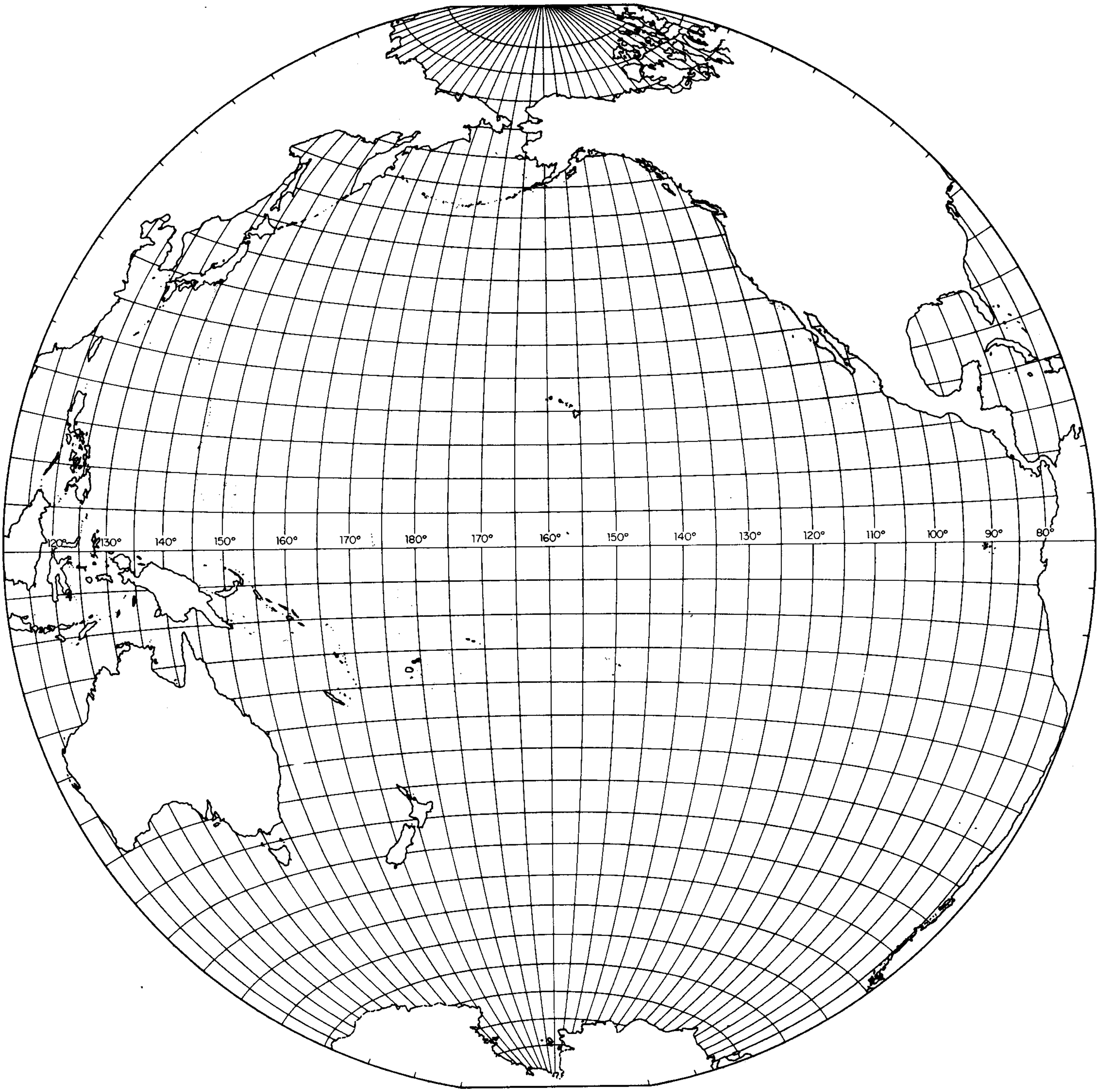
STATE OF CALIFORNIA
MARINE RESEARCH COMMITTEE



CALIFORNIA COOPERATIVE OCEANIC FISHERIES INVESTIGATIONS

REPORTS

VOLUME VIII
JANUARY, 1961

STATE OF CALIFORNIA
DEPARTMENT OF FISH AND GAME
MARINE RESEARCH COMMITTEE

CALIFORNIA COOPERATIVE OCEANIC FISHERIES INVESTIGATIONS

Reports

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Cooperating Agencies:
CALIFORNIA ACADEMY OF SCIENCES
CALIFORNIA DEPARTMENT OF FISH AND GAME
STANFORD UNIVERSITY, HOPKINS MARINE STATION
U. S. FISH AND WILDLIFE SERVICE, BUREAU OF COMMERCIAL FISHERIES
UNIVERSITY OF CALIFORNIA, SCRIPPS INSTITUTION OF OCEANOGRAPHY

1 January 1961

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LETTER OF TRANSMITTAL

January 1, 1961

EDMUND G. BROWN
Governor of the State of California
Sacramento, California

DEAR SIR: We respectfully submit the eighth report on the work of the California Cooperative Oceanic Fisheries Investigations.

The report consists of two sections. The first contains a brief review of the administrative and research activities during the period July 1, 1959 to June 30, 1960, a description of the fisheries, and a list of publications arising from the program. The second section is comprised of original scientific contributions. These papers are either the direct results of the CalCOFI research programs, or represent research directly pertinent to resource development in the pelagic realm off California.

Respectfully,

THE MARINE RESEARCH COMMITTEE
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PART I

REVIEW OF ACTIVITIES

July 1, 1959 - June 30, 1960

REPORT OF THE CALCOFI COMMITTEE

INTRODUCTION

It is the purpose of this review by the CalCOFI Committee to elucidate the present position of the program and to point out the directions in which the program is developing and our thinking is evolving. The objectives and statements of objectives of the CalCOFI program have been given much thought and expression during the life of the program, and, naturally, have evolved. In August 1960, the CalCOFI Committee reformulated the objectives as follows:

> To acquire knowledge and understanding of the factors governing the abundance, distribution, and variation of the pelagic marine fishes. The oceanographic and biological factors affecting the sardine and its ecological associates in the California Current System will be given research emphasis. It is the ultimate aim of the investigations to obtain an understanding sufficient to predict, thus permitting efficient ultilization of the species, and perhaps manipulation of the population.

This statement formalizes some aspects of such research that have long been recognized: first, that no pelagic fish, such as the sardine, can be studied in nature as a creature isolated from his natural associates; second, that there is an ultimate responsibility of such research to the needs of society and that this responsibility takes the form of an ultimate goal of attaining an understanding sufficient for the guidance of society in the utilization of the resource.

To examine this matter further, it is a responsibility of the scientist to ask questions of nature. In this case, to ask questions about pelagic fish: what is their food? how does it vary? what ultimately kills them? how is their spawning carried out? how successful is their spawning? what is the water like in which they live and how does it affect these creatures? and a myriad of similar important inquiries.

In addition, scientists in a program such as this have two further essential tasks. The first is to weld their findings with previous knowledge, thus furthering the general or basic understanding of the way nature functions in order that future questions can be formulated more meaningfully. At the same time, the scientist must be in a position to answer the questions of society to the best of his knowledge. Yet the needs of society change, and it is essential that these questions change to fit the changing needs. For example, what was once the important question to the CalCOFI program: how large will be the available sardine stock next year?—perhaps is not now so immediately important as is: what can be expected of the sardine stocks in the more distant future?; and: are there under-utilized stocks of fish that are complementary to the sardine, that is stocks that increase at a time of diminution of the sardine stocks and vice versa. Surely the changing answers that society needs in this area can best be drawn from the most general knowledge, extensive yet intimate knowledge on the stocks of pelagic fishes off our coast, their numbers, biology, needs, habits, fluctuations, and their fishery.

This matter of the dual obligations of the scientist who must integrate the findings, the scientific synthesist, has been discussed above at some length for it is this position of research that is occupied by the CalCOFI Committee, with an attendant duality of "masters." As the research progresses, the members of the CalCOFI Committee must look in both directions and attempt to answer both questions: how does a finding or line of inquiry help us understand the pelagic environment of the California Current System? and how does it help us answer the questions of society?

Rephrasing these thoughts to the conduct of research, the following emerges. Specialized research to answer an immediate question posed by society is a consumer of basic knowledge and understanding. This specialized research will be most successful when there is adequate basic knowledge, and, as a corollary, failure of the specialized research to supply society with significant practical results is most likely ascribable to inadequate basic understanding. It follows that the principal tasks of the CalCOFI Committee are to: develop projects to answer questions posed by the public to the extent that there is sufficient basic knowledge; and encourage research in disciplines and areas where lack of basic knowledge blocks the success of the program.

When the program was initiated it was realized that the principal lack was basic knowledge, so even though there was a most alarming and serious fisheries crisis, the originators and sponsors established the research on a broad fundamental basis. Because of this we are now approaching the answers to the original questions. Even more important we are also approaching a position from which we can answer a broad spectrum of questions about our pelagic resources. This is an important and happy aspect of this program of investigation, and its truth will be increasingly apparent in the discussion to follow.

FINDINGS

What have been the major findings and what is the picture that has emerged and is emerging from this inquiry?

We know that the sardine has not recently been a major component of the pelagic fish fauna of the California Current. It has often been a conspicuous component because of its habit of schooling relatively close to shore, but many other species of fish have been and are now greatly more abundant in the California Current waters. This includes several species of ecologically important deep-sea smelts, lantern fish, and the anchovy, hake, and jack mackerel, which are also commercially important.

From the years up to 1949 the sardine maintained a population comparatively larger than in more recent years, although the years of the earlier period were markedly varying in character, with warm and cold years and years of other character in alternation. During this period the populations of sardines and anchovies were about the same size, with anchovies possibly in slightly greater abundance.

The years of the decade beginning about 1948 to 1957 were, however, of a different character, relatively colder, but not so cold as some of the cold years of the previous two decades that produced good year classes of sardines. The outstanding characteristic of this recent decade was its relatively monotonous steadiness of temperature, winds and salinity. During this period, the population of sardines off California fell to new lows while the population of anchovies apparently reached new highs. Plankton volumes reached very high values during this latter decade, but it is doubtful if the food material in the plankton that is of value to the sardine increased similarly. In other words, much of the increased plankton consisted of jellies, salps, doliolids and pyrosomes that have little food value in themselves and, that as a matter of fact, compete with the sardine and anchovy for planktonic food.

Why then should the anchovy population increase while that of the sardine declined, and why should this occur when previously an occasional moderately-cold year produced a good year class?

This is possibly so because the anchovy spawns at a somewhat lower temperature than the sardine and at a more favorable season with respect to zooplankton food. In addition the anchovy may be better fitted to feed on phytoplankton than is the sardine, and, hence, can better compete with salps and other cold-water plankton.

In addition an important factor in the survival of sardine larvae is their opportunity to migrate to the coastal nursery grounds. That is, much of their larval mortality may consist of their being swept away into inhospitable waters from which they cannot return. The anchovy with its more northerly distribution along the Pacific Coast, has a greater opportunity for its spawn to remain in the California Current as larvae during periods of strong currents.

That these factors may be important ones is supported by a number of findings: Smaller year classes were produced during the years 1949-56, when the California Current was strong and steady and the good year classes were produced when the California Current was often weak and unsteady. In the period when sardine spawning was general along the entire Pacific Coast, the sardine larvae had a much improved opportunity to remain in the California Current and to reach the nursery grounds, much to the same degree as the anchovy now does, and sardine spawning was more successful.

Other tentative findings indirectly support this general picture. It appears that large sardine larvae are very spottily distributed. Thus, it is possible that good survival of the sardine larvae is not the result of general environmental conditions, but the combination of many favorable conditions and few unfavorable conditions in small patches in the ocean. One would expect such patchiness of favorable and unfavorable conditions to be more common in rapidly varying years than in steady years.

How does this hypothesis stand up under the most recent history? We believe that the years 1957 and 1958 were years much like those of the early period when sardine recruitment was strong. That is, they were variable years, warmer than average, with a decreased strength of the California Current, and a decrease of the northern forms. Yet in these two years the sardine apparently had only modest year classes!

Apparently a reversion to many of the conditions under which the sardine previously was successful did not result in a return of success to the sardine. The continued presence of a large population of anchovies was one conspicuous condition that did not reverse, and it is possible that this and other competitors are obstacles to the return of the sardine's success.

Superimposed on these physical and biological conditions is, of course, the effect of the fishery. Although the fishery may have little effect on the total amount of all forage fish, the selective nature of the fishery probably favors the survival of competitors of the sardine to some unknown degree.

This experience has led also to a greater understanding of the relationships between the large predaceous fishes that constitute one trophic level and the sardine and other plankton-feeding forage fish that constitute a lower trophic level. The yellowtail, barracuda, and bonito appear to be as abundant as ever. When the waters warmed up in 1957 these three species became available by moving into the range of the sportfishery, even though the sardine population and sardine fishery remained at a low level. The sardine population shifted northward *one year later* in 1958 and the commercial catch rose to 107,000 tons. Thus the predators in 1957 moved north in the virtual absence of sardines, presumably content with the other forage fish and the increased temperatures. Apparently these predators can do well if the total forage-fish population is adequate, that is they are not specific in their forage-fish associations.

Perhaps it is not inappropriate to reiterate here that it takes more than a large population of fish to guarantee good fishing, the fish must be where they can be caught. Apparently the populations of yellowtail, barracuda and bonito were just as high during the cool years, but they were abundant only off Mexico. Similar to many of the game species, sardines are located farther north during warm years and farther south during cool years. For example, the outstanding 1939 year class of sardines may have appeared larger than it actually was because it was so available as two-year old fish during the hot year, 1941. Clearly, availability of pelagic fishes is influenced by water temperatures.

Other vital parts of this picture are emerging; many of them long anticipated.

A particularly important finding is the verification of the existence of two genetically-separated populations of sardines—a northern group and a southern group. It has long been suspected that sardines off the central and lower Baja California Coast and the fish from the northern Baja and California Coasts were distinct stocks. Subsequently it has been found that some of the sardines in the southern area were fall spawners while those in the north spawned in the spring and summer. These may be the stocks that constitute the two genetically-distinct groups of sardines as determined by blood type.

There is reason to believe that it is the northern stock which has decreased most over the last decade. The southern group also migrates north, but in greater or lesser amounts depending on oceanographic conditions. The migrants contribute at least to the southern California fishery.

Also, it has been found that the major fluctuations of the oceanographic conditions of the California Current undoubtedly are a part of fluctuations involving most of the North Pacific if not the entire Pacific. These, in turn, appear to result from or to be associated with, major changes in the atmospheric circulation. Apparently, the events that trigger these changes take place some distance from the California Current System and as much as a year passes before the changes are fully felt on this coast. This gives real hope for prediction of oceanographic conditions, in a general way perhaps a year ahead.

There exists a basic aspect of the sardine problem that requires other answers intimately related to the public need. The most frequent question is: can man influence the future size of his catch or the population by voluntarily changing the harvest? That is, for example, by catching fewer or more sardines. This has been studied longer and with less satisfactory results than any other aspect of the sardine problem. The problem is very difficult because it involves primarily the relation between the numbers of spawners and the numbers of progeny. Obviously, an animal that spawns many thousands of eggs per year does not have a simple, steady relation between numbers of parents and numbers of young. An additional complexity is that removal of adult fish does more than decrease the spawning stock of the species. Such removal tends to enhance the survival rate of its own young, but similarly, it may also allow competitors of the species to be more successful by increasing the food supply available to them and other effects. On the other hand it may divert predators to the competing species.

Thus the problem on the relation between numbers of parents and numbers of progeny is very complex, and it has never been successfully resolved with respect to any marine fish. Most of the studies of marine fish, and the regulations, involve managing the age at which recruits are harvested, not managing the *numbers* of recruits, and our research clearly shows there is nothing to be gained by managing the age of harvesting the sardine. Theory states there must be *some* relation between spawning stock size and the numbers of recruits. Yet, we know there is no *simple* relation. We need to define the extent of this relation and to define the extent to which it will yield point to point predictions. This latter will, of course, involve the interplay of the population and the environment.

The attempts to understand the environment have already been discussed. In order to focus on the effect of the fishery we need to know the catch in detail, a routine project for a number of years. In addition we need to know the size of the spawning population and the size of the recruited population. The present program of sampling the fishery provides much of this information and can perhaps provide more in the future if additional information is gathered. Spawning stocks have been estimated from egg surveys, and have and are being estimated from "fish surveys." When all these data are fully available, which will be soon under present plans, we should have a fresh look at the population problems insofar as the direct influence of man is concerned.

SUMMARY

The picture that emerges from these results is that the sardine, a rather minor part of the biomass, can prosper when there is much variation in the environment, but that under steady conditions, or at least under steady cool conditions, the sardine, perhaps abetted by the pressure of man, gives way to its competitors. However, with the firm establishment of competitors in the habitat of the sardine, a brief return of otherwise favorable environmental conditions is inadequate to re-establish stocks of sardines in the more northerly portions of its range, although in warm years the southern stocks become available to California fishermen.

It is also clear that shifts in the relative abundance among sardines and other forage fish has little effect on the population of predators.

With this picture developing from the inquiries of the CalCOFI program we must slowly change the program to make the most of our new understanding. Since we must understand the broad changes of the oceanic conditions, the routine surveys are being expanded. Since we can recognize the types of oceanographic changes from fewer data, the major surveys are being made less frequently (quarterly) and the lines farther apart. The ship time so released is being used for more direct studies of the environment, the conditions and competitors in the sardine spawning area, spottiness of larvae and plankton, countercurrents, etc.

This intensification of effort also is being devoted to the sardine itself, the conditions of its eggs, its light preferences, its distribution and associates as larvae and juveniles, and its growth rate as associated with the strength of year classes.

It is clear that we soon will have considerable detailed understanding of the actual conditions under which sardines and perhaps other pelagic fishes experience high survival.

To date in this program there have been extensive scientific results. There has been a long period of pioneering and exploration and the slow development of a picture of the place of the pelagic fishes in the California Current System. With this development of perspective, there is increasing opportunity to feed the findings back toward more meaningful research and greater opportunity to answer the question of society.

Perhaps the most important product of the program is a perspective of the sardine and its associates. We know that the sardine was once a conspicuous and valuable component of the population. Well may it be again. But we now realize that the sardine is like the gold of California, a conspicuous, valuable, easily-harvested element in the midst of less-conspicuous riches of far greater potentialities but requiring painstaking development.—E. H. Ahlstrom, J. D. Isaacs, G. I. Murphy, and J. Radovich.

AGENCY ACTIVITIES

California Academy of Sciences

Studies on the behavior and reactions of sardines and related species were continued, utilizing one investigator and assistance as needed. Specific investigations during the year included studies on the responses of anchovies to ultraviolet and infra-red radiation, and their responses to gradients of white light. In addition, further tests were completed on the responses of anchovies, jack mackerel, Pacific mackerel, and sardines to various electrical fields. Studies on the schooling of anchovies were conducted at Marineland.

California Department of Fish and Game

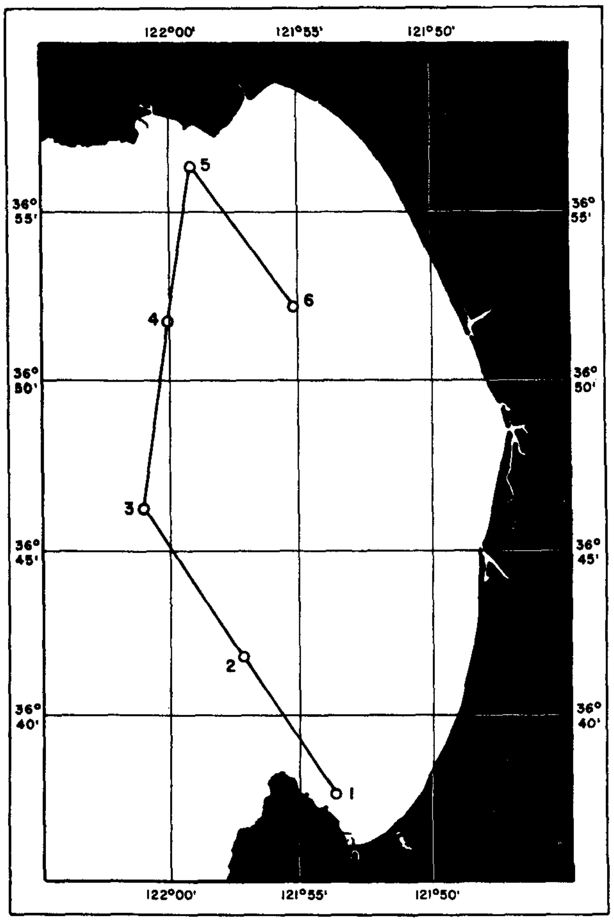
The Department of Fish and Game continued its basic monotoring of the pelagic wet fish fisheries of California. This includes: sampling sardines, anchovies and Pacific and jack mackerel, to determine the age and length composition of the catch; interviewing fishermen to obtain information on fishing localities and fishing effort; and working with the Department of Fish and Game statistical unit to insure that the catch records are accurate.

The department also continued its fish survey work which, in effect, extends the type of information obtained from the fishery to areas beyond those presently occupied by the fishing fleet. The pelagic species are sampled at sea and information is obtained on the distribution and relative abundance of fish. The fish are aged and measured, live samples are saved for genetic studies by the U. S. Bureau of Commercial Fisheries, and other fish are preserved for further study ashore by the Department.

These two routine projects for four species represents most of the Department's effort in the CalCOFI program. Although routine, they are basic to the needs of the entire program, since before causes of variation in abundance and availability can be investigated, the variation must be described.

In addition to the routine work, measurements were made for morphometric studies on about 2,500 sardines. This is part of a study to determine if sufficient differences can be recognized in fish from different regions of the coast to enable one to recognize "types" and thereby, follow sardine movements from year to year. One other aspect of the morphometric study is to look critically at samples of fish whose blood has been typed to see if phenotypic differences can be detected which correspond with the genetic separation obtained from serological work.

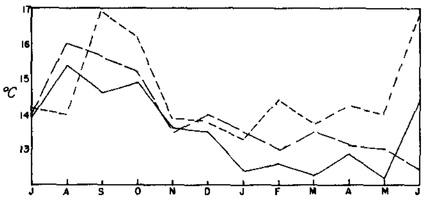
The live bait catch sampling was continued as was the airplane surveys of the anchovy population. Studies on the effect of water temperatures on fish distribution continued and the results will be published.



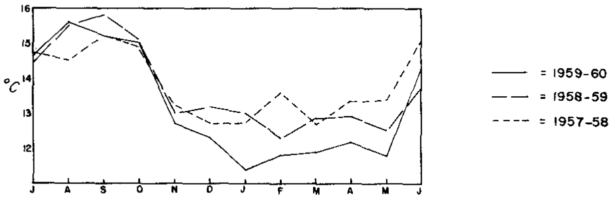
Monterey Bay, showing cruise pattern and station locations.

Hopkins Marine Station, Stanford University

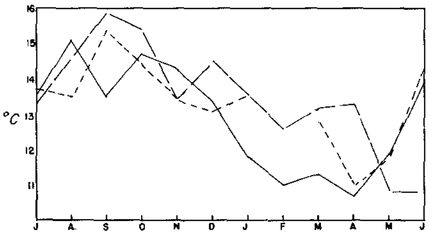
Throughout the year the Hopkins Marine Station has continued to keep a finger on the pulse of the Pacific in the central California area through a program of three correlated activities: 1) Daily shore temperatures were taken at Pacific Grove and Santa Cruz. 2) At approximately weekly intervals, dependent upon the weather, cruises were made covering six stations in Monterey Bay. At each of these stations reversing thermometer temperatures and water samples for salinity determinations were taken at the surface and 15 meters. A bathythermograph was also lowered to 50 meters, except at stations 1 and 5 where shallow water limited the depth of the casts to 30 and 20 meters respectively. Vertical hauls for phytoplankton and zooplankton were also made at each station. 3) Each month 26 shore temperature stations were occupied between Monterey and Islay Creek, 20 miles south of Morro Bay on a day during or close to the period when CalCOFI ships were operating off-shore in the same latitudes.



SHORE TEMPERATURES - PACIFIC GROVE



SHORE TEMPERATURES - SANTA CRUZ



COASTAL TEMPERATURES-MONTEREY to MORRO BAY

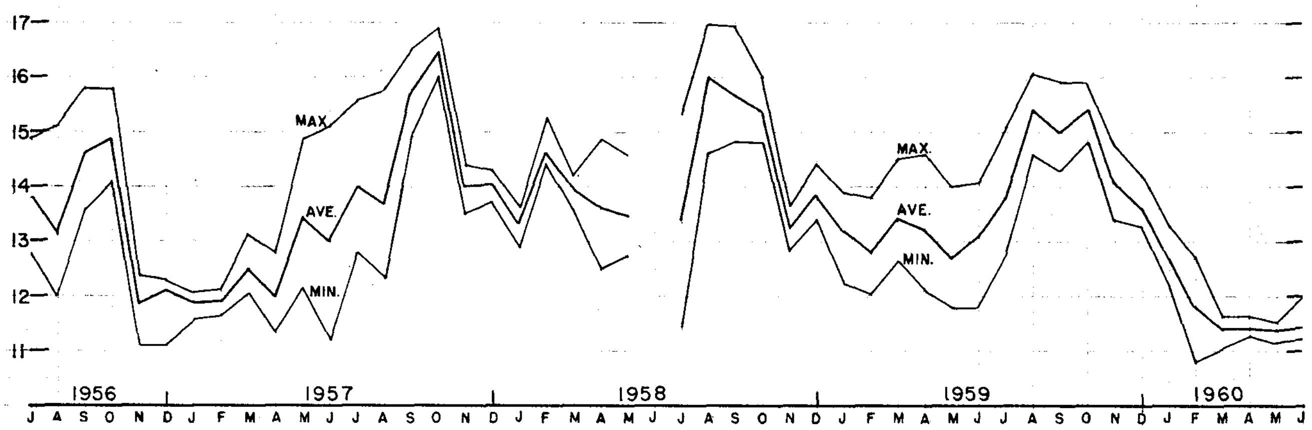
During the early part of the period covered by this report (July 1959-June 1960), monthly averages of daily shore temperatures taken at Pacific Grove and Santa Cruz indicated conditions only slightly cooler than those of the warm-water periods prevailing during the previous two years. At Pacific Grove the period averaged about 0.6° C colder than in 1957 and about 0.4° C colder than 1958, but during August and October the water was actually somewhat warmer than during the corresponding month in one or the other of the preceding two years. At Santa Cruz the temperature differences were much less; they were about equal to those of 1957 and averaged only 0.2° C colder than those of 1958. During each of these first five months the temperatures were equal to or warmer than those of one of the preceding two years, and in August they were warmer than both.

During the next six months from December, 1959 through May, 1960, the situation changed markedly. At both extremes of Monterey Bay, the average temperature in each of these months was markedly colder than that of the corresponding months of the two preceding years. At Pacific Grove this period averaged 1.30° C colder than that of 1957-58 and 0.7° C colder than that of 1958-59. The situation was similar at Santa Cruz; the corresponding values were 1.2° C and 0.9° C June provided what might be considered a return to warm water conditions with temperatures above those of 1959, but below those of 1958. It should be mentioned here, that although winter and spring were characterized by water colder than that of the prior two years, temperatures between October and February were still higher than those prevailing in 1956-57 just before the onset of warmer conditions along the California coast.

The temperature situation in Monterey Bay, as outlined above and based on daily observations, was extremely well corroborated by the averages of 26 shore stations occupied at monthly intervals along the coastline to the south. Here, too, the summer and fall of 1959 appeared to be typical of the recent warm-water period, but the following winter and spring yielded temperatures markedly colder than in the preceding two years. The warming noted in June in Monterey Bay, took place somewhat earlier toward the south and the curve of the coastal run approached that of 1957-58 in May as well as in June.

The abrupt decline in surface temperatures during the winter and spring is perhaps more strikingly shown by monthly averages of the data collected on the weekly cruises. These are not so strongly influenced by shallow-water warming as are those taken along shore. They show clearly that the surface temperatures are depressed well below those of 1957-58 and 1958-59. In fact, the surface temperatures during these months are comparable to the very cold period of 1955-56.

Bathythermograph temperature averages showed little change over those of the previous year in the first half of the period under discussion, although there was a slight lowering at all depths in September, October and January. However, with the onset of upwelling in February, there was a concomitant overall lowering of temperatures to approximately 1° C below those of the previous year. Although this condition prevailed until June, at which time the temperature rise noted at inshore areas prevailed in the upper 10 meters, the persistence of relatively low values was probably not due to continued upwelling. Lowered temperatures of late winter and early spring are normally the result of upwelling. Upwelling is typically indicated by a spread between the maximum and minimum values for any given month. This temperature



SURFACE TEMPERATURES — MONTEREY BAY, CALIFORNIA
MONTHLY AVERAGES

difference is due to the presence of cold freshly upwelled water at stations over or adjacent to Monterey Canyon, and of surface-warmed eddies at the extremities of the Bay. It is noteworthy that between March and June, 1960, a period which in normal years is characterized by a conspicuous spread in the maximum and minimum curves, these lines ran close together. Although it must be admitted that this may throw doubt on the validity of the spread as an index of upwelling, it may also indicate that the cooling was due to factors other than upwelling. In this connection, it may be pointed out that the only sizeable plankton bloom (another indicater of upwelling) occured in March, just subsequent to the upwelling of February as shown by the spread of the maximum and minimum in that month. No further sizeable plankton production was noted and it is probable that no enrichment from deep waters took place. Evidently the cooling was not due to upwelling but was a result of a widespread phenomenon affecting a large area of the North Pacific.

Salinities in the Bay were slightly higher from July through September over the previous year. They were somewhat lowered in the period from January to March, especially in February when rainfall and runoff affected surface salinities. It was not possible to interpret differences in salinities of corresponding months in various years as indicators of upwelling.

Phytoplankton volumes have remained low throughout the past year, and the total volume of samples was less than half of that obtained in each of the previous two years. The most noticeable bloom was in March, when hauls were far above those of 1958 and 1959, and comparable to 1957 volumes, the latter being the last year when phytoplankton was present in marked quantity in the Bay.

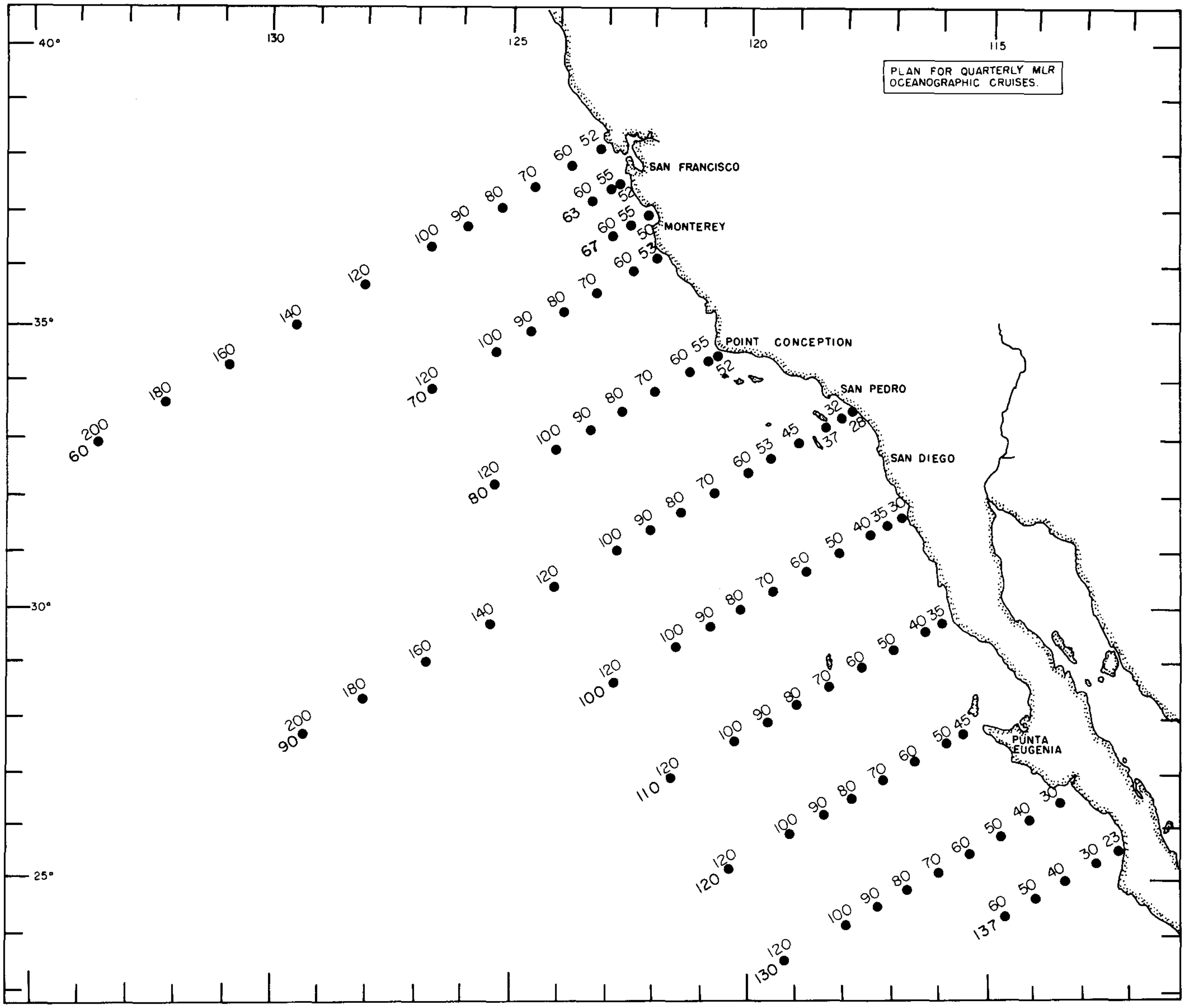
Division of Marine Resources Scripps Institution of Oceanography University of California

With the completion and publication of almost ten years of measurements of the oceanic conditions of the California Current System, the CalCOFI's oceanographic program is being modified. To a great extent this modification is the result of the perspective and the broader recognition of problems presented and summarized in the CalCOFI's report of last year Volume VII. In particular, the fact that the changes in the local waters of the California Coast are related to fluctuation in conditions over much of the Pacific, is receiving increased recognition. The surveys are being extended to reach farther north and farther to sea, and the number of station lines occupied is being reduced. These changes stem from: the need to obtain a broader and more general look at the California Current; the ability to recognize change from fewer data as a result of understanding from previous studies; and the necessity to carry out concentrated studies on special features of the environment that have been pointed up. The modified field program will thus consist of a basic extensive survey plan, as shown, and a series of special oceanographic studies concerned with such subjects as: the nature of the countercurrent circulation, direct current measurements, the ecology of spawning areas, and the nature of plankton succession.

