YALE
PEABODY
MUSEUM

**P.O. BOX 208118 | NEW HAVEN CT 06520-8118 USA | PEABODY.YALE. EDU**

## JOURNAL OF MARINE RESEARCH

The *Journal of Marine Research,* one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The *Journal of Marine Research* has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the *Journal of Marine Research*.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
https://creativecommons.org/licenses/by-nc-sa/4.0/

# CONSIDERATION OF MIDOCEAN FISH PRODUCTION AS RELATED TO OCEANIC CIRCULATORY SYSTEMS

By

OSCAR E. SETTE

*Director, Pacific Oceanic Fishery Investigations*
*U. S. Fish and Wildlife Service*

The sea receives most of the radiant energy reaching the earth simply because there is more sea than land, especially in middle and low latitudes where the angle of incidence is greatest and the loss by reflection is least. Therefore, so far as total absorption of energy is concerned, the sea's productive capacity should greatly exceed that of the land. Indeed Riley (1944) has estimated carbon production in the sea to be about 86% of the total carbon production on the earth, both land and sea combined. Steemann-Nielsen (1952), by a different method of measuring carbon fixation in sea water, arrived at a much lower rate of production, but even this lower rate would leave the production capacity of the sea equal to that of the land.

By contrast, man's total harvest of organic material from the sea is at least a whole order of magnitude lower than that from the land. Practically all of this harvest is taken from the margins of the sea. The oceanic part, beyond a depth of 1,000 m, comprises nearly 90% of the sea area, and from this major portion man's present harvest is trivial.

It is proposed in this essay to examine the means by which man may extract some of the organic wealth from this major pelagic fraction of the sea. Illustrative material will be drawn from what I believe to be the first attempt to focus scientific effort of nearly adequate scale directly on this problem. For this reason, it will be convenient to use a narrative arrangement, and consideration will be limited to the oceanic middle and low latitudes of the Pacific Ocean and to the extraction of organic materials in the form of edible fish.

The scientific effort to which I refer is the activity of the Pacific Oceanic Fishery Investigations of the U. S. Fish and Wildlife Service, headquartered at Honolulu, Hawaii, and assigned to the task of investigating the high-seas fishery potential of the tropical and subtropical mid-Pacific waters. Three vessels, the Hugh M. Smith, the John R. Manning, and the Henry O'Malley, later replaced by the Charles H. Gilbert, have now been operating on this program for 4½ years. The first-named has performed most of the oceanographic work while the other two have been engaged primarily in assaying the fish stocks through systematic fishing surveys.

Hawaii is located near the middle of the sluggish westward-moving North Equatorial Current. In this Current a warm upper layer overlies the colder water and forms a two-layer system of persistent stability. Typically, the warm surface layer is at least 100 m thick and has a phosphate concentration of 0.2 to 0.4 $\mu$g-at/l; zooplankton is sparse, averaging 20 ml displacement volume per 1,000 $m^3$ in the upper 200 m layer as sampled with a 0.65 mm meshed net. Such waters are obviously an unpromising environment for supporting large fish stocks unless there exist situations where the vertical stability of the two-layer system is modified so that the underlying nutrient-rich water is mixed into the lighted upper layer in greater proportion than is prevalent in the North Equatorial Current.

It was our hypothesis that in situations of such modified vertical stability there would be chemical enrichment of the euphotic zone, supporting increased biological productivity and large stocks of fish, just as is true wherever there are mechanisms for enrichment in the marginal seas flanking the continents.

Three such situations have received varying degrees of attention during the last four years: the equatorial divergence-convergence system south of Hawaii; the boundary between the North Equatorial Current and the North Pacific Drift north of Hawaii; and the perturbations within the North Equatorial Current as it flows past or through the Hawaiian Islands group. Each of these involves a different physical mechanism for energy transformation into vertical motion: upwelling in the first situation; current interface shearing in the second; and eddies and wakes in the third. All of these situations appear effective for producing important concentrations of fish. Our knowledge regarding the first is now considerable. It is only fragmentary for the second and third. Even in the first situation there remain large areas of ignorance in our understanding of the physical and biological phenomena involved.

At the outset of our investigation, upwelling along the Equator, as recorded in the data of the Carnegie expedition of 1928–1929 and as interpreted by Sverdrup, *et al.* (1942; 710), appeared to be the most promising large-scale mechanism for producing concentrations of fish. Here, some kinds of fish should be abundant if our hypothesis was valid. It was hoped that these would include the two tropical and subtropical species of tuna that are of greatest commercial importance, namely the yellowfin tuna, *Neothunnus* *macropterus* Temminck and Schlegel, and the skipjack, *Katwuwonus pelamis* Linnaeus.

Accordingly we undertook an intensive study of the equatorial current system. It has now been under way for four years. In this period we have made 16 hydrographic traverses of the current system at various meridians from Long. 140° to 180° W. On all of these traverses, bathythermograph casts were added between stations, usually at 10-mile intervals, and about 30 additional BT sections were made on fishing voyages. These extend our knowledge of the detailed temperature field down to 900 feet as far east as Long. 110° W. Several of the hydrographic traverses extended to Lat. 24° N and one to 14° S. However, the rectangle between Long. 140° and 180° W and Lat. 12° N and 10° S has been the most thoroughly explored. On many of the traverses, zooplankton hauls were made with a conventional meter-net, hauled obliquely from the surface to 200 m, with the flow through the net measured by a current meter.

These observations proved that there was indeed an upward movement of water at the Equator (Cromwell, 1951) and that it was accompanied by a greater concentration of zooplankton (King and Demond, 1953) in the vicinity of the Equator than in adjacent higher latitudes.

Despite the consistent evidence of chemical enrichment accompanied by zooplankton abundance, extensive fishing trials made by the three principal methods used in the California commercial tuna fishery (live-bait chumming, purse-seining, and trolling) proved disappointing. Except for small areas in the immediate vicinity of the few low-latitude islands in the region, tuna were not caught in the zonal band of enrichment.

