

TUNA OCEANOGRAPHY PROGRAMS IN THE TROPICAL CENTRAL AND EASTERN PACIFIC

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As recently as a decade ago, knowledge of the biology and ecology of the tropical tunas was almost entirely lacking. In the subsequent period substantial research programs have been initiated, in the Central and Eastern Pacific, which have gone a long way toward elucidating the ways of life of these very important pelagic fishes. The major features of their life histories have been described in a general way, and fair progress has been made toward understanding their population structure and population dynamics, in some regions at least. At the same time fairly broad studies in physical, chemical and biological oceanography have led to some understanding of features of their oceanic environment which control, in part, their distribution and abundance, or, at least, have brought out some relationships between the occurrence of the tunas and features of the environment which appear to be of predictive value.

In speaking of the "tropical" tunas, I refer to the yellowfin tuna, *Thunnus (Neothunnus) macropterus*, and the skipjack, *Katsuwonus pelamis*, both of which occur right across the equatorial Pacific between, approximately, the isotherms of 20°C. In these tropical waters there also occur bigeye tuna, *Thunnus (Parathunnus) sibi*, and sometimes, in deeper, cooler subsurface layers, the temperate-water albacore, *Thunnus germon*.

Some preliminary field observations on the tropical tunas were made by scientists of the U.S. Fish and Wildlife Service in waters off Central America, and in the Central Pacific south of Hawaii and westward through the Trust Territories, in 1947 and 1948, aboard fishing vessels of the Pacific Exploration Company. However, systematic, large-scale research was not initiated until 1949 when the Pacific Oceanic Fishery Investigations (POFI) were established by the U. S. Fish and Wildlife Service at Honolulu. This laboratory has, since then, conducted extensive studies during several years of the tropical tunas in the equatorial region to the south of Hawaii, and detailed studies in the vicinity of the Hawaiian Islands, as well as research in the region about the Marquesas and Society Islands, south of the equator.

In 1951, the Inter-American Tropical Tuna Commission commenced investigations of the tuna resources of the tropical Eastern Pacific in the region of the large commercial fishery off the west coast of the Americas. These investigations are directed toward the classic "conservation" problem, the elucidation of the effects of the fishery and of natural, fishery-independent factors on the tuna populations, as a basis for management of the fishery. It was realized from the

beginning that such investigations could not be very fruitful unless we obtained some understanding of the ecology of the tunas, in consequence of which investigations of the physical, chemical, and biological oceanography of the Eastern Pacific have constituted an important part of the Commission's continuing research program and have been indispensable in understanding the spatial and temporal variations in the occurrence of the tunas. The Commission, fortunately, established its headquarters at the Scripps Institution of Oceanography (SIO) which has made possible very fruitful cooperation with the staff of that institution in studying the oceanography of the Eastern Pacific in relation to the ecology of the tropical tunas.

By 1957, the researches had progressed sufficiently to indicate to the tuna fishing industry that a more detailed understanding of some features of the oceanography of the Eastern Pacific could be expected to be helpful in directing the operations of the fishing fleet to locate and catch tuna more rapidly. The U. S. Fish and Wildlife Service, therefore, two years ago provided funds for a group of scientists of the Scripps Institution (headed by Dr. Maurice Blackburn) to commence working intensively on this particular avenue of investigations.

Meanwhile, the government of Peru, off the shores of which occurs a very rich fish fauna due to the biological effects of the Peru Current, and whose fisheries have been growing very rapidly, also established in 1957 a research organization, the Consejo de Investigaciones Hidrobiológicas, first under the direction of Dr. Warren Wooster, and now under Dr. Zacarías Popovici, to study the fisheries oceanography of that region.

From the results of these various investigations we are beginning to understand some of the relationships of the tropical tunas to their environment, but there are yet many interesting unsolved problems. One important environmental factor appears to be food, since there has been shown, both in the equatorial Central Pacific and in the tropical Eastern Pacific, a good correspondence between the abundance of the tunas and the production of organisms lower in the food chain, related to the enrichment of the euphotic zone by nutrient-rich water from deeper layers. At the extremes of their ranges, in the Eastern Pacific at least, there also appears to be a direct effect of temperature on the tropical tunas. Other variations in the occurrence of the tropical tunas seem to be related to oceanographic phenomena of other kinds, but no good understanding of these is yet available.