In the area of interpretation of the oceanographic data, the program is becoming more involved with prediction. The basic correlation of temperature, wind, and sunshine has been worked out and the next step will involve dynamic prediction, that is, prediction that considers currents. Studies of the broad climatology of the Eastern North Pacific are receiving increased emphasis.

Correlation between the oceanographic conditions and the plankton of the areas is receiving attention. Work is proceeding on the zoogeography of the region, and all major groups of *zooplankton* are now receiving attention. It is now possible to examine associations of zooplankters, the association of zooplankton, and, for example, fish larvae, and the association of these organisms with the oceanographic conditions, and this is under way.

In this direction, preparation of charts displaying the oceanographic conditions throughout the years is



being undertaken, to permit a more facile comparison of biological conditions with the oceanographic weather. This is also a step in the preparation of a comprehensive description of the California Current System.

In the field of instruments, progress has been made toward substituting moored stations for ship observations, although these are not yet routinely in use. Nets to solve special problems of fish and plankton behavior and distribution have been constructed, the deep-free vehicle has been expanded to include carrying an experimental current meter, and equipment for routine direct observation of the ecology of pelagic areas are under development.

***U.S. Bureau of Commercial Fisheries* (BCF)**

The program of research of the La Jolla Laboratory, Bureau of Commercial Fisheries, is made up of 10 investigations, 8 of which center directly on the sardine and 2 that are tangential. In the former category are investigations of population dynamics, population size, year-class size, availability, age and growth, fecundity, genetics (subpopulations) and physiology; the tangential programs include plankton studies (data on plankton volumes are issued annually) and ecologically associated fishes (including anchovy, jack mackerel and Pacific mackerel).

Perhaps the most exciting research results were obtained in the genetic studies of subpopulations. The "C" system, one of three blood systems that have been distinguished, has proven of value in separating subpopulations of sardines. A more northerly distributed group of sardines (off California and at times northern Baja California) average over 13% "C" positive individuals, while a more southerly distributed group (Magdalena Bay, Baja California, to as far north as San Diego) averages less than 6% "C" positive fish.

The most recent investigation initiated by the La Jolla Laboratory, physiology studies, is obtaining interesting results in several fields: osmoregulation and energy requirements of sardine eggs and larvae, organic constituents (fatty acids) of the ovary, nutrition of sardine-related species and rearing of post-yolk sac sardine larvae.

Availability studies are concerned with investigating the manner in which the environment influences the distribution and behavior of the sardine. A phase of the behavior project completed during the year compares, on the basis of eye structure, the relative visual capacities of the Pacific sardine, northern anchovy, Pacific mackerel, jack mackerel and some other fishes. The sardine has the highest visual acuity and the lowest sensitivity, thus should be able to discriminate objects better than the other species in bright light, but not as well as others in dim light. Exploratory behavior experiments are being started, and the experimental facilities are being improved. An improved plankton pump is being built to be used in studies of the distribution dynamics of sardine food organisms.

Sardine spawning in 1960 had the type of distribution that has been typical of warm years since 1957. Spawning was less widely distributed and closer inshore than previously, with major centers in the Channel Island area of Southern California and in Sebastian Viscaino Bay, Baja California. Based on preliminary scanning of samples, the amount of spawning appears to be low. Fecundity studies have shown that during the recent warm years, sardines off Southern California mature at much smaller sizes, have a more prolonged spawning season and are much less uniform with regard to stage of ovarian development. A preliminary examination of sardine larval data for 1952-1957 indicates that larval survival after the yolk sac stage has been relatively constant—larger larvae (15.5 mm and longer) comprising between 1.5% and 3% of the total larvae.

REVIEW OF THE PELAGIC WET FISHERIES
During the 1959-60 Season

SARDINE

The enthusiasm generated by the 104,000 ton 1958-59 sardine fishing season was short lived, as a soft market kept the catch from reaching a higher value. The poor foreign market continued into 1959-60 and as the season unfolded, it became apparent that catch would be limited even further by the supply. At the end of the 1959-60 season, the catch of sardines totaled only about 37,000 tons.

During the summer of 1959, before the season began, fish surveys off the California fishing grounds conducted by the California Department of Fish and Game and egg and larvae surveys conducted by the U. S. Bureau of Commercial Fisheries, revealed the

TABLE 1

SEASONAL CATCH IN TONS OF SARDINES ALONG THE PACIFIC COAST—EACH SEASON INCLUDES JUNE THROUGH THE FOLLOWING MAY[1]

	PACIFIC NORTHWEST				CALIFORNIA[2]							
					NORTHERN CALIFORNIA							
Season	British Columbia	Washington	Oregon	Total	Reduction Ships	San Francisco	Monterey	Total	Southern California	Total California	Baja[3] California	Grand Total
1916-17	----	----	----	----	----	----	7,710	7,710	19,820	27,530	----	27,530
1917-18	80	----	----	80	----	70	23,810	23,880	48,700	72,580	----	72,660
1918-19	3,640	----	----	3,640	----	450	35,750	36,200	39,340	75,540	----	79,180
1919-20	3,280	----	----	3,280	----	1,000	43,040	44,040	22,990	67,030	----	70,310
1920-21	4,400	----	----	4,400	----	230	24,960	25,190	13,260	38,450	----	42,850
1921-22	990	----	----	990	----	80	16,290	16,370	20,130	36,500	----	37,490
1922-23	1,020	----	----	1,020	----	110	29,210	29,320	35,790	65,110	----	66,130
1923-24	970	----	----	970	----	190	45,920	46,110	37,820	83,930	----	84,900
1924-25	1,370	----	----	1,370	----	560	67,310	67,870	105,150	173,020	----	174,390
1925-26	15,950	----	----	15,950	----	560	69,010	69,570	67,700	137,270	----	153,220
1926-27	48,500	----	----	48,500	----	3,520	81,860	85,380	66,830	152,210	----	200,710
1927-28	68,430	----	----	68,430	----	16,690	98,020	114,710	72,550	187,260	----	255,690
1928-29	80,510	----	----	80,510	----	13,520	120,290	133,810	120,670	254,480	----	334,990
1929-30	86,340	----	----	86,340	----	21,960	160,050	182,010	143,160	325,170	----	411,510
1930-31	75,070	----	----	75,070	10,960	25,970	109,620	146,550	38,570	185,120	----	260,190
1931-32	73,600	----	----	73,600	31,040	21,607	69,078	121,725	42,920	164,645	----	238,245
1932-33	44,350	----	----	44,350	58,790	18,634	89,599	167,023	83,667	250,690	----	295,040
1933-34	4,050	----	----	4,050	67,820	36,336	152,480	256,636	126,793	383,429	----	387,479
1934-35	43,000	----	----	43,000	112,040	68,477	230,854	411,371	183,683	595,054	----	638,054
1935-36	45,320	10	26,230	71,560	150,830	76,147	184,470	411,447	149,051	560,498	----	632,058
1936-37	44,450	6,560	14,200	65,210	235,610	141,099	206,706	583,415	142,709	726,124	----	791,334
1937-38	48,080	17,100	16,660	81,840	67,580	133,718	104,936	306,234	110,330	416,564	----	498,404
1938-39	51,770	26,480	17,020	95,270	43,890	201,200	180,994	426,084	149,203	575,287	----	670,557
1939-40	5,520	17,760	22,330	45,610	----	212,453	227,874	440,327	96,939	537,266	----	582,876
1940-41	28,770	810	3,160	32,740	----	118,092	165,698	283,790	176,794	460,584	----	493,324
1941-42	60,050	17,100	15,850	93,000	----	186,589	250,287	436,876	150,497	587,373	----	680,373
1942-43	65,880	580	1,950	68,410	----	115,884	184,399	300,283	204,378	504,661	----	573,071
1943-44	88,740	10,440	1,820	101,000	----	126,512	213,616	340,128	138,001	478,129	----	579,129
1944-45	59,120	20	----	59,140	----	136,598	237,246	373,844	181,061	554,905	----	614,045
1945-46	34,300	2,310	90	36,700	----	84,103	145,519	229,622	174,061	403,683	----	440,383
1946-47	3,990	6,140	3,960	14,090	----	2,869	31,391	34,260	199,542	233,802	----	247,892
1947-48	490	1,360	6,930	8,780	----	94	17,630	17,724	103,617	121,341	----	130,121
1948-49	----	50	5,320	5,370	----	112	47,862	47,974	135,752	183,726	----	189,096
1949-50	----	----	----	----	----	17,442	131,769	149,211	189,714	338,925	----	338,925
1950-51	----	----	----	----	----	12,727	33,699	46,426	306,662	353,088	----	353,088
1951-52	----	----	----	----	----	82	15,897	15,979	113,125	129,104	16,184	145,288
1952-53	----	----	----	----	----	----	49	49	5,662	5,711	9,162	14,873
1953-54	----	----	----	----	----	----	58	58	4,434	4,492	14,306	18,798
1954-55	----	----	----	----	----	----	856	856	67,609	68,465	12,440	80,905
1955-56	----	----	----	----	----	----	518	518	73,943	74,461	4,207	78,668
1956-57	----	----	----	----	----	----	63	63	33,580	33,643	13,655	47,298
1957-58	----	----	----	----	----	----	17	17	22,255	22,272	9,924	32,196
1958-59	----	----	----	----	----	----	24,701	24,701	79,270	103,971	22,334	126,305
1959-60[4]	----	----	----	----	----	----	16,109	16,109	21,146	37,255	21,424	58,679

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[1] Data for British Columbia were supplied by the Canadian Bureau of Statistics and the province of British Columbia; those for Washington by the Washington Department of Fisheries, and for Oregon by the Fish Commission of Oregon. Tonnages delivered to the reduction ships and data for Baja California were compiled by the United States Fish and Wildlife Service from the books of the companies receiving fish. California landings were derived from the records of the California Department of Fish and Game.

[2] Prior to the 1931-32 season fish landed in Santa Barbara and San Luis Obispo Counties are included in Southern California. Beginning with the 1931-32 season fish landed north of Pt. Arguello are included in the Monterey landings and those south of Pt. Arguello are included in the Southern California landings.

[3] The amount of sardines landed in Baja California prior to the 1951-52 season are not known. Beginning with 1951-52, the period of fishing approximates that of the rest of the Pacific Coast. Figures are preliminary.

[4] Preliminary records.

presence of sardines in sufficient numbers to yield only a slightly smaller catch than that of the preceding season. This was with the assumption that the sardines would behave in the same manner as in 1958. In addition, the blood genetic studies of the U. S. Bureau of Commercial Fisheries showed that a ''southern type'' of sardine extended northward from Mexico into southern California during the summer.

Although the season officially opened August 1, for central California and September 1, for southern California, price negotiations prevented the fleet from fishing off central California during August and off southern California during September. After the price was finally settled at $35 a ton, the central California fleet began fishing on September 1, and the southern California fishery began on October 4.

When the fleets finally ventured forth, sardines were somewhat scarce. This appears to have been the result of two things: sardines were not schooled densely, probably because the ''southern type'' present off southern California were spawning at that time; and the fish moved southward as winter arrived. By February the line separating the ''northern type'' from the ''southern type'' was about 150 miles south of the International Border.

The 1959-60 season resulted in landings of 16,110 tons off central California and 21,150 tons off southern California, for a total California catch of 37,260 tons. As in 1958-59, most of the catches in southern California were made north of San Pedro. The fishing fleet totaled 128 vessels, 38 from central California and 90 from southern California. Again two-year-olds (1957 class) dominated the catch. The 1956 class which made up the bulk of the 1958-59 season's landings did not appear outstanding, reaffirming the earlier conclusion that the 1956 class was not large but extremely available during 1958.

TABLE 2

COMMERCIAL LANDINGS AND LIVE BAIT CATCH OF ANCHOVIES IN TONS IN CALIFORNIA, 1939-1959

(Live Bait Catch 1943-45 Not Recorded)

Year	Commercial Landings	Live Bait	Total	Percent Live bait
1939	1,074	1,503	2,577	58.3
1940	3,159	2,006	5,165	38.8
1941	2,052	1,582	3,634	43.5
1942	847	258	1,105	23.3
1943	785			
1944	1,946			
1945	808			
1946	961	2,748	3,709	74.1
1947	9,470	2,854	12,324	23.2
1948	5,418	3,725	9,143	40.7
1949	1,661	2,802	4,463	62.8
1950	2,439	3,824	6,263	61.1
1951	3,477	5,142	8,619	59.7
1952	27,892	6,810	34,702	19.6
1953	42,918	6,391	49,309	13.0
1954	21,205	6,686	27,891	24.0
1955	22,346	6,125	28,471	21.5
1956	28,460	6,332	34,792	18.2
1957	20,274	4,110	24,384	16.9
1958	5,801	4,236	10,037	42.2
1959	*3,587	4,737	8,324	56.9

* Preliminary estimate.

ANCHOVY

Commercial landings of anchovies in 1959 dropped to a total of only 3,600 tons from 5,800 tons landed in 1958. These were the poorest catches since 1951, despite a large anchovy population present off the California coast. The low catch reflects market conditions rather than availability of anchovies, since the anchovy catches are generally low when sardines are abundant and high when sardines are scarce. The scarcity of sardines in 1959, did not increase the demand for anchovies, however, because of the large inventories of sardines left over from the previous year.

The catch of anchovies for live bait was about 5,000 tons compared with approximately 4,000 tons in 1957 and 1958. The live bait fishery continued to be dependent on the very small ''pinhead'' (fish of the year) and one year old anchovies. This was no indication of scarcity, however, as large anchovies apparently moved offshore and deeper to ''cool off'' when the ocean warmed up. Egg and larvae surveys of the U.S. Bureau of Commercial Fisheries indicate that a large spawning population was present during 1958 and 1959. In addition, offshore sampling by the California Department of Fish and Game revealed the presence of large anchovies between 20 and 60 miles off the coast, and some large anchovies were killed during offshore seismic operations. Another piece of evidence

TABLE 3

CALIFORNIA SEASONAL CATCH IN TONS OF PACIFIC AND JACK MACKEREL

(Each Season Includes May through the Following April)

Season	Pacific Mackerel	Jack Mackerel	Total	Percentage Pacific Mackerel
1926-27	1,797	183	1,980	90.8
1927-28	3,228	213	3,441	93.8
1928-29	19,703	278	19,981	98.6
1929-30	28,347	337	28,684	98.8
1930-31	6,403	155	6,558	97.6
1931-32	7,576	336	7,912	95.8
1932-33	5,425	233	5,658	95.9
1933-34	36,437	553	36,990	98.5
1934-35	56,732	827	57,559	98.6
1935-36	73,194	4,925	78,119	93.7
1936-37	50,373	2,879	53,252	94.6
1937-38	35,223	4,121	39,344	89.5
1938-39	38,032	1,948	39,980	95.1
1939-40	49,980	559	50,539	98.9
1940-41	53,777	875	54,652	98.4
1941-42	35,877	959	36,836	97.4
1942-43	24,110	4,897	29,007	83.1
1943-44	38,902	4,228	43,130	90.2
1944-45	40,393	6,871	47,264	85.5
1945-46	26,001	4,635	30,636	84.9
1946-47	29,448	15,573	45,021	65.4
1947-48	19,814	71,330	91,144	21.7
1948-49	19,101	27,845	46,946	40.7
1949-50	25,031	32,494	57,525	43.5
1950-51	16,945	68,187	85,132	19.9
1951-52	15,953	37,495	53,448	29.8
1952-53	10,109	75,750	85,859	11.8
1953-54	4,415	18,369	22,784	19.4
1954-55	13,605	9,417	23,022	59.1
1955-56	13,448	29,674	43,122	31.2
1956-57	28,592	48,173	76,765	37.2
1957-58	28,119	19,917	48,036	58.5
1958-59	12,388	11,352	23,740	52.2
1959-60*	20,641	33,280	53,921	38.3

* Preliminary estimate.

which indicates that the large anchovies moved offshore, comes from examination of stomachs of bluefin tuna caught in purse seines between Santa Catalina and San Clemente Islands. These stomachs were gorged with freshly ingested large (7 inch) anchovies.

Therefore it is apparent that the low commercial anchovy catch was due to a lack of demand, and the scarcity of ''hook size'' anchovies in live bait catches was a result of an offshore movement of the larger fish.

MACKEREL

Commercial landings of Pacific mackerel during the 1959-60 season rose to 21,000 tons from 12,000 tons in 1958-59, while the jack mackerel catch of 33,000 tons tripled that of the previous year.

The higher price paid for both species of mackerel in 1959 ($50.00 per ton compared with $35.00 per ton for sardines) reflected a better market, and undoubtedly contributed to the increased mackerel catches in 1959-60, augmented by the scarcity of sardines causing more fishing effort to be directed toward the higher priced mackerel.

Pacific mackerel less than one-year-old dominated the catch with fair numbers of one- and two-year-olds, also present.

TABLE 4

ANNUAL COMMERCIAL LANDINGS IN TONS OF THE PELAGIC WET FISH IN CALIFORNIA FROM 1926 THROUGH 1959

Year	Sardines	Anchovies	Pacific Mackerel	Jack Mackerel	Herring	Squid	Total
1926	143,371	30	1,805	118	227	1,568	147,119
1927	171,138	184	2,364	231	584	3,007	177,508
1928	210,135	179	17,626	269	570	676	229,455
1929	325,886	191	28,987	349	479	2,330	358,222
1930	251,031	160	8,266	184	359	5,485	265,485
1931	182,176	154	7,127	282	343	869	190,951
1932	211,305	150	6,237	268	383	2,115	220,458
1933	313,199	159	34,807	505	301	412	349,383
1934	559,966	129	56,924	791	401	765	618,976
1935	547,879	90	73,214	4,992	464	408	627,047
1936	731,772	98	50,271	2,300	420	473	785,334
1937	535,745	113	30,468	3,270	316	251	570,163
1938	511,695	368	39,924	2,067	252	800	555,106
1939	580,397	1,074	40,455	1,880	151	581	624,538
1940	452,987	3,159	60,252	716	227	900	518,241
1941	631,240	2,053	39,084	1,034	395	716	674,522
1942	484,874	847	26,277	2,674	95	476	515,239
1943	486,135	785	37,607	6,350	315	4,582	535,774
1944	573,604	1,946	41,828	6,388	211	5,468	629,445
1945	422,531	808	26,858	4,516	230	7,613	462,556
1946	255,380	961	26,938	7,547	241	19,012	310,079
1947	127,757	9,470	23,239	64,524	827	7,271	233,088
1948	181,018	5,418	19,693	36,449	4,001	9,628	256,207
1949	316,690	1,661	24,886	25,625	190	3,430	372,482
1950	357,261	2,439	16,325	66,628	713	2,998	446,364
1951	164,450	3,477	16,759	44,919	2,462	6,191	238,258
1952	7,165	27,891	10,302	73,261	4,748	1,836	125,203
1953	4,734	42,918	3,751	27,875	3,901	4,459	87,638
1954	68,252	21,205	12,696	8,667	456	4,078	115,354
1955	72,804	22,346	11,655	17,877	973	7,136	132,791
1956	34,777	28,460	25,006	37,881	868	9,742	136,734
1957	22,931	20,274	31,022	41,006	594	6,225	122,052
1958	103,723	5,801	13,824	11,033	1,200	3,729	139,310
1959*	37,183	3,587	18,801	18,754	864	9,826	89,015

* Preliminary estimate.

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During the period covered, a major change occurred in the distribution of sardine spawning. In 1952 and 1953 sardine spawning was mostly confined to the waters off central Baja California. In 1954, sardine spawning spread northward to waters off southern California, and this distribution has continued through 1955 and 1956. Estimates of total eggs spawned during these years ranged from 136×10^{12} to 436×10^{12}.

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PART II

SCIENTIFIC CONTRIBUTIONS

SYMPOSIUM ON FISHERIES OCEANOGRAPHY

MAURICE BLACKBURN, Editor[1]

INTRODUCTION

At the Eastern Pacific Oceanic Conference of 1957, Mr. Townsend Cromwell (Inter-American Tropical Tuna Commission) explained the need for a symposium for exchange of information and views about the usefulness of oceanography in fisheries investigations, and was asked to suggest a scientific meeting in which such a symposium could appropriately take place.

Mr. Cromwell was killed while on duty in June 1958. At the Eastern Pacific Oceanic Conference of 1958, the matter was raised again by Dr. Maurice Blackburn (Scripps Institution of Oceanography, University of California) and discussed by conference participants.

As a result, arrangements were made to include a "Symposium on Fisheries Oceanography" in the programs of the forthcoming meetings of the American Society of Limnology and Oceanography (Pacific Division) and the American Society of Ichthyologists and Herpetologists, to be held as part of the 40th annual meeting of the Pacific Division of the American Association for the Advancement of Science. Dr. Blackburn was invited to organize the Symposium and preside over it.

The Symposium took place at San Diego State College, California, on the afternoon of June 17 and the morning of June 18, 1959. It took the form of presentation of papers (recorded), questions and discussion from the floor (not recorded), and summaries and comments by persons who had been invited to present them (recorded).

Publication in this medium was arranged by one of the participants, Mr. Garth I. Murphy, with the consent of all concerned.

The organizer of the Symposium wishes to thank all who participated in it, the office bearers of the societies who sponsored it, and the Marine Research Committee of the California Department of Fish and Game which published the proceedings.

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[1] The heading of each paper states the organization to which the author belongs. An additional contribution of a general nature presented by Richard H. Fleming, Department of Oceanography, University of Washington, Seattle, is not available for publication.

PROBLEMS IN FISH POPULATION FLUCTUATIONS

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Our chairman has defined "fisheries oceanography" as meaning "any kind of oceanography required for the appraisal or exploitation of any kind of organism useful to Man". This, as intended, is a very broad definition. My contribution to this symposium will be confined to a discussion of only one particular set of problems that I believe to be most important in the utilization of fishery resources and afford most exciting opportunities for oceanographic research—namely, fishery fluctuations.

By fishery I mean any harvesting of any living ocean resource, and by fluctuations I mean any irregularity in the amount or the quality of the harvest. Since most of our present commercial harvest from the sea consists of fish, my discussion, terminology and examples pertain to fishes, but most of the concepts are also appropriate to the invertebrates and some even to the flora of the sea.

In considering the problem of fishery fluctuations I have come to realize that there are a great many parallelisms in the discipline and the state of knowledge in fishery biology with those in oceanography. By fishery biology I mean the study of fish populations as dynamic systems—and by oceanography I mean the parallel thing: The study of the ocean as a dynamic system. In defining each of these in this way I am ignoring a great deal that could be included, but I believe I am retaining the central core of each.

The first parallelism is that there are only a few things we can measure. In fishery biology we measure only the fisherman's harvest and the effort he puts into making it, when we really want to know the size of the fish population and how fast it is changing. In oceanography we can only measure the temperature and salinity when we want to know which way the water is running, and how fast. To be sure, in each field we can, by a one-time special effort, get a direct measure (estimate). We can lay a tag-and-recapture project—or a multiple-ship drogue expedition. But these are not routine, every-day events. For the most part we have to deduce what we want to know from something else that we can measure.

Second—and this is largely a consequence of the first—for fish populations we have only a theory to tell us how a fish population reacts to fishing. This relates to a fish population living in a steady environment. In some few instances, and for a limited period of time, we find that a population really does react approximately as the theory says it should. For oceanography we have more theories. But practically all relate to an equilibrium ocean. For some parts of the ocean, sometimes, one of these theories, or a combination of them, seems to explain approximately what actually happens.

Of course the trouble with the theory of fishing is that a fish population reacts to other things besides fishing—things in the variable environment. We assume these things average out—and sometimes they do. But often the time dimension for averaging out is intolerably long. And of course the same thing is true of the ocean. Over a long enough period of time the average ocean probably is an equilibrium ocean, but the measurements we take must be mostly those of an ocean in disequilibrium. I believe it can be said for fishery biology, as it has been said for oceanography, that there is a peculiar dreamlike quality characterizing our descriptions and discussions of the things that we are studying.

As a fishery biologist I venture the further thought that it would be easy to relax and enjoy this dream were it not for fluctuations. They have a nightmare-ish quality that jolts one into reality. And I am reminded that this could be true for oceanographers as well. A year ago this month a group of oceanographers (including the one who first voiced the phrase "peculiar dreamlike quality"), meteorologists, marine biologists, and fishery biologists met at Rancho Santa Fe, bringing with them meteorological, oceanographic, biological and fishery data, to describe what happened in the Northeast Pacific Ocean in 1957 and 1958 and why. It was abundantly clear that there had been a sudden and marked warming of at least the eastern margin of the Pacific from Alaska to Peru, with an assortment of consequences to the oceanic biota. The results of pondering over these events will be published and I will not here attempt to put them before you, except to remark that we still do not know, with any precision, what happened, nor with any degree of assurance, why.

Henry Stommel, in his book on the Gulf Stream, has this to say about fluctuations: (Stommel 1958, p. 136)

> "Many catastrophes of an economic kind, such as the failure of the rice crop in Japan, or of a certain fishery, or years of unusual numbers of icebergs in shipping lanes, are attributed to fluctuations in ocean currents. Very little is really known about such fluctuations. It takes years of careful and expensive observation to produce even a very crude description of them. The scientific programs of our oceanographic institutions are not geared to long-term problems of this kind; there is much pressure for novelty, much temptation to follow the latest fad, and a persistent though erroneous notion that all worth-while problems will eventually be solved by some simple, ingenious idea or clever gadget. A well-planned long-term survey designed to reveal

fluctuations in ocean currents would be expensive and time-consuming. It might even fail, because of inadequacies of the tools we have at hand. But until this burdensome and not immediately rewarding task is undertaken, our information about the fluctuations of ocean currents will always be fragmentary.''

Henry Stommel seems somewhat overwhelmed by the task of making the observations needed for describing and elucidating fluctuations in the Gulf Stream. The task probably is even more difficult for describing and elucidating the fluctuations in fish populations, because it is likely that the effects on fish populations of physical and chemical changes in the environment are mediated through several trophic levels in the biota. We will come back to this later.

It seems clear that the problem of fluctuations lies at the research frontier in both fishery biology and oceanography, and that it is going to be difficult to break through the frontier.

Let us consider again, for a moment, the anatomy of fishery fluctuations. We can discern three principal elements operating to determine the amount of the catch: The abundance of the organism, its availability to the harvester, and the amount of harvesting effort. We shall not here be concerned with the last of these. The amount of harvesting effort is determined by economic conditions. Changes in the amount of effort can be measured, though not easily, and its effects on the amount of catch can be determined and discounted. It is not a problem in biology or oceanography.

Abundance and availability, in contrast, present problems both in biology and oceanography.

We suspect that availability varies widely. For instance, the failure of the albacore fishery from 1928 to 1938 was, we think, an availability phenomenon. The albacore population probably was as large as usual, but did not approach close enough to the coast to enter the range of the fishing fleet.

Availability is a matter of distribution and behavior, both on a coarse-grained pattern as in the albacore failure, and on a fine-grained pattern as in the schooling of fish. It is highly important to the strategy of fishing and to the economy of the fishing industry. Since Professor Uda will, I think, discuss availability in some detail later in this symposium, I shall confine myself to fluctuations in abundance (population size).

Fishing theory says that the annual increase in a population is a function of population size and environmental capacity. If a population ''fills'' its environment, births and deaths are equal and the population is in equilibrium. When fishing takes place, catch mortality is imposed, the population is reduced below the environment's capacity, births exceed ''natural'' deaths and the population tends to increase toward the environmental limits. With very intense fishing and a very low population level, the reproductive increase is near its maximum, natural mortality near its minimum, but the annual increase is low because there are few spawners. When fishing is very light and the population near the environmental limits, the spawning population is large but the back-pressure from the environmental limit depresses reproduction or increases natural mortality, or both, so that the annual increase is again small. At some level of population size intermediate between these extremes, where the spawning stock is moderately large and back-pressure from the environment moderately gentle, the annual increase is maximal. Of course, at any level, the population size will be in equilibrium when the annual catch equals the annual increase, but the annual harvest that can be sustained without disturbing the equilibrium will be maximal at the level of population abundance that affords the maximum annual increase.

Fishery biological research has been directed mainly toward determining this level of maximum sustainable yield, using the concepts embodied in this theory. A number of mathematical models have been developed to express these concepts. They assume that the environmental capacity is constant or fluctuates moderately and randomly, and that the observed or computed changes in recruitment and mortality and hence annual yield are functions of population size (or density) alone. These models have proved very useful in studying the population dynamics for some fisheries.

In other populations, including some that support very important fisheries, the effective birthrate, that is, the relative numbers reaching recruitment age, varies widely from year to year, apparently without relation to the size of the spawning stock. This is known by studying the age composition of samples of the catch. From the data on age composition through sufficient number of years, it is possible to estimate the relative number of individuals surviving to fishing size or age from each year's spawning. I shall call this relative number ''year-class strength''.

I have looked up a few data on relative year-class strength:

	Successive year classes	*The largest was*
Western Atlantic mackerel	among 14	15,000 times the smallest
Eastern North Pacific sardine	21	700
Kodiak (Alaska) herring	28	34
Southeast Alaska herring	20	13

These are all very gross estimates, and should be taken only to indicate that year-class strength often varies through several orders of magnitude.

Year-class strength obviously must be a function of number of eggs spawned, or of survival through the egg stage, through the planktonic larval stages or through the post-planktonic juvenile stages, or a combination of these. No doubt irregularities occur in all stages, but the evidence, still regrettably scanty, points to the survival through planktonic egg and larval stages as being the most likely critical one in determining year-class strength.

Where year-class strength fluctuates widely it is not a function of population size and we must look to environmental causes.

How shall we do this?

Because it is difficult to speak in generalities, I shall employ an hypothetical example. Let us consider a fish population of a species, like the mackerel, the sardine or the anchovy, that spawns in the waters off California.

Through evolutionary time, in the members of such a fish population, there must have evolved an internal biochemical system and a related pattern of behavior that determines the responses to the things sensed in the environment. The behavior pattern must have been so adjusted that it lead to successful reproduction through all of the time involved in its evolution. Otherwise the species would be extinct. If I may speak teleologically, the members of a living fish population, or at least the vast majority of them, must work out problems of navigation and prediction to enable them to find and occupy a specific kind of water mass for spawning.

This water mass must have physical and chemical properties which are tolerable to the biochemistry and biophysics of the eggs to be spawned and the larvae to be hatched from the eggs. Further, by the time larvae have hatched out, and by the time they have fully absorbed the yolk sac, this water mass must contain other organisms suitable for the larvae to feed upon and in such concentrations as will permit the larvae to get enough food for maintenance of metabolic activity and growth. Doubtless the larvae will require larger food particles or more of them as they grow larger. So this water mass must continue to afford an increased and probably different diet through the subsequent months of planktonic larval existence. Finally, when the larvae metamorphose into the juvenile stage and take up an active, rather than a passive, drifting existence, this water mass must have reached a place or a condition which is suitable for juvenile existence. Many marine species spawn in the open sea at a considerable distance from the juvenile nursery grounds. For such a species, the parent must have predicted the trajectory of the water mass over a period of weeks or months.

To be sure, many individuals of the population may fail to navigate properly or to predict accurately and it seems that often the whole population, or most of it, may be in error. Or, alternatively, the conditions in the sea may in some seasons become so anomalous that there are no water masses suitable for the species spawning or the survival of the eggs and larvae after spawning. In any event, there are many year-class failures or near-failures in our widely-fluctuating fisheries. Such failures, of course, must be interspersed with enough successes for the population to be perpetuated. For species with an adult life of several years, several annual failures can happen in succession, and apparently do happen in our widely fluctuating fish populations, without exterminating the species.