Faced with this contradiction, we employed a fourth fishing method heretofore used only by the Japanese. Known as the "longline," this consists of a mainline suspended from surface buoys at intervals and provided with baited hooks hung by dropper lines at intervals along the mainline. This gear is constructed in units, known as "baskets," which are joined end to end and which may extend many miles. In our survey fishing, 12 miles of line are set, with the buoy-line lengths and the slack in the mainline so adjusted that the hooks fish at various levels from 100 to 400 feet, or for all practical purposes, throughout the entire warm layer and down partly into the transition layer.

This method of fishing proved to be satisfactory for sampling the larger pelagic carnivores and gave results consistent with the oceanographic findings. It has now been employed to delineate the distribution of tunas over a rectangle of about 4,000,000 square miles

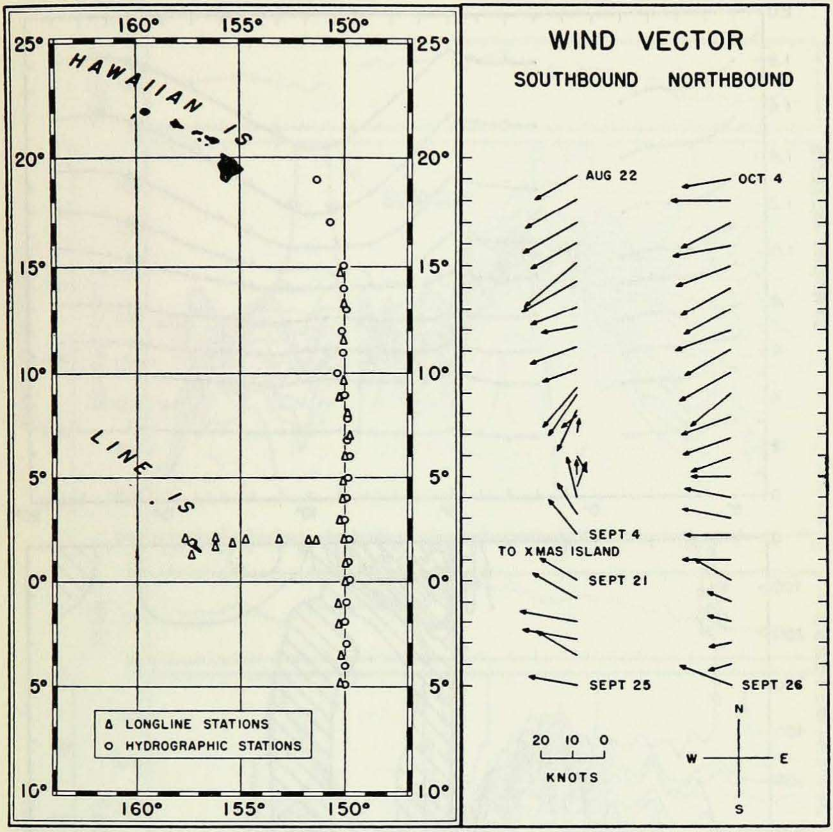

Figure 1. Hydrographic and fishing stations occupied by the Hugh M. Smith from August 22 to September 26, 1951 (left) and the average direction and force of the wind at intervals along her track (right).

from Lat. 10° N to 5° S and from Long. 110° to 180° W. Further, the efficiency of this gear, first thought to be too low for use in the American economic structure, has proved sufficiently high to support American commercial operations when such gear is used in the areas of the greatest concentration of tuna as delineated by our surveys.

The findings with this sampling instrument in relation to the equatorial current system may be illustrated by an example along Long. 150° W. During her Cruise 11 in August and September 1951, the Hugh M. Smith combined hydrographic, plankton, and longline operations along the track shown in Fig. 1. On the southbound traverse the winds were nearly typical for the region: northeast trade

