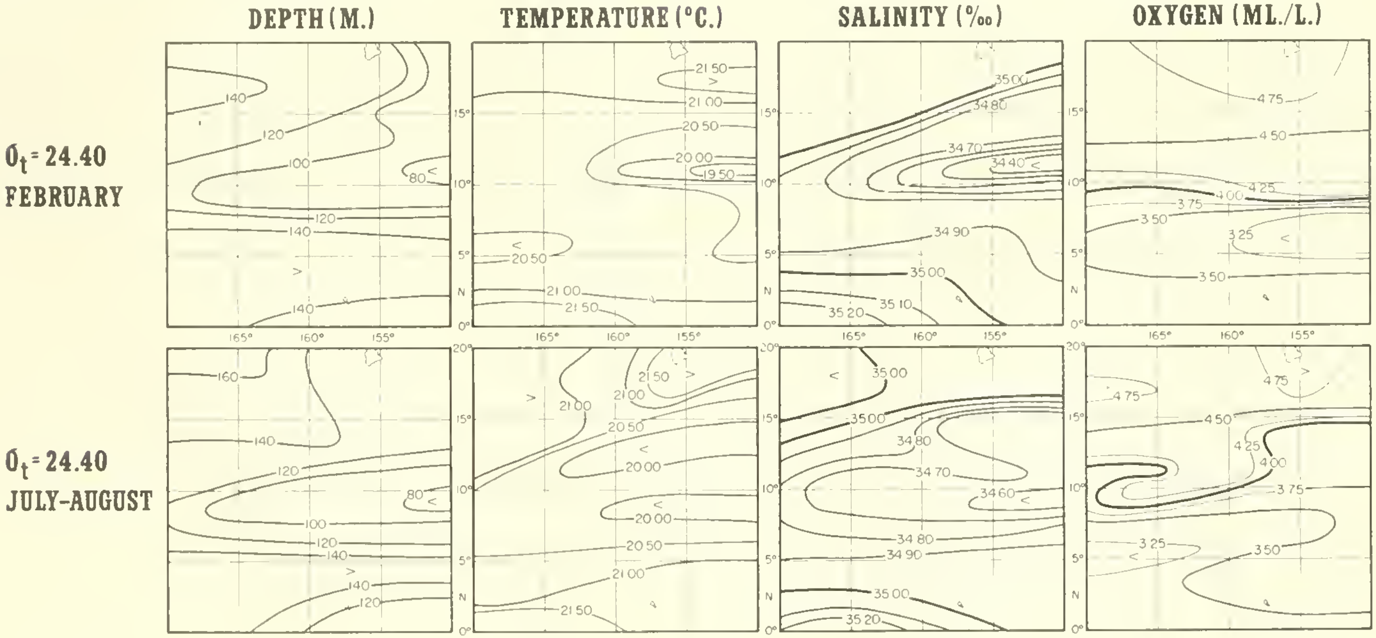

Figure 25.--Summer and winter values of depth, temperature, salinity, and dissolved oxygen content of the water layer of density 1.0244 grams per cubic centimeter.

having a density of 1.0244 grams per cubic centimeter and lying in an area between Hawaii and the Equator. This density layer lies within the thermocline (the layer below the sea surface that exhibits the most pronounced vertical temperature gradient) in the latitudes shown in the figure, and intercepts the sea surface in winter somewhat farther north. As a result of increased contact with the atmosphere, a seasonal increase in the dissolved oxygen content of this water layer occurs each winter, an effect which can be seen by comparing the northernmost parts of the two charts showing dissolved oxygen concentration. Other seasonal changes can be detected in the salinity and temperature charts. Changes in the current systems can be deduced from changes in the depth of the water layer under consideration.

The distributions of temperature, salinity and dissolved oxygen can also be shown in vertical sections which demonstrate how these factors vary with depth and geographic location. Figures 26, 27, and 28 show average annual temperature, salinity, and oxygen conditions between 10° and 20° N., immediately to the south of the Hawaiian Islands. These figures