I have spoken of the water mass as a thing which maintains its integrity over considerable periods of time. This probably does not happen often for water masses in the surface layer. They undoubtedly undergo changes through insolation and through mixing horizontally and vertically with adjacent waters. In a sense, we could think of a water mass as undergoing an evolution as to its physical and chemical properties and also as to the trophic succession in its biota. Perhaps more frequently than not, the water mass may undergo dissolution instead of evolution and such cases may indeed lead to failure of survival of its larval fish population.

In this connection, it is interesting that there have been reported two instances in which it appears that a water mass was changed so rapidly that the contained fish larvae died almost immediately. One instance, reported by John Colton (1959), was of larvae contained in a mass or parcel of water at the southern edge of Georges Bank in which the temperature, apparently by mixing with Gulf Stream water, had risen rapidly enough to kill the fish larvae it contained. The other instance, reported by Donald Strasburg (1959), was the occurrence of dead larval Frigate mackerel in plankton tows in Hawaiian waters under circumstances suggesting water mixing as the cause. We do not know whether or not such sudden changes can occur in really large enough water masses to determine the failure of a year class, but these reports are suggestive.

However this may be, it appears that one mode of attack on the problem of year-class strength would be the study of the source, the life history, the movements and, perhaps the dissolution of water masses. This infers sea work to observe, with continuity through space and time, many properties of the water and its biota. It suggests, further, that a joining of the physical and biological disciplines might facilitate such a study. The joining of the laboratory experimentalists would probably facilitate the study still more. If we know what properties of the environment the fish is able to sense, and how the fish reacts to the things it senses, we would be led more quickly to observing the things which cause the fish population to maintain or change its distribution, and if we could identify in the laboratory the survival requirement of fish larvae, we would be led more quickly to our observing the critical events in the sea.

In effect, I am proposing the joining of four disciplines: oceanography, fishery biology, marine biology and experimental biology. Possibly additional disciplines may be required. Certainly, instrument systems for recording automatically, with time and space continuity, a number of properties of sea water and its motions would be of tremendous importance. On the biological side, it is quite possible that fish pathology, especially the study of fish larva diseases, may be germane to this study.

To speak in more general terms, it is my belief that in fishery oceanography the challenge and the opportunity lies in studying the changing sea rather than the equilibrium ocean, and in studying the biological consequences of the changes at the various trophic levels. In speaking of "consequences" I mean to include not only the effects on the population numbers, which I have dwelt upon at some length, but also on population distribution and behavior which Professor Uda will soon discuss with us. In the aggregate this implies the necessity of observation of physical and chemical properties of sea water, its motions and mixings, and the numbers, kinds and perhaps stages of the biota inhabiting the waters, all with space and time continuity sufficient to describe the events that take place and to investigate their interrelationships. The biological determinations probably would more readily be made with the aid of laboratory experimental determinations of environmental requirements critical for survival of the various organisms, particularly pelagic fish larvae.

It would seem that this amounts to an undertaking of such vast scale that it may be quite out of line with the importance of fishery resources to our society. However, fluctuations of the ocean and of its plant and animal populations is a problem of significance not only to fisheries. Modern military systems no longer can be based on the average state of the sea, and modern meteorology is no longer uninterested in the possibility that the feed-back to the atmosphere from anomalous sea conditions may have to be considered in extended weather forecasts. We can hope, therefore, that progress in the field does not depend alone on research activities in the interests of developing and utilizing fishery resources, but will benefit also from activities undertaken in the interest of other important activities of mankind.

An indication of trends in this direction is the recent report of the National Academy of Sciences Committee on Oceanography, which, among other things, proposes a great augmentation of effort, much of it along the lines we have considered in this discussion.

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FISHERIES OCEANOGRAPHY IN JAPAN, ESPECIALLY ON THE PRINCIPLES OF FISH DISTRIBUTION, CONCENTRATION, DISPERSAL AND FLUCTUATION

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INTRODUCTION

Oceanographic studies of existing fishing grounds and exploratory expeditions into new areas to discover new fishing grounds have aided very materially in increasing the efficiency of fishing, and have contributed greatly to the tremendous yield of the Japanese fisheries in recent years. After the first investigation of oceanic currents around the Japanese Islands by drift bottle experiments started by Yuji Wada in 1893, Tasaku Kitahara founded a fisheries oceanographical organization in Japan in 1909 and proposed (1918) the principle of fish assemblage near a line of convergence ("Siome"). This principle was further developed by M. Uda (1927-58), K. Kimura (1940-58), and others.

A fishing ground may be defined as a locality or area where a fishery is economically conducted on large forms such as whales or on populations of fish, such as salmon, herring, sardine, and tuna, etc.

Fisheries science, in dealing with fish shoals (or fish schools) on the fishing grounds, must determine the reasons for their general distribution, their concentrations in certain areas and their general dispersal. It is important, of course, that enough research be available and that equipment be highly efficient in tracking down and capturing the school of fish. The fishing operations, both in amount of area covered and actual fishing done, are restricted by weather and ocean conditions. There are a number of problems associated with the safe and efficient conduct of fishing operations such as methods of locating schools—fish finders, aerial scouting, observation of the oceanographic structure of water, etc.; maritime meterological knowledge and information to prevent or at least effectively reduce the damage due to storms, abnormal currents, etc.; processing and transport to market of the fish caught; the management of the fishery to assure continued maximum sustained yield; and safe navigation.

Fisheries science, from the view point of fisheries oceanography, seeks to find the principles controlling the abundance of fish in the four dimensional (x, y, z, t) field of fisheries and includes the theory of fishing conditions, fishing areas or grounds, fishing periods or seasons in any time section, as well as the variations in fishing conditions in any spatial section. As a practical extension, it seeks to develop fisheries forecasts or predictions, not only of the fishing grounds and fishing seasons, but also of the distribution and the extent of the catches, in both good and poor years. With reference to the progress acquired by fisheries during the first half of this century, the following principles of fish distribution, concentration, dispersal, and fluctuation proposed by the writer, based on his research (1927-1958), are illustrated.

PROPOSED PRINCIPLES

(1) Marine organisms are distributed according to the variable environmental (hydrobiological) conditions which they require for successful development.

(2) The basic pattern of the fish shoaling curve in response to normal environmental conditions is shown by the probability curve which is modified by special sea conditions, such as a cold front, etc., or by the composition (size, etc.) of the fish schools.

H. O. Bull (1952) found marine fishes to be sensitive to temperature changes of 0.03° in his experiments.

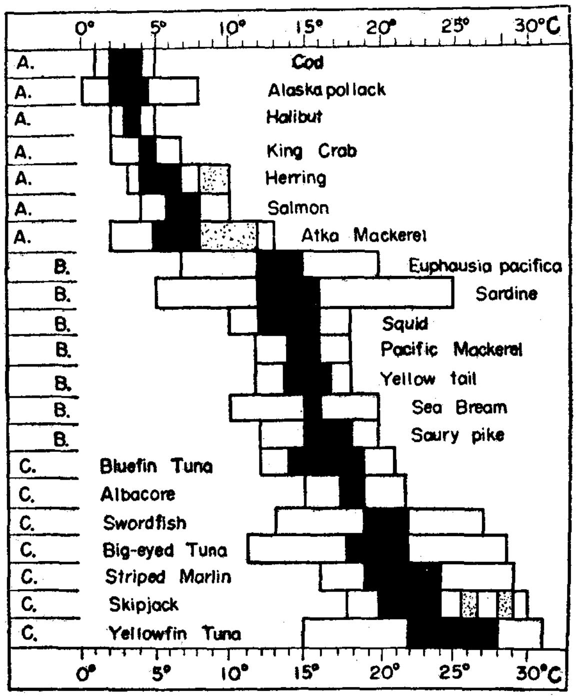

FIGURE 1. Optimum water temperature spectra of important fishes in Japan (Uda 1957).

Uda (1940, 1957) prepared a diagram (Fig. 1) of optimum temperature spectra for some of the important commercial fishes of Japan, in which the optimum temperatures (range about 4°–5° C) are shown as each characteristic "proper value" (θ_o) in the following equation.

$$N = N_o e - \frac{(\theta - \theta_o)^2}{2\delta^2}$$

where δ is the standard deviation, a measure of the range, θ is the water temperature and θ_o is its mode, N is the number or catch of fish, with N_o representing its peak. When δ is large it is called eurytherm, when small, stenotherm, and in the range ($\theta_o \pm 2\delta$) 98 percent of N are included.

A similar probability curve for salinity can be prepared.

(3) The localization of fish concentrations is determined by the narrowness of the optimum water zone and each special three-dimensional oceanographic structure. Especially good fishing grounds correspond to the zone of the oceanic fronts (boundaries) of water masses, including "siome" or lines of convergence, and to the zone of up-welling (area of divergence) and other factors, as stated below such as ridging, entrainment, eddies, turbulent mixing, etc.

(a) Kitahara's law (first postulated by T. Kitahara, 1918, and extended by M. Uda, 1936, 1958) states that the "oceanic front" corresponds to the area where marine life is concentrated and where fishing is good, having a "siome" (line of convergence) on the ocean surface as an indicator.

(b) Nathansohn's law (first laid down by A. Nathansohn, 1906, and extended by others), states that highly productive and consequently good fishing grounds are found in areas of up-welling. The Scripps Institution of Oceanography has conducted some basic work on the mechanics of productive up-welling in the California Current System.

(c) Topographically-developed back-eddy systems (near a strait, channel, peninsula, cape, island, estuary-mouth, etc.) are rich feeding areas, and are good fishing grounds for mackerel, squid, yellowtail, etc. (Uda, 1958).

(d) Thermoanticlines or ridgings occur in some sub-surface fishing grounds (e.g., tuna fishing areas in the Equatorial Pacific) as pointed out by T. Cromwell, 1958. This is due to a variety of underwater up-welling or some type of entrainment.

(e) Entrainment (J. P. Tully, 1952, 1956) in estuaries, on the continental shelf edge, insular shelf edges, or near fishing banks, produces a highly fertilized zone and produces good areas for fishing or other aquiculture.

(f) Dynamically-produced eddies along oceanic fronts are rich feeding areas, supplied with an abundance of planktonic food and small fish. These attract the fish which tend to remain there and consequently develop into suitable fishing regions.

(g) In the northern hemisphere, cyclonic (counterclockwise) eddies representing cold eddies, constitute good fishing areas in the marginal zones of up-welling (e.g., saury, whales, squids, etc., in the Polar Frontal Zone; albacore in the Kuroshio Front) and are associated with favourable water temepartures.

In the southern hemisphere clockwise eddies develop along the Antarctic Convergance as favourable whale grounds just north of the pack ice zone (M. Uda, 1954, K. Nasu, 1959) (Fig. 2).

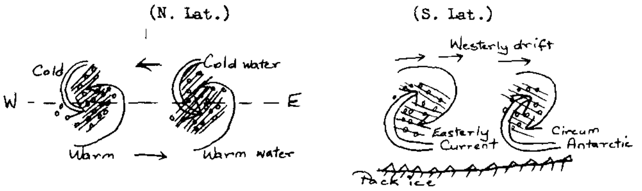

FIGURE 2. Eddy formation at polar fronts, schematic (Uda 1959a).

(4) Warm and cold water intrusions into well-developed suitable water temperature zones bring about concentrations of fish and produce good fishing areas. By the intrusion of unfavourable water masses (e.g., abnormally warm, saline, or cold, fresh water) the fish also become concentrated. For example, the meteorologically abnormal onshore current "Kyutyo" (rapid current or storm current) produces a heavy catch of yellowtail, sardine, tuna, etc., to the coastal set-net fishery.

(5) According to K. Brandt's theory (1899) of the development of the organic life cycle of the food chain, productive zones which are fertilized either naturally or artifically by certain physical and chemical processes become potential areas for fishing or for acquiculture by having available ample supplies of the primary nutrient substances.

Physical factors important in developing productive areas include:

(a) Turbulent mixing, due to waves and currents, which has been observed in coastal areas or around oceanic banks and islands (e.g., the shrimp grounds, etc., along the S.W. coast of India in the summer monsoon period, as pointed out by N. K. Panikkar, 1958). Productivity of the fishing grounds of herring, cod, etc., in the coastal straits of British Columbia may be attributed to the mixing effect of the strong tidal currents, similar to the straits in the Inland Seas of Japan.

(b) Internal waves (of the tidal period) as studied by C. Cox, K. Yoshida and T. Morita in 1958 in the southern sea of Japan. The fertilization of the tuna grounds on the deep oceanic banks or sea mounts may be due to internal waves. L. N. Cooper (1957) has suggested that internal waves on the continental shelf edge may contribute to the fertilization of the mackerel fishing grounds in the Celtic Sea and A. R. Miller (1950) has studied the mixing processes over the shelf edge.

(c) Mixing by convection due to winter cooling, which is important in the seas of higher latitudes. The productivity of the Okhotsk Sea, Bering Sea, Japan Sea, Yellow Sea and China Sea depends largely on the winter monsoon.

(6) Schooling of fishes (N) is a function of a special group of hydrobiological conditions (S), the spatial gradient (∇S) and the rate of time variation ($\dot{S}$). Thus, $N = f_n\ (S, \nabla S, \dot{S})$. Where continuously stable or uniform ocean conditions prevail, the concentration of fish and consequently the development of good fishing areas cannot be expected. A marked spatial gradient in water temperature, etc., or a sudden change in these features is a promising indication of a good fishing area or of a good catch.

(7) During the feeding migration, schools of fish seek out areas where the food organisms are abundant and arrive normally at the time when the food is abundant. The food forms vary according to the par-

ticular likes and dislikes of the species and according to their size. The feeding migration appears to follow along a definite route in which the areas or zones of abundant food organisms are connected by a series of eddy systems, lines or areas of convergence ("siome"), or areas of upwelling related to the prevalent offshore winds (e.g., yellowfin, sardine, squid fishing grounds).

Topographical peculiarities along the coasts, such as capes, long headlands, inlets, islands, etc., affect the current and wind-flow patterns and produce back eddies which become, at appropriate times of the season, good fishing grounds. Oceanic islands and banks located along volcanic chains (such as Kyusyu—Formosa, Idu Islands—Ogasawara—Mariana, etc.) constitute the migration routes of tuna and skipjack.

Cold streams in which there is an abundance of food organisms make up portions of the migration routes of some species of fish, such as the saury, squid, chum salmon, etc., and the "loop-sack" formations at the end of cold and warm currents along the frontal zone represent very excellent feeding and fishing areas for saury, whales, albacore, skipjack, etc.

A useful indirect estimation of fish abundance and concentration may be made by considering the amount (or concentration) of food plankton or fishes as shown by echo traces or DSL (Uda 1956).

(8) The spawning migration, stimulated by the sexual hormones as the gonads mature, and occurring as the temperature changes reach a maximum, appears to follow an instinctively determined route corresponding to the same environmental pattern, though in reverse. The biological features bringing about the schooling of the fish and their return to the natal spawning ground, as influenced or directed by environmental and physiological factors are of great interest. Physiological and ecological experiments in salmon tanks are planned (J. Brett 1958, and others).

(9) Fishing by means of fish lamps depends on the phototaxis of the fish, related to the prey-predator sequence in the food chain, each having a specific and favourable range of luminosity (saury, sardine, mackerel, horse mackerel, squid, etc.). The attraction of fish schools by light sources in a limited confined space has been studied by M. Tauti and H. Hayasi in 1927, and more recently at Lowestoft Fisheries Laboratory, England, using supersonic fish finders.

Bright moonlight seems to disperse fish over a wider area, and commonly fish lamps are much less effective in attracting fish during the period of full moon.

(10) The electrotaxis of fish (sardines, etc.) by attracting them to the anode pole has been under experimentation at the California Academy of Sciences and elsewhere. It shows promise of being of use in future fishing (e.g. success in the U.S.S.R. in freshwater fishing) and also may have some application in studying migration of fishes. Electric screens have already been successfully used in rivers (in Japan, M. Okada first made experiments in 1929). Fishing by using an electric pulse was investigated by T. Kuroki (1956). Since in the ocean a gradient of electromagnetic potential is associated with current, as indicated by G.E.K. based on the Faraday effect, the electromagnetic patterns in fish migration in the ocean present a very fascinating problem for the future.

(11) During the spawning migration, fishes are confined to comparatively narrow zones of favourable temperature (stenotherms) and become more densely schooled the closer they approach their spawning areas. After spawning, they tend to disperse again. Some die, while others migrate to new feeding grounds. The eggs and larvae are transported by the currents and gradually are scattered widely, some of them, in due course, finding favourable nursery areas. In 1909, J. Schmidt reported that Icelandic cod larvae, spawned on the south coast of Iceland, were carried by currents to the northern nursery grounds. Subsequently, in 1922, he reported on his famous studies of the migration of eel larvae from the Sargasso Sea to the European and American coasts by means of the Gulf Stream.

In Japan, within the last ten years, much information has been obtained concerning the transport and dispersal of larval fishes from the spawning ground to nursery areas for squid, mackerel, horse mackerel, sardine, anchovy, yellowtail, saury, etc. From early spring to early summer great numbers of floating larval fishes are carried by the Kuroshio and Tusima Currents and their branches.

It is most important to study the natural mortality or rate of survival, as well as the growth rate, in these early critical periods of sea life, particularly in relation to the environmental conditions. J. Hjort (1926) first remarked upon the importance of wind and current at such periods and J. N. Carruthers *et al.* (1951) postulated the effect of prevailing wind conditions in the North Sea on the brood strength of bottom fishes. H. B. Hachey (1955) also studied the effect of wind and current on the brood strength of cod and haddock on the Newfoundland Grand Banks. Therefore, studies of currents and wind conditions, etc., on the spawning and nursery grounds can indicate (foretell) the subsequent fate of new broods and consequently the probable yield of commercial species, and can provide useful information on the routes of adult migration and on the availability of the fish, as related to environmental conditions.

In connection with spawning migrations, the occurrence of unfavourable counter currents may delay the arrival of the maturing fish at the normal spawning season, or may shift the spawning area to a less favourable region, or may shorten the normal and favourable spawning period for the area, all of which are likely to lead to a reduction in the reproductive potential. A succession of such situations over a number of years results in a decline in the fishery (sardine, herring, etc.). Conversely, continued favourable currents during the period in question increases spawning success (longer, favourable spawnings) in well-fertilized productive areas. Thus good fishing years result.

(12) Submarine topography and bottom characteristics, including the bottom sediments, may affect the

migrations of fish. For example, the yellowtail follows along the 50-100 m. isobaths of the continental shelf; the sea bream prefers a fine sand and shell bottom near a bank or reef. Some fish tend to assemble on banks or reefs, on the margin of sea-valleys or canyons, on sea mountains, close to the continental shelf edge or near the coast (ground fishes and pelagic fishes).

Such topographical or geological irregularities bring about the localization or concentration of fish, as contrasted to the smooth, unbroken flat sea bottom. Therefore, the exploration of the sea bottom by means of echo sounders, dredges, core samplers, etc., is important in fisheries.

(13) Fish which migrate in mid-water areas, i.e., in the optimum temperature zone, are concentrated there by the vertically confining influences of the upper and lower unfavourable temperature strata and also horizontally by flows of less favourable waters (e.g., squids, mackerel, tuna).

(14) Fish tend to move upward into relatively shallower strata for feeding and collect in those areas where the prey-food forms are concentrated. Feeding in these areas usually extends from twilight or dusk ("Yu Mazume") to dawn ("Asa Mazume") or sunrise, and during the late evening, night, and early morning is the best period for fishing (angling, netting, lining). The time of the turn of the tide (ebb to flood, or flood to ebb) is another very good fishing period, especially for angling.

These above-mentioned periods correspond to the time when the fish are actively feeding, as indicated by echotraces and catch samples (e.g., Uda, 1957).

(15) Generally speaking, coincident with the approach of meteorological disturbances such as typhoons, cyclones and fronts, the fish present in coastal waters swim up closer to the surface and feed very actively. Consequently, both before and after such atmospheric disturbances good fishing occurs. On the high seas, however, the fish tend to scatter widely at such times and seek out new feeding areas. To follow such fish or locate them again is a difficult problem.

(16) In accordance with the state of development of the convergence and the temperatures prevailing (i.e., whether favourable or not) the productiveness of the fishing grounds and the development of the fish thereon will differ for each species present.

(17) During the season of the spring tide (full moon, dark) the fish schools tend to approach closer to the coast (whales, tuna, etc.).

(18) Stormy gales or severe monsoons cause fish to collect to the leeward of islands and headlands, etc., to avoid the rough seas (yellowtail, saury, flying fish, etc.).

(19) After severe earthquake, heavy storms, volcanic eruptions, "tunami", etc., the fishing areas and fishing conditions may become quite disorganized and altered.

(20) "Red Tides" and other abnormal "bloomings" of plankton (e.g., *Phaeocystis* in the North Sea herring areas) drive away fish schools and disrupt fishing. Near the margin of such discoloured areas we sometimes find good catches.

(21) Long term cyclic fluctuations in commercial fisheries are the result of changes in the reproduction, development, distribution or availability of fish stocks as caused by cyclic enviromental changes. The effect of such changes depends on the degree to which the conditions depart from those laid down by Uda (1958) as the optimum conditions and defined by the temperature spectra of Fig. 1. Fluctuations occur in all fishes whether they be associated with cold currents (Group A in Fig. 1), intermediate cold-warm currents (Group B), warm currents (Group C) or coastal water areas (Group D, not shown in Fig. 1).

FLUCTUATIONS IN FISHERIES: LONG TERM TRENDS AND PREDICTION

A. *General*

Fish populations (P) in nature repeatedly increase and decrease (accompanied by extension and contraction of their ranges) under some unknown and complex natural environmental conditions. The fishing conditions and the resulting amount of catch (N) for each fish species (sardine, herring, tuna, etc.) fluctuate from year to year (in a periodic or some irreg-

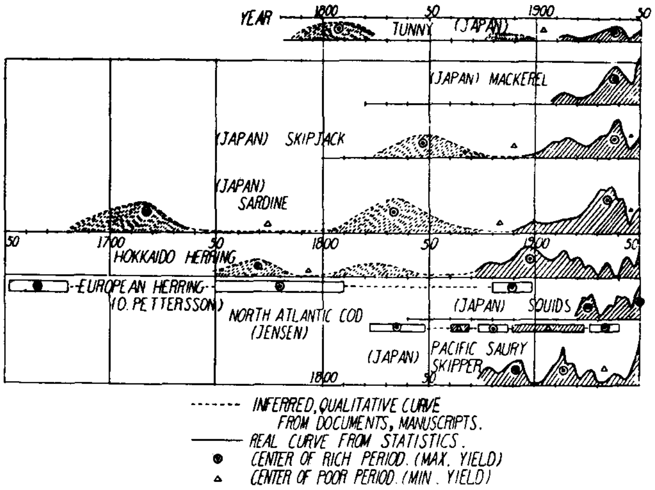

FIGURE 3. Long period variations of the catches of important fishes (Uda 1952).

TABLE 1

RECENT FLUCTUATIONS OF THE FISHERIES IN THE JAPAN SEA

(b-bad; bb-very bad; g-good; gg-very good)

	Period (interval of years)	Sardine	Tuna	Squid	Herring
1	1868-1905	b	g	--	g
2	1906-1912	gg	b	--	b
3	(1913-1917)	gg	--	g	gg
4	1917-1921	g	--	b	(1913-20)
5	1923-1931	b	--	g	--
6	1932-1940	gg	gg	--	b
7	1941-1948	b	bb	gg	g
8	1949-1955	gg	gg	gg	b
9	1956-1957	--	gg	b	b

ular way) with intervals of nearly a century, or 20-30 years, or 50-60 years (See Fig. 3 and Table 1.)

In general, the periodic decay (or growth) of yield can be expressed as:

$$N = N_o e^{-rt} \sum \cos (wt - \mu) \quad . \quad . \quad . \quad . \quad (1)$$

The actual fluctuations of a fish population (or catch) is the result of its natural fluctuation modified by some artificial factors (e.g. fishing, or some bad effects of industrial wastes) (M. Uda, 1957).

Following M.B. Schaefer (1954):

$$\frac{dP}{dt} = f(P) - KPF \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

(where *K, F, P,* are all functions of environmental factors).

In company with the movement of predominant warm currents and cold currents, the zones of favourable and unfavourable catch shift and undulate from north to south or south to north meridionally (y-direction) along the coast, and from offshore to nearshore, or nearshore to offshore laterally (x-direction). As the function of the movements in each direction, x, y, with velocities c_1, c_2 respectively, we have:

$$N = \Phi \ (x - c_1 t, \ y - c_2 t) \text{------------} (3)$$

The migration route of fish shoals approaches the coast in rich years and moves further away from the coast in poor years (e.g. sardine, yellowtail, etc.).

The fishing gears suited to each fishing locality change from set-net near the coast to purse seine in the intermediate waters, to drift gillnet and longlines offshore.

We can find groups of important fish species which show positive and negative variations, respectively, and also indicator species for each group (euphausiids, copepods, *Sagitta*, porcupine-puffers, tiny horse mackerel, some kinds of jelly-fishes, etc.).

Apparently there are certain biological associations in the seas and oceans, i.e. the cold current group (A), the intermediate group (B), the warm current group (C) and the coastal water group (D) etc., and for each of them there are representative indicator organisms. Groups A, B, C and D appear in succession, corresponding to the order of optimum temperatures arranged as "optimum temperature spectra" in recent years. The growth and flowering of the C group appears in company with the development of a warm current. Contrariwise, the A group flourishes along with the development of a cold current (Table 2).

TABLE 2

PHASE LAG OF THE MODE (MAXIMUM) OF CATCH CURVES AND THEIR OPTIMUM TEMPERATURE

	Fish species	Period I (years)	Period II (years)	Optimum water temperature
		→		
A	Herring	↑ 1944–45	--	3°–8°C
A	Atka Mackerel	1944–48	↓ (1951–53)	2°–6°(–13°C, young)
B	Squid	↑ 1941–43	1951 ('52)	12°–16°C(10°–18°)
B	Sardine	1933–39	1947–50	12°–16°C
B	Yellowtail	1942–43	1951–52	14°–16°C
B	Mackerel	1939	1954 ('51–'52 Japan Sea)	13°–18°C
B	Saury	1932–40	1955	15°–18°C
B	Horse Mackerel	1940–41	↓ 1954–57	15°–18°C
C	Bluefin tuna	↑ 1936–41	1956–57	(12°)–14°–19°–(21°C)
C	Albacore	1935–40	1954–57	18°–21°C
C	Skipjack	1936–38	↓ 1955–57	20°–24°C
D	Anchovy	--	1955–58	17°–19°–(21°C)

Considering the fluctuations over a long period of years, we can distinguish unstable periods and relatively stable periods of at least several years' duration and at most several decades when referred to some standard level of fisheries yield, and moreover periods when the sea regions are correspondingly unstable and relatively stable.

The conditions in the regions of the sea on the route of feeding migrations, especially near the oceanic fronts, fluctuate greatly and show unstable (rich or poor) catches. Regions of the sea near the spawning grounds and along spawning migration routes show comparatively stable catches.

The spawning grounds and nursery grounds move not only from south to north or from north to south, but may vary in the relative percentage abundance of fish present on the grounds as we see in the cases of sardine, herring, etc. The sudden change in the long-term variation is brought about by the sudden growth or decay of warm and cold currents (e.g. in the years of 1923, 1941 and 1951).

Apart from artificial causes (overfishing, water pollution, etc.), the ultimate cause of the fisheries fluctuations may be found in variation of reproduction potential, survival, recruitment and availability in relation to variations in environmental conditions.

Fluctuations in fisheries for some important pelagic fishes (clupeids, tunas, salmons, etc.) seem to occur on a world-wide scale which may correspond to global geophysical variations (climatic change or the fluctuation of oceanic currents, polar ice, precipitation and evaporation over the oceans or zonal regions).

Herring (F.H.C. Taylor, 1955) along the Pacific coast of Canada exhibited heavy larval mortality from the offshore current when northeasterly winds prevailed in April. Even in the case of bottom fishes (haddock, cod, etc.) the effects of environment, especially the wind conditions at the larval stage, are very serious, as shown by H. B. Hachey (1955) and J. N. Carruthers *et al.* (1951). Dominant year-classes of important fish populations (e.g. sardine, herring, bluefin tuna, etc.) and favourable environmental conditions may occur over several (10 to about 20) years, and the appearance of large-sized (old fish) populations without the succeeding year-classes (small-sized fish) give warning of the approaching end of good fisheries. Conversely, the increase of young and adults year by year may foretell a growing fishery.

The inverse relation between sardine and anchovy or others may suggest some law of balance of law of alternate predominance in the seas, or correlational balance sheet between pisci-predator, plankton feeder, and benthos feeder.

Concerning sardine, mackerel, herring, Pacific saury or other fish populations, we can recognize the fluctuation of the spawning grounds in the course of spawning migration routes, and the corresponding environmental fluctuation may be the fundamental cause of this fluctuation. A special phase for each prosperity of fish populations can be pointed out, as we see in Fig. 3, Tables 1 and 2. In conclusion, we should define the abundance and maximum sustainable catch as a function of environmental factors (W. E. Ricker, 1958).

B. Examples of fluctuation

(a)

Cold years	*Warm years*
1900-1910-1915	1926-40
1941-49	(peak: 1932-37)
(1940—Baltic heavy ice, 1942-44—Arctic heavy ice)	(Kuroshio northerly extended, Atlantic current strong)
	1951-55; Japan
	(1954-58; Pacific N. America)

(b) In 1958 the Japanese high sea salmon fishing grounds in the Bering Sea and Aleutian waters changed remarkably, compared with those in 1957, due to the change of meteorological and oceanographic conditions (Uda, 1959a).

(c) The decline of Asiatic and Alaskan salmon and herring fisheries in the past 50 years suggests to us the effect of Arctic and sub-Arctic warming on land and in the sea.

The historically big catch of sockeye salmon and herring in British Columbia (Fraser River) in 1958 suggests local variation of environmental conditions. Because of the pressures of fisheries and man-made civilization (water pollution, deforestation, traffic and construction, disturbances, etc.) the complex fluctuation of fisheries in relation to environments (natural and artificial) should be studied.

CONCLUDING REMARKS

The effect of environmental conditions on the early stages of life cycles of fishes is a very important factor in the study of fisheries and should be studied intensively in the future. Within recent years such studies concerning mackerel, sardine, herring and tuna, etc. have been started. Fluctuations in fisheries for important pelagic fishes seem to occur on a world-wide scale. There is a need for international co-operation in the study of environmental variations.

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FISHERIES OCEANOGRAPHY IN EUROPE

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Any review of the status and accomplishments of fisheries oceanography would be incomplete without an account of fisheries oceanography in Europe, where the science began and is still vigorous after more than 50 years.

Fisheries oceanography may be said to have begun with the establishment in 1902 of the International Council for the Exploration of the Sea, by representatives of north-west European governments. The form that fisheries oceanography was to take was foreseen and described by the Council in its first Administrative Report (1903), in the following words:

"It was thereby shown that the research work might best be divided into two main divisions, of which the one had in view the physical conditions of the sea, the other the biological—more especially in regard to the animals most useful as human food. Naturally it was seen from the beginning that the study of the physical conditions, of the chemical nature of the ocean waters, of the currents, etc., was of the greatest importance for the investigation of the problems connected with life, that on the other hand, the study of the floating organisms had particular worth for the solution of hydrographic problems, and consequently that a sharp line should never be drawn between these two main divisions . . ."

FIGURE 1. Surface currents in the Norwegian Sea (from Helland-Hansen and Nansen 1909).

Most marine scientists know in a general way how, mainly under the aegis of this Council, the north-west European countries have co-operatively and individually planned, performed, discussed, and published an immense amount of oceanographic work which was, or was hoped to be, pertinent to fisheries problems. The remarks in this paper will be confined to the investigations in the region between the English Channel, the Barents Sea, and Greenland. There has, of course, been much work also off the Atlantic coasts of France, Spain, and Portugal, which are in the International Council's area, and in the Mediterranean and Black Seas, which are not.

Figure 1, the well-known surface current chart of Helland-Hansen and Nansen (1909), shows how the warmer more saline North Atlantic water enters the region, mainly through the Faroe-Shetland Channel, as the Norwegian Current, while colder less saline Arctic water flows out, between Greenland and Iceland, as the East Greenland Current. An outflow of low-salinity water from the Baltic contributes to the Norwegian Current. The shallow North Sea receives Atlantic water from the north, around Shetland; and to a less extent from the south, through the English Channel, as indicated in Figure 3.

Another kind of summary of the hydrography of part of this region is the chart of Dietrich (1950) showing natural regions based on distribution of salinity and temperature (Fig. 2).