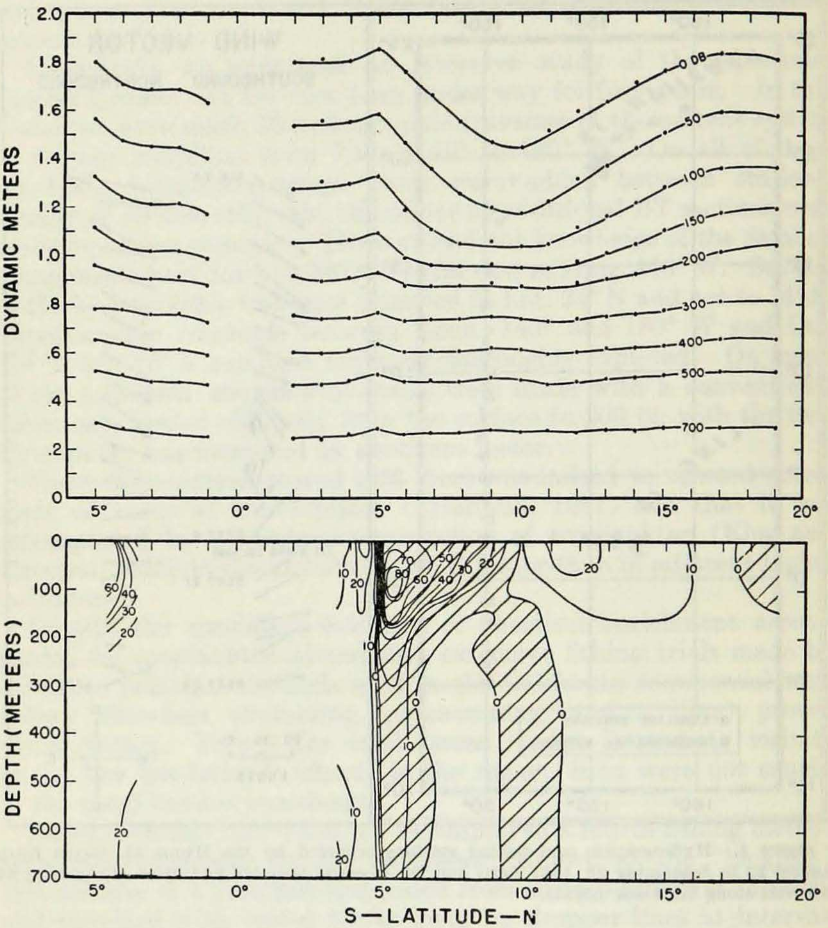

Figure 2. Dynamic topography (upper) and field of horizontal velocity (lower) inferred from geostrophic analysis of hydrographic data taken along the 150th W meridian by the Hugh M. Smith, August 22 to September 25, 1951. The unshaded portion represents flow to the west, the shaded portion flow to the east.

winds in the northerly portion of the traverse, southeast trade winds in the southerly portion, with light and variable winds between Lat. 5° and 9° N in a doldrum belt that separates the two trade wind systems. On the northbound traverse a month later, the doldrum belt was not in evidence, easterlies prevailed in the south, and the transition to northeast trade winds at 5° N was immediate. Geostrophic analysis (Fig. 2) of data from the northbound traverse

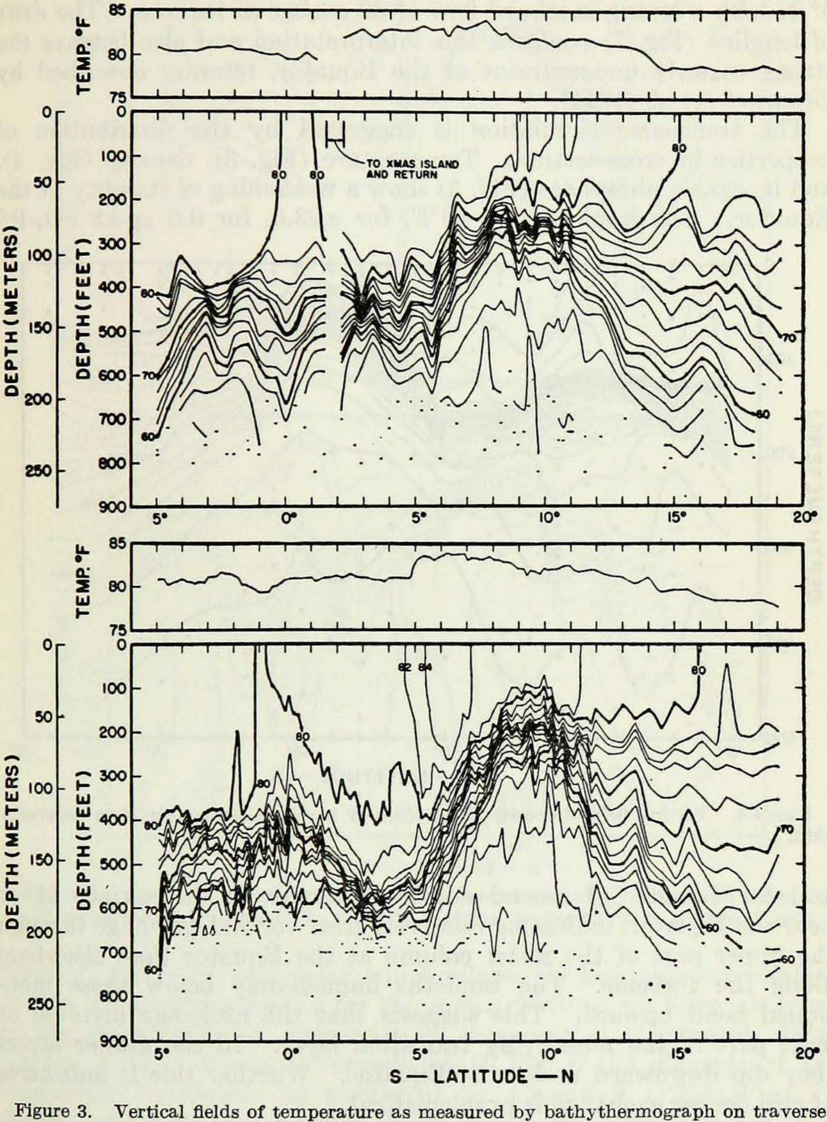

Figure 3. Vertical fields of temperature as measured by bathythermograph on traverses along the 150th W meridian: August 22 to September 25, 1951, southbound (upper) and September 26 to October 4, 1951, northbound (lower).

places the Countercurrent in its usual position between Lat. 5° and 9° N with a strong eastward flow of 80 cm/sec at its core. The drift of longline (Fig. 7) confirms this interpretation and also betrays the strong easterly undercurrent at the Equator, recently described by Cromwell, *et al.* (1954).

The transverse circulation is suggested by the distribution of properties in cross-section. Temperature (Fig. 3), density (Fig. 4), and inorganic phosphate (Fig. 5) show a weakening of stability at the Equator. The isopleths for 80°F, for $\sigma_t$23.0, for 0.6 $\mu$g-at $PO_4$-P/l and for 4.5 ml $O_2$/l ascend nearly vertically to the surface at or near the Equator, indicating relatively freer vertical exchange through the upper part of the water column at the Equator than elsewhere along the traverse. The isopleths immediately below those mentioned bend upward. This suggests that the exchange involves at least part of the underlying transition layer. In the deeper layers they dip downward under the Equator. Whether this is indicative of still deeper exchange is problematical.