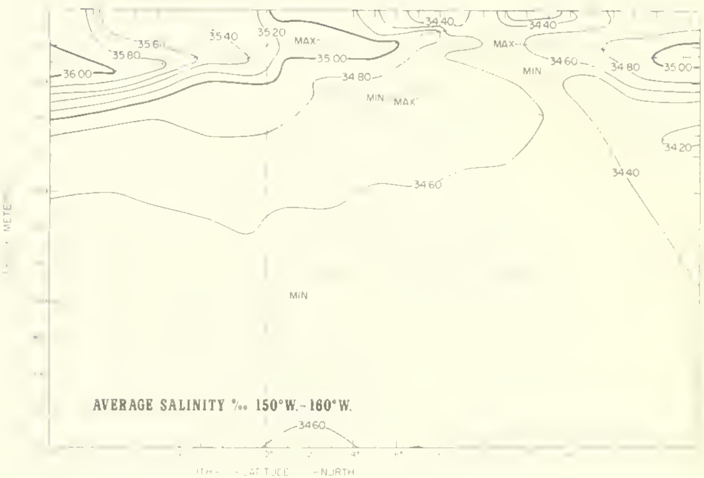

Figure 27.--Average vertical distribution of salinity between 10° S. and 20° N.

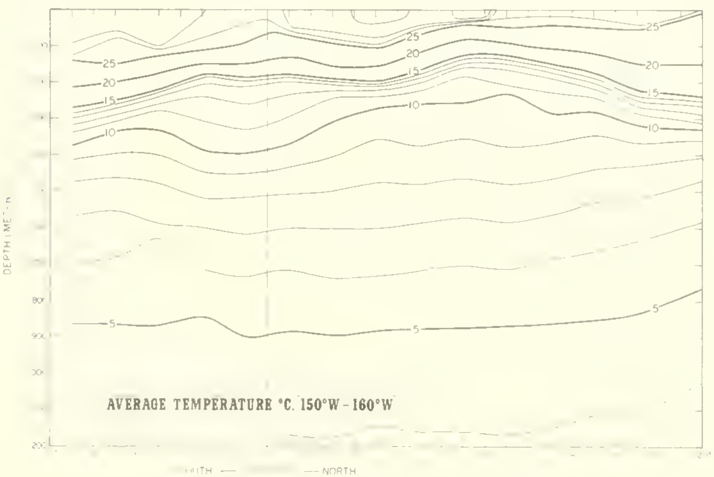

Figure 26.--Average vertical distribution of temperature between 10° S. and 20° N.

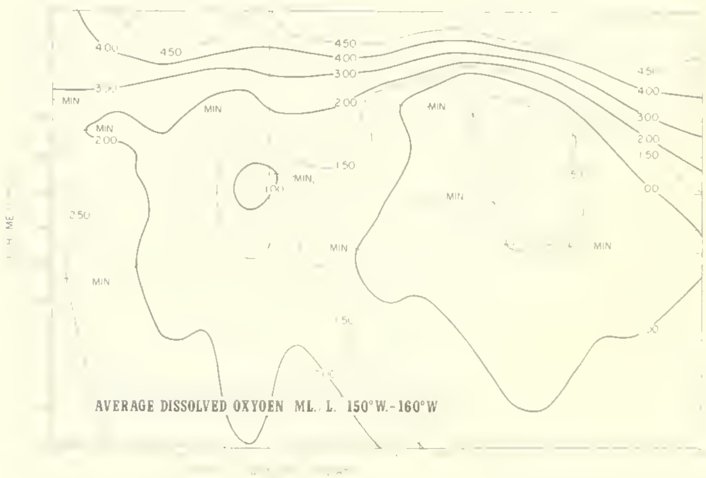

Figure 28.--Average vertical distribution of dissolved oxygen 10° S. and 20° N.

show the sharp temperature change associated with the thermocline in the tropics--from about 25° C. at 50 to 100 meters to 10°C. at 200 to 300 meters, as well as the tongues of low and high salinity associated with the thermocline and the region of low oxygen concentration below the thermocline. All of these features are characteristic of the tropical ocean, and all are probably of considerable importance to animals living in these regions.

In addition to analyzing data collected by other agencies, the Laboratory's oceanographers have also been active in collecting data; in the central Pacific Ocean, approximately 80 percent of the oceanographic data was collected by the Laboratory's research vessels. The most recent studies have included the use of three means for direct measurements of currents: drift cards, drogues, and a scale model.