These figures demonstrate the great differences in the environment of the fishes of the region. Much of the early fisheries oceanographic work consisted of collection, description, and analysis of material in sufficient mass to show what species or populations of fish reacted to what properties of the environment and in what ways. The results have been summarized by Tait (1952, Chapters 1, 2). They gave rise, among other things, to a few rather useful, though not entirely dependable, rules; e.g. that fish populations breed at particular temperatures (Orton 1920) and that breeding migrations are contranatant (E. S. Russell 1937). Mention must be made at this point of the aquarium experiments of Bull (1952), which demonstrated the ability of fishes to perceive and act purposively to changes as low as 0.03° C., $0.2\ ^{0}/_{00}$ of salinity, and 0.05 units of pH, in the water around them; this made the conclusions from the field work more acceptable.

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[1] Contribution from the Scripps Institution of Oceanography.

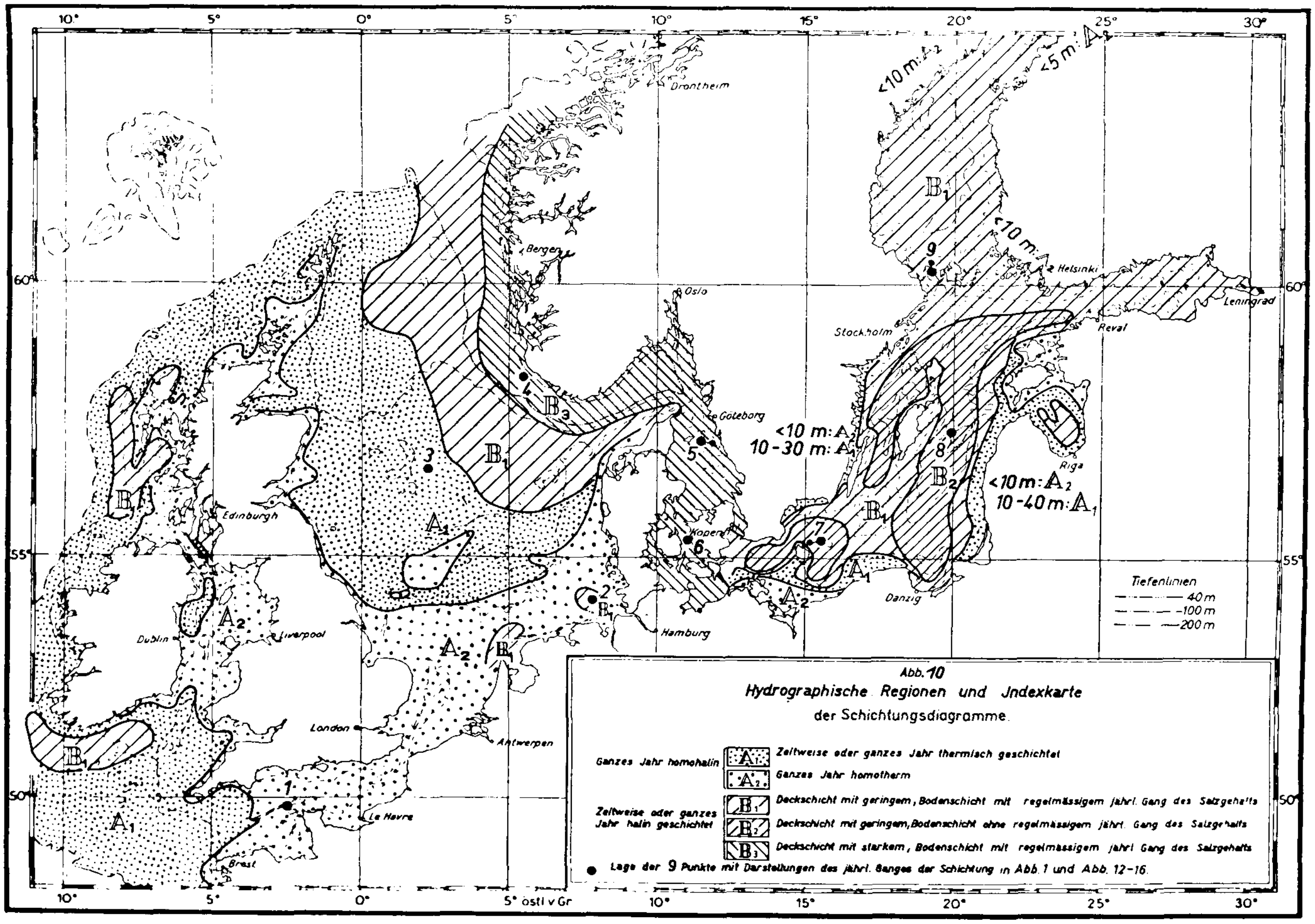

FIGURE 2. Hydrographic regions in the North and Baltic Seas (from Dietrich 1950).

This kind of work was more straightforward than that which came later. In the period between the wars several lines of fisheries work were progressing in a way that seemed to leave the hydrographers and planktologists with a minor role to play as far as practical fisheries problems were concerned. The hydrographers and planktologists found plenty to do on their own account, but their connection with fisheries biology was temporarily weakened.

One reason was that it had become clear that the condition of many important fish populations, especially demersal populations, could be improved by restricting man's fishing (E. S. Russell 1942). This meant: that there was no need of oceanography to help fishermen find these fish, since the fishermen were already too efficient at that for their own good; and that oceanography's promise to understand and predict changes, nothing more, seemed less attractive than the promise of fisheries biology to control changes by regulating fishing. This affected the work on plaice, haddock, hake and other species, and the programs of the countries concerned—especially England, Holland, Belgium, Denmark, and Germany—and continues to do so. The work on the pelagic herring and the semi-pelagic cod was not greatly affected.

Another reason was the well-merited popularity of the theory of natural fluctuations in fish populations according to Hjort (1914). The essential points of the theory were: that year-classes may vary greatly in size because of differing natalities and mortalities of young from year to year; that the progression of these rich, medium, and poor year-classes through the older fishable part of the population has a decisive effect upon the numbers present and catchable each year; and that this effect is predictable in detail if the initial year-class strengths, and average growth-rate of the fish, are known. Although Hjort perceived the probable significance of environmental factors in causing the differences in the year-classes, he pointed out that the causes would have no great importance for practical forecasting if one could measure the differences themselves before the year-classes became important in the fishable segment of the population. It turned out that the differences could be so measured in several populations, by study of age-composition of numerous samples of fish taken before or just at their entry into the fishery, and that useful predictions could be made. This was done particularly for herring, in south-east England (Hodgson 1932) and elsewhere.

In proposing his theory of natural fluctuations, Hjort (1914) had considered and virtually rejected the idea that the coastal food-fish penetrate the ocean waters. Coastal fishermen everywhere tend to believe that fish must be offshore when they cannot be found inshore, and persistently ask their scientists to investigate these waters for them. We will see later that the

Norwegian fishermen were partly right in this belief, and that Hjort was wrong when he disagreed with it. However his conclusion was reasonable in the light of the evidence available to him, and it is salutary to give his words:

"In the course of the Norwegian fishery investigations carried out under my supervision, I have endeavoured in various ways to discover whether any fish move out beyond the coastal banks . . . Numerous experiments have been made with drift net and floating lines, for the most part, however, with negative result."

He then explains that he did find *Sebastes*, the redfish, in many places; some herring in deep water between the North Sea and the Faroe area, but virtually none in the main part of the Norwegian Sea; and little or nothing in the way of cod, haddock, coalfish, and catfish; and he continues:

"Experiments of this nature are, however, by no means easy to carry out, and negative or mainly negative results are scarcely sufficient to warrant the conclusion that the species in question do not occur in any quantity in the waters investigated; there is always the possibility that the fish might occur in shoals, which it would be a matter of merest chance to encounter in so great an expanse of sea. One thing at least is certain; we have no other grounds for supposing the existence, in any considerable numbers, of coastal fish in the deeper parts of the Norwegian Sea, beyond (occurrences of *Sebastes* and restricted occurrences of herring noted above)."

This helped to divert attention from the ocean waters, and was another disservice to the kind of fisheries oceanography that the founders of the International Council had envisaged.

We now turn to what some fisheries oceanographers, physical and biological, did while some fisheries biologists were specializing in the above-mentioned ways; and how some common ground has now been reached again, especially in herring and cod research.

There were workers in England and Scotland who believed that the varying influx of Atlantic water to the North Sea and English Channel was the key to many fluctuations in fish populations.

Plymouth, in the western English Channel, had a herring fishery until about 1938; its extinction began in 1931 when the first of an unbroken series of poor year-classes appeared. The same year marked the beginning of a fall in the standing crop of planktonic young fish generally, and the beginning of a large drop in the winter maximum of inorganic phosphate. It was also the period at which *Sagitta elegans* was replaced in the plankton by *S. setosa*. It was concluded that the influence of Atlantic ocean water upon the Channel, and with it the possibility of renewal of nutrients to the levels of the nineteen-twenties, had receded (F. S. Russell 1939). There has been no definite improvement since that time.

Cooper (1955), noting no evidence that Atlantic surface waters have ever been rich enough to account for the phosphate levels found off Plymouth before 1931, considered various possibilities by which deeper nutrient-rich Atlantic water could have been carried or mixed upwards, in the Channel approaches, during the nineteen-twenties. Observing that this would be facilitated by the elevation of a layer fairly rich in phosphate by a few hundred metres, he supposed the arrival of a suitably large body of water at greater depth, formed by cooling and sinking of water between Faroe and Greenland. Winter temperatures in those regions were particularly low in several years ending about 1921, a year before the beginning of the phosphate record at Plymouth. The effect of the heavy water in keeping the nutrient-rich water elevated in the mouth of the English Channel is supposed to have continued for some years after the recruitment of the heavy water ceased.

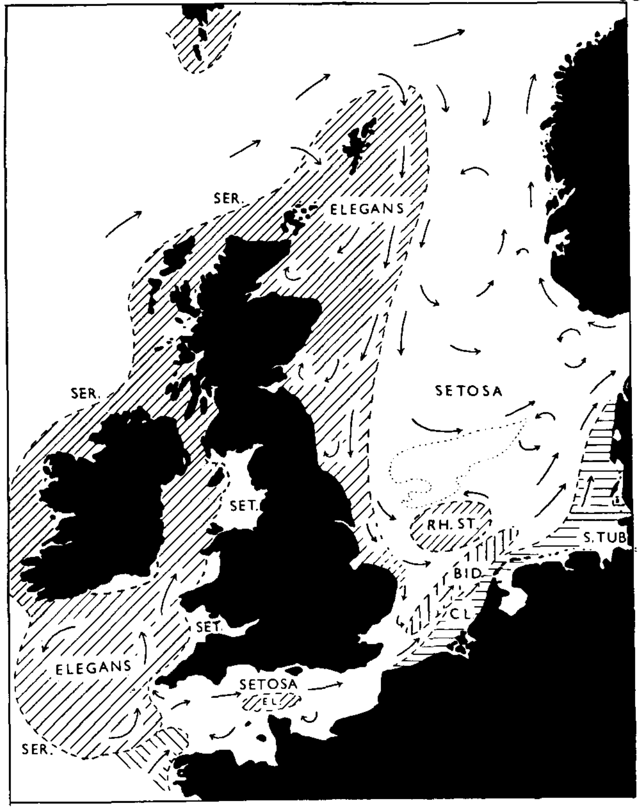

FIGURE 3. Generalized picture of distribution of plankton indicators in the North Sea area: showing occurrence of *Sagitta elegans*, *S. setosa* (SET.), and other species; arrows indicate general water circulation (from F. S. Russell 1939).

Figure 3 shows that *Sagitta elegans*, the plankton-indicator of good conditions for fish in the English Channel, is also distributed in the North Sea in a way that suggests an association with Atlantic water entering through the Faroe-Shetland Channel (F. S. Russell 1939). The idea of plankton organisms as indicators of hydrographic conditions has been so popular in England and Scotland that plankton has been routinely collected, along regular steamship and weathership tracks radiating out from Britain, in most peace-time years since 1932. The convenient Hardy Continuous Plankton Recorder is used. Figure 4 shows the coverage now being obtained (Hardy 1956).

The surface currents of the Northern North Sea region are shown, from the drift-bottle work of Tait (1937), in figure 5. Tait (1955) has also studied vol-

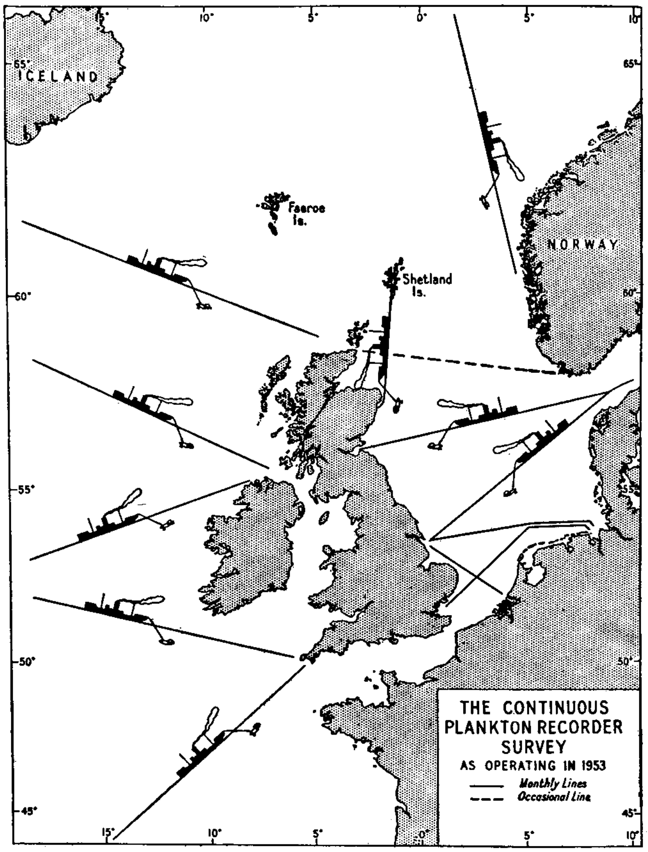

FIGURE 4. Scope of Continuous Plankton Recorder survey in 1953 (from Hardy 1956).

ume transport of oceanic water (salinity $>34.99\ ^0/_{00}$) through 68 sections made across the Faroe-Shetland Channel from 1927 through 1952, noting various seasonal and annual changes. Scottish biologists have been trying to link such changes with fluctuations in distribution of plankton organisms on the above-mentioned sampling lines around the north of Britain, and with events in the herring fishery off the northeast coasts of Scotland (Glover 1955).

Another aspect of plankton work related to herring must be mentioned, the aggregation of the herring on to the plankton, especially the copepod *Calanus,* which it eats. This has been investigated several times in different areas, frequently in the hope that the relationship would prove sufficiently close to enable fishermen to locate herring from their own plankton surveys with simple collecting instruments. This has happened sometimes but not always (e.g. Hardy, Lucas, Henderson, and Fraser 1936, in the North Sea). It is now clear that a close positive relationship between herring and food is much more likely to occur in some situations than in others, as shown for example from the work of Manteufel (1941) in the Barents Sea, where the study was simplified by the fact that only one brood of *Calanus* occurs per year. The relationships between this brood and the herring are summarized diagrammatically in figure 6.

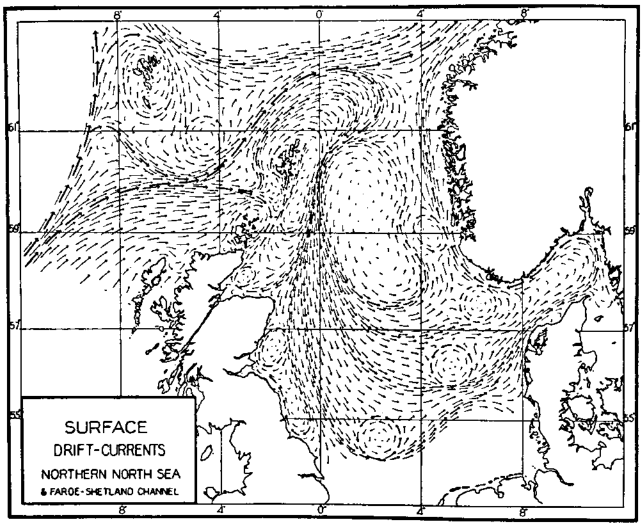

FIGURE 5. Surface currents in the northern North Sea (from Tait 1937).

Finally, for the herring, we must note the appearance in the last decade of an important herring fishery and herring-oceanography program in the middle of the Norwegian Sea, from Iceland to Spitzbergen (Fig. 1), in the very region where Hjort (1914) thought no appreciable amount of herring existed. Location of the resource was primarily the result of equipping a new research ship with asdic (sonar) and using it in regions where a new generation of Norwegian and Icelandic biologists had concluded, from tagging experiments, that herring must occur. But oceanographic work accompanied these surveys from the start, and is producing a picture of herring shoals concentrated, in summer, along the eastern boundary of the cold East Iceland and East Greenland Currents (Devold 1952, Marty 1956). Plankton and productivity (C^{14} method) observations indicate that this is the best part of the region for production of herring food (Berge 1958). Much has been added to our knowledge of currents in the region (Alekseev and Istoshin 1956).

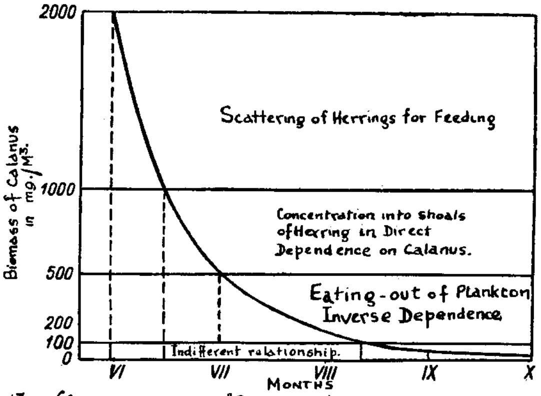

Fig13. (Assumed sense of Russian text)
Showing how the changing biomass of Calanus is related to the correlation between Calanus and the Catch of Herrings and to the scattering and Shoaling of the Herring

FIGURE 6. Summary of *Calanus*-herring relationships in the Barents Sea (from Manteufel 1941).

The amount of work done on oceanography in relation to cod has likewise been large. Much of it has been planned around the belief that cod are particularly selective about temperature, which arose in part through the work of Thompson (1943) at Newfoundland. The fact that the cod extended its range northwards, from Iceland well into Greenland waters, after the middle nineteen-twenties when the waters of this region were warming, gave further support to the general idea and encouraged the expansion of cod research generally. Biological and hydrographic observations regarding this extension of the cod's range were given by Hansen (1949). Fishery records of the early nineteenth century suggest previous invasions and retreats of cod in Greenland waters. Sea temperature data do not go back quite so far, only to 1876; they show the recent warming very well, of course, and also the preceding cold period about 1920 to which reference has been made (Smed 1949).

There was an unexpected increase in the abundance of cod in the Baltic Sea in the nineteen-forties which Alander (1952) has explained in terms of a series of rich year-classes associated with increased salinity of Baltic water.

Returning to Arctic cod, we note an important investigation by England, commencing in 1949, of the distribution of cod in relation to the environment around Bear Island, between Norway and Spitzbergen. Bear Island lies in the region where the warm Norwegian Current divides and cold water penetrates from the north-east (Fig. 1). The intention was to study relationships of cod to temperature, not so much to predict abundance changes of the whole population through year-class strengths as to predict the location of any payable concentrations of the fish (i.e., similar in motive to some of the herring studies).

The results of this work are still appearing. The results available are somewhat inconclusive on the value of temperature observations to fishermen in the area as a whole, but they point to some situations in which measurement of bottom temperatures would facilitate location of fish (Lee 1952). It was shown that paying quantities are rarely caught in water colder than 1.75°C, except in summer when the fish are feeding heavily to the east of Bear Island and may be found down to –0.5°C. Another finding was that on grounds west of Bear Island, in early summer and in autumn, Atlantic water touching the Bear Island bank can give good catches with bottom temperature between 3° and 5°C. For the area as a whole the range of temperature associated with cod is wide—about –0.5° to 5°C—in the summer feeding season, and narrow—about 2° to 4°C—in the winter non-feeding season. Even in the winter there may be waters of "suitable" temperature without fish.

Another member of the Bear Island research team has attempted to explain the distribution of cod in the area in a different and more comprehensive way (Trout 1957). The hypothesis, derived from tagging experiments and other biological observations on the cod, is that cod are carried along with currents during summer when they leave the bottom in response to light, and work back against currents in the dark of winter when they have resumed a bottom-living existence.

The report of the first two years of this program provides interesting reading for those interested in European fisheries oceanography from the point of view of outlook, organization, facilities, and methods (Graham *et al.* 1954).

There have been many other investigations on the effects of oceanographic variables on European fish, some conclusive and some not. Much of the work has been done in the "Transition Area" at the entrance of the Baltic (Jensen 1952), on many species. Other references to such work, and to oceanographic work less intimately connected with fisheries at the present time, may be found in papers in the International Council's "Rapport Jubilaire" (1952), and in reviews by F. S. Russell (1952) and Fleming and Laevastu (1956). It is proper also to mention the immense contribution made over about 20 years by Britain, to the fisheries oceanography and general oceanography of the Antarctic Ocean, through the "Discovery Committee". The fisheries in this case were for whales, whose relationships to environment have been summarized by Hardy and Gunther (1935). The effort continued as a general oceanographic survey of the Antarctic and adjacent seas, including the Peru and Benguela Currents, and the ships and personnel finally became the nucleus of the National Institute of Oceanography (Mackintosh 1950).

We may return to the matter of whether or not it is important to understand the causes of year-class fluctuations. It is now generally held that they should be known, if only because it is not always possible to measure the changes properly by sampling juvenile fish. Carruthers has for some years approached this problem *ex hypothesi;* he has assumed that the differences are mainly differences in mortality of young and that they occur in the North Sea because of the vagaries of currents that may carry the young into favorable or unfavorable situations; and he has examined the relationships between year-class sizes and measurements of the winds held responsible for the currents, and has found some satisfactory agreements. The idea is shown in figure 7 which is from one of his earlier papers (1938), showing the correspondence over a series of years between the relative size of haddock year-class and sum of east components in the wind, in the North Sea. Since the war he and his colleagues have produced similar arrays

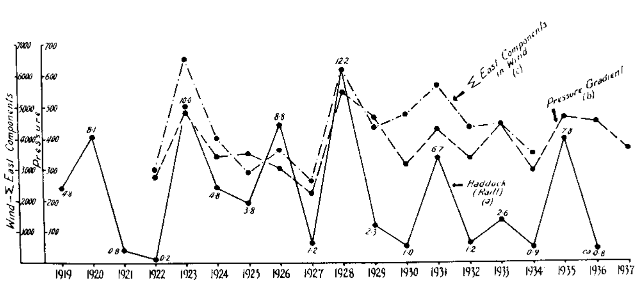

FIGURE 7. Comparison of annual changes in haddock year-class size, pressure gradient, and sum of east components in wind; North Sea data (from Carruthers 1938).

of data, regarding year-class strength and wind, for other species including herring, plaice, cod, and sprat (Carruthers, Lawford, and Veley 1951; other references in Carruthers 1954).

As a result of this work Carruthers (1951) has taken what he calls ''An attitude on fishery hydrography'' which amounts to this: oceanographers who are not obliged to produce practical results may study what they like, but fisheries oceanographers should study winds. Wind data, he emphasizes, are cheap. Warming to this theme in other papers (1953, with Lawford and Veley; 1954) Carruthers asks whether the complex kind of work now thought of as fisheries oceanography, the kind we have been considering, can do the fisheries any good within reasonable time, or ever. He says (1953) of Tait's work:

''Tait is well known of course for the meticulous detail of his work carried out over many years on water movements in the sea areas to which attention has to be paid by those whose task it is to study the fish of the North Sea. Unless the reviewer has got quite a wrong impression, Tait wants more detail still . . . If so, we must wait a goodly time yet before 'Fisheries Hydrography' can pay the dividends which the biologists seem to expect. There is at least the chance, however, that fruitful associations of the kind needed may be worked out between fish fortunes and environmental conditions in a more simple way involving less industry and less cost.''

However, the pattern of fisheries oceanography in Europe has not yet changed much. The work of the last decade has reflected the following recommendation made by the Consultative Committee of the International Council in 1951, after a special scientific meeting on ''Fisheries Hydrography'' which featured many of the above-mentioned papers.

''As the proceedings of this meeting have shown that a combination of biological, hydrographical, meteorological, physiological or statistical researches has furthered our knowledge of biological productivity, of the habits of the fish stocks, and also the fisheries themselves, it is recommended that researches along these lines should be continued.''

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TUNA OCEANOGRAPHY PROGRAMS IN THE TROPICAL CENTRAL AND EASTERN PACIFIC

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Inter-American Tropical Tuna Commission

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 germo*.

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 indispensible 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 C^{14} 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 POFI 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. Therefore, 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 occurence 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.

OCEANOGRAPHY AND NORTH PACIFIC ALBACORE

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The purpose of this presentation is to summarize briefly the Honolulu Biological Laboratory's (HBL) oceanographic studies in the North Pacific and the oceanographic features with which are associated albacore distribution and abundance. These studies were begun in 1954 following two rather significant developments. On the negative side, the Washington and Oregon landing had fallen from a high of 34 million pounds in 1944 to less than a million pounds in 1953. On the positive side, at least scientifically, recoveries of albacore tagged with the "spaghetti" tag (Wilson 1953) had clearly demonstrated that the albacore could and did migrate from the American to the Japanese fishery (Ganssle and Clemens 1953), thus giving evidence that the oceanwide stocks are interrelated.

The HBL oceanographic and biological surveys north of Hawaii were planned to determine (1) the geographical limits and relative abundance of albacore and (2) the relationship, if any, of these to the environment, as described by oceanographic data. These studies were coordinated with those of the other research agencies through an informal Albacore Steering Committee composed of representatives of the Bureau of Commercial Fisheries and the States of Washington, Oregon, and California.

Three years were alloted for exploratory cruises to determine the distribution of albacore in the North Central Pacific, and three for the study of their abundance, migrations, and seasonal fluctuations in abundance. The latter effort was based on the premise that concentrations of commercial potential would be found. The results of a commercial charter in 1958 were disappointing, primarily because the locations of commercial concentrations of albacore are subject to large annual variations.

The major portion of both the fishing and oceanographic efforts have been to the west of 140° W. longitude. Cruises have, however, been made to the coastal areas in cooperation with other agencies and as part of our studies of the geographical and seasonal limits of albacore and their migration routes. There has been at least one complete systematic fishing survey, with limited oceanographic observations, of the area north of the Hawaiian Islands from 180° to the west coast of North America during each season of the year.

Both the oceanographic features and the summer distribution of albacore indicate that the area can be divided at about 150°-135°W. longitude, and we will follow this division in our discussion.

Figure 1 shows the extent of our oceanographic coverage to the west of 140°W. All the cruises were made in summer or winter with the exception of one made during the 1954 September-November period.

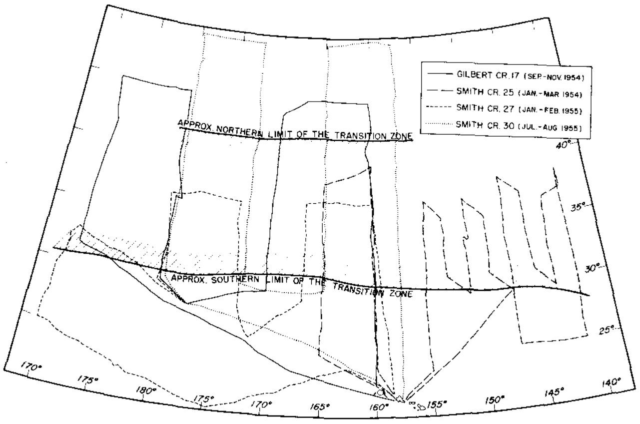

FIGURE 1. Tracks of four HBL oceanographic cruises to the central North Pacific.

Figure 1 is from an earlier paper (McGary et al., 1958) in which the oceanographic features were reviewed in a discussion of the possible enrichment patterns of the area. In that report the term "Transition Zone" was used to refer to the area in which the water characteristics changed from those typical of the two central North Pacific Water masses to those of the Subarctic Water mass. It was used because the authors preferred to avoid the use of the term "Polar Front", which implies a single, abrupt change. Oceanographic data showed, instead, a series of small but frequently abrupt changes. Furthermore, the large seasonal migration attributed to the Polar Front was only apparent in the surface temperature field. The zone of most abrupt change observed in winter at about 35°N. is not comparable in structure or origin to the similar zone located farther north during summer at about 43°-46°N.

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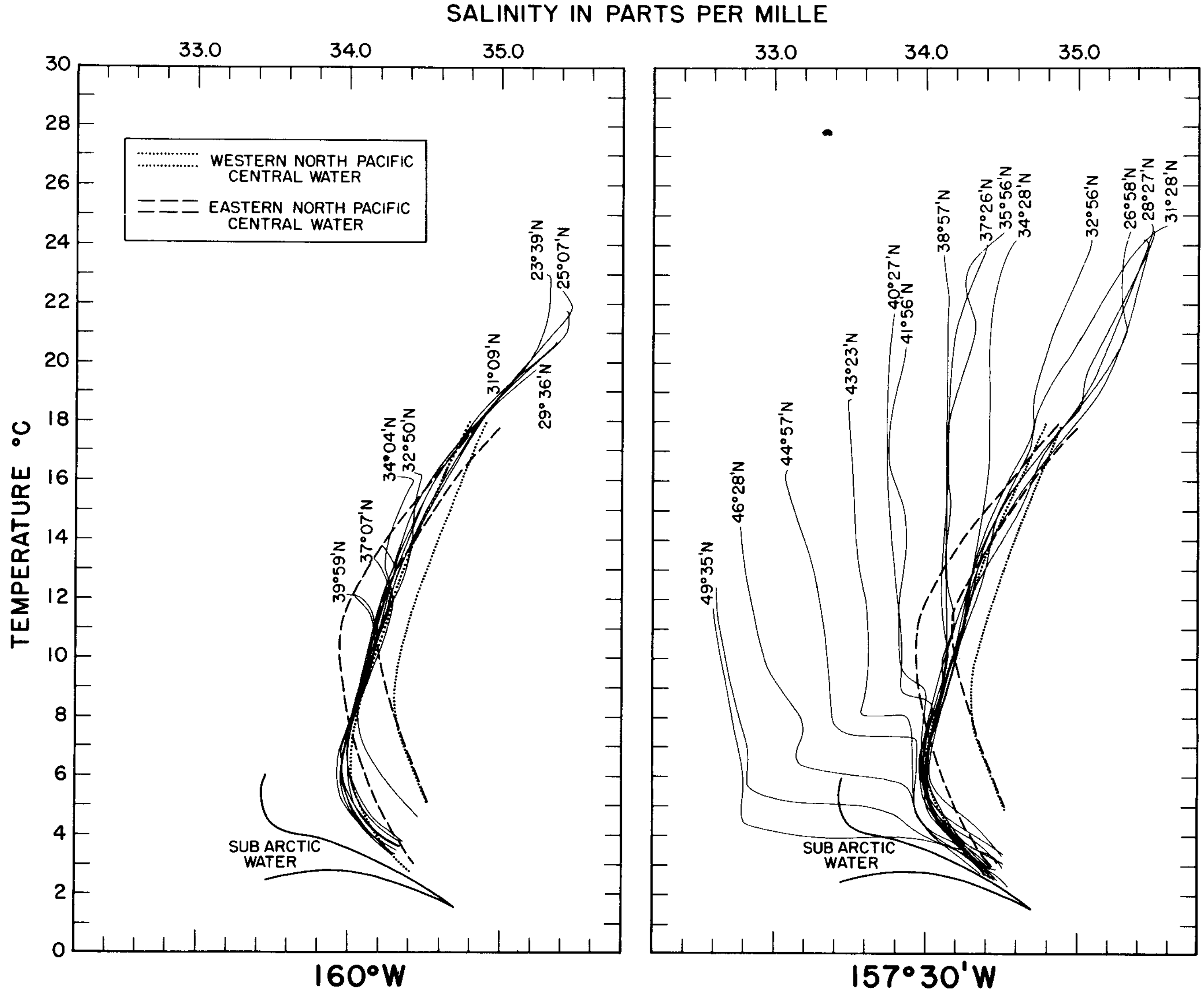

FIGURE 2. LEFT PANEL—superimposed temperature-salinity curves for the meridional station series along 160°W. longitude *Hugh M. Smith* cruise 25, January 1954. RIGHT PANEL—same along 157°W. longitude *Hugh M. Smith* cruise 30, August 1955 (McGary et al. 1958).

The temperature-salinity curves (fig. 2) from HBL winter and summer cruises, in the vicinity of 160°W., show the features used in a preliminary definition of boundaries, as well as the effect of seasonal temperature changes in the surface portion of the curves. Those from *Hugh M. Smith* cruise 25, January 1954, (McGary and Stroup 1956), show an abrupt shift in the T-S characteristics of the surface waters between 31°09′N. and 32°50′N. Shifts in the T-S curves continued northward and corresponded to areas of relatively large geostrophic currents. The position of the northern boundary cannot be defined with confidence, since this cruise did not extend far enough north to reach Subarctic Water. T-S curves from *Hugh M. Smith* cruise 30 (NORPAC) [3] (McGary et al., 1958; Hida 1957) shows two regions of abrupt shift in the surface portions of the curves. The most abrupt shift occurred between 32°56′N. and 34°28′N. Farther to the north another such shift occurred between 41°56′N. and 43°23′N. North of that latitude, the shifts were large but were uniform latitudinally. At 43°23′N. and northward, a salinity minimum was present at the surface, which is in keeping with the definition of Subarctic Water (Sverdrup et al., 1942, p. 722).