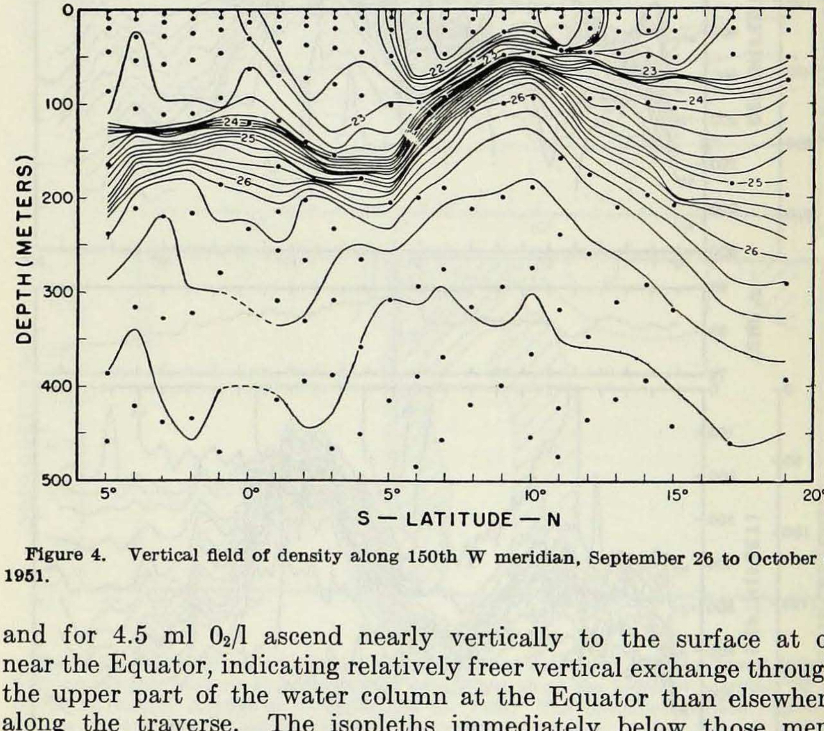

**Figure 4.** Vertical field of density along 150th W meridian, September 26 to October 4, 1951.

It is not my intention here to elucidate fully the dynamics of this transverse equatorial circulation. As already suggested, there are features of it which are only partially understood and others are not understood at all. However, Cromwell (1953) has offered a model,

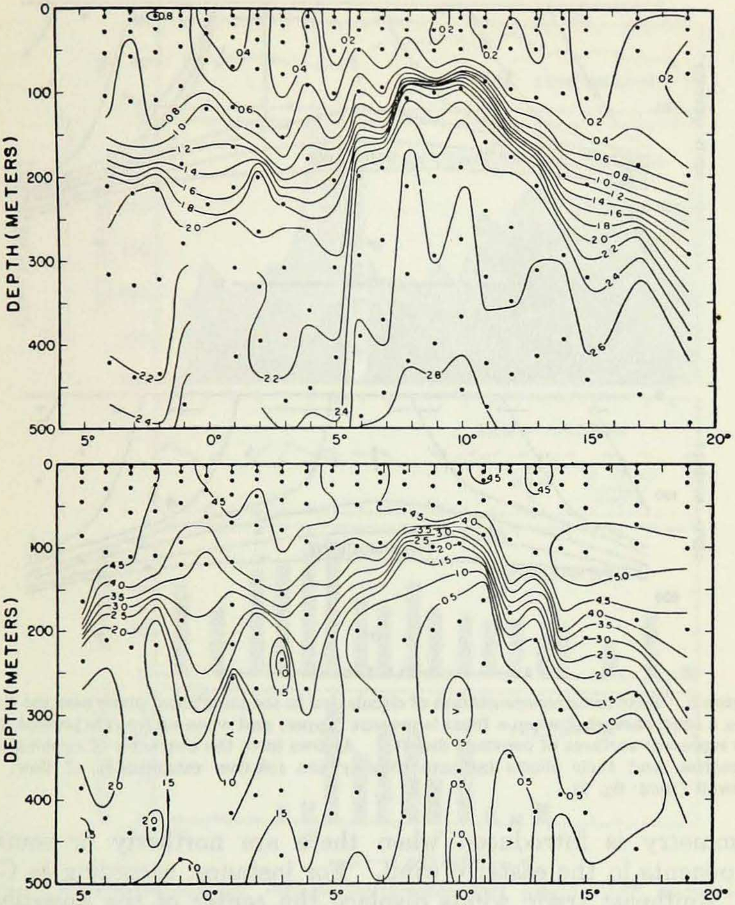

Figure 5. Inorganic phosphate in microgram atoms per liter (upper) and oxygen in milliliters per liter (lower) along the 150th W meridian, September 26 to October 4, 1951.

based on isentropic principles, which relates the transverse circulation to the winds and accounts for the major features we have observed in the distribution of properties in cross-section (Cromwell, 1954; Austin, 1954). We have reproduced in Fig. 6 the diagram of the transverse circulation as published by Cromwell (1953: Fig. 7). Briefly, the stress of easterly winds impels the surface water in a westerly direction at the Equator, but the Coriolis force north and south of the Equator tends to deflect the surface water poleward away from the Equator, where deeper water rises toward the surface.