TUNA ABUNDANCE IN RELATION TO FOOD SUPPLY

The tropical ocean, in general, tends to be a two-layer system of persistent stability, with the upper mixed layer separated by a strong pycnocline from the lower layer, and lacking the seasonal renewal of the upper layer which occurs in high latitudes due to the annual thermal cycle. In these circumstances, much of the upper layer in the tropical seas becomes depleted of nutrients and is, therefore, a biological desert where a few poor organisms barely survive. In some places, however, the winds and currents cause upwelling or upward mixing of deeper water into the upper, sun-lit zone, and here there is high biological production, leading to large crops of phytoplankton, zooplankton, forage organisms, and finally the large carnivores such as the tunas.

One such situation has been beautifully documented by the Pacific Oceanic Fishery Investigations in the equatorial Central Pacific. The stress of the southeast trade winds, plus the Coriolis force north and south of the equator, causes a divergence of the South Equatorial Current along the equator, bringing to the surface nutrient-rich water which moves westward and away from the equator. North of the equator there appears to be a zone of convergence near the southern boundary of the Equatorial Counter Current. Due to unequal wind stress at different longitudes along the equator, the upwelling is most intense near the 120th meridian. The standing crops of zooplankton have been found to be maximal some distance downstream from this meridian, their abundance being greatest at about 150° to 160°W longitude (nearly due south from Hawaii), and displaced to the north of the equator. The yellowfin tuna, as shown by longline catches, are most abundant near the area of zooplankton maximum, but perhaps displaced somewhat further to the north. These observations are consistent with the hypothesis that the tuna are most abundant where their forage is best, and that this occurs as a consequence of the equatorial upwelling, but "downstream" thereof, due to the water's drift during the time between fertilization by upwelling and the production of tuna forage.

It further appears that this system is not entirely steady, but that the upwelling varies in extent both within years and between years. Fishing trials and temperature observations near Christmas Island (which is located a bit north of the equator in the rich fishing zone) over several years indicated that the abundance of yellowfin tuna at this locality was directly correlated with surface water temperature. This was interpreted to mean that when the water was "older", that is a longer time had elapsed since enrichment by upwelling, allowing more time for the development of tuna forage, it provided a better feeding area for the tuna. If this interpretation is correct, one would expect associated changes in biological factors, such as zooplankton volumes, and also one would expect increased tuna catches north and west of Christmas Island during cold periods near the

island. Data of this sort, however, have not yet been published.

In the Eastern Pacific, near the eastern boundary, it has been found that the yellowfin and skipjack tuna are encountered in greatest abundance in regions where there are high standing crops of zooplankton, and Dr. Blackburn's group has also recently found that where there are high zooplankton volumes there are high volumes of tuna-forage organisms. It has, furthermore, been shown that the zooplankton crop is quite well correlated with phytoplankton (measured by chlorophyll) and basic productivity (measured by C¹⁴ uptake). The regions of high basic production, and consequent increased crops of organisms higher in the food chain, culminating in the tunas, are places where the euphotic zone is enriched by the upward admixture of nutrient-rich deeper water. The physical mechanisms of this enrichment are several, however. Along the coast of Baja California and along the coast of Peru the mechanism appears to be coastal upwelling induced by winds blowing more or less parallel to the coast toward the equator. Another zone of high production is off the Gulf of Guayaquil, which is at the boundary between the water of the Peru Current and the warmer, less saline water to the north. Whether the enrichment is due to mixing along this boundary, to nutrients brought down the Guayas River, or by other means not now known, is not understood.

Coastal upwelling may also occur in the Gulf of Tehuantepec during the winter months when strong winds from the north blow there. Recent studies, however, indicate that this may not be simple upwelling, but vertical mixing associated with the development of a cyclonic circulation and a thermal dome.

The high biological production off the coast of Central America is apparently due to upward mixing processes (not well understood) associated with the thermal dome located there. This dome, over which the mixed layer is characteristically less than 10 meters thick, is present at all times of year, though it may shift somewhat in position and extent, and at times extend right to the surface. Other areas with persistent or regular seasonal development of thermal domes occur off the coast of Colombia and off Cape Corrientes in Mexico. The hydro-dynamics of these features are not well understood, but their effects on biological productivity and on the abundance of tropical tunas in their vicinities are quite evident.

Smaller scale oceanographic features also appear to be of importance in causing local tuna aggregations. Both fishermen and scientists have often observed tunas, and other fishes as well, associated with surface temperature discontinuities, "tide rips", and slicks. Investigations of these features by scientists both at POPI and here at SIO have shown that these are surface indications of "fronts", marking the boundary between water masses of different temperature characteristics, and that along such fronts there is convergence, which results in accumulation of zooplankton organisms. It is believed that these, in turn, attract the predatory fishes. It is likely that certain oceanic areas, such as the region of the boundary

between the Peru Current and the more tropical waters to the north, or the boundaries of the Equatorial Counter Current, are especially likely places for the formation of fronts, and that such areas may, therefore, be favorable for the surface-feeding tunas. The mechanisms of fronts, their causes, and their geographic distribution deserve much more study.