The salinity cross sections were examined and boundaries roughly set by the following criteria (see fig. 3). The southern boundary was set as the northern limit of the area within which the warming during all seasons was sufficient to maintain a lens of high salinity water at the surface. The northern boundary was taken as the southern extreme of the area in which the lens of low salinity water, from precipitation or other sources, was sufficient to withstand the effects of winter cooling or was not mixed

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[3] NORPAC was the code name given to a quasi-synoptic oceanographic survey of the North Pacific during the summer of 1955 by research agencies of Canada, Japan, and the United States.

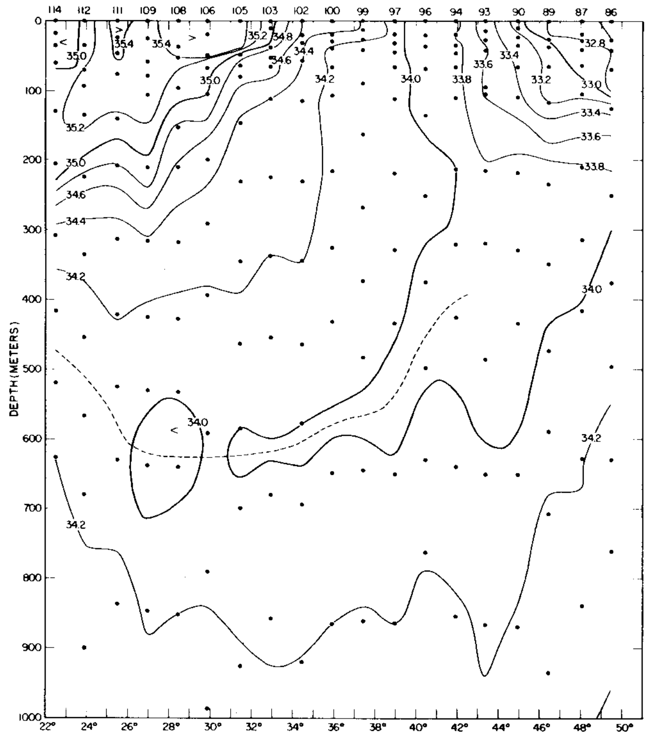

FIGURE 3. Salinity cross section 157°30'W., *Hugh M. Smith* cruise 30, August 1955.

sufficiently with more saline water to the south to cause it to sink even during winter. The limits of the Transition Zone shown in figure 1 were drawn on this basis. The differences in the sections for the various seasons showed, as expected, that the southern limit was 1°-2° of latitude farther south in winter than in summer. Only summer data were available to the north but no doubt the northern limit shifts to the north in winter, since cooling would break up the shallow southern limit of the lens.

Comparison of the longitudinal sections from *Hugh M. Smith* cruise 25 (January-March 1954) showed that boundaries and sharp changes in the T-S curves became less distinct from west to east (Stroup and McGary, 1956).

Reports by Japanese oceanographers suggest that the Transition Zone extends westward to the area immediately off Japan and that it narrows to the west. Uda (1943) described a double frontal system in the Kuroshio, and Masuzawa (1957) discussed the structure in more detail. The latter reported the width of the "Frontal Zone" between the warm and cold water to be 200-300 miles within about 500 miles of the coast. In general, he stated that the "Polar Frontal Zone" shows particularly predominant discontinuities along both the northern and southern edges. He also found that the northern edge was not as well defined as the southern edge.

The surface and vertical temperature distributions typical of the Transition Zone are shown in figure 4. The contrast between the summer and winter profiles shows the effect of seasonal heating and cooling. During both cruises the subsurface isotherms rose abruptly, e.g. 60°F., in the vicinity of the southern limit of the Transition Zone. In winter, the northern limit of this ascent marked the beginning of the zone with little or no distinct surface layer; in summer, it marked the beginning of a very shallow surface layer with an extremely sharp thermocline. At the northern limit of the Transition Zone, the 50°F. isotherm marked the boundary of a distinct difference in the subsurface structure; to the north it marked the beginning of an area with frequent small inversions below the thermocline. The surface temperatures of both seasons showed a striking coincidence in the temperature range at which the greatest horizontal gradient occurred: on both sections inspection showed it was between 56° and 68°F. with the maximum usually occurring between 58° and 62°F. Inspection of other transects shows that this is true of all seasons of the year, both in the central and eastern Pacific (Shomura and Otsu, 1956; Graham, 1957). In spring, the zone of surface temperature discontinuity is associated with the development of the shallow thermocline and its northward advance as summer approaches. It also coincides with the southerly movement of the breakup of the shallow warm surface layer in fall and winter.

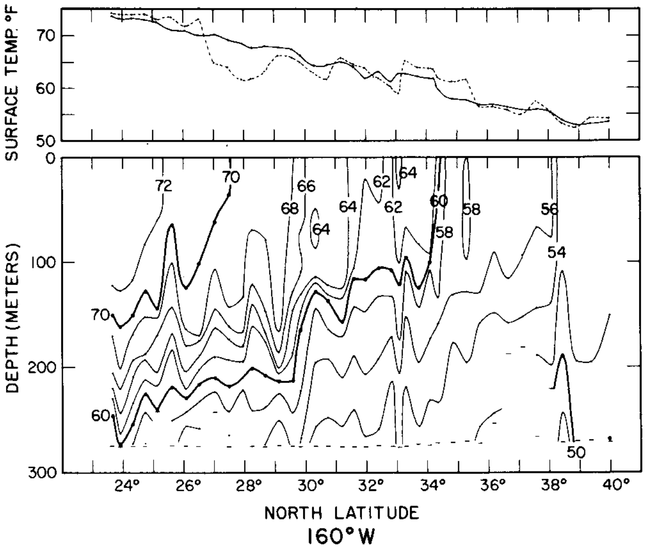

FIGURE 4a. Temperature section from BT casts along 160°W., *Hugh M. Smith* 25, January 1954. Broken line in upper panel shows surface air temperature.

Hida (1957), in a study of the distribution of chaetognaths and pteropods in the North Pacific, found that these oceanographic divisions coincided with faunal divisions and, in fact, the term "Transition Zone" in the sense used here was introduced in his report. Jones (McGary et al., 1958), in a study of copepods, found that the formation of the warm surface layer apparently offered favorable conditions for phytoplankton blooms, followed by an increase in zooplankton standing crop. However, the latter was not characterized by a meridional advance of tropical species, but rather by the development of "blooms" of eurythermal forms such as *Calanus helgolandicus* and *C. tonsus.*

It cannot be ascertained from the data at hand whether (1) the distribution of albacore is controlled directly by surface temperature (presumably through physiological mechanisms) or whether (2) the distribution of albacore is related only indirectly to surface temperature through the seasonal march of events leading to a large standing crop of forage organisms. In rebuttal to the hypothesis of direct relationship, data from other areas do not always show the same albacore-temperature relationship, and within the survey area uniform distribution with temperature did not occur from area to area or season to season. In rebuttal to the forage hypothesis, the seasonal movement of the biological frontier coincided with the movement of the isotherms, but it did not indicate the presence of albacore in all seasons nor in all parts of the survey area.

In figure 5, the total catch of albacore is shown as the percentage of the catch made at different surface temperatures. The total catch includes all of the albacore taken by HBL in the central Pacific by troll and gill net during all seasons. For comparative purposes, similar examples from the east and west have been included. The curve shows that the central Pacific catches were made within a narrow temperature band, with a dominant mode between 58° and 60°F. The overall range may be narrowed to about 55°F-66°F., since almost all of the catches at temperatures below 55°F. were made in the fall immediately after periods having winds of Force 6 or greater and it was evident that the area had experienced a recent sharp temperature decline because of wind-induced overturn (Shomura and Otsu 1956, Graham MS[4]). The *Cobb* data are typical of the fishery which frequently develops off the coast of British Columbia, Washington, and Oregon during the late summer (Powell and Hildebrand, 1950) and indicate that the albacore occur in the same narrow temperature range as in the central Pacific. The *Jini Maru* plot was constructed from data collected in the spring live-bait fishery off Japan during a cooperative tagging program conducted in the spring of 1956 by the Japanese Fishery Agency and HEL (Van Campen and Murphy, 1957). These data are representative of this fishery. Here, the temperature range and mode are even more sharply defined than in the other two plots. These conditions

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[4] J. J. Graham, "Macroecology of the albacore, **Thunnus germo** (Lacepede), in the central North Pacific" MS.

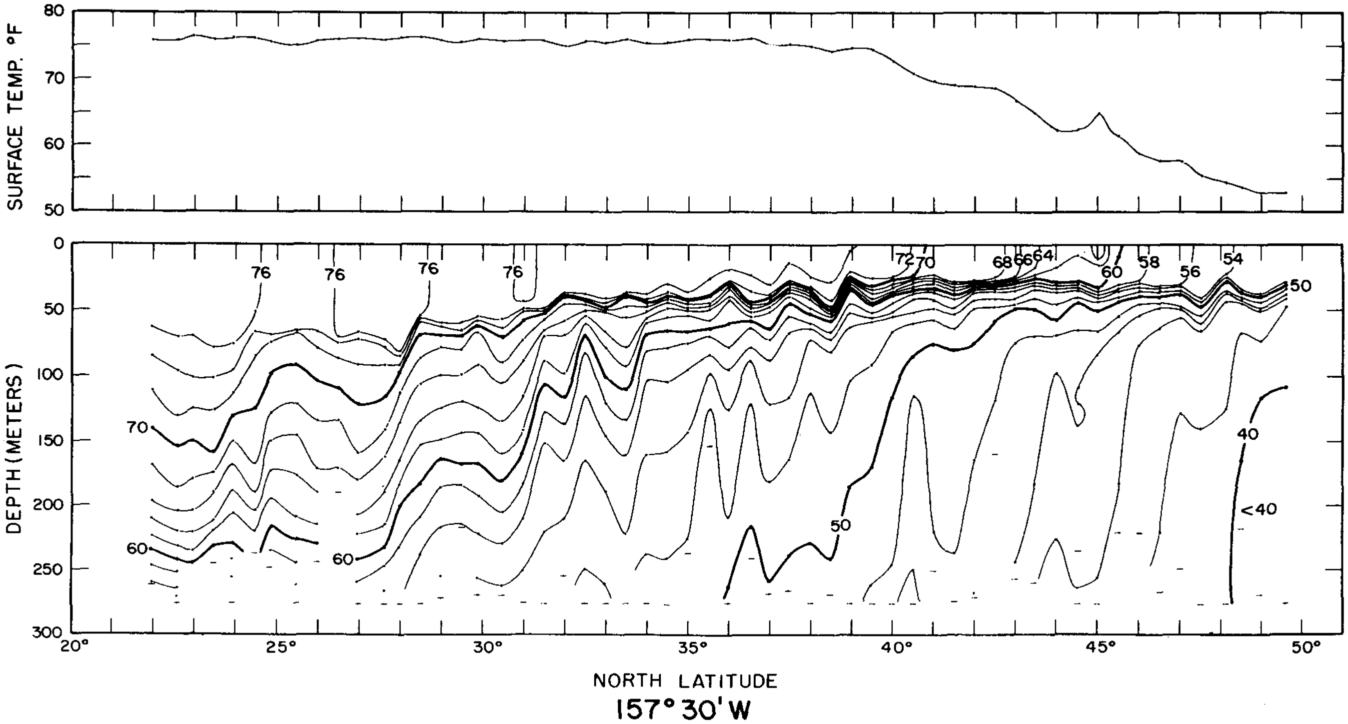


FIGURE 4b. Same along 157°30′W., *Hugh M. Smith* 30, August 1955 (McGary et al. 1958).

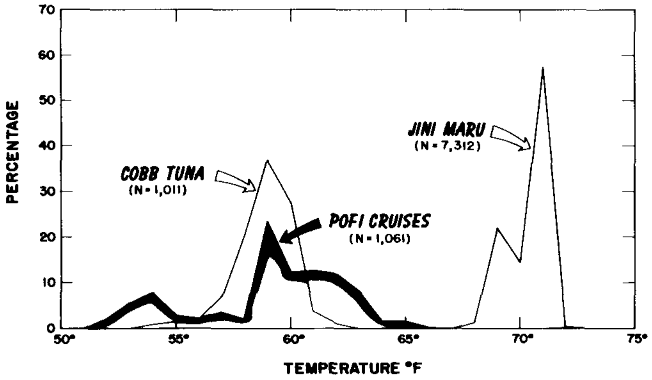


FIGURE 5. Percentage of albacore catch versus temperature of catch.

arise in part from the fact that the *Jini Maru* was engaged in commercial fishing and an effort was made to stay with the maximum concentration of fish. However, in spite of the fact that the general oceanographic features of the area indicate that the *Jini Maru* data were taken in the western extremity of the Transition Zone, the temperature range does not even overlap that of the central and eastern Pacific.

A discussion of the seasonal distribution of albacore will serve to illustrate the use and limitation of temperature as an indicator of the areas in which albacore might be expected to occur. Beginning with winter, a comparison of the catches of *John R. Manning* cruise 19 along 160°W. (fig. 6) during January 1954 with the temperature profile from *Hugh M. Smith* cruise 25 (see also fig. 4a) shows that the deep swimming albacore captured on longline gear occurred in an area having surface temperatures of 56°-66°F. and just south of the point where the largest horizontal temperature gradients occurred.

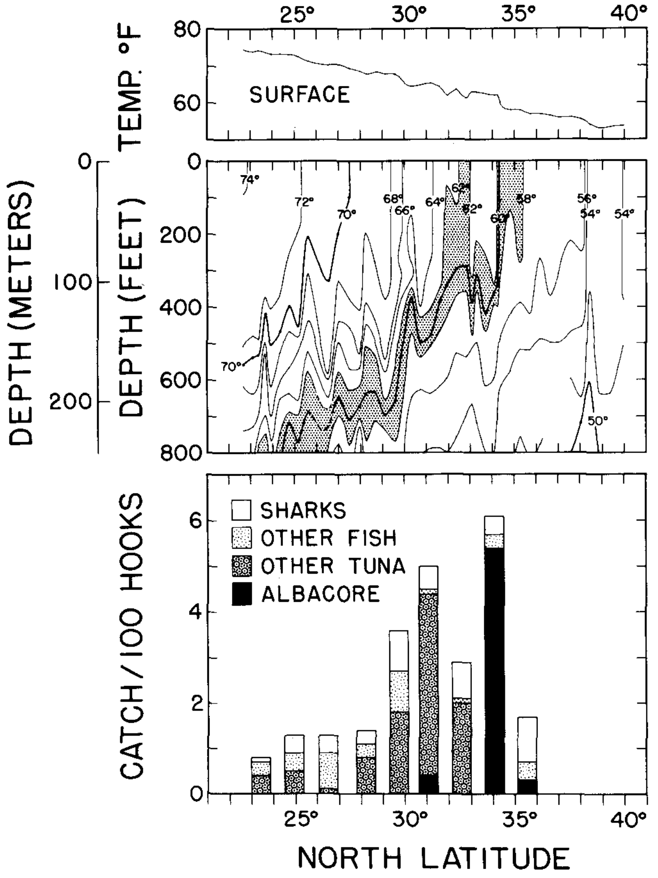


FIGURE 6. Vertical temperature profile, *Hugh M. Smith* cruise 25, January 1954 and longline catch/100 hooks, *John R. Manning* cruise 19, January 1954, along 160°W. longitude.

Figure 7 shows the winter distribution of albacore in the eastern North Pacific as indicated by the surveys of 1955 and 1956 and the Japanese winter fishery. It shows quite clearly that the latitudinal limits are almost coincident with the southern boundary of the Transition Zone (fig. 1) and the temperature front (fig. 4 and 6) and are not associated with the subtropical convergence as originally hypothesized. The dynamic topographies from the 1954 and 1955 winter cruises indicate that the subtropical convergence was in the vicinity of 24°-27°N. during both years (McGary and Stroup, 1956 and 1958). Suda (1958) also described the subtropical convergence as an area of minimal albacore catch in the western Pacific.

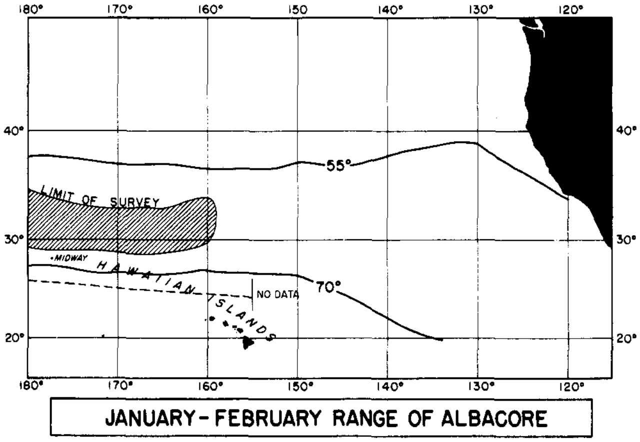


FIGURE 7. Winter distribution of albacore in the eastern North Pacific. Dashed lines indicate position of Subtropical Convergence from *Hugh M. Smith* cruises 25 (January-March 1954) and 27 (January-February 1955).

Our spring cruises (1955 and 1956) showed a conspicuous band of phytoplankton and zooplankton abundance in the 55°65°F. surface temperature range between 180° and 140°W. There was an abundance of forage organisms and a rich phytoplankton bloom was indicated by the Forel color of the water, but few albacore were caught. Only one was taken east of 170°W., and only a few scattered fish to the west of 170°W. on all three types of gear (troll, longline, and gill net).

During the fall of 1954, 1955, and 1956 albacore were taken in considerable quantities from offshore of San Francisco to 170°E. longitude, the western limit of the survey area. They were taken in waters with surface temperatures between 55°F. and 65°F., with the peak catches ocurring in the 58°-60°F. range.

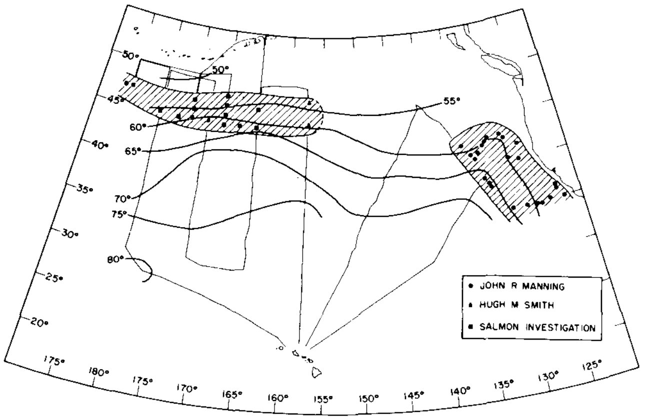


FIGURE 8. Location of albacore taken in the North Pacific by exploratory vessels, July-September 1955.

Again, this temperature appeared to coincide quite well with the biological frontier.

During the summer of 1955, because of NORPAC and the activity of the North Pacific Salmon Investigations, there was excellent coverage between 175°E. and the west coast of North America. The results showed two interesting features. Firstly, the albacore were divided into two groups, one in mid-ocean extending as far east as 155°W. (fig. 8) and the other extending northwest from the California fishery. The existence of the area of albacore scarcity has been at least partially verified in all subsequent summer surveys. Secondly, comparison of figure 4 and figure 8 shows that the mid-ocean albacore were in a shallow surface layer in Subarctic Water (figure 2) and at about the same surface temperature range as during the other seasons. The *J. R. Manning* returned to the area in 1956 and found a similar situation (fig. 9) with an even more pronounced biological frontier indicated by the plankton abundance and light penetration readings. In 1958 the 1955 and 1956 summer surveys were followed up by a commercially unsuccessful gill net effort from the chartered vessel *Paragon*. Again the fish were found in the warm layer in the southern limits of Subarctic Water, but the center was 3°-4° farther south, and the standing crops of plankton and forage were much less than observed at corresponding temperatures for the previous years.

The hydroptic charts for the mid-August period for the past four years illustrate the amount the temperature field can shift in mid-ocean and the radical changes in local temperature that result. The lower panel, figure 10, shows the variation in location of the 55° to 66°F. surface temperature band that approximates the limits of albacore distribution. As a result of such variations, annual differences of up to 10°-12°F. can occur at a given locality. This could make considerable difference in the development of the seasonal plankton cycle in the area, particularly when one considers that the average seasonal range in temperature is only 15°F. The upper panel shows the latitudinal changes in the temperature range that corresponds to the peak of the albacore abundance in the central and northeastern Pacific. It illustrates the small amount of latitudinal change necessary to produce the 10°-12°F. temperature anomalies.

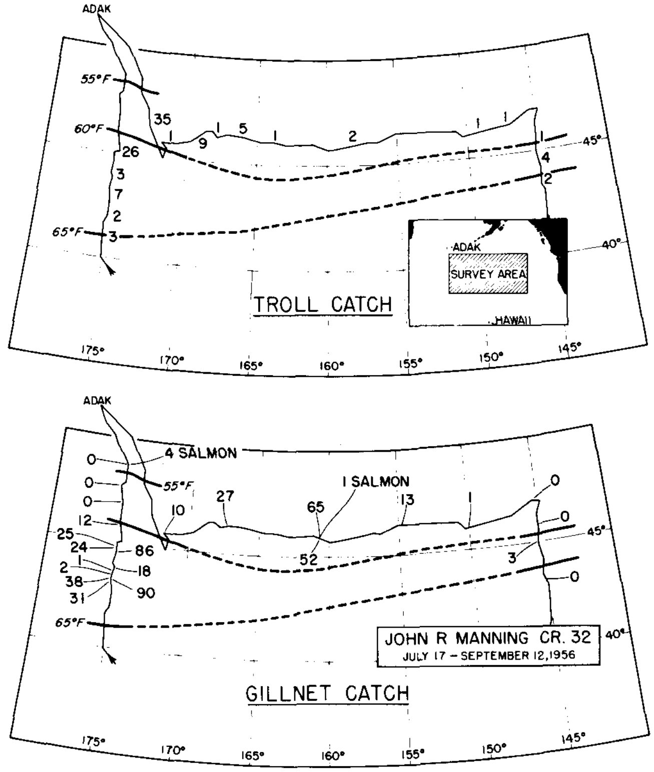


FIGURE 9. Summer 1956 albacore survey, *John R. Manning* cruise 32.

The existence of a "tongue" of albacore extending northwest from the California fishery in 1955 (fig. 8) and the work of Powell and Hildebrand (1950), Powell et al. (1952), Shaefers (1951), and Partlo (1950) suggest conditions under which the Pacific Northwest fishery develops. First, albacore may be present in the summer off the northwest coast during all years but move into and concentrate in the coastal waters of British Columbia, Oregon, and Washington only when oceanographic conditions (exact nature unspecified) are favorable. Second, the extent in time and space of the coastal band of upswelling may also influence the development of the fishery and limit its shoreward extent.

During the last 10 days of July 1957, nine chartered commercial trollers and two HBL vessels made a synoptic survey of the distribution and abundance of the albacore in the coastal area between 35°N. and 47°N. The results of the survey (fig. 11) showed that these fish were present in a wide band along the coast. In the northern part of the survey area, albacore were most abundant offshore of the area of largest surface temperature gradient which indicated the outer limit of the band of upwelling (fig. 12). However, their distribution was far from continuous and was not completely associated with any feature of the boundary, such as the tongues of relatively warm water which penetrated shoreward.

The radical annual temperature differences shown in hydroptic charts of the coastal areas (fig. 10) might

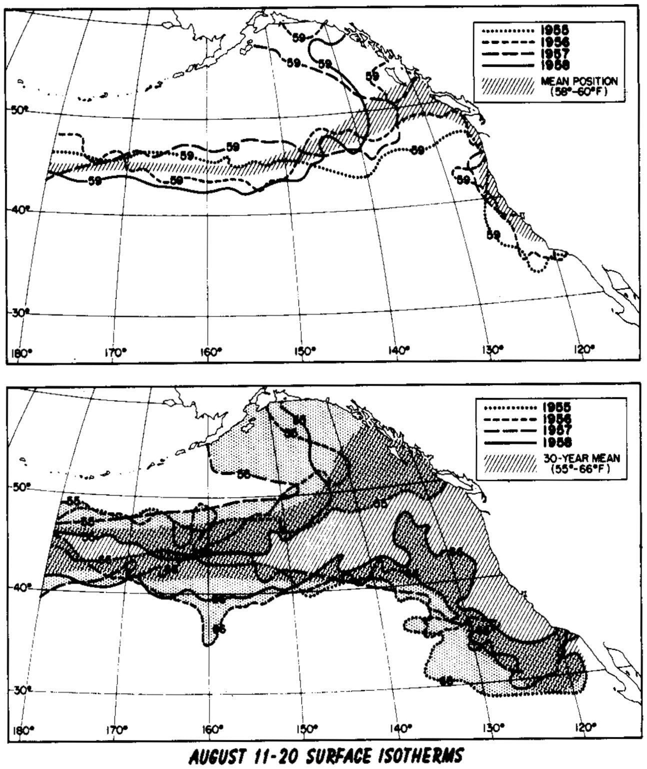


FIGURE 10. LOWER PANEL—mid-August mean and 1955 through 1958 positions of the 55° and 66°F. isotherms; UPPER PANEL—mid-August mean and center of the 58°-60°F. isotherms for 1955 through 1958.

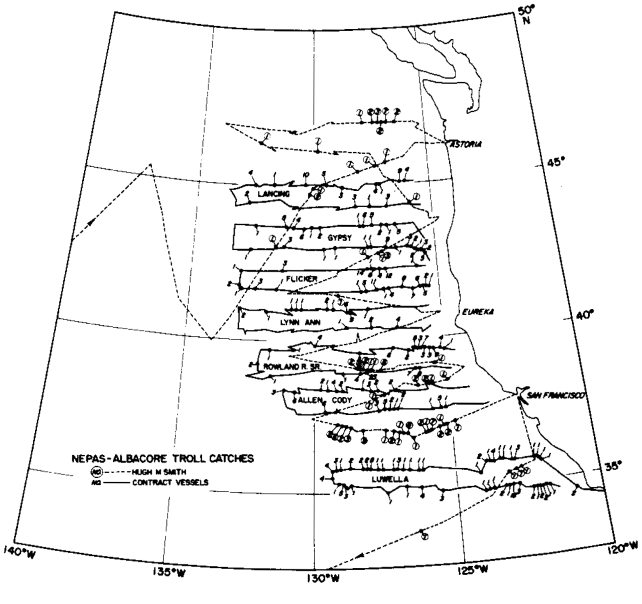


FIGURE 11. NEPAS (Northeastern Pacific Albacore Survey) troll catches, July 1957.

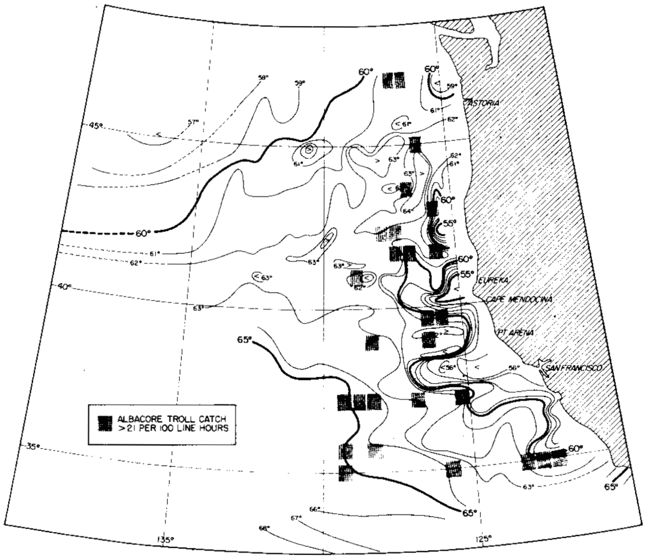
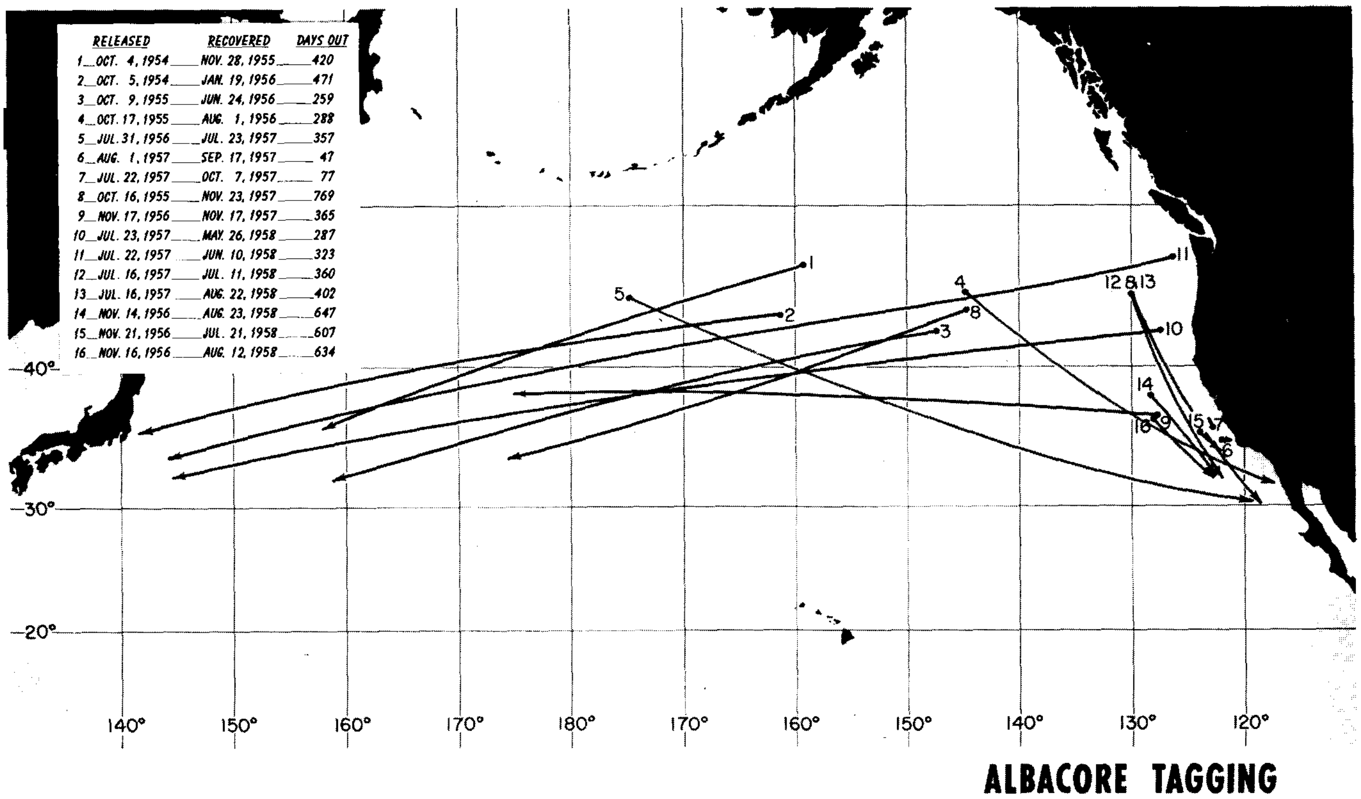


FIGURE 12. NEPAS surface temperatures and best albacore catch rates.

also account in part for the yearly fluctuations in the landings of the California fishery as well as the radical fluctuations in the Pacific Northwest fishery. The charts show that suitable temperature conditions for albacore may in some years occur as far north as Kodiak Island and lend credence to reports of albacore in the Gulf of Alaska in 1957 and 1958.