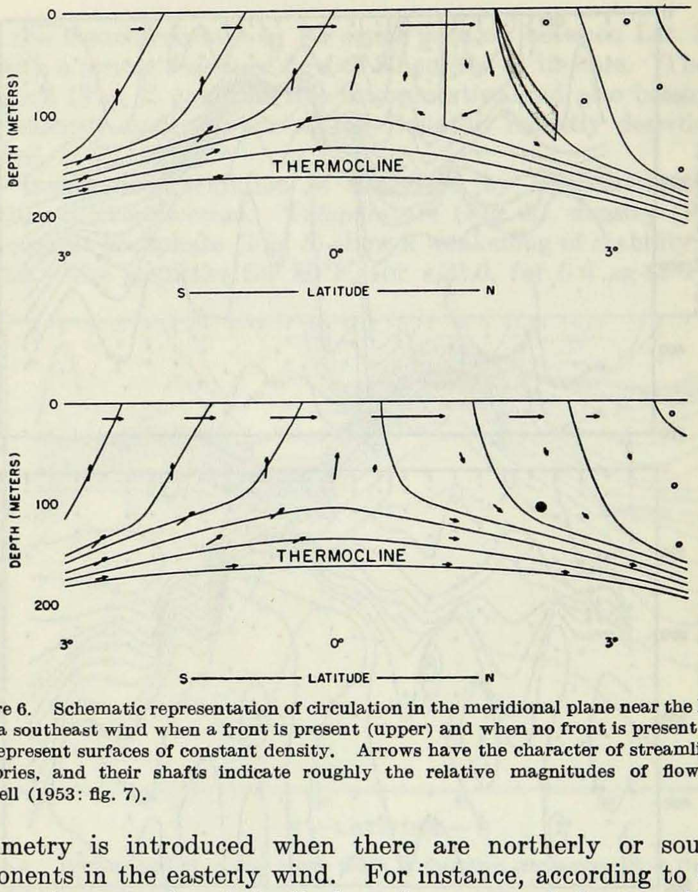

Figure 6. Schematic representation of circulation in the meridional plane near the Equator during a southeast wind when a front is present (upper) and when no front is present (lower). Lines represent surfaces of constant density. Arrows have the character of streamlines, not trajectories, and their shafts indicate roughly the relative magnitudes of flow. After Cromwell (1953: fig. 7).

Asymmetry is introduced when there are northerly or southerly components in the easterly wind. For instance, according to Cromwell, southeast trade winds displace the center of the upwelling to the south of the Equator. This appears to have been the condition during Cruise 11 of the HUGH M. SMITH.

North of the Equator the upwelled water probably sinks, forming a zone of convergence between the center of the upwelling and the southern edge of the Countercurrent. Fronts are sometimes present in this convergence zone. The sinking water may return southward at deeper levels, thus completing a cell, or it may continue northward, diving under the Countercurrent. In the latter event, associated movement in other directions would be required by the principle of continuity.

When the zooplankton and fish catches along Long. 150° W are compared with the temperature section (Fig. 7), it is seen that the

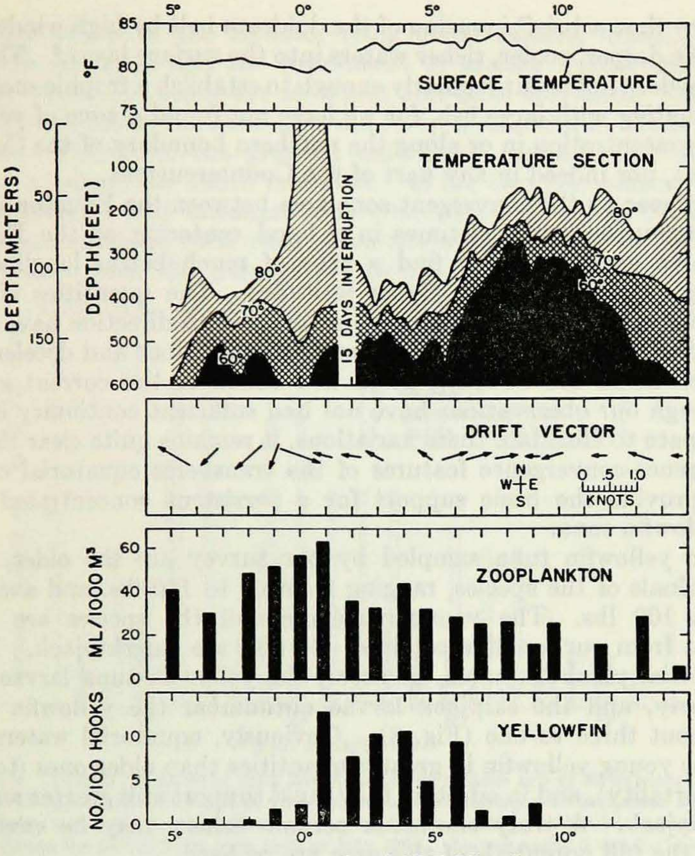

**Figure 7.** Surface temperature, vertical temperature field, longline drift, zooplankton abundance in the upper 200 m, and the yellowfin tuna catch along Long. 150° W, August 22 to September 25, 1951.

plankton concentrations are high in the vicinity of the Equator and that the tuna concentration is high in the zone of convergence. The displacement of the tuna northward from the plankton maximum is not unexpected since at least one trophic level (small fishes, crustacea, and squids) intervenes in the food chain.[1]

True upwelling seems to be absent at the northern boundary of the Countercurrent, though the transition layer here ascends so near the

---

[1] A speculative discussion of this displacement and also of the lack of a comparable tuna concentration south of the Equator was given at the 8th Pacific Science Congress (Sette, in press).

surface that a brief[2] invasion of the doldrum belt by high winds might stir the deeper, cooler, richer waters into the surface layer.[3] This evidently does not occur regularly enough to establish a trophic succession culminating with large fish, for we have not found a zone of yellowfin tuna concentration in or along the northern boundary of the Countercurrent, nor indeed in any part of the Countercurrent.

However, in the convergent zone area between the Equator and the Countercurrent, or sometimes in a band centering at the Equator, we have never failed to find a zone of much better longline tuna fishing than at adjacent higher latitudes. The quantities of catch and the positions of the zone in the north-south direction have varied considerably,[4] probably in response to accelerations and decelerations as well as to the swaying north and south of the current system. Although our observations have not had sufficient continuity in time and space to elucidate these variations, it remains quite clear that the divergence-convergence features of the transverse equatorial circulation provide the basic support for a persistent concentrated stock of yellowfin tuna.