Drift bottles and cards have been used to study surface currents in the central Pacific since 1961. The drift bottle used by the Biological Laboratory is shown in figure 29, which is a photograph of a poster placed in schools and other public

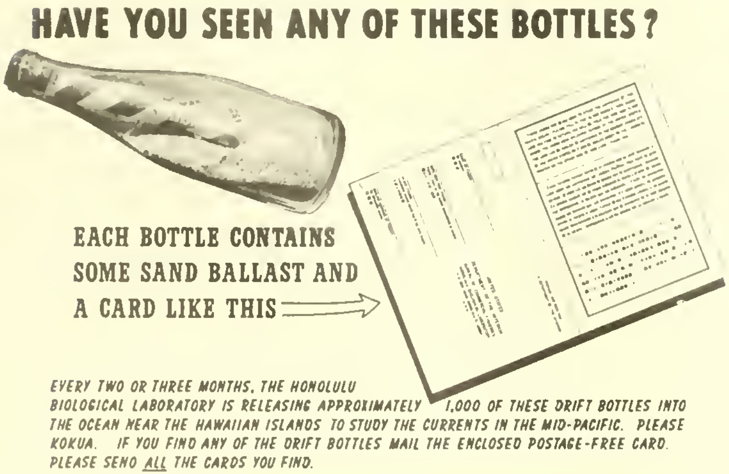

Figure 29.--Poster used to publicize drift bottle program in 1961-62.

buildings in Hawaii in 1961 to publicize the program. These bottles performed well, but took up too much space aboard our research ship and could not be dropped from aircraft, so a drift card was developed that performed as well as the bottles and was considerably more compact and less fragile. Figure 30 shows one of these drift cards, together with the plastic envelope and the weight that was added as ballast. These cards were dropped from aircraft regularly each month to provide information on month-to-month changes in the surface currents near the islands.

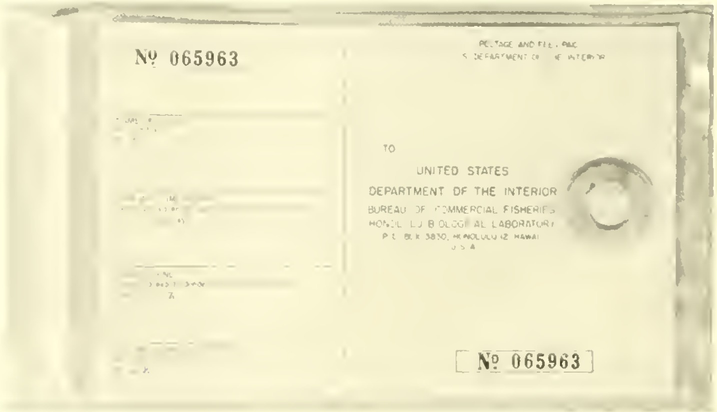

Figure 30.--Drift card sealed into plastic envelope.

Drift bottle returns can provide valuable information on ocean movements both large in scale (fig. 31) and small (fig. 32).

For example, of the releases shown in figure 31, those made nearest the Equator traveled fastest, at speeds of more than 36 miles a day. Releases away from the Equator moved more slowly; at 10° N. the speeds were about 20 miles a day, while at about 20° N. the speeds dropped to about 12 miles a day.

Figure 32 shows drift bottle and card releases and returns in the Hawaii area for January through March in 1961, 1962, and 1963. Similar charts showing the year-around pattern of returns for these years are being published in a Fish and Wildlife Service Special Scientific Report. These releases and recoveries reflect the lower winter velocity of the surface current system near the Hawaiian Islands and the predominant drift to the northwest which prevails in winter. The seasonal changes indicated coincide with seasonal changes in the strength of the trade-wind system.

Drift card returns showed certain interesting and important features of the currents near the islands, such as a large eddy to the southeast of Oahu. Such eddies have profound effects on the distributions of temperature and other properties of the water, as well as on the movements of the small organisms that form the major sources of food for the commercially valuable tunas.

To learn more about these eddies, two cruises were made in 1963 in which the currents were measured directly by the Laboratory research vessel Charles H. Gilbert. This was done by attaching a parachute, which acts as a sea anchor, to a surface float equipped with lights and a radar reflector. Nine such drogues were put out during the cruise made in April (fig. 33). The drogues were placed in the northern part of what is clearly a large counterclockwise eddy. The drogues toward the outer edge of the eddy moved at speeds of almost 2 knots, while those near the center moved at half a knot or less. The eddy appeared to rotate at the rate of 1 revolution in about 8 days and to move westward at about 7 miles a day. The eddy was at least 50 miles in diameter. In August 1963, an eddy of about the same size was found 100 miles farther east and followed with drogues. It rotated more rapidly, making about 1 revolution in 5 days, and its center appeared to be stationary.