Not all of our efforts have been confined to exploratory fishing work. Results from our tagging experiment, literature research, and age, growth, and spawning studies have given us a reasonably plausible picture of albacore migration routes in relation to oceanographic features. One thousand two hundred and six albacore have been tagged. In addition, we have helped establish a tagging experiment in the Japanese live-bait fishery. Figure 13 shows the points of release and recapture of our 16 returns. It shows migration from the mid-ocean area to both the American and the Japanese fisheries and movement from the American to the Japanese fishery. Recoveries from California Fish and Game tag releases (Ganssle and Clemens 1953) also show this latter movement. Japanese tag returns (K. Mimura, personal communication) have shown rapid easterly movements within their spring live-bait fishery. On the basis of these returns, the oceanography, our spawning and growth studies (Otsu and Uchida, 1959a and b), and Suda's (1958) paper on migration within the Japanese fishery, we have arrived at the somewhat incomplete pattern of albacore migrations shown in figure 14. Here we show an easterly spring and summer migration along the 55°-65°F. temperature frontier in the Transition Zone and a westward migration along it in the fall and winter. The lack of an apparent connective link between the two segments of the eastern migration may be because the Japanese tagging experiment has only begun recently. Also, their tagging has been primarily in their live-bait fishery, which, in general, takes larger fish than the American west coast fishery. The postulated spawning area is located



	RELEASED	RECOVERED	DAYS OUT
1	OCT. 4, 1954	NOV. 28, 1955	420
2	OCT. 5, 1954	JAN. 19, 1956	471
3	OCT. 9, 1955	JUN. 24, 1956	259
4	OCT. 17, 1955	AUG. 1, 1956	288
5	JUL. 31, 1956	JUL. 23, 1957	357
6	AUG. 1, 1957	SEP. 17, 1957	47
7	JUL. 22, 1957	OCT. 7, 1957	77
8	OCT. 16, 1955	NOV. 23, 1957	769
9	NOV. 17, 1956	NOV. 17, 1957	365
10	JUL. 23, 1957	MAY 26, 1958	287
11	JUL. 22, 1957	JUN. 10, 1958	323
12	JUL. 16, 1957	JUL. 11, 1958	360
13	JUL. 16, 1957	AUG. 22, 1958	402
14	NOV. 14, 1956	AUG. 23, 1958	647
15	NOV. 21, 1956	JUL. 21, 1958	607
16	NOV. 16, 1956	AUG. 12, 1958	634

FIGURE 13. Chart of points of release and return of tagged albacore.

in the North Equatorial Current and is based on studies of albacore landed in the Hawaiian longline fishery as well as on HBL's exploratory cruises and data from the Japanese longline fishery in the west.

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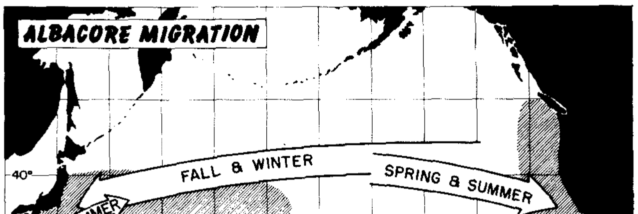

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OCEANOGRAPHY AND VARIATIONS IN THE PACIFIC SARDINE POPULATION

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The Pacific sardine fishery has produced catches ranging from 789 thousand tons in the 1936-37 season (Schaefer et al, 1951) to 10 thousand tons in the 1953-54 season (Felin et al, 1954). Fishing pressure has remained sufficiently constant so that most of this fluctuation can be safely interpreted as the result of variations in abundance and availability of the sardines themselves.

With respect to abundance the basic variable is year class size, and the most readily available estimates of year class size are the virtual populations, that is the summation of those individuals actually taken by the fishery. These have ranged from over seven billion fish for the 1939 year class (Clark and Marr, 1955) to a low of .1 billion fish for the 1949 year class (estimated from published and unpublished catch statistics). This is a range of 70 times but the virtual population can be severely distorted by variations in availability, particularly during the second, third and fourth years of life. Variations in availability (in the sense of Marr, 1951) are difficult to document precisely. The results of one study (Widrig, 1954) suggest that availability might have had a range of five times during the period 1941-50, and the inclusion of more recent years would undoubtedly increase this range.

In terms of the fishery the obvious need is to understand and predict these fluctuations in abundance and availability. This may also be viewed as a problem in ecology; that is, the response of a population to its changing environment. The California Cooperative Oceanic Fishery Investigations is inquiring into these fluctuations, and attempting to define the relative role of nature and man in influencing the size of the population.

The objectives and general results of the programs have been documented in a series of six progress reports (Marine Research Committee; 1950, 1952, 1953, 1955, 1956, 1958), which include bibliographies of completed scientific papers so there is no need to report general results here. Rather, I wish to discuss certain aspects of the oceanographic material that seem to bear most directly on the problem of abundance.

AVAILABILITY AND ABUNDANCE

Before examining some of the facts it is well to consider the theoretical basis underlying the application of oceanography to fisheries problems. The fishery problem may be conveniently separated into availability, defined as the accessability of such sardines as exist to the commercial fishery, and abundance, defined as the absolute magnitude of the sardine population or some segment of the population such as a year-class.

By and large, availability is a reflection of the momentary response of the population to the environment. This response takes the form of variations in distribution and behavior. Oceanographic studies related to availability generally include estimating the appropriate parameters of the environment of the fish population in question. As the studies progress, attempts are made to predict where and when environmental patterns associated with high availability will occur. Examples of this type of study are described by Sette (1955) who discussed several environmental mechanisms occurring in mid-Pacific Ocean that are associated with high concentrations of tuna, and Cushing (1955), who was able to relate the distribution of herring to changes in the food supply. All such studies suggest a more or less instantaneous response of the fish population to a parameter in the ocean.

In contrast to availability studies, investigations of abundance must consider the integrated response of the population to the environmental pattern over a period of time. The inherent difficulties of this approach are suggested in figure 1. Four curves are shown, each representing the relative change in instantaneous survival rate *(Z)* needed to reduce a particular initial survival rate *(S)* over a fixed period of time. The abcissa is the ratio of the initial survival rate (indicated on the curve) to any given lower survival rate. On the ordinate is a scale of the ratio of

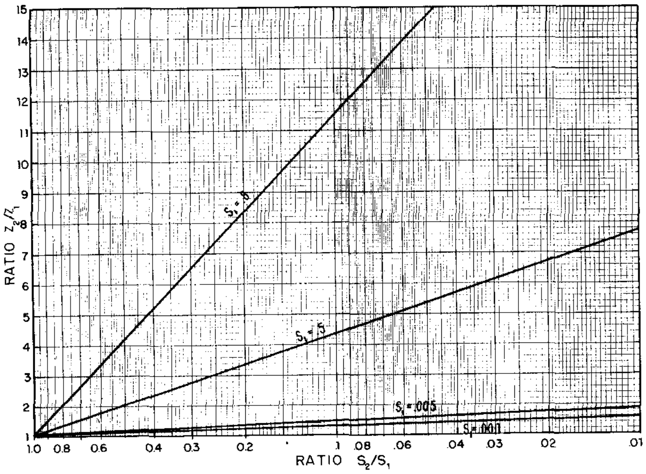

FIGURE 1. Diagramatic representation of the relation of changes in survival rate (S) to changes in the instantaneous mortality rate (Z), that is $S_2/S_1 = e^{-(Z_2 - Z_1)}$.

the instantaneous mortality rate associated with the initial survival rate to the instantaneous rate associated with the lower survival rate. For example, taking the curve representing $S = 0.8$ at initial survival, a change to $S = 0.08$, a reduction to $\frac{1}{10}$, would be associated with an 11.5 times increase in the instantaneous mortality rate.

Unfortunately when studying the California sardine we must deal with survival rates in the order of .001 during the first 45 days of life and of course much lower if a longer time-span is considered. At this initial level of survival (.001) an increase in the instantaneous rate of 1.6 times results in a hundredfold decrease in the number of survivors.

In terms of an investigation we can hope to measure survival at some point(s) in the life of the sardine (the result of integration) but we cannot measure an integrated environmental effect; all that it is possible to measure is an instantaneous value of the factor(s) contributing to the mortality rate. In practical terms a large change in the integrated results, i.e., a spectacular change in survival, may be associated with very small changes in the instantaneous measure of the environment as suggested above. Thus the problem of understanding the relation between changes in the environment and changes in survival of the California sardine may be much more difficult than an investigation of availability.

It would appear that it is necessary to identify precisely the operating factors because if small changes in the operator(s) result in large changes in survival, it will be nearly impossible to achieve success by measuring factors merely associated with the true operators; we must know the precise manner in which the operators affect the population in order to permit some form of integration either formal or conceptual, and there must be precise inventories of the fish populations at critical stages. The alternative is to content ourselves with a rather general approach to changes in the ocean and changes in the populations without serious consideration of cause-effect relations. This is an analogue of the water mass approach of explaining the geographical distribution of animals with time substituted for space. For certain purposes this is not without profit but it falls short of being fully satisfying.

Historically, many attempts to relate the environment to survival have centered around the larval period because the major reduction in the numbers of a given year class occurs then. Moreover, it is at this stage of the life of the sardine, prior to its acquiring the ability and motivation to aggregate, that the factors responsible for mortality are most likely to operate in a density-independent manner; this should simplify the analysis.

The fundamental support for the assumption of density independence is that sardine eggs and/or larvae are a very small fraction of the biomass. For instance, sardine larvae comprised only four percent of the total fish larvae during 1955 and 1956 (Ahlstrom and Kramer, 1957, Ahlstrom, 1958) and, of course, a much smaller portion of the plankton in general. This statement seems to hold true even in areas where spawning has been heavy. For instance at a moderately high density station (117.50, Cr. 5602, Ahlstrom, 1958) there were about 800 eggs, with a volume of about 2.5 ml. per 1000 m^3 of water. At this station the total catch of small plankton in the tow net was about 100ml. and total plankton was 425 ml. (Thrailkill, 1957). Eggs were therefore about 1/40 of the biomass of small plankton. If the water added to the perivitelline space after spawning is deducted from the egg mass the fraction is reduced to about 1/120, and, of course, if all the plankton were caught and considered, the fraction would be much smaller. Finally, random dispersal of the suspended eggs should serve to rapidly reduce such high concentrations.

Food is frequently considered the key to larval survival but in the instance of the California sardine this does not seem likely. Arthur (1956) showed that the standing crop of potential food organisms was 1,000 m^{-3} or greater in 70% of his stations and 3000 m^{-3} or greater in 50% of his stations in the general area of sardine spawning (figure 2). Referring to the high density station discussed above, the ratio of larvae (if all eggs survive to hatching and there is no dispersal, and if all eggs were assumed to be in the top 50 meters) to food organisms would have been 1 to 500 or 1 to 1,500 or greater in 70 percent or 50 percent of the station respectively.

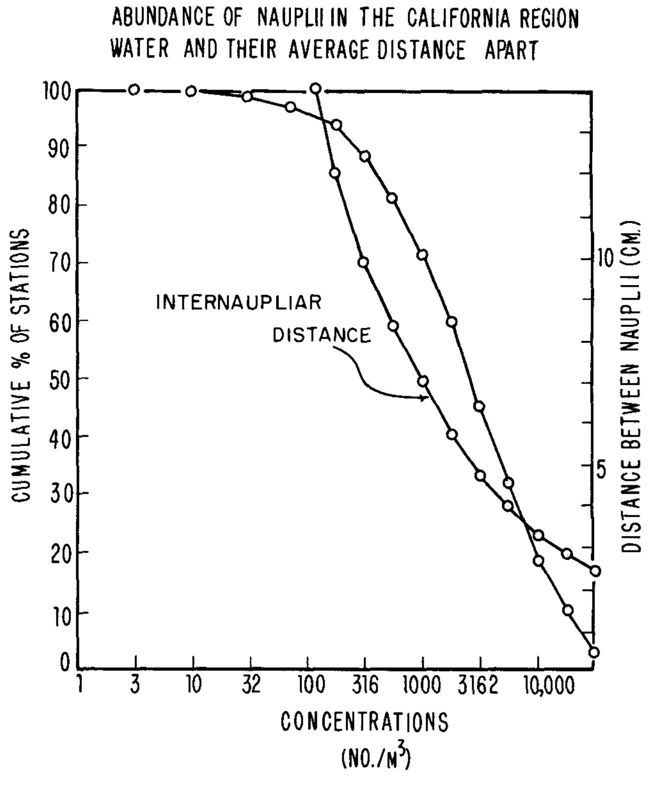

FIGURE 2. Cumulative summary of the density of the nauplii of microcopepods in the California Current, and the computed mean distance between nauplii associated with each density assuming they are randomly distributed in the water column, (after Arthur, 1956).

Arthur also shows that the mean distance between food organisms was 10 centimeters or smaller at 70% of his stations and 7 centimeters or smaller at 50% of his stations. The mean distance between a larva and a food organism would be one half this. Because of motion of food and larvae, only a very short time need pass before a larva has a food organism within easy reach. This information suggests that there is little or no competition among sardine larvae for food, and that there is always or nearly always sufficient food within easy reach of the larvae. The qualifications in this statement stem from the fact that occasional tows reveal concentrations of eggs about 10 times as great as the high density station under consideration. Maximum observed concentrations of larvae in a given year, however, are about the same as the above described concentration of eggs. Variations in food supply may not then be a significant factor in larval survival, except in rare instances.

The arguments above are based on what amounts to an instantaneous view of the numerical and spatial relations of the larvae and their food. Their validity turns on whether or not it is possible to regard this instantaneous picture as a sample from a system in a reasonably steady state. That is, the implicit assumption is made that the observed food supply at a given instant is the integrated steady state result of its renewal rate, its ''death'' rate from predation, and its growth to a size too large to serve as food for the larvae. Though it is difficult to prove the assumption formally, the fact that an apparently favorable supply of food seems generally to prevail lends strong intuitive support.

Predation remains for consideration. It seems reasonable that fish larvae will be subjected to roughly the same rates of predation as are other organisms in the plankton possessing their same general dimensions and behavioral characteristics. I am unaware of precise data on this point but the rates appear to be extremely high. For instance, Cushing (1955) concluded that over 90 percent of the diatoms produced during the period April 10 to May 16 in his study area were consumed. Because the larvae are typically a small fraction of the biomass it seems unlikely that variation in their numbers results in variations in the population of predators. Presumably the arrival through hatching and departure (through growth) of a relatively few sardine larvae elicits little or no special response from the population of predators, suggesting that predation is density independent.

The arguments above indicate that environmental data should be examined in the light of three working assumptions. (1) The sardine egg-larva is a minor element in the pelagic fauna and therefore the factors affecting the survival rate operate in an essentially density-independent manner. (2) Food supply is not an important survival factor, but rather (3) the intense predation typical of the plankton community is responsible for the rapid decline in numbers of the sardine larvae, and variations in this rate of predation are primarily responsible for variations in the rate of larval survival. How observed changes in the California Current System can operate to vary the rate of predation will be considered in the next section.

OCEANOGRAPHY AND LARVAL SURVIVAL

The most conspicuous variable likely to affect animals directly or indirectly in the California Current System has been temperature. Reid, Roden, and Wyllie (1958) have summarized certain aspects of these changes. The years prior to 1944 were characterized by more or less alternating positive and negative anomalies from the mean. From 1944-1956 the anomalies were predominantly negative, and from 1957 to the present (1960), they were mainly positive. The variations in temperature are essentially the result of the interaction of the strength of the California Current, upwelling along the coast, and the strength and character of the countercurrent. Because the historical record suggests that warm years tend to be associated with good year-classes, and cold years with poor ones (see Clark and Marr, 1955, Reid et al. 1958, and Marr, in press), I wish to examine the possibility that cold temperatures can act to increase larval mortality through predation and/or that cold temperatures are associated with other phenomena that adversely affect the sardine population.

Ahlstrom (1954) has presented evidence indicating that survival during the first 45 days of life is approximately .001 (figure 3). The mean instantaneous mortality rate associated with this is 6.9. Graham (1956, p. 244) suggested, but did not elaborate, that colder temperatures might prolong the larval phase, lengthening this period of high mortality, and therefore decrease survival. Ricker and Foerster (1948) conclude that mortality of sockeye fry is a function of growth rate. In their data, growth is accelerated or retarded as a function of population density, but the operator is predation, mortality being greater as the length of time spent at small, very vulnerable sizes is prolonged. Certain aspects of this problem are also treated in Beverton and Holt (1957, p. 55), and Ricker (1958, p. 263). Ahlstrom (1954) finds little evidence of serious mortality in the egg stage, which might well be associated with the extreme transparency of the eggs, and I have already noted that eggs are not aggregated densely enough to attract filter feeders. Thus the mortality (99.9%) under consideration occurs after hatching and before the stages at which the larvae are no longer sampled in the routine plankton hauls (a period of about 45 days).

If these high mortalities after hatching are simply a reflection of the larva's belonging temporarily to the relatively helpless plankton community, mortality will be sharply reduced or enhanced if the period of this association is altered. The only way a sardine can escape this community is by growth and this is a function of food and temperature, and larval food seems to be adequate for survival though the supply may not always be adequate for maximum growth. Thus, if predation is held to be the main source of larval mortality its effect can vary with the density of predators, and the duration of the vulnerable stages. The latter can be a function of food, temperature, or both. There is some indication (Reid et al.

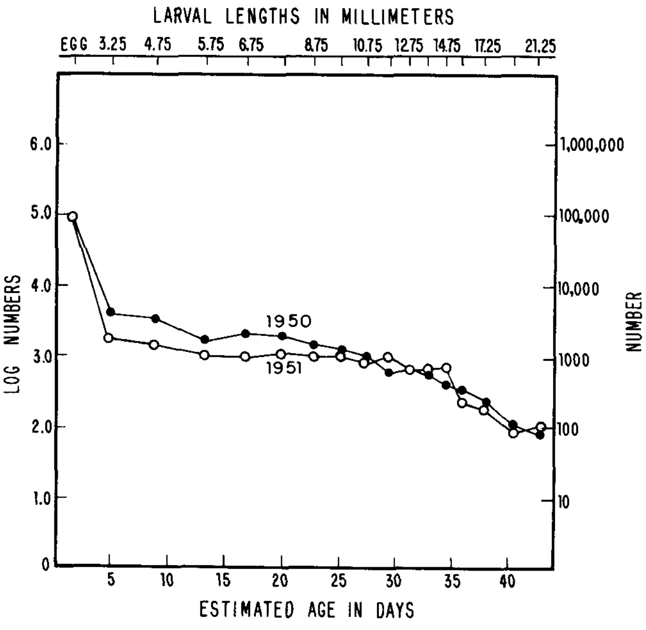

FIGURE 3. Apparent mortality curve of sardine larvae, (after Ahlstrom, 1954).

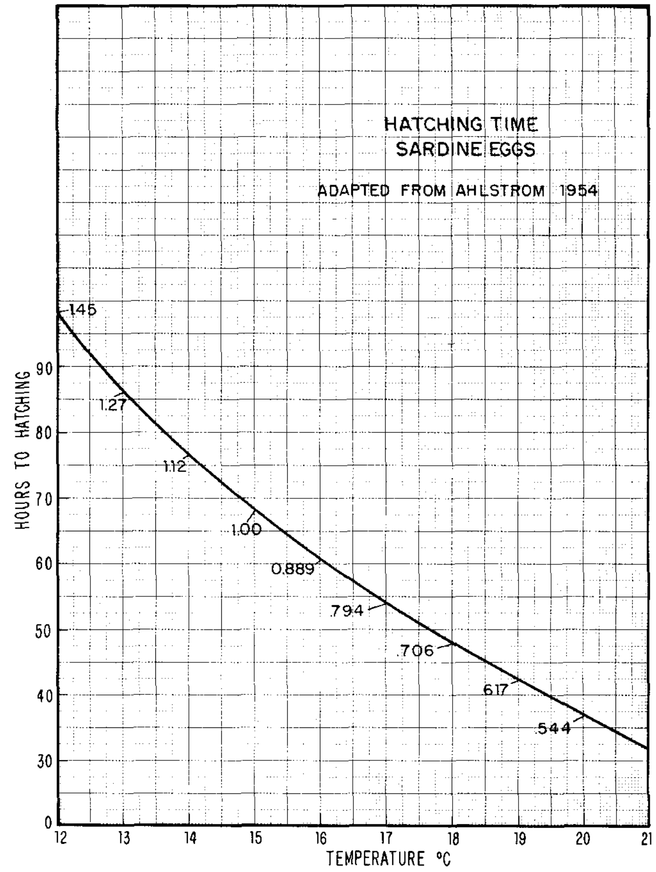

FIGURE 4. Hatching time of sardine eggs as a function of temperature. The numbers along the curve represent the relative hatching time taking 15°C. as a base, (adapted from Ahlstrom, 1954).

1958) that food was more abundant during the cold years associated with poor year classes so it seems logical (though not necessarily correct) to discount food, and examine the associations among temperature, larval growth, and the density of predators.

Temperature, through its control of the metabolic processes, can alter the growth and development rate. Data from Ahlstrom (1954) show that eggs hatch in 54 hours at 17°C, 60 hours at 16°C, 68 hours at 15°C and 77 hours at 14° C (figure 4). If these rates are projected into larval development which, at least in part, is an extension of embryonic development, we can estimate the relative larval survival from the equation:

$$S = e^{-Zt}$$

where S denotes survival, Z is the mortality rate and t denotes time. Because the survival to 42 days or 24 mm (Ahlstrom, 1954) was based on years in which the average temperature was about 15°C, I use this temperature as the base setting 42 days as $t = 1$. Simple computation then gives the following relative survivals to 24 mm.

Temperature (C)	*Relative Survival*
14.0	0.43
15.0	1.00
16.0	2.12
17.0	4.14

Thus a three degree range of temperature, approximately the difference between warm and cold years in the California Current during the spring months (Reid and Roden and Wyllie, 1958), might result in a 10 fold variation in survival. The effect of growth on survival is clearly shown with respect to one predator (a plankton net) in figure 5.

Other effects of lower temperature on the survival of the sardine larva can be postulated. For instance, Brett, et al (1958) have shown that the swimming speed of small fish varies with temperature. Tempera-

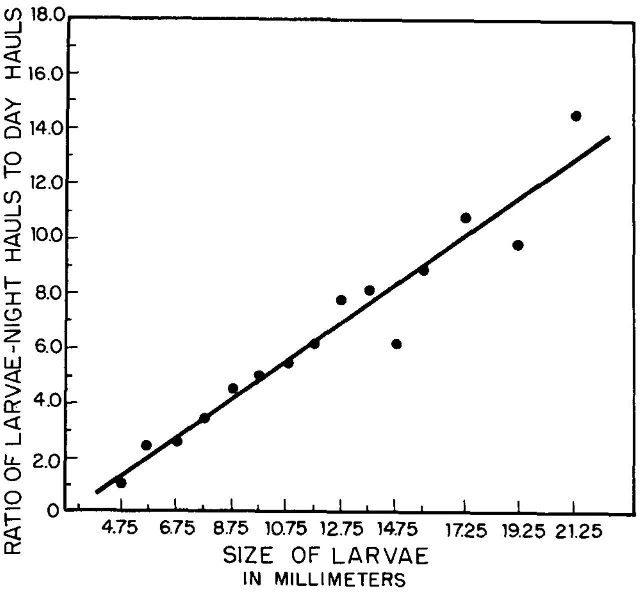

FIGURE 5. Relative efficiency of the one meter net in capturing sardine larvae between day and night as a function of larval size, (adapted from Ahlstrom, 1954).

tures below the optimum for sardines would place them at a disadvantage, particularly in the face of cool water predators.

Possibly even more important, in the California Current region a decrease in temperature has been accompanied by an increase in the standing crop of zooplankton (Reid et al, 1958). For example, off southern California the temperature during February to August ranged from 14.3° to 15.4° Centigrade among the years 1949 to 1956. The zooplankton volumes varied from about 50 to 800 ml. per thousand cubic meters, larger volumes being associated with cooler temperatures. This must be accompanied by an increased rate of predation, depending, of course, on the qualitative composition of the net zooplankton. Assuming the type of organism to be constant, the instantaneous mortality rate from this source might vary as much as 20 times judging by the variations in plankton abundance. Thus, lower temperature, in addition to prolonging the duration of the larval stages, and hence the vulnerable period with respect to predation, seems to be accompanied by an increase in predators. Because of the relationships shown in figure 1 only a fraction of the combined effects could easily produce more than the total observed range in sardine year-class strength. The increased food that must accompany the lower temperatures and higher plankton volumes might operate in the opposite direction, though probably not strongly enough to overcome the adverse effects. Definitive examination of the problem awaits, among other things, point-by-point examination of the in situ environment of the eggs and larvae.

A third effect associated with temperatures arises from the fact that in general lower temperatures are associated with a more vigorous California Current and more vigorous upwelling. If there is any loss of larvae due to the drift into unfavorable locations offshore and/or to the south, this loss would tend to be greater during years of cold water. At the present, however, it is impossible to state whether this is a major or minor source of mortality. The fact that the larva develops the ability to elude the plankton net at an early age argues against it. However, the cooler temperatures attendant on vigorous coastal upwelling would tend to induce the sardine to spawn further offshore, seemingly, increasing the likelihood that larvae will be swept to unfavorable areas. A full discussion of this problem is included in Sette (In press).

Finally, of course, cooler temperatures would tend to favor northern fishes, some of which might be competitors or predators of the sardine. With respect to the larval state during which sardine mortality is assumed to be density independent, the larvae of a more northern form such as the anchovy, which presumably is better adapted to cool temperatures, might grow relatively faster, and as a byproduct might prey on the sardine larvae. At the moment this is conjecture, and in any event it would simply be a special case of the general predation by the plankton community. A hypothesis involving the anchovy (some of these ideas together with documentation) has also been advanced by Marr (In press), but his working assumption is that the anchovy larvae affect sardine survival by competing for food in a density dependent model.

JUVENILES AND ADULTS

Almost nothing is known concerning the sardine between age 45 days and age six months. During this period they develop the schooling habit, and apparently move inshore (Phillips and Radovich, 1952). Because of this they will then be a significant element of the fauna at their points of aggregation, and the sizes of the past catches (nearly a million tons) suggest they are a significant element in the general biomass of their habitat. Mortality must be now assumed to be at least partially density dependent. Direct competition may exist among young sardines and between the young sardines and the young of other fishes. It also suggests that predation might operate in a density dependent manner. The only positive indication of a density dependent effect on record is a study by MacGregor (1959) which showed that condition factor of the catches of adults varies inversely with population size suggesting competition for food.

Because of the scarcity of data, reliance must be placed on the general principle that as the range of an animal is decreased for a protracted period during density dependent stages of its life, its numbers will decrease. The sardine is an inshore, pelagic, south-temperate form. The southernmost end of its range abuts on tropical water and this boundary is relatively steady geographically because of the nature of the eastern Pacific circulation. The northern end of its range is near Vancouver Island but this can vary greatly. Between these limits flow is generally parallel to the coast and temperature isotherms and other physical attributes tend to parallel the coast. If we assume that the population spreads over its available range, with the limits set by its own inherent responses to the physical environment, and by competition, the stage is set for large fluctuations in the population. For instance, a change in the temperature regime will be transmitted down the coast, as far as the relatively constant southern limit of the California Current, thus producing a large change in the habitat available to the sardine.

Regulation of the population during a shift from warm to cool conditions can then be postulated as follows: A regime that cools the waters "pushes" the adults south. Their southern boundary remains relatively fixed thus temporarily increasing the density of large fish in the now restricted habitat, a phenomenon that must result in increased mortality until the population adjusts to a new appropriate size. Following or paralleling this, recruitment is reduced by the several effects associated with lower temperatures on larval survival, because of the reduced extent of the inshore nursery area and because of competition from species better adapted to the altered environment.

EFFECT OF THE FISHERY[1]

Though it is not appropriate to consider the fishery in detail, for the sake of continuity it is necessary to review briefly how the fishery might affect the natural "environmental" regulation of the population size. The effects of a fishery can be expressed qualitatively with reasonable exactness; the difficulties emerge in attempting to quantify these effects. Hence, this discussion will be in the main qualitative, and for this reason will do little more than attempt to identify the problems.

The fundamental effect of a fishery on adult sardines is to increase the mortality rate of the fished stocks. This results in four secondary effects: (1) the numbers of eggs spawned each year are reduced; (2) the total biomass of the population is reduced; (3) the average age of the population is reduced; and (4) the size of the population relative to the sizes of the populations of competitors is reduced.

Effect number 4 is not necessarily characteristic of all fisheries, and is perhaps one of the fundamental reasons why the changes in the sardine population have been intractable to the usual fisheries theory. Conventional theory was largely established on stocks of fish that seem to lack serious competitors such as the Pacific halibut, or on relatively non-selective fisheries such as North Sea trawling. An extreme, of course, is a mono-specific fish population in a pond. Here, clearly, competition with other species is absent in the sense of the fisheries problem.

Taking each of the four points in turn, in the light of the earlier discussion, it is clear that reducing the numbers of eggs reduces the numbers of sardines passing through the density independent mortality stages, during which mortality is postulated to be largely a function of predation. The problem then narrows down to whether the combination of egg number times a density independent survival rate provides enough individuals to occupy efficiently the available environment during later stages when survival is expected to be density dependent. The term "efficiently" requires definition. For this discussion it means to occupy the environment to the extent that the addition of more individuals to a year-class at the beginning of the density dependent stage will not significantly increase the year-class when it enters the fishery.

Reduction of the size of the population by the fishery also interacts with the environment, because the *amount of environment* available to an organism is a function of the absolute amount of environment available and the numbers of individuals competing for that environment. Thus a fishery should enhance the survival of those individuals remaining and those individuals in a pre-recruit stage. Or paraphased the classical formula: a (annual mortality) $=$ m (fishing mortality) $+$ n (natural mortality) $-mn$ will not apply in a predictive sense to the extent that a reduction in population decreases n. It can be concluded that a fishery exerts a positive effect on year-class size by relieving density dependent environmental pressures. Possibly the size of the 1939 year-class (the largest on record) was in part a function of this effect, as it was produced by a population that had been heavily fished for several years.

Reduction in the average age of the population as a result of a fishery has the general effect of making the size of the fishable population less stable, simply because the size of the adult or fishable population tends to become a function of the size of only the most recently recruited age class, and thus the population becomes more sensitive to short term changes in the environment. So long as environmentally induced fluctuations in year-class size coupled with the effect of the fishery do not reduce the population below the level at which it can provide sufficient recruits to the density dependent phases of sardine life, and so long as the time scale of the environmental fluctuations is short, the effect of a decreased average age will be to increase the amplitude of the fluctuations in population size, but it will not necessarily reduce the average size of year-classes. They may, in fact, be increased. If the time axis of the environmental changes is long compared to the average age of the adult population, the relative amplitude of the fluctuations will tend to be the same in the presence or absence of a fishery, the effect of the fishery induced mortality being confined to affecting the shape of the curves, particularly by steepening a decline.

The fourth effect of a selective fishery such as that on the sardine is to reduce the numbers of the population in relation to its competitors and predators. In

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[1] This and subsequent sections of this discussion were not presented at the symposium because of time limitations. They have been freely revised since the symposium.

the absence of competitors or significant predators this effect will, of course, be zero. This does not seem to be true in the instance of the sardine which has predators and probable competitors. Projection of the effects is difficult. There is little insight to be gained by reference to agriculture or pond culture, or even forestry, for here man is able and does intervene to counteract some of the adverse effects of the heavy mortality he induces. It would appear more appropriate to refer to the principles of evolution and survival for guidance.

In nature, most of the attributes acquired by a population are probably directed at one goal, survival of the species at a maximum commensurate with the environment. In nature there is no survival significance in maximizing annual production of protein at the species level, though there may be at the community level. What we interpret as potential production in a virgin stock may be the energy utilized by the species to maintain itself in the ecosystem. If the particular population in question either by accident or design has no significant predators or competitors man may then utilize this potentially available surplus production, e.g., a fish farm or a wheat field. If, again by accident or design, the population has predators, but no competitors, i.e., is the sole occupant of its trophic level, man may still safely utilize the potentially surplus production though to a lesser extent for he is simply competing with another predator, and the population of that predator will probably shrink to a size commensurate with the now smaller prey population.

In the instance of the Pacific sardine it appears that there need not be great concern over species that simply prey on the adults. If man reduces the population of sardines these predators will eventually reduce their predation, either by becoming less numerous, or by utilizing alternate foods. Competitors are another matter, particularly in the instance of a selective fishery. The sardine's range greatly overlaps that of species that share its diet in large part, share its living space, and prey on the sardine at some stages in its life, e.g., jack mackerel, and anchovies. Such species as these, though they obviously do not occupy precisely the same niche as the sardine, are potentially its serious competitors. To the extent that a proportion of the productive potential of the sardine which was "wasted" was in fact necessary for its survival in the presence of its competitors, removal or reduction of this "buffer" by a selective fishery will be detrimental to the species.

To some extent, then, the increased opportunity for survival of younger stages that man provides by thinning down the adult sardine population may be more than countered by increases of other species which occupy the space made available. Carried to a logical extreme, in the face of increasing pressure by man the selected species (in this instance the sardine) would ultimately be restricted to an ecological range and population size such that its ecological niche involved little or no overlap with other species at its trophic level.

It seems doubtful that this would ever occur in nature. More likely is the possibility that the selective pressure on the population by man might "sensitize" the Pacific sardine so that slight changes in the environment in unfavorable directions would tip the scale in favor of some other species or combination of species at the same trophic level, and thus precipitate a decline much greater than would be expected from the environmental change alone.

APPLICATION TO DEÇLINE OF THE PACIFIC SARDINE

The first section of this discussion sought to show specifically how recent changes in the California Current System, particularly cooler temperatures and associated changes, could adversely affect the Pacific sardine. In the second section an attempt was made to determine qualitatively how a fishery might modify the effect of the environment on the population, and it was shown that the minimum effect would be to make the population more responsive to environment changes, particularly because the sardine fishery acted selectively within the trophic level. By way of a summary, this section will review the history of the sardine population and fishery to see if the approach fits the facts. Temperature will be used in the discussion, not in the sense that it is the sole operator, but rather as a convenient index of the oceanographic information.