The yellowfin tuna sampled by our survey are the older, larger individuals of the species, ranging from 60 to 180 lbs. and averaging about 100 lbs. The younger members of the species are nearly absent from our longline catches. So also are the skipjack. In our equatorial plankton hauls, however, the yellowfin tuna larvae occur regularly, and the skipjack larvae outnumber the yellowfin larvae by about three to one (Fig. 8). Obviously, equatorial waters must harbor young yellowfin in greater quantities than older ones (to allow for mortality), and in addition they must support still greater numbers of skipjack. A truly enormous oceanic fishery may be envisioned when the full potentials of this area are realized.

The east-west extent of the equatorial stock is limited only by the two continents, which at the Equator lie 10,000 miles apart. To be sure, this entire extent does not enjoy the high concentration we have found south of Hawaii. This concentration seems to be the consequence of the unequal stress of the easterly winds along the Equator. According to Cromwell's model, the upwelling should occur along

[2] The probably short-lived invasion by moderate northeast winds during the northbound traverse of the HUGH M. SMITH apparently was without discernible effect on the vertical distribution of phosphate.

[3] This may have happened sometime prior to July 1952, for in that month unusually high plankton catches were taken in and immediately north of the Countercurrent along Long. 140° W. This is the only instance of such catches among the many zooplankton sections we have made across the Countercurrent.

[4] Some examples are given by Murphy and Shomura (1953).

the entire extent of the Equator lying under easterly winds, but it should be strongest and the enrichment of surface waters should be greatest where the winds are strongest and most sustained. According to Pilot Charts, the average wind force is maximal at about Long. 120° W. Therefore, the greatest enrichment should occur on the average at about the 120th meridian. If the two phenomena, maximal enrichment and maximal tuna concentration, are in cause and effect relationship to each other, then the westward flow of the water concurrently with the passage of the biota through at least three trophic levels (phytoplankton, zooplankton, and smaller nekton) should have rates in reasonable relation to the distance involved. A parcel of water travelling westward from Long. 120° to 150° W at the rate of ½ to 1 knot (an estimate based on drift of longline in the convergence zone just north of the Equator) would be carried 1,800 miles to the zone of best tuna fishing in about 75 to 150 days. Whether or not this is a reasonable period of time for the three trophic levels of development is a speculative question. It does not appear to be fantastic, however, and it is the most cogent explanation I can offer for the special concentration of tuna at Long. 150° to 170° W (Fig. 9).

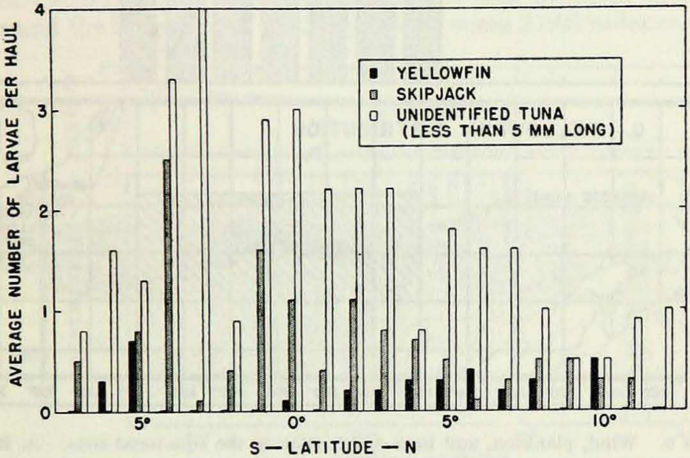

Figure 8. Average numbers of tuna larvae taken per oblique tow of 30 minutes duration through the upper 200 m layer with a one-meter tow-net having 0.65 mm mesh apertures. The samples were collected along various longitudes from 140° to 180° W and in various months during the period from June 1950 to July 1952. Larvae under 5 mm in length were not identified as to species.

This concentration of tuna directly south of Hawaii is now undergoing development as a commercial tuna fishery resource by American fishermen. The lesser concentrations of yellowfin tuna lying west