A topographic scale model of the Hawaiian Islands and the ocean floor surrounding them was designed and used to study eddies near the islands and other phenomena associated with the effects of the islands on the ocean nearby. The model is 4 feet wide, 8 feet long, and 1 foot high. It is placed in a large

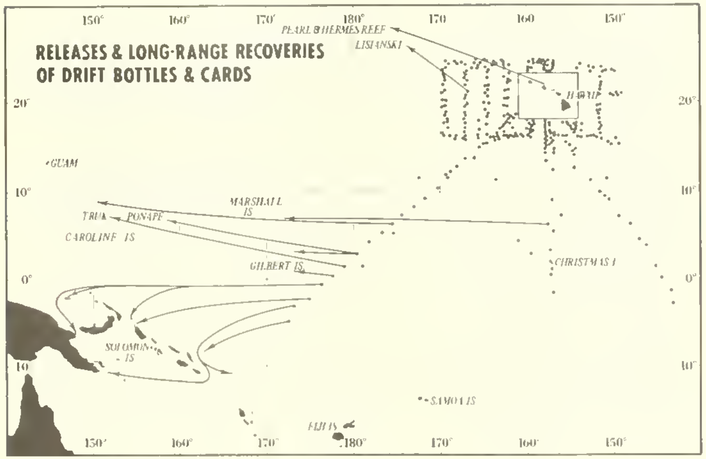

Figure 31.--Long-distance releases and recoveries of drift bottles.

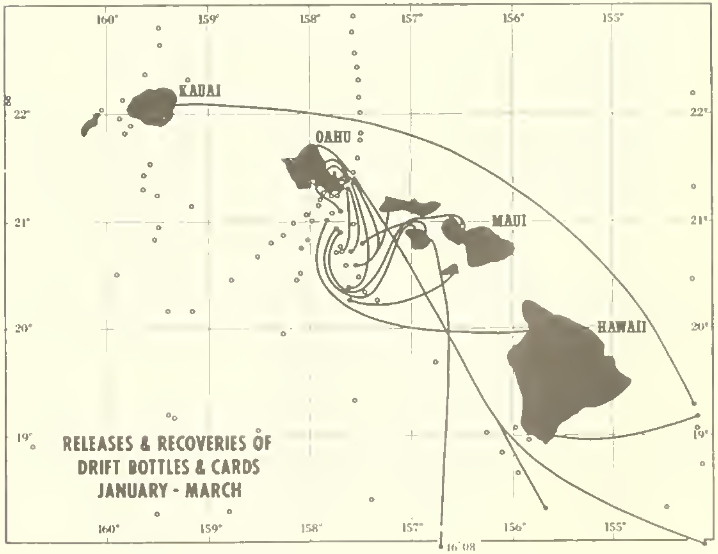

Figure 32.--Releases and recoveries of drift cards and drift bottles near the Hawaiian Islands, January through March in 1961, 1962, and 1963.

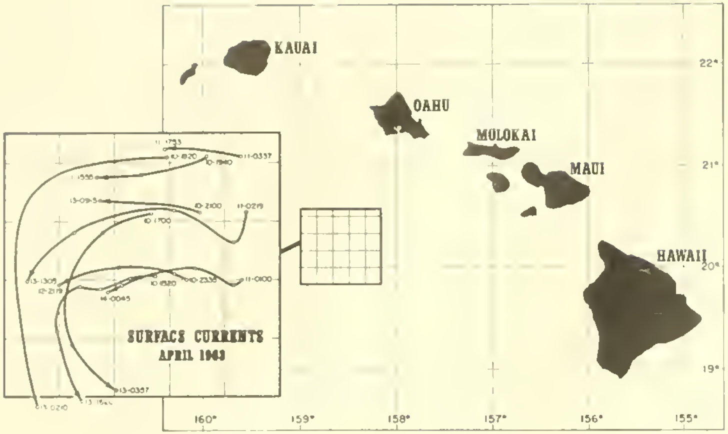

Figure 33.--Tracks of drogues placed in a large eddy near Oahu.

tank where ocean surface currents can be simulated by flowing a mixture of fresh water and sea water over a heavier layer of sea water which fills the tank to within an inch or less of sea level on the model. The currents then can be marked with dye and photographed for later analysis. Preliminary results from the model show eddies and other features of the near-surface currents agreeing well with field observations. The model has the important advantage of making it possible to study events that take place simultaneously over large areas, instead of point by point, as in field work. At the same time, conditions such as current speed, angle between the current and the island chain, and depth to which the near-surface current extends can be varied in the model, with the result that events requiring weeks to develop in nature occur within minutes in the scale model.

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