Very briefly, cooler temperatures along the California Current are associated with accelerated southward transport, and more vigorous upwelling with its attendant offshore movement of water. Plankton densities are increased. Warmer temperatures are associated with the converse of the above, as well as greater influence of southern water and/or the warmer water to the west.

Schaefer, Sette, and Marr (1951) described the growth of the fishery from 1916 to 1942. They found that the growth pattern could be fitted to a logistic curve with an upper limit of about 600,000 pounds. Though they attributed this growth primarily to economic factors, they also concluded, from biological information available, that this limit was close to the productive potential of the then existing population. In addition they suggest that, "Indeed, the limit attained, about 600,000 tons, may have been the result of a series of years during the late 1930's, which were exceptionally favorable for reproduction and survival of the pilchard, in which event the average maximum stabilized yield may be expected to be lower than this value." In point of fact, the largest year class by a factor close to 2 resulted from the 1939 spawning, during the period of heaviest exploitation.

In the light of present knowledge oceanographic conditions during the late 1930's and very early 1940's were generally warm (Reid et al 1958) and judging from the year classes produced appear to have been favorable for sardine spawning, and the adult population was certainly large and well distributed over the spawning grounds. Finally, heavy cropping by the fishery must have served to some extent to increase the habitat for the pre-recruitment sardines. Thus it appears that the fishery, by making the population more responsive to the *favorable environment,* was a positive factor with respect to the production of large year-classes during the period of favorable environment, and because a young population is more efficient with respect to food conversion, growth, and natural mortality, the standing crop of adult sardines may well have been larger than during earlier years.

Beginning in 1944-45 the northern fisheries (British Columbia, Oregon, and Washington) began to decline (Clark and Marr, 1955). These were somewhat cooler years, and years when the salinity at La Jolla suggested little influence of tropical water, so this decline, which initially resembled earlier fluctuations, may have been caused at first by inhibition of the seasonal northward migration of the sardines by cooler water and accelerated flow.

The decline, unlike earlier dips, continued; the far northern fisheries virtually ceased to exist after 1946; the Monterey-San Francisco fishery virtually ended in 1950; and the southern California fishery declined in 1953 to about one percent of its peak, later rising to fluctuate around 50,000 tons a year until 1958.

Coincident with this, the cooler than normal temperatures in 1943 and 1944 strengthened and persisted through 1956 (Reid et al, fig. 18) instead of oscillating between cold and warm anomalies as in the past, though there was a slight warming in 1946 and 1947. In 1944 and 1945 quite poor year-classes were produced and the catch fell dramatically during 1946-48. During 1946-48 moderate sized year-classes were produced and the catches rose to over 300,000 tons in 1949 and 1950, though nearly all the catches were made off Southern California. Among other things, this series of events illustrates the sensitivity of a young, heavily fished population to fluctuations in year-class size which may have been caused by environmental changes.

During earlier years the Pacific sardine ranged from lower Baja California to British Columbia. By 1950 the population was essentially confined between lower Baja California and Point Conception, roughly a 50 percent reduction in range. Most generally, a reduction in the range of an animal must be accompanied by a reduction in numbers. One critical question is which came first. A reduction in numbers does not necessarily involve a dramatic change in range; the population may simply become more thinly dispersed. In the present instance the coincidence of the contraction in range with cooling of the ocean climate lends support to the thesis that a change in the environment restricted the habitat of the sardine, and that the population adjusted to a new level commensurate with its new range.

The reduction in range could have come about simply because the adults were unable, in the face of swifter currents and/or keener competition, to occupy their range. This probably was one of the factors, but more significant is the probability that the contraction in the range was a result of failure of northern spawning because of the environment. Felin (1954) and Radovich (in press) show that the relative significance of a year-class to the fishery, especially the Monterey-San Francisco fishery, is a function of the apparent origin of the year class as judged by the relative catches when they are one year olds; those originating in Central California weighing more heavily in the catch, in particular the Central California catch during subsequent years. Thus it seems that sardines spawned to the north have a predilection to occupy the northern part of the range, and vice versa. The last northern year-class (by Felin's and Radovich's definition) was that of 1947, apparently the progeny of a fairly small stock of spawners judging by the distribution of the fishery that year.

The Monterey fishery collapsed in 1950 and 1951, three and four years later, that is when these 1947 fish were three and four year olds. Since they contributed heavily to the southern California catch those years (in fact, the 1947 year-class made its greatest contribution in southern California as three year olds during 1950-51, strongly suggesting that its distribution changed), it must be concluded that the environment altered their normal northerly oriented distribution during those fishing seasons. It thus appears that contraction of range was brought about by failure of the adults to migrate as far north as usual during the spawning season which of course would in itself preclude a northern year-class, and also was caused by failure of spawn to survive in the north, a phenomenon that feeds back into the first operator.

After 1949 the sardine population was essentially confined to the area from Point Conception south. Substantial catches (over 300,000 tons) were made during the fall of 1949 and 1950, so there must have been substantial spawning in the spring. Yet, the resulting year-classes were apparent failures. A further major effect of the environment with respect to these year-classes is suggested by their catch curves. The 1949 year-class shows pronounced negative mortality between ages 4 and 5, the catch of five year olds being six times as large as the catch of four year olds, and almost as large as the catch as of two year olds. Previous to this year-class the typical pattern was for maximum contribution as two year olds or three year olds. Similarly, the 1950 year-class made its maximum contribution at age four. From this record it is obvious that the virtual population method markedly underestimates their size relative to other year-classes though there is no evidence they were large year-classes. Perhaps more important the catch curves clearly show that the time-space distribution of these year-classes with respect to the fishery clearly departed from the normal, presumably in response to the same kinds of environmental changes that altered the distribution of the 1947 year-class after its second year of life.

The ocean climate remained cold until 1957, and the now reduced population remained centered in the south. During these years, the southern California fishery, instead of being located in the center of the range of the species, was stationed at the northern edge of the range, and since the fishery has the essential character of a day fishery it was exceedingly sensitive to minor changes in the north-south distribution of the sardine, the landings ranging from 3 to 76 thousand tons. From 1957 through 1959 the ocean climate warmed and the sardine population ranged farther north in 1958 and 1959 (as far as San Francisco), though the catches have not suggested a significantly larger population.

The recent warming of the California Current and slackening of its speed is the reverse of the events that were associated with the decline, so presumably a recovery should ensue if the oceanic climate continues to be favorable. If the recovery follows a course which is the reverse of the decline it should proceed as follows: (1) more northerly distribution of existing adults and more northerly spawning (already underway but involving very small numbers of sardines), (2) maturity of northerly spawned fish, and a spawning by them, and (3) growth of these northerly spawned fish to commercial age (2 year olds). Obviously this will take time, and a real recovery could not be expected before 1961 at the earliest. In the meantime the population of competitors such as the anchovy should decline as a result of the shift in ocean climate and increased competition from the sardine.

In conclusion, it is possible to divide the natural pressures that regulate the Pacific sardine into three groups. The first is the physical-chemical environment and trophic levels below the sardine. These seems to affect the sardine directly in a density independent manner and indirectly in a density dependent manner by contracting the available habitat. The second is the within-trophic level competition. This involves the sardines themselves and such species as anchovies. These would seem to exert their effect in a density dependent manner either by competition for food and space or by specialized predation, e.g., adults eating larvae, large larvae eating small larvae, etc. The third is predation of various sorts from higher trophic levels. The rate of this source of pressure may well be density dependent and self-adjusting, and perhaps this regulatory mechanism is of secondary importance. (Man, of course, preys heavily on many of the potential predators tending to produce a compensatory effect.)

Finally, there is the role of the fishery. It seems clear that the minimum effect of the fishery is to sensitize the population to environmental changes. It is equally clear that the growth-mortality regime of the sardine leaves little to be gained by manipulating a year-class after it enters a fishery (Clark and Marr, 1955). This leaves the question as to whether or not the fishery has or will reduce the pre-spawning population to a point that there are not enough survivors through the density independent mortality stages to efficiently utilize the environment during density dependent stages. Even a positive answer to this question leaves unresolved the problem of the practicality of population manipulation through regulation of the catch.

The fact that at this writing it is possible to identify environmental changes that parallel changes in the sardine population along the Pacific Coast (and elsewhere in the world, Proceedings of the World Sardine Conference, in press), and for which it is possible to assign a logically significant effect on the Pacific sardine, suggests that the environment has played the major role in the regulation of the population. In a purely negative sense, the impossibility to date of being able to satisfactorily apply any of the existing and in some instances highly successful mathematical models of fish populations to the excellent series of catch statistics on the sardine is evidence that the environment is playing a major and possibly dominant role, and that the fishery's chief but not necessarily exclusive effect is to make the population more responsive to changing environmental pressures.

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RELATIONSHIP OF VARIABLE OCEANOGRAPHIC FACTORS TO MIGRATION AND SURVIVAL OF FRASER RIVER SALMON

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INTRODUCTION

Management of the various Fraser River salmon fisheries requires an intimate knowledge of the abundance and movements of salmon runs, which is drawn largely from a detailed study of commercial catches. Abnormalities in abundance, in routes of migration or times of occurrence, unless forecasted, may negate the beneficial effect of fishing regulations formulated in advance of the fishing season. A flexible method of regulatory adjustment during the course of fishing may help rectify the adverse effects of vagaries in the salmon population but it cannot be accepted as a substitute for advance knowledge and planning.

OCEANOGRAPHIC FACTORS AFFECTING SOCKEYE SALMON MIGRATIONS IN THE NORTHEAST PACIFIC

The formulation of fishing regulations in advance of the fishing season requires knowledge of abundance, timing and migration routes of the Fraser River sockeye runs. It is known that adult sockeye abundance has been affected considerably by marine survival rates which have ranged from 4.22 to 18.54 per cent in recent years. However, since there is some reason to believe that freshwater and estuarial factors as well as the physiological condition of seaward migrants may influence subsequent marine survival, an oceanographic or ecological study of marine conditions, as related to sockeye survival, appears rather impractical until these factors are more fully understood. While variations in survival are important, it is relatively simple to make compensatory adjustments in fishing regulations for unexpected changes in abundance, provided that the timing of the runs is inherently consistent, as it is in most years, and the routes of inshore migration follows a consistent pattern. If, however, the measurement of abundance from commercial catches in initial fisheries is confused by a delay in arrival, or a change in the route of migration, or both, then the problem of properly managing the fishery becomes most complex.

Normally the bulk of the maturing Fraser River sockeye arrive off the west coast of Vancouver Island and approach the Fraser River around the south end of the Island through Juan de Fuca Strait (figure 1). A smaller part of the population, less than ten per cent, passes around the northern tip of Vancouver Island and approaches the Fraser River from the north through Queen Charlotte and Johnstone Straits. In 1957 it was noted that a larger share of the population approached Vancouver Island from the north, a larger percentage (approximately 16 per cent) diverted through Queen Charlotte Strait and it was also noted that the fish were slightly delayed, and migrated over a longer period of time.

In 1958, the sockeye run of approximately 19,000,000 fish failed to appear off the west coast of Vancouver Island in its usual initial landfall and arrived northerly of Vancouver Island in the Queen Charlotte Sound area. The fish then moved in a southerly direction with an estimated thirty-five to forty per cent of the total population entering Queen Charlotte Strait, thus approaching the Fraser River from the north instead of the usual route through the Juan de Fuca Strait. In addition to the vagary in their route of migration the fish appeared in the fishery ten days later, and over a longer period of time than was anticipated on the basis of previous catch records.

The effects of the radical departure from normal in the route and timing of the 1958 Fraser River sockeye populations were serious. A surplus escapement of 1,500,000 fish occurred. These could have been harvested had the fish followed the usual migration route at the usual time. The delay in the arrival of the escapement on the spawning ground disturbed the normal relationship of the spawning population to its reproductive environment, and may have seriously jeopardized its reproductive potential. The physiological development of the fish was so disturbed in the latest arriving section of the population that an estimated ten per cent of the total escapement failed to reach their spawning grounds, some 350 miles upstream.

In analyzing all possible causes of the vagaries of the route and timing of the 1957 and 1958 runs of sockeye to the Fraser River it is logical to conclude that the physical marine environment, at least during the maturing year, must have been responsible. Oceanographic observations over recent years show that when the fish went to sea the normal currents and water masses were present off the approach to Juan de Fuca Strait, and that anomalous oceanographic conditions first developed off the southern British Columbia coast in 1957 and were intensified in 1958.

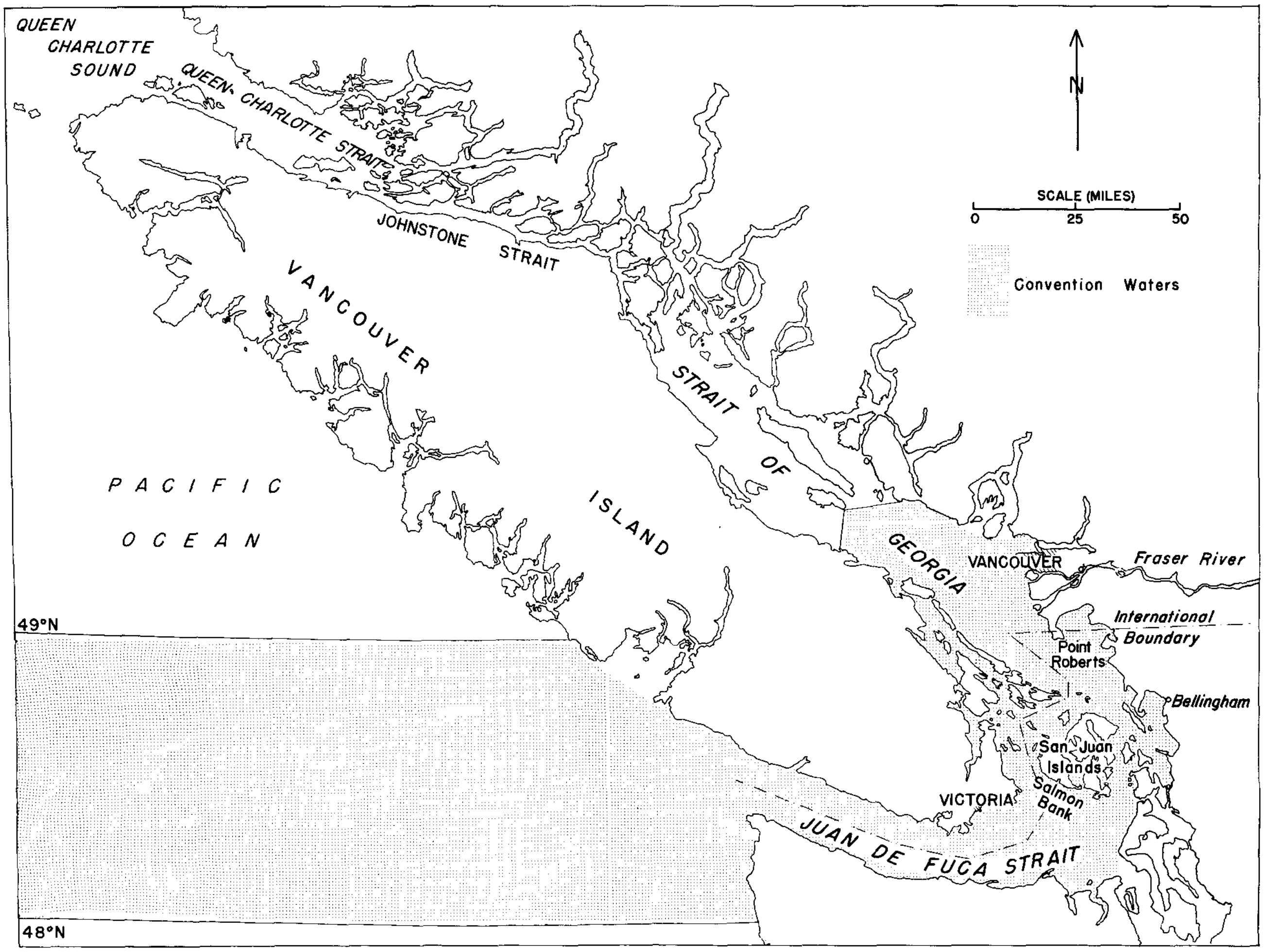

FIGURE 1. Vancouver Island and Fraser River approaches.

The trans-Pacific drift current normally flows eastward into the Canadian approaches. In the spring of 1957 this flow began to veer towards the north. By mid-summer 1958 the flow was due north in the region within 600 miles of the Canadian coast. Associated with this change of current direction, warm water intruded northward. It was evident as far as the northern end of the Queen Charlotte Islands. It reached its maximum extent in August 1958, and has degenerated somewhat since then. In the affected region the seawater temperatures were 2° to 3° centigrade warmer than is considered normal at the surface. The temperature anomaly decreased with depth, and vanished at about 500 meters. The occurrence, duration, and extent of the intrusion was determined by observing the temperature increase at 180 meters depth, well below the influence of seasonal heating and cooling. The increase in surface temperature is significant because the normal seawater temperatures in this area, at the time of the summer shoreward migration of sockeye salmon, are near the upper limit of preference for sockeye.

Sampling by investigators in the northeast Pacific during 1956, 1957 and 1958 under the sponsorship of the International North Pacific Fisheries Commission showed that the distribution of feeding Fraser River sockeye apparently tended to shift northward coincident with the warm water intrusion, and that no concentrations of these fish were found in the area westward of Vancouver Island as in preceding years. It may be postulated that the more northerly landfall of the 1957 and 1958 sockeye runs was the direct result of temperature preference on the part of the feeding sockeye in the ocean. The lateness in arrival might be ascribed to the consequent displacement of the sockeye to more distant feeding grounds or to a circuitous migration path to avoid the warm water intrusion. This concept is tenable because in 1958 there was a narrow band of cooler, near normal water, close along the west coast of the Queen Charlotte Islands. This would provide a coast-wise migration route into Queen Charlotte Sound. A modification of this concept would be that strengthened ocean currents slowed the migration rate of the fish. It can be further postulated that the more northern distribution of the fish brought the sockeye into higher latitudes where the days were longer during the late spring and summer months. This may have the effect of retarding maturation and thus delaying the correlated migration. A study of the degree of maturation and energy reserves of sockeye arriving at the mouth of the Fraser River commencing in 1956 reveals that maturation and energy reserves were approximately the same in 1958 as were those of sockeye in the preceding years, in spite of the ten day differential in arrival. These findings tend to support the latter of the above hypotheses. The increased temporal dispersion of the run can also be explained on the basis of light response. If the fish were spread over a range of latitudes wider than normal, the resultant greater variation of day-length encountered would account for the increased interval over which fish arrived in the fishery.

Whatever the pattern of forces that created the vagaries in 1957 and 1958 Fraser River sockeye runs, a serious derangement in the management of the 1958 fishery resulted. The economic importance of predicting these vagaries in advance has been established.

THE RELATION OF OCEANOGRAPHIC CONDITIONS IN GEORGIA STRAIT TO PINK SALMON SURVIVAL

Great variability in the abundance of pink salmon populations has been well established in North America and the runs of this species to the Fraser River are no exception. Annual catches of pink salmon in the approaches to the Fraser River have varied from 950,000 to over 11,000,000 fish during the last twelve biennial runs. Predictions of ultimate adult survival based on the success of fry emergence have been notable for their inaccuracy, hence any reliable method of predicting adult survival must be based on something more than the number of pink salmon fry migrating to their marine feeding grounds.

Studies of the relationship of various fresh water and estuarial environmental factors to ultimate adult survival have resulted in what appears to be a fairly reliable method of predicting the approximate abundance of adult pink salmon populations destined for the Fraser River. Surface seawater temperature for the period April to August in Georgia Strait, which lies adjacent to the mouth of the Fraser River, has shown a close inverse correlation with the total pink salmon catch of the following year ($r = -0.8595$). The period April to August includes the time during which young pink salmon may be expected to be residing in Georgia Strait in advance of their emigration to the Pacific Ocean. Whether the water temperature of Georgia Strait has a direct or indirect relationship to survival is not yet known and further knowledge regarding the relationship can be obtained only by a detailed study of the young pink salmon during their estuarial existence.

OCEANOGRAPHIC FACTORS AFFECTING THE MIGRATION OF SALMON THROUGH COASTAL CHANNELS ADJACENT TO THE FRASER RIVER

The Fraser River salmon fishery is composed of several individual units each of which is highly efficient and subject to severe restrictions in order to allow for equality in the total catch of each of the two national groups involved and for adequate escapement. The pink and sockeye runs entering Juan de Fuca Strait are highly vulnerable to a Canadian fishery operating on the north side of the Strait. A U.S. fishery on the south side of the Strait has never been consistently effective and its lack of success has been attributed in a large part to the vertical distribution of the fish in the southern area. If the U.S. fishermen were to develop a successful fishery in the southern side of the Strait the whole scheme of regulation would have to be revised with a major displacement of the existing over-all fishery.

A study of the currents in Juan de Fuca Strait reveals that in the northern half of the Strait the ebb transport of mixed saline and land drainage water greatly exceeds the flood transport of highly saline ocean water. The reverse situation occurs on the southern side. Since the fish are apparently seeking waters of reduced salinity as they approach the Fraser River they probably prefer the lower salinities of the northern shore and for this reason it is highly doubtful if salmon are available at any depth or in any great numbers on the southern side.

The eastern end of the Juan de Fuca Strait lying principally in Washington State consists of a zone of mixed water made up from the flood transport of seawater and land drainage. In this area the Fraser River salmon separate from other stocks destined for southern Puget Sound streams and apparently proceed northerly to a major extent through Rosario Strait (east of San Juan Islands). The alternate channels represented by Haro Strait (west of San Juan Islands) and San Juan Channel are available to them but based on availability indices these channels are not utilized to any great extent except by fish migrating during the late summer and early fall period. Occasionally, however, the northerly movement of fish will shift suddenly from Rosario Strait to Haro Strait, and very occasionally the principal movement will shift into Canadian waters. These shifts in migration have a drastic effect on the management of the fishery and must be related to changes in the physical environment of the available channels. Studies of salinity and temperature changes as related to variations in the flow of the Fraser River and to wind direction in the approach channels to the Fraser River would probably provide reasons for sudden and periodic shifts of the fish from their normal approach channels, to those which are not normally used by the majority. It is well established that the major flood tide transport is through Rosario Strait and the major ebb transport is through Haro Strait. Local and temporary fluctuations in temperature and salinity or in daily net transport through the various channels from Georgia Strait and the Fraser estuary have not been determined. An understanding of the causes of the shift in migration and an ability to anticipate the change even twenty-four hours in advance, would eliminate a very serious problem in the proper management of the fishery.

SUMMARY

It appears that offshore variations in physical oceanographic features have an effect on the feeding distribution, path and time of inshore migration, temporal dispersal of the inshore migration and the survival of Fraser River sockeye salmon. Oceanographic influences in inshore waters largely control the ultimate survival rate of the pink salmon and the approach characteristics of both Fraser River sockeye and pink salmon migrations.

OBSERVATIONS ON THE ECOLOGY OF THE PACIFIC COD *(GADUS MACROCEPHALUS)* IN CANADIAN WATERS[1]

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(Abstract)

The Pacific cod (*Gadus macrocephalus*) occurs in economic concentrations around the great arc of the North Pacific Ocean from Korea to Oregon. Near the southern limit of its range in the eastern Pacific (British Columbia waters) the cod inhabits much warmer water than in the apparently more productive regions of western Alaska to Kamchatka. Possibly as a consequence of these warmer conditions, growth rate is much more rapid; maturity is reached at a much earlier age; and lifespan is relatively short. There are more pronounced fluctuations in the year-to-year average catch per unit of effort.

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[1] This paper will be published in the *Journal of the Fisheries Research Board of Canada.*

FISHERIES OCEANOGRAPHY

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This symposium has emphasized the importance of two concepts in fisheries biology: 1) that of *population abundance* including the *fluctuations* to which populations are subject, and 2) that of availability including those factors which result in the aggregation or dispersal of a species. By interest and preference I am going to speak principally about the first of these—population abundance.

Dr. Sette, in the introductory speech at the symposium, outlined very lucidly the problems of fluctuations in marine fish populations. He gave instances of the magnitude of such fluctuations. You will recall that in the Atlantic mackerel the observed fluctuations in year class size were of the order of 15,000 to 1. Instances of such fluctuations could be drawn from most fish populations that have been studied. In the Pacific sardine, with which I am better acquainted than other kinds of fish, the most successful year class on record was several hundred times as large as the least successful. The only exception that has been advanced is the population of yellowfin tuna, a tropical species. Dr. Schaefer indicated that there was no evidence of marked fluctuations in success of year classes of yellowfin. Differences between year classes were of the magnitude of 4 or 5 to 1.

Certainly in temperate latitudes, large fluctuations in the success of individual year classes is the rule for any species that has been investigated over a period of years.

There have been a number of attempts to account for fluctuations in fish populations. Among the causal factors that have been suggested are the following seven:

winds
currents
temperature
salinity
general productivity
competition, either interspecific or intraspecific
predation

Dr. Blackburn discussed the emphasis placed by Carruthers on "winds". Winds are important indirectly in effecting transport of larvae into favorable or unfavorable conditions. Rollefson postulated another effect of winds on the success of year classes—that of direct injury to eggs through turbulence resulting from strong winds. Rollefson was led to this conclusion by observing the high proportion of "abnormal" appearing eggs that are taken in most plankton hauls. Rollefson was working with cod eggs, but this observation applies to pelagic fish eggs in general. It is one of our vexing problems with sardine eggs. Rollefson noted that there was a higher percentage of abnormal eggs among young stage eggs, in which the embryo had not yet completely encircled the yolk mass. He found that by dropping eggs from a height he could produce this condition in eggs that were normal before dropping. He was led to the conclusion that the injury was mechanical and that it could be produced in the sea.

Temperature has often been suggested as an important factor in year class fluctuations. Garth Murphy has pointed out the effects of warmer water on success of sardine survival, and in this hypothesis he is following in the footsteps of various other workers. Dr. Sette prepared a paper some 20 years ago which stressed the relation between warmer temperatures and good year broods of sardines. Unfortunately this paper was never published, but it has been commented upon fairly frequently. Although successful year classes are more frequent during warm periods, yet there have been middling or poor ones during such periods also. 1941, for example, was one of the warmer years on record—yet the 1941 class was only middling large. There is no evidence as yet that the 1958 year-class of sardines was at all successful, yet 1958 was a year of unusually high water temperatures.

Walford postulated a correlation between salinity and successful year-classes of sardines. His model was actually an attempt to correlate good year broods with high productivity. High salinity was assumed by Walford to have resulted from intense upwelling with the attendant enrichment and increased productivity. There are quite positive ways of identifying upwelled water, but a combination of several observations are needed: temperature, salinity, oxygen, and nutrient concentrations such as phosphate. Upwelled water is characterized by its high salinity and phosphate content and its low temperature and oxygen content. Walford obtained an excellent correlation over the period of years he was using—which were the years between 1934 and 1941. The correlation breaks down entirely in more recent years.

If any hypothesis can be laid at rest it is that which associates successful year broods of sardines with high productivity. Productivity, as measured by plankton volumes, has been high during the past ten years; success of sardine survival has been low.

In fact, if productivity is a major consideration in the success of a year-class of fishes, one would expect that the increased food should result in better than average survival of all species which are primarily plankton feeders. This has not taken place. In fact the northern anchovy, a direct competitor with the sardine, has prospered during a period when the sardine has had unusually poor survival. This contrast is so marked that one is justified in posing the problem in another way: What is there in the environment or the response of these two species to the environment that has favored successful year broods of anchovies at a time when the success of sardine year-classes has been unusually low? The differences in survival may result from inherent physiological differences between the two species. The threshold temperature for sardine spawning is approximately 13°, that of the anchovy is approximately 1° lower. Is the adjustment of an organism to its environment so critical that a decrease of say 1° C. in average water temperatures can mean the difference between successful and unsuccessful year-classes? I am only going to pose this question—not attempt to answer it.

FISHERIES OCEANOGRAPHY

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In considering how to summarize the oceanographic aspects of the papers we have just heard, I found my thoughts falling into several distinct categories—the definition and goals of fisheries oceanography, current practice in this field, and the success of this approach.

Some may feel that fisheries oceanography is nothing more specific than the broad assemblage of problems being studied by oceanographers working for fishery laboratories. The interests of marine fisheries scientists and those of oceanographers overlap in so many areas that almost any marine research can be included in a suitably broad definition. But unfortunately such broad definitions have little operational value.

One might speak, however, of a somewhat restricted area of marine research which could be called ecological oceanography. This deals with the relationship between the ocean as a physico-chemical environment and the populations of organisms inhabiting it. A special case exists in which the populations consist of species of commercial interest. This point of view leads to the following definition:

Fisheries Oceanography—the study of oceanic processes affecting the abundance and availability of commercial fishes.

Obviously populations of commercial fishes are affected by other than oceanic processes. In particular they are subject to the pressure of an aggressive nonenvironmental factor, the fisherman. Much of fisheries research has resulted from the fear that this pressure was excessive and would soon lead to decimation of the stock; thus it has concentrated primarily on the dynamics of the populations involved. The working hypothesis of the fisheries oceanographer, on the other hand, is that variations in apparent abundance are due primarily to changes in the environment. These changes must be described and understood before the role of man can be properly evaluated.

The relationship is traced out in a model which starts with the observation that significant changes in the atmospheric pressure field occur from place to place and from time to time. These changes lead to variations in the stress applied to the sea surface by the wind. It is now generally believed that the major near-surface circulation of the ocean is wind driven, so that the changing wind stress causes changes in the velocity, depth, breadth, transport or other characteristics of the surface currents. Furthermore, the processes whereby the surface layer is refertilized with nutrient elements from below appear to be either directly wind-produced (for example, wind stirring and coastal upwelling) or secondary effects of the wind-driven circulation (for example, doming or ridging).

The near surface circulation may affect directly the distribution or abundance of organisms at all trophic levels. In addition, changes in the intensity of the refertilizing processes are reflected in the time and space distribution of primary production. This in turn affects production in the next higher trophic level, and so on, with assorted time and space lags, to the desired fish. At each step in this line of reasoning, refinements and complications are involved, but the basic theme of the model remains:

"Changes in the wind field lead eventually to changes in the success of fishing."

The goal of investigation of this model is often considered to be prediction. Certainly if one could forecast accurately the changes in abundance, distribution and availability of fish, this would be of great economic significance. But, conceivably, a useful prediction could result from the blind statistical treatment of a large number of variables, rather than from a fundamental understanding of the interplay of the pertinent atmospheric, oceanic, and biospheric processes. It is the acquisition of this fundamental knowledge which is the scientific goal of fisheries oceanography.

Current practice in fisheries oceanography has concentrated on documenting and trying to interpret the changes in the marine environment. One of the leaders in this field in the United States was the late Townsend Cromwell, who originally proposed this symposium. His first important work, in Honolulu, was a study of wind-induced upwelling along the equator. Subsequently, the Honolulu group has examined the mechanisms of surface enrichment near the Hawaiian Islands and to the north. At Scripps Institution and the Tuna Commission, there have been studies of coastal upwelling, oceanic fronts, and of processes such as those Cromwell labelled "doming" or "ridging". Dr. Sette and his colleagues have been examining past weather and the marine climate, looking for long-term changes related to those in the fisheries. All of these investigations have been facilitated by the presence of certain conspicuous features or discontinuities. As Henry Stommel has suggested, studying the oceans resembles dissecting a lobster—if is easier to do at the joints.

What has been the success of fishery oceanography in recent years? Certainly in the Pacific it has had no dramatic impact on the commercial fisheries. And if the goal be considered prediction, very little success can be recorded. Yet the fund of basic knowledge of

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[1] Contribution from the Scripps Institution of Oceanography.

the ocean has increased tremendously. The near surface circulation and the distributions of properties such as temperature, salt and oxygen have been much more adequately described. The theory of wind-driven circulation is well established. The variations in time and space of coastal upwelling are recognized, and other important surface-enriching mechanisms are known. In short, the general scheme by which atmosphere, ocean and biosphere are interrelated is taking form, and we are ready to formulate and test hypotheses having bearing on important and specific problems in fisheries science.

EVIDENCE OF A NORTHWARD MOVEMENT OF STOCKS OF THE PACIFIC SARDINE BASED ON THE NUMBER OF VERTEBRAE

ROBERT L. WISNER[1]

INTRODUCTION

Evidence on the movements of stocks of sardines along the Pacific Coast of the United States and Mexico has been derived from tagging, from counts of vertebrae, and from related data. The present study represents a second major attempt using numbers of vertebrae. Previous studies, reviewed below, have demonstrated an unknown but presumably significant amount of heterogeneity within the range of the sardine, as well as considerable intermingling of stocks between the regions of Punta Eugenia (in central Baja California), California, and the Pacific Northwest.

Tagging studies: An extensive tagging program, initiated in 1936 and carried on continuously until 1942, demonstrated that the sardine stocks intermingle considerably within the area from Pta. Eugenia to Central California and from Southern California to British Columbia (Hart, 1943; Clark and Janssen, 1945). Some fish tagged in Southern California were recovered along the west coast of British Columbia and some tagged in the latter region were recovered in Southern California. The tag-recoveries demonstrated a rather rapid migration: sardines tagged off Southern California in February and March were retaken off British Columbia in the following July; others, tagged off British Columbia in July and August, were caught off San Pedro, California, in the succeeding December and January (Hart, 1943). Associated with this rapidity of migration is a size relationship. Clark and Janssen (op. cit.) stated that, "The largest sardines may be expected to move quickly to distant fishing grounds whereas the smaller fish tend to remain longer in the locality where tagged or to make short migrations. These smaller fish reach distant grounds in later years when they have grown to larger sizes."