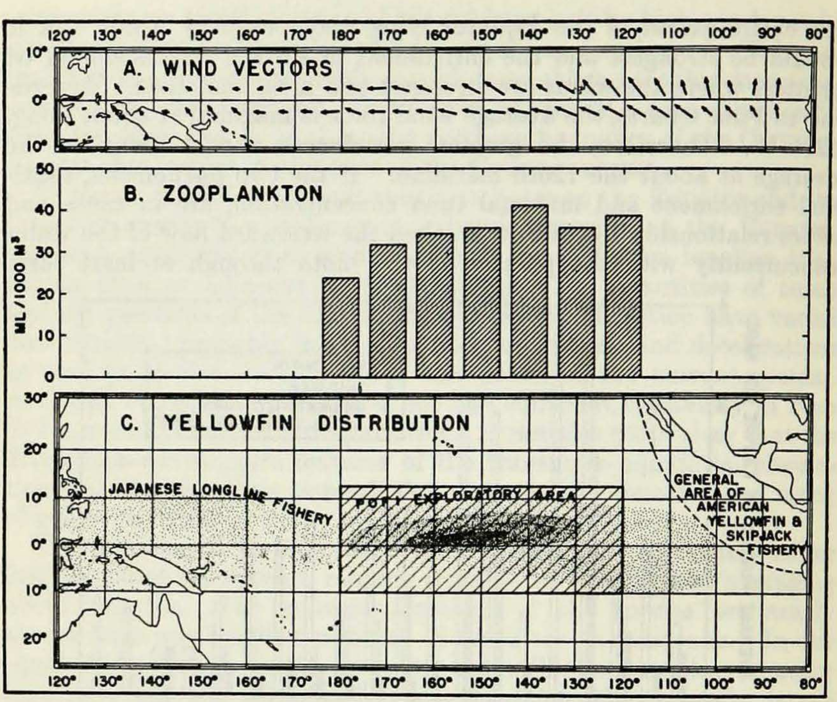

Figure 9. Wind, plankton, and tuna distribution in the equatorial zone. *A.* Resultant wind vectors were computed as the weighted means of frequency and speed from the several compass points for 5-degree squares bordering the Equator as published in the U. S. Hydrographic Office Pilot Chart for the North Pacific for August 1952; the arrows point in the direction of travel and their shafts are propertional to the weighted mean speed. *B.* Mean plankton volumes at several longitudes were computed as the mean of all hauls taken between Lat. 5° S and 10° N at or near the given longitude. *C.* Distribution of yellowfin tuna in the mid-Pacific equatorial region is estimated from longline catches. The light stippling in the POFI area represents less than three yellowfin tuna per hundred hooks, the heaviest represents more than nine per hundred hooks, and the intermediate stippling represents intermediate catching rates. For orientation as to location and area, the extensive band of light stippling represents the area of the Japanese prewar longline fishery; the dashed outline shows the area of the American west coast live bait and purse seine fishery for yellowfin and skipjack tuna. Since preparation of the above chart, a line of fishing stations along Long. 110° W has proved the continuity of the band of yellowfin tuna across the "unexplored area."

of the 180th meridian are already commercially useable in the Japanese economy. The lesser concentration to the east of Long. 150° W should ultimately be useable in the American economy when oceanographic advances make the finding of local concentrations within the convergence zone more sure and when technological advances make the fishing methods more efficient. It is perhaps not overly optimistic to say that a vast oceanic fishery resource is well on the way toward full utilization.

This initial success of our hypothesis as a working tool for discovering fishery potentials in the oceanic two-layer system encouraged us to extend this type of approach in research to the second situation, the shear zone between the North Equatorial Current and the North Pacific Drift. In this more northerly latitude a cool-water tuna, the albacore, *Germo alalunga* (Bonnaterre), may be expected. Indeed, the Japanese have already developed a fishery for this species in the western Pacific between Lat. 30° and 40° N and between their home islands and the longitude of Midway Island some 2,500 miles eastward.

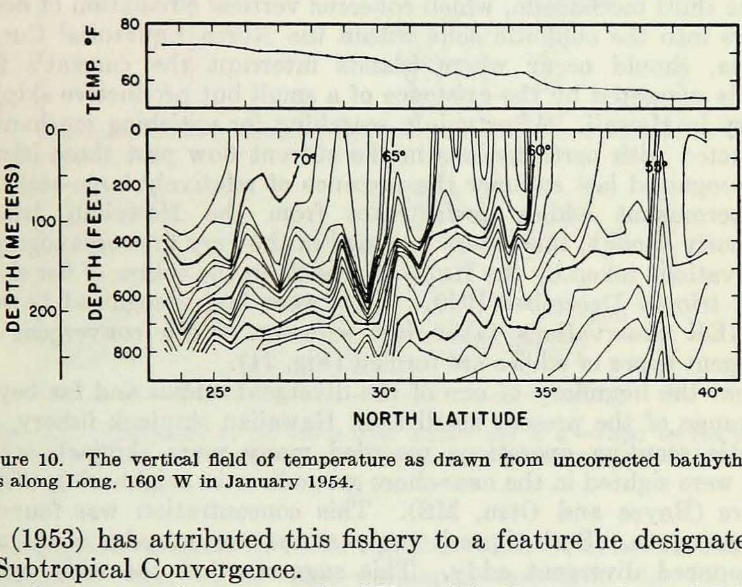

**Figure 10.** The vertical field of temperature as drawn from uncorrected bathythermograms along Long. 160° W in January 1954.

Uda (1953) has attributed this fishery to a feature he designates as the Subtropical Convergence.

Our first reconnaissance north of Hawaii in January through March 1954 crossed the North Equatorial Current into the North Pacific Drift along 10 meridional lines between Long. 140° and 165° W. The data from these crossings are not yet processed.[5] A preliminary temperature section (Fig. 10), drawn from uncorrected bathythermograph recordings, suggests a broad zone of complex thermal structure with most pronounced transitional features at Lat. 34° N. In several instances the bunching of isotherms in their vertical ascent from the

[5] The fishery research vessel N. B. SCOFIELD of the California Department of Fish and Game, in cooperation with the Scripps Institution of Oceanography, made four more meridional sections between 140° W. longitude and the American west coast.

transition layer to the sea surface may result from eddy fragmentation in the shear zone. Their significance to vertical exchange must await further study. Between Lat. 30° and 35° N the longline fishing gave evidence of abundant fish life, including bigeye tuna, *Parathunnus sibi* Temminck and Schlegel, a species presently not considered a good canning variety, sharks, lancet fish (*Alepisaurus* sp.), and miscellaneous others including what is probably a new species of pelagic sting ray. At 34° on this section an outstanding catch of albacore was made. It seems quite likely, therefore, that we have here a general locality where the second type of vertical circulation provides the potentials of a fishery.

The third mechanism, which concerns vertical circulation of deeper waters into the euphotic zone within the North Equatorial Current system, should occur where islands interrupt the current's flow. This is suggested by the existence of a small but productive skipjack fishery in Hawaii. After vainly searching for enriching mechanisms connected with perturbations in the current flow past these islands, we recognized last summer the presence of relatively large-scale and semipermanent eddies downstream from the Hawaiian Islands. Curiously enough, these were recorded in the very first oceanographic observations taken by the HUGH M. SMITH in the course of her shakedown trip in December 1949. They were first recognized however by GEK observations taken last summer. Both convergent and divergent types of eddies are formed (Fig. 11).

Near the boundary of one of the divergent eddies and far beyond the range of the present small local Hawaiian skipjack fishery, systematic scouting operations recorded many more skipjack schools than were sighted in the near-shore grounds or in neighboring offshore waters (Royce and Otsu, MS). This concentration was found on two occasions. Both times it was near the western edge of the most pronounced divergent eddy. This suggests that the eddy system has within it a train of physical and biological events of significance to the support of the fish. Also, the finding of these concentrations well outside the range of the present fishery suggests further that the productivity of this middle portion of the North Equatorial Current has potentials far beyond those suggested by the existing small local fishery.