It has been demonstrated that the tunas are much more abundant in the vicinity of islands and seamounts than elsewhere in the open sea. It has been hypothesized that these geological features modify the local circulation so as to result in higher biological production, but this hypothesis cannot be regarded as yet confirmed. Studies which we have made near Clarion Island and Shimada Bank do show some modification of the distribution of physical and chemical properties, and some increase in productivity and chlorophyll very near the island, but zooplankton volumes are not much, if any, higher than in the offshore waters near Clarion Island, although some increase was found over Shimada Bank. There is a possibility that benthic forms feeding directly on detritus or benthic plants may constitute an important part of the tunas' diet in such places and thus provide more forage with little or no increase in basic production (by utilizing a shorter food chain), but this has not been conclusively demonstrated. There is evidence of increased standing crops of zooplankton near Cocos and Clipperton Islands, but these locations have not yet been studied in detail.

POFI researchers have demonstrated the existence of a complex system of eddies on the downstream side of the Hawaiian Island chain, and that concentrations of skipjack seem to be associated therewith. Whether the association is because of effects on the tunas' food is, however, not clear.

The physical and biological effects of islands and seamounts is a very fruitful subject for further study.

TUNA AND TEMPERATURE

At the northern and southern extremes of their ranges, at least, the tropical tunas almost certainly respond directly to temperature changes. Off Baja California and California there are large crops of food organisms at all times of the year, yet the yellowfin tuna are found in commercial quantities only in waters of about 19°C and warmer (skipjack occur in somewhat cooler water, down to about 16°C). The seasonal appearance and disappearance of these tunas on the local "banks" off Baja California follows the march of the isotherms. In years, such 1957 and 1958, when the warm water extends further up the coast, the tropical tunas are likewise taken further north, and the persistence of warm water on the banks off Baja California beyond the normal season corresponds to a similar persistence in the occurrence of tuna catches. Analyses by G. Roden of SIO have indicated that the seasonal advance and retreat of these isotherms is due almost entirely to the balance of incoming and outgoing heat from the sea surface, advection of warm water being small or absent. There-

fore, it appears that an active migration of the tunas is involved.

The relationship of tuna and temperature is even more striking off Peru and northern Chile, although the hydrography has been less well investigated. Along the Peruvian and Chilean coast occurs cold, upwelled water associated with the Peru Current, extending to the vicinity of Cape Blanco, where the Peru Current turns west to become the South Equatorial Current. North of this is warmer, less saline water. Seasonally, each year in the early months, the warmer water moves further south, the extent and persistence of its southern movement being variable from year to year. It also appears that this warm water south of Cape Blanco is characteristically a fairly thin layer overlying colder water of the Peru Current. There is, furthermore, offshore from the Peru Current at more southerly latitudes again warm water, but of high salinity, in contrast to the low-salinity water to the north of about Cape Blanco. For reasons not yet understood, there frequently occur at certain fairly well defined locations, such as off Chimbote, Peru and off Iquique, Chile, tongues of this warm, high salinity water, extending in toward the coast, which at their inshore ends, at least, occur as thin layers over the cold Peru Current water. Tropical tunas are found in abundance only in the warm water; that from the north contains both yellowfin and skipjack, while the "tongues" off Chimbote and Iquique contain almost exclusively skipjack.

Some years the warm water from the north, and perhaps the warm water from offshore, are especially widespread and persistent in inshore areas. In such years, the so-called El Niño years, the tropical tunas are apparently much more widely scattered than in non-El Niño years, and also occur in abundance further to the south than normal.

Although it seems clear that the tunas in this region are directly influenced by temperature, and that the variability of the oceanographic circulation is a causative factor of the variations in the distribution of the tunas, we have no clear understanding of how and why the oceanographic changes occur. It is hoped that the continuing hydrographic studies of the Consejo de Investigaciones Hidrobiológicas, and other agencies, will elucidate them.

OTHER PHENOMENA

The tropical tuna research programs have also brought to light other variations in the occurrence of the tunas which are evidently related to variations in the oceanic circulation, but the way in which they operate is not yet understood.

In the near vicinity of the Hawaiian Islands the skipjack tuna appear high in abundance seasonally, from about May to October, and are in low abundance during the rest of the year, although there is little or no seasonal variation in food supply and the temperature is at all times of the year above the minimum for commercial abundance of this species in other regions. Furthermore, the abundance during the "season" varies markedly from year to year.

POFI investigators first found a rather good inverse correlation between the percentage of northeast trade winds during February to April and the skipjack catches of the following summer "season", over the years 1951 to 1956. Subsequently, it has been shown that there is a close relationship between skipjack catch in the Hawaiian fishery (on a weekly basis) and salinity, the skipjack occurring most abundantly when the water of lower salinity is present in the region. It has also been shown that the time of occurrence of the seasonal sharp temperature increase (which occurs in February and March each year) is well correlated with the tuna catch of the following summer "season"; the earlier the warming occurs the better the catch, over the years 1951 through 1958.

From these observations, POFI scientists have developed the following hypothesis: During the winter months the Hawaiian Islands are bathed by the waters of an extension of the Kuroshio Current, which are of relatively low temperature and high salinity. In the spring, there is a northerly movement of these waters and they are replaced by water, of lower salinity and higher temperature, of the California Current extension. Coincident with the movement of the boundary between these waters through the Islands, the skipjack appear in abundance. In years when the boundary does not move through the area, but merely approaches it, there is a poor summer fishery.

Why the skipjack are associated with the water of the California Current extension is not at all understood, but the observed relationship does seem to have fairly good predictive value. It is also possible that this might point the way to an offshore fishery to the southeast of the islands during the winter months.

This study is, of course, being further pursued.

POFI researchers have also conducted, during the past three years, studies of the tunas (primarily skipjack) of the Marquesas Islands area and simultaneous oceanographic investigations. These investigations have shown a marked seasonal cycle in skipjack abundance, which is highest in the southern summer (January-February), but which bears no currently understandable relationship to the hydrography. In a recent progress report, it has been written "Although the data do reveal a pronounced seasonal variation in the apparent abundance of skipjack in the Marquesan waters, we have been unable as yet to pin down the reasons for these variations. In general, indices of productivity are higher during the months when fish are least abundant. There are no evident seasonal variations in type or abundance of forage. As yet, the oceanographic data have not revealed any significant seasonal variations in circulation features, such as those described for Hawaiian waters".

FUTURE DEVELOPMENTS

I would sum up the present status of our tuna oceanography programs about as follows: Broad surveys of the circulation and distribution of physical,

chemical, and biological properties and of the tuna distributions are fairly adequate. A start has been made on more detailed studies of some smaller-scale features which appear to be of importance to tuna ecology, but very much more needs to be done. Likewise, temporal variations on both the large scale and small scale have only begun to be studied.

Perhaps the greatest need for making progress both on the study of particular features, such as the hydrodynamics of thermal domes or island effects, and for studies of temporal variations, is for better means of data collecting. Collecting observations from ships is expensive and not very satisfactory, because the observations lack both synopticity and continuity. In those cases where semicontinuous observations have been possible, such as the Hawaiian temperature and salinity series, or sea-surface temperature series which it has been possible to piece together from merchant vessel and fishing vessel observations, a great deal has been learned that could not have been obtained with any reasonably small number of research ships. Unfortunately, we now are able to get time series of quasi-synoptic data for only a few parameters at the sea surface from merchant vessel observations. Likewise, data from shore and island stations are of limited utility, because they are seldom located where we want them, and, in any case, need to be supplemented by data from further offshore. The crying need is for observing stations which can be operated, where we want them, at modest expense, for both short and long time periods, and which can make continuous observations both at the surface and to depths of at least a few score meters.

Fortunately, the same need has become evident to people in other branches of oceanography. Consequently, both the tuna programs (particularly the Tuna Oceanography Program at SIO) as well as other programs related to military oceanography, marine meteorology, and basic research in physical oceanography, are supporting effort to develop unmanned stations which can be put where required and operated for both short and long time periods. The successful development of such unmanned data-collecting devices should make possible a great advance in the study of the sort of problems which are of special pertinence to tuna ecology.

CONCLUSIONS

The researches accomplished by tuna oceanography programs in the Eastern and Central Tropical Pacific during the past decade have made great progress toward elucidating the effects of the ocean circulation on the geographical and temporal variations in the abundance of the tunas, and have been indispensable to the understanding of the ways of life of these completely pelagic, high-seas fishes. Of special importance, to my mind, is the demonstration of how much can be accomplished by physical, chemical and biological oceanographers working in close cooperation toward joint objectives.