Thus it appears that there are three situations in oceanic waters where the two-layer system is sufficiently modified to permit the vertical exchange necessary for supporting commercial fish stocks. Others may become apparent as our knowledge increases.

In comparison with the fisheries of marginal seas, the utilization of such oceanic fishery resources affords special opportunity for

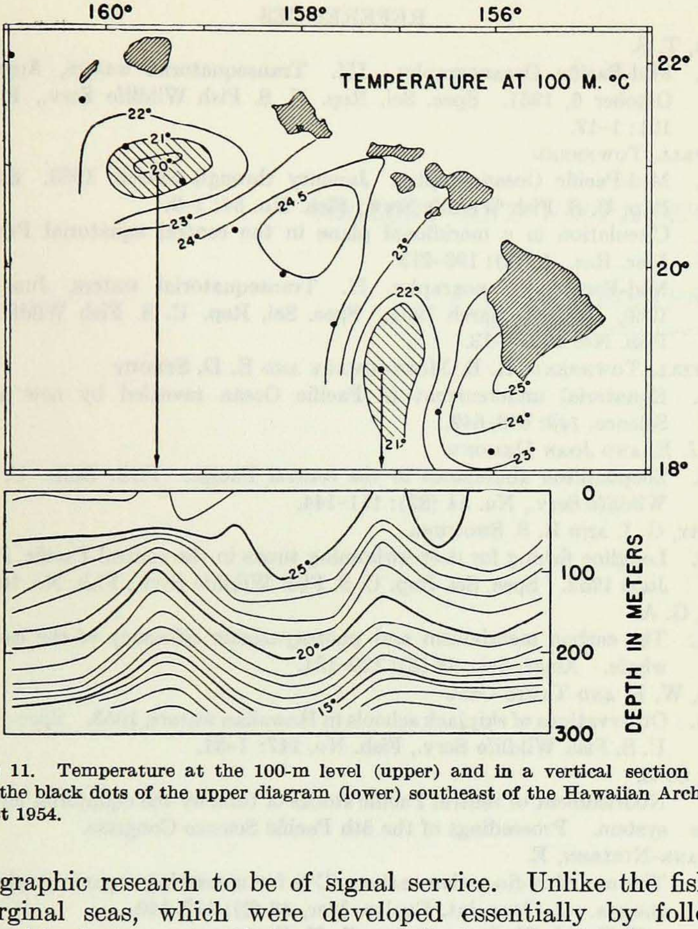

Figure 11. Temperature at the 100-m level (upper) and in a vertical section passing through the black dots of the upper diagram (lower) southeast of the Hawaiian Archipelago in August 1954.

oceanographic research to be of signal service. Unlike the fisheries of marginal seas, which were developed essentially by following topographic features to their seaward limits, the development of oceanic fisheries requires launching out beyond topographical landmarks literally into the deep blue. Success in locating fish resources in the deep blue does not reward the hit or miss method. Past ventures in the hands of so-called practical fishermen have proved this for the oceanic Pacific. At least four such ventures, incurring millions of dollars of expenditure, took place during the five years preceding the commencement of our work. None was successful. Fishermen's lore, evolved in the topographical setting of marginal seas, is not effective for guidance in oceanic fishing. Oceanographic research, on the other hand, promises to be effective in providing the needed guidance.

## REFERENCES

Austin, T. S.

1954. Mid-Pacific Oceanography. III. Transequatorial waters, August 20–October 6, 1951. Spec. Sci. Rep. U. S. Fish Wildlife Serv., Fish. No. 131: 1–17.

Cromwell, Townsend

1951. Mid-Pacific Oceanography. January through March, 1950. Spec. Sci. Rep. U. S. Fish Wildlife Serv., Fish. No. 54: 1–9.

1953. Circulation in a meridional plane in the central equatorial Pacific. J. Mar. Res., *12* (2): 196–213.

1954. Mid-Pacific Oceanography. II. Transequatorial waters, June–August 1950, January–March 1951. Spec. Sci. Rep. U. S. Fish Wildlife Serv., Fish. No. 131: 1–13.

Cromwell, Townsend, R. B. Montgomery and E. D. Stroup

1954. Equatorial undercurrent in Pacific Ocean revealed by new methods. Science, *119:* 648–649.

King, J. E. and Joan Demond

1953. Zooplankton abundance in the central Pacific. Fish. Bull. U. S. Fish Wildlife Serv., No. 54 (82): 111–144.

Murphy, G. I. and R. S. Shomura

1953. Longline fishing for deep-swimming tunas in the central Pacific, January–June 1952. Spec. Sci. Rep. U. S. Fish Wildlife Serv., Fish. No. 108: 1–32.

Riley, G. A.

1944. The carbon metabolism and photosynthetic efficiency of the earth as a whole. Amer. Sci., *32* (2): 129–134.

Royce, W. F. and Tamio Otsu

1955. Observations of skipjack schools in Hawaiian waters, 1953. Spec. Sci. Rep. U. S. Fish Wildlife Serv., Fish. No. 147: 1–31.

Sette, O. E.

In press Nourishment of central Pacific stocks of tuna by the equatorial circulation system. Proceedings of the 8th Pacific Science Congress.

Steemann-Nielsen, E.

1952. The use of radio-active carbon ($C^{14}$) for measuring organic production in the sea. J. Cons. int. Explor. Mer, *18* (2): 117–140.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming

1942. The oceans, their physics, chemistry, and general biology. New York: Prentice-Hall, Inc. 1087 pp.

Uda, Michitaka

1953. On the convergence and divergence in the NW Pacific in relation to the fishing grounds and productivity. Bull. Jap. Soc. Sci. Fish., *19* (4): 435–438.