The one lot of sardines that was tagged south of Pta. Eugenia, in April, 1938, comprised 963 fish in Magdalena Bay. No recoveries were made from this lot, possibly because the number was too small to insure a return, or, as the authors suggested, because sardines from the area do not intermingle with the more northern fish.

Vertebral Studies: Clark (1947) compiled the results of vertebral counts made by previous investigators in the United States and Canada—Hubbs (1925), Thompson (1926), Hart (1933), and Clark (1936). The 1947 data, when grouped by latitude, showed a rather definite trend from north to south, particularly within the 0 and 1 age groups. No adults (2-year fish or older) were available from south of San Diego with the exception of a small sample of 31 fish from the Gulf of California. The areas treated ranged from Alaska to the Gulf of California and the years sampled from 1921 to 1941.

From the combined age-group data Clark (1947) reached a tentative conclusion that, "sardines found in southern Lower California and the Gulf of California constitute a separate population which rarely intermingles with the more northern population, but that a considerable, and perhaps variable, amount of interchange takes place throughout the range of the northern population from Alaska to Pta. Eugenia in central Lower California." The results of the tagging in the Magdalena Bay area, though somewhat inconclusive, recounted above, augmented Clark's interpretation of vertebral data from the area and strengthened the hypothesis that the stocks of fish in the area may well constitute a separate population that intermingles little if at all with the more northern stocks.

Growth Studies: Felin (1954) attempted to assay the heterogeneity of the sardine populations from the standpoint of growth characteristics, using age and length data gleaned from samples of the commercial landings in Southern and Central California during the years 1942-1950. The following excerpts from her conclusions appear to be pertinent to the present study:

> Complete intermixture and homogeneity in population of adult fish as sampled by the fishery in different regions is not evidenced from data on mean calculated lengths. The apparent cline in the growth characteristic . . . appears indicative of intraspecific populations in which there is limited intermingling, and suggests a series of overlapping coastal migrations of more than one stock.

Wolf and Daugherty (1960) have reported that two-year-old fish comprised the bulk of the Southern California catch in the 1958-59 season (to be discussed later). These fish were unique in that they averaged 191 mm. (7.7 inches) in standard length, 12 mm. (0.5 inches) smaller than the previous recent minimum (1954-55), but not much smaller (3 mm. or 0.1 inch) than the 1939 year-class as two-years-olds, an outstanding year-class. It has further been reported (Ibid., 1960) that the fish in Baja California averaged even smaller (162 mm., 6.4 inches)—so much smaller as to suggest that the fishery there was not utilizing the same stocks of fish as was the Southern California

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[1] Contributions from the Scripps Institution of Oceanography.

fishery. Also, the two-year-olds landed at Monterey were smaller than the San Pedro fish, indicating somewhat more population heterogeneity than usual (no samples from the Monterey landings were available for the present study).

These previous studies have all pointed either to a mixture of stocks, of phenotypic or genotypic origin, that intermingle more or less completely within the area from north and central Baja California to Southern California and from the latter area to British Columbia, or to more or less sporadic influxes of non-intermingling fish from other areas, presumably the south.

The present study attempts to cover essentially the same areas (Fig. 1) reported on by Clark, with the exception of Central and Northern California, and provides a body of data well separated in time from any previous similar data. No samples were available from these northern areas, as it was not until the 1958-59 season that the sardines reappeared there in sufficient numbers, since about 1950, to warrant a fishery or a sampling program (Marine Research Committee, 1960). No samples were available for study from the 1958-59 central California fishery, although about 25,000 tons were landed at Monterey and San Francisco (Ibid., 1960). In general, the present data agree with Clark's findings only for the areas south of Pta. Eugenia. From there northward to San Pedro, California, the data show that a major portion of the samples studied are characterized by a marked reduction in average number of vertebrae.

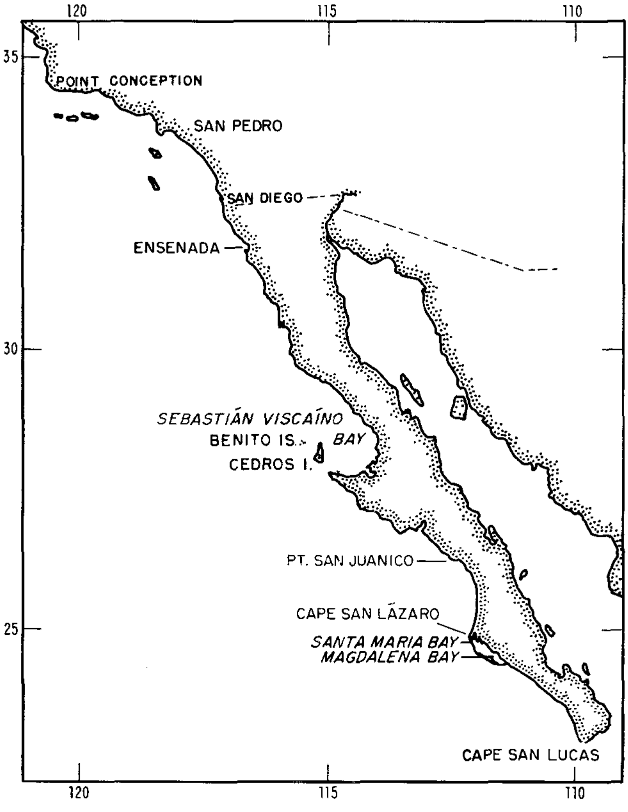

FIGURE 1. Chart of areas discussed, showing the localities from which samples were secured in the present investigation and in that of Clark (1947).

METHODS

As age determinations were not available for samples from most of the localities treated, all age-groups are combined. Only the 1957-58 Ensenada and San Pedro samples were aged (by CalCOFI personnel, employing a subsample amounting to approximately 20 percent of each sample studied). In the other areas studied, aging would have been possible only by arbitrarily assigning an age to any given length frequency. This was not attempted as age-length composition studies have shown that adult sardines (2 years or older) vary in length from 1.5 to 2.5 inches in each age-group. Thus, an arbitrarily assigned age may result in an error of two or three years.

All fish, except one sample of 500 postlarvae from the Gulf of California, were X-rayed for determination of vertebral numbers. The postlarvae were stained with alizarin and cleared in glycerin before counting. All vertebrae were counted by the author. The urostyle was included in the count.

The nature of the data does not warrant detailed statistical analyses, and the study is not intended as a purely racial one. The real significance lies in the differences in average values, both in individual and in grouped samples, between the present body of data and that presented by Clark (1947) for the region north of Pta. Eugenia, Baja California.

Because of the rather small range in total numbers of vertebrae the standard deviations about the mean do not differ markedly. For the region north of Pta. Eugenia the range of deviations, including both Clark's and the present data, is 0.5980 to 0.6719 (ave., 0.6191). The range of standard errors of the means is 0.0006 to 0.0225 (ave., 0.0149). This large range in standard error values is due to the quite large variation in numbers of specimens used (Table 1).

An indication of the significance of the difference between means of Clark's and the present data, for the northern region, is the average difference of 0.23, nearly one-fourth of a vertebra. In comparing this with the almost three-fourths of a vertebra that separates the Gulf of California fish (average mean, 51.00) from those reported by Clark for northern Baja California and northward (average mean, 51.70), elementary statistical treatment will provide odds of but one in hundreds of thousands of chances that the two sets of data comprise a single population or stock of fish. Such orders of significance do not, of course, pertain to the southern areas—from Pta. Eugenia southward and into the Gulf of California—because of the striking similarity of the two sets of data in this southern region.

RESULTS

Figure 2 is a plot of all samples embodied in the present data, arranged by area. Wherever the areas are closely comparable, Clark's 1947 data are also plotted. Each solid dot represents an individual sample of the present data, and each open circle repre-

TABLE I

VERTEBRAL NUMBERS—ALL AGE GROUPS

Locality	Year, Month	Number of Vertabrae						Number of Fish	Average Vertebrae
		49	50	51	52	53	54		
San Pedro	1951: I	----	1	33	40	3	----	77	51.58
	X	----	4	52	39	3	----	98	51.42
	XI	----	2	31	28	3	----	64	51.50
	XII	----	1	11	10	----	----	22	51.41
	1954: X	----	1	18	17	1	----	37	51.49
	1957: X	----	7	78	69	4	----	158	51.44
	XII	----	10	225	228	20	----	483	51.53
	1958: I	----	7	88	101	8	----	204	51.54
	II	1	5	87	74	12	----	179	51.51
	V	----	2	39	49	1	----	91	51.54
	VII	----	4	101	99	7	----	211	51.52
	VIII	----	----	40	35	5	----	80	51.56
	IX	1	7	68	78	6	----	160	51.51
San Pedro total		2	51	871	867	73	----	1,864	51.51
Clark total		4	119	3,039	5,802	677	11	9,652	51.73
San Diego	1950: VII	----	2	89	96	5	1	193	51.55
	1951: I	----	1	10	13	1	----	25	51.56
	1952: VII	----	1	11	22	2	----	36	51.69
	1957: III	----	2	4	7	2	----	15	51.60
	V	----	----	8	16	1	----	25	51.72
	1958: VI	1	1	26	26	1	----	55	51.45
	VII	----	1	32	21	4	----	58	51.48
	X	----	2	46	41	2	----	91	51.47
	XII	----	1	26	25	1	----	53	51.49
	1959: I	----	1	17	19	2	----	39	51.56
	XII	----	4	37	34	1	----	76	51.42
San Diego total		1	16	306	320	22	1	666	51.52
Clark total		2	86	2,085	3,923	452	5	6,553	51.73
Ensenada	1952: IV	----	----	8	18	----	----	26	51.69
	VIII	----	1	19	13	1	----	34	51.41
	XI	----	1	16	23	----	----	40	51.55
	XII	----	----	15	21	2	----	38	51.66
	1956: IX	----	1	33	26	----	----	60	51.42
Ensenada total prior to 1957		----	3	91	101	3	----	198	51.53
	1957: IX	----	5	83	102	8	----	198	51.57
	X	----	17	315	434	33	----	799	51.60
	XI	----	10	265	230	8	----	513	51.46
	XII	1	35	562	494	24	----	1,116	51.45
1957 total		1	67	1,225	1,260	73	----	2,626	51.51
	1958: I	----	2	22	23	2	----	49	51.51
	II	1	2	112	158	14	----	287	51.63
	III	----	16	383	435	42	----	876	51.57
	IV	----	12	197	240	17	----	466	51.56
	V	----	9	181	200	13	----	403	51.54
	VI	----	19	296	268	5	----	588	51.44
	VII	----	20	362	340	12	----	734	51.47
	VIII	1	27	346	299	18	----	691	51.44
	IX	----	24	497	422	17	1	961	51.45
	X	----	18	358	363	18	----	757	51.50
	XI	----	31	600	581	45	----	1,257	51.51
	XII	----	32	390	339	16	----	777	51.44
1958 total		2	212	3,744	3,668	219	1	7,846	51.50
Ensenada total		3	282	5,060	5,029	295	1	10,670	51.50
Cedros and San Benito Islands	1946: VIII	----	9	89	71	3	----	172	51.40
	1952: XI	----	1	10	11	1	----	23	51.52
	1955 ----	----	----	31	99	13	----	143	51.87
	1958: VIII	----	2	21	27	----	----	50	51.50
	IX	----	1	107	85	5	----	198	51.47
	XI	----	1	44	48	4	----	97	51.54
	XII	----	5	45	44	6	----	100	51.51
Cedros and San Benito total		----	19	347	385	32	----	783	51.55

TABLE I—Continued

VERTEBRAL NUMBERS—ALL AGE GROUPS

Locality	Year, Month	Number of Vertabrae 49	50	51	52	53	54	Number of Fish	Average Vertebrae
Sebastián Viscaíno Bay	1953: IV	----	6	27	20	1	----	54	51.30
	1958: VIII	----	7	72	24	1	----	104	51.18
	VIII	----	7	19	24	----	----	50	51.34
	IX	1	2	11	17	----	----	31	51.42
	XII	----	3	70	58	1	----	132	51.43
	1959: I	----	2	36	35	----	----	73	51.45
	IV	----	8	54	53	----	----	115	51.39
Sebastián Viscaíno Bay total		1	35	289	231	3	----	559	51.36
Clark total		----	22	420	596	55	----	1,093	51.63
Pta. Eugenia to Cape San Lázaro	1951: V	1	18	146	141	----	----	306	51.40
	IX	----	14	105	130	6	1	256	51.51
	1952: II	----	----	7	11	----	----	18	51.61
	IX	2	8	39	25	----	----	74	51.18
	1953: II	----	2	5	5	----	----	12	51.25
	V	----	3	63	54	3	----	123	51.46
	VIII	----	----	15	18	1	----	34	51.59
	XI	----	21	178	117	5	----	321	51.33
	1956: VII	----	6	73	55	3	----	137	51.40
	VIII	----	3	51	87	3	----	144	51.63
	IX	----	3	22	23	1	1	50	51.50
	X	----	2	9	23	----	----	34	51.62
	1958: VIII	----	9	103	55	1	----	168	51.29
	IX	----	20	190	78	1	1	290	51.22
Pta. Eugenia Cape San Lázaro total		3	109	1,006	822	24	3	1,967	51.39
Clark: total Pta. Eugenia to Pt. San Juanico		----	32	417	248	13	----	710	51.34
Santa María Bay	1951: VII	----	----	27	17	1	----	45	51.42
	X	----	3	31	43	1	----	78	51.54
	XI	----	----	4	7	2	----	13	51.85
	1952: IV	----	1	8	3	1	----	13	51.31
	VII	----	7	57	6	----	----	70	50.99
	VIII	----	1	7	10	1	----	19	51.58
	1953: VII	----	5	68	51	----	----	124	51.37
	VIII	----	5	51	41	6	----	103	51.47
	1955: VIII	----	3	20	25	3	----	51	51.55
	IX	----	1	14	18	----	----	33	51.52
	X	----	1	11	9	----	----	21	51.38
	XI	----	2	23	24	2	----	51	51.51
	1956: VI-VII	----	9	10	----	----	----	19	50.53
	XI	----	----	33	22	----	----	55	51.40
	1959: II	----	19	107	21	----	----	147	51.01
Santa María Bay total		----	57	471	297	17	----	842	51.33
Magdalena Bay	1949: II	----	1	27	17	1	----	46	51.39
	1951: VI	----	1	8	10	3	----	22	51.68
	1952: VII	1	4	38	9	----	----	52	51.06
	VII	----	8	43	39	----	----	90	51.34
	VIII	----	5	41	13	----	----	59	51.14
	IX	----	----	32	35	1	----	68	51.54
	1953: VI	----	1	23	20	2	----	46	51.50
	1958: VI	----	7	105	27	----	----	139	51.14
	VI small	----	18	82	20	----	----	120	51.02
	VI larger	----	2	23	12	----	----	37	51.27
Magdalena Bay total		1	47	422	202	7	----	679	51.25
Clark total		1	44	500	243	7	----	795	51.27
Pt. Marquis	1952: X	----	6	38	18	3	----	65	51.28
Gulf of California	1953: VIII	----	15	71	25	----	----	111	51.09
	1956: XII (postlarvae)	4	84	315	97	----	----	500	51.01
Gulf of California total		4	99	386	122	----	----	611	51.02
Clark total		2	91	521	118	3	----	735	51.04

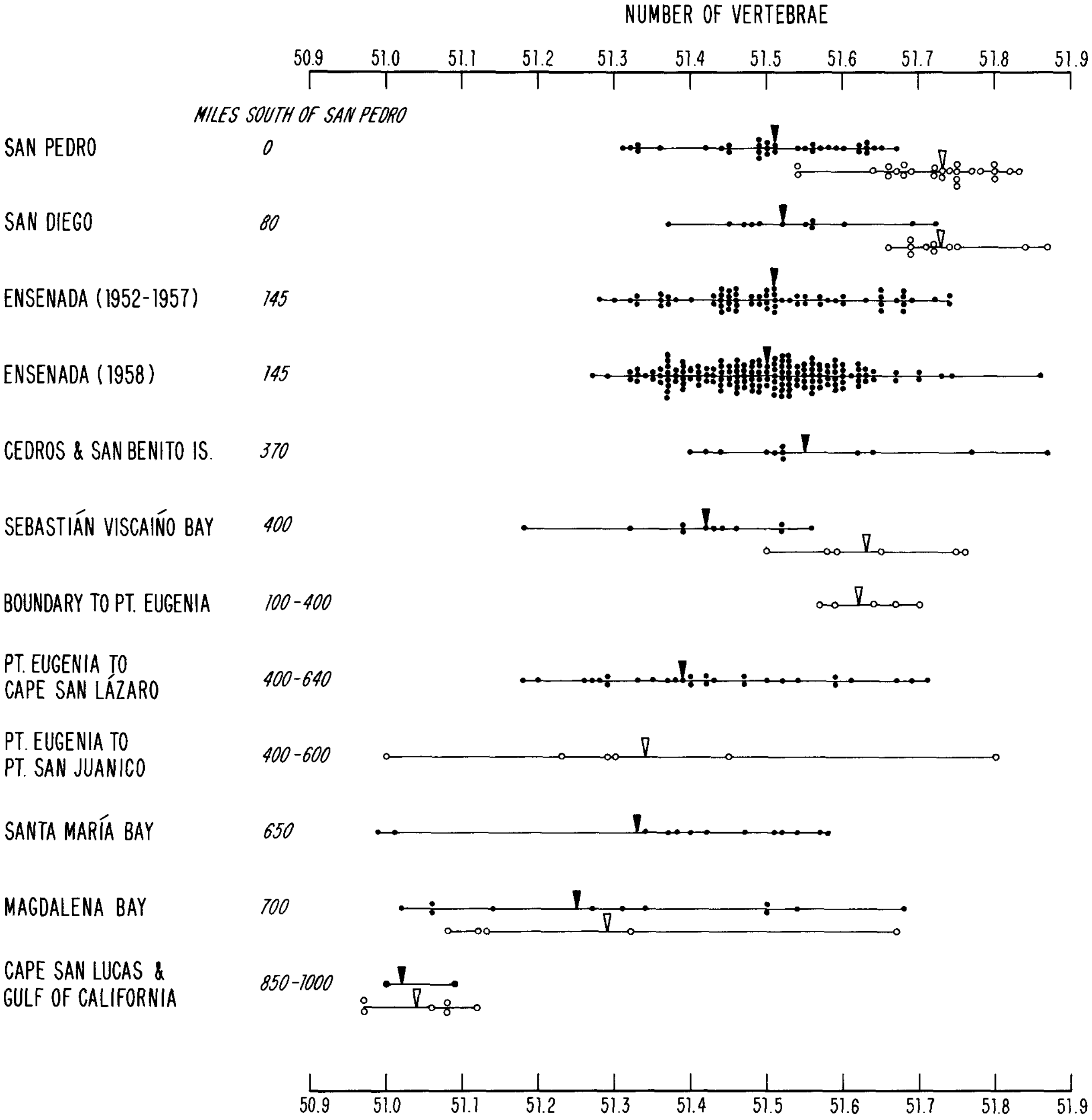

FIGURE 2. Frequency distribution of individual sample means and the mean of each area. Each solid dot (present data) or open circle (Clark's data) refers to an individual sample. The acute triangles represent the area means.

sents a sample listed by Clark (1947). Table 1 summarizes the present data in Fig. 2 by year and month.

Clark's 1947 data, with all age-groups combined, indicate that prior to 1942 the mean vertebral values changed abruptly in the vicinity of Pta. Eugenia, Baja California: average values south of this point were markedly lower than those to the northward. The higher values to the northward formed the basis for Clark's statement that "The average number of vertebrae is approximately 51.7 for all sardines north of southern Lower California and about 51.2 for sardines from southern Lower California." These numerical values have since been considered to be "standard" for sardines spawned under what has been thought to be "normal" oceanographic conditions. For Southern California alone Clark's average for all age groups combined was 51.73. She reported on only five samples with a combined mean value of 51.62, sampled from 1938 to 1940 from the Boundary to Pta. Eugenia—excluding Sebastián Viscaíno Bay samples, considered separately.

Whereas Clark's data from north of Pta. Eugenia comprised samples taken between 1921 and 1941, the present data stems from samples taken between 1950 and 1959. A distinct and significant change has taken place in the decade that separates the sampling efforts (Fig. 2). The plotted mean values of all samples from each area and the area means for the present data show a rather marked reduction in areal mean values as well as a very great number of sample mean values that fall well below the lowest reported by Clark. It will be noted that this reduction persists from Southern California to Pta. Eugenia. Both sets of data are in excellent agreement from Pta. Eugenia southward and into the Gulf of California.

It is unfortunate that very few samples from the region, "Boundary to Pt. Eugenio," were available to Clark, as compared with the much larger number from Ensenada that are used in the present study. Clark's five sample means from this region all fall within the range of those from Ensenada, though they are distinctly on the high side. Clark's data from Sebastián Viscaíno Bay alone correspond very closely with those for the broad areal grouping from the Boundary to Pta. Eugenia. The higher averages appear to have persisted further south in 1921-41 than in 1950-59.

It is of considerable interest that so many sample means from the northern region should fall well below those reported by Clark. For areas south of Pta. Eugenia, excluding those of Cape San Lucas and the Gulf of California, very few samples in the present body of data (only 21 percent) have lower vertebral mean values than do those from Ensenada and Southern California (Fig. 2). Clark's data alone show 82 percent of the samples from these southern areas to have appreciably lower values than do the samples from Southern California reported on in 1947. This difference of 61 percent is striking evidence of the reduction in mean numbers of vertebrae between the two time periods in the samples from Southern California and northern Baja California. The populations, or stocks, of fish from areas south of Pta. Eugenia may intermingle to at least a small degree with those from the Gulf of California: of all samples from south of Pta. Eugenia, excluding those from the Gulf, about 23 percent have vertebral mean values similar to those reported from the Gulf (Fig. 2).

In contrast to the expected lower mean values for the areas south of Pta. Eugenia are the several relatively high values. The value of 51.795 for 78 fish (0 age-group), listed by Clark for the "Pt. Eugenio to Pt. San Juanico" area, and the value of 51.669 for 127 fish (I age-group) from Magdalena Bay, are generally considered as typically "northern" or "high" means. The present data includes one sample of limited significance (comprising only 22 fish) from the same area with a high mean of 51.68. The reasons for these higher mean values are difficult to assess.

McHugh (1950) offered a possible explanation of these high values, which average 51.71. Postlarval sardines from southern Baja California, spawned in spring and summer, were found to have significantly different mean vertebral numbers of 51.54 and 51.21 respectively (as McHugh did not count the urostyle, his counts are increased by one to conform to those of the present study). The values of 51.79 and 51.17 for spring- and summer-spawned fish in samples from northern Baja California differ even more significantly. Whereas McHugh's high value of 51.54 for postlarvae spawned in the spring in southern Baja California falls well below the average figure of approximately 51.71 for the older fish under consideration from these southern areas, it does indicate the possibility that environmentally induced meristic differences may result in abnormally high mean vertebral numbers in at least some samples from these areas, and, possibly, for all areas throughout the range. Of course the reverse situation may also occur as is shown by two samples taken near the San Benito Islands, about 15 miles west of Cedros Island. In 1946, 172 0-year fish furnished a mean vertebral value of 51.40 and in 1955, 143 fish (estimated at nearly two years of age) provided a mean of 51.87 vertebrae. This is an area that was quite "northern" in the data presented by Clark, but considerably less so in the present data: the means are about 51.64 and 51.50, respectively.

Both Magdalena and Santa María Bays also show a tendency to produce some samples with relatively high mean vertebral numbers. Excluding the two low mean values, 50.99 and 51.01 (Fig. 2, Table 1), raises the Santa María Bay average to 51.44, a figure notably higher than the combined average for the Bay and one that would appear to fit the plotted distribution of sample means (Fig. 2). It is reasonable to assume that as Santa María Bay is entirely open to the sea any migrating northern stock may readily enter. In contrast, the relatively enclosed Magdalena Bay is presumably less accessible to coastal migration and may be expected to harbor a more indigenous population. The number of samples from each bay is hardly adequate to resolve the question. Actually the highest mean value recorded for Magdalena Bay in each set of data exceeds any of the means for Santa María Bay. However, the high value of 51.68 listed in the present data is derived from a sample of only 22 specimens and may not be of great significance. The next highest value, 51.54, is derived from 68 fish. It thus appears probable that higher values may occur in the Bay. Clark's 1947 data includes a sample of 127 I-year fish which furnished the more significant mean value of 51.669. Thus it is apparent that either migrations from the north may enter these bays or that local spawning conditions may occasionally be such that higher average vertebral numbers may result. It is also apparent that the same situation pertains to those samples having lower vertebral mean values comparable to those listed for the Gulf of California. From the standpoint of migration these bays may be considered to be more within the range of Gulf stock than those from more northern waters, particularly those from north of Pta. Eugenia.

As noted by Clark (1947) the Gulf of California may well harbor a separate population of sardines that intermingles little if at all with the northern populations, but that may mix to a degree with stocks occurring below Pta. Eugenia. The present data has strengthened Clark's conclusion, for the two sets of data are remarkably similar, considering both the time interval between the two sets of data and the total number of years involved. Whereas Gulf samples consist of O fish or postlarvae, except for the 31-fish sample of adults reported by Clark, affording a mean of 50.968, all samples have provided mean values of about 51.00.

Year Class Data and the "Warm" Years: The occurrence of abnormally high ocean temperatures in 1957 and 1958, and the observed reduction in average numbers of vertebrae in samples from northern Baja California and Southern California, requires that some consideration be given to year classes comprising the present data. As a major portion of the samples were taken in 1957-58, particularly in these two areas, the age data are considered for these areas only.

Daugherty and Wolf (1960) show that, for the 1957-58 season in Southern California, the 1957 year class contributed only 1.3 percent to the commercial catch. During the same period of the northern Baja California season (including Ensenada and Cedros Island landings) these authors show that the 1957 year classes contributed only 1.4 percent. The 1958-59 catch data for Southern California showed that 1957 fish comprised only 10.2 percent of the catch and in Baja California only 11.6 percent (Wolf and Daugherty, 1961).

Thus it is clear that the 1957 and 1958 year classes, presumably hatched in warmer water, were a minor constituent of the catches and the vertebral count samples. Therefore, the recent "warm water" can be almost completely discounted as contributing to the low vertebral numbers off Southern California and northern Baja California during the 1957-58 and 1958-59 fishing seasons.

DISCUSSION

If the effect of the warm years may be discounted as being a major cause for the observed reduction in average vertebral numbers in the area of northern Baja California and Southern California, other hypotheses may be erected: (1) The environment had begun to change as early as 1950 and the change was reflected in the reduced average number of vertebrae (but there is no oceanographic evidence of such a change); (2) Micro-environmental changes affected the vertebral numbers and morphometry of the individual spawnings that were later sampled (such an event is, of course, always possible; however, there are great odds against the chance that such spawnings and samples make up the bulk of the present data); (3) Stocks of fish migrated northward from the southern areas, which are characterized by lower average numbers of vertebrae, accompanied by a reduction in the numbers of northern-type fish. This is the most attractive hypothesis.

Ahlstrom (1959) has reported that such a northward movement did occur in early 1954. Associated with this northward movement was an appreciable rise in water temperatures, particularly in the early spring. Clothier and Greenhood (1956) reported that 67,258 tons of sardines were landed during the 1954-55 season in contrast to the slightly more than 3,000 tons in 1953-54 and some 4,500 tons in 1952-53.

Unfortunately, the present data are not adequate to test whether or not this observed migration of sardines into Southern California contributed to the lowering of the average number of vertebrae within the area in 1954, though they are suggestive. Only one sample of 37 fish, from San Pedro, was available for study. This sample afforded a mean of 51.49 (Table 1), quite characteristic of the recent period in the Southern California fishery, whereas the average for the earlier period reported on by Clark was 51.73.

That these 1954 fish, and those of subsequent and earlier samples to 1950, were probably not spawned in the area of capture during any warm period is evidenced by the following statement by Reid, Roden, and Wyllie (1958), "the period from 1949 to 1956 is distinguished from the previous 15 or 20 years by substantially colder waters in the first few months of the year."

The foregoing evidence of the period of 1949-1956 being colder than the previous 15 or 20 years adds further interest to the comparison of the two sets of data on vertebral numbers. If most specimens in the present study are presumed to have been spawned in waters colder than those in which Clark's must have been (all spawned prior to 1941), it could also be presumed that the average numbers of vertebrae would be higher than observed. This obviously is not the case in those samples studied from northern Baja California and Southern California; thus by every test the change in vertebral numbers is opposite that suggested by the environmental changes. There must, then, have been major changes in the stocks on the fishing grounds.

One question posed by the present body of data is, what happened to the "northern" type of sardine? Temperature data indicate that sufficiently cold water was available to have produced high vertebral numbers. The number of samples studied would appear to afford an adequate representation of the fish available to the sampling techniques. It may be that the northern types were "somewhere else" and not available to the fisherman or the sampling techniques. It may also be that the influx of southern fish in 1954 continued and that interbreeding with the northern types has resulted in lower average numbers of vertebrae, or that the northern types were still present but in considerably reduced numbers.

In review, south of Pta. Eugenia there was no change in vertebral numbers between the earlier and later period, all counts being low. North of Pta. Eugenia, vertebral counts during the recent decade are lower than the earlier period, the average being intermediate between the stable southern average and the earlier northern average. Further, the direction of the change, i.e., a decrease, has been contrary to that expected to have resulted from the cooler environment during the recent period. Thus, there is good evidence that there has been a change in the "racial" composition of the stocks taken by the fishery in Southern California and northern Baja California.

The precise nature of the change is not so clear. There has been a severe decline in the stocks available to those fisheries compared to the early period (Clark and Marr, 1955). This almost rules out the possibility that the lowering of the vertebral numbers was caused only by an influx of southern fish. Rather, the change in vertebral numbers must have been associated with a reduction of the population of the northern, high vertebral number, ''race,'' possibly, but not necessarily, accompanied by additional influx from the south.

SUMMARY

1. The results of the summarized three widely differentiated earlier approaches to the problem of heterogeneity of sardine stocks throughout the range indicate the presence of more than one population, or stock, of sardines inhabiting the total range.

2. The present study demonstrates that a marked reduction in average numbers of vertebrae, for sardines sampled in northern Baja California and Southern California, has occurred throughout the period from about 1950 through 1958. This reduction results in a much lower average value than that reported by Clark (1947), the respective values being 51.50 and 51.73.

3. The plot of average numbers of vertebrae for each sample within a given area, and the area averages (Fig. 2), indicates that many of the samples taken in northern Baja California and Southern California, in the period from 1950 to 1959, have sufficiently low values to have originated in the waters off Central or Southern California.

4. Year-class data for a major portion of these fish with low values indicate that only a small percentage of the total catch could have been spawned in the area of capture during the abnormally high ocean temperatures that began in 1957.

5. For the areas of southern Baja California (Pta. Eugenia into the Gulf of California) the present data is in excellent agreement with that presented by Clark (1947). The two sampling efforts cover a period of time from 1926 to 1958 for this broad area. This fact indicates that these areas may harbor indigenous populations in that no apparent change in the average vertebral numbers has occurred in the 32-year period.

6. It is concluded that the sardines caught in northern Baja California between the years 1950 and 1959 were comprised of a different ''racial'' mixture than those taken prior to 1941, because the recent reduction in vertebral numbers is contrary to the phenotypic increases usually associated with cooler water. Concurrently, abundance has declined, so the change in vertebral number is most easily explained by postulating reduction in a northern ''race,'' possibly accompanied by an influx of additional southern fish.

ACKNOWLEDGMENTS

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THE WATER MASSES OF SEBASTIAN VIZCAINO BAY

JOHN G. WYLLIE[1]

INTRODUCTION

This report is a descriptive analysis of the water masses and certain processes, which combine to produce the major changes in the physical environment observed throughout the year in Sebastian Vizcaino Bay. No effort is made to explain the forces involved or mechanics of the changes described. A discussion of the currents of the bay has been avoided since it is felt sufficient measurements for such a discussion have not yet been obtained.

GENERAL AREAL DESCRIPTION

Sebastian Vizcaino Bay is located 350 miles (all distances are expressed in nautical miles) south-southwest of San Diego on the Pacific Coast of Baja California (Fig. 1). The bay has the shape of a fish-hook completely exposed to the sea toward the northwest. The distance from the northern end of Cedros Is. due north to Punta Canoas on the mainland measures 63 miles; the distance from Punta Canoas to the southernmost shore of the bay is about 115 miles. The narrowest dimension of the bay measures 48 miles from the northern end of Cedros Is. to Punta Maria. The inset in Figure 1 shows Monterey Bay of central California for a size comparison. Two channels, separated by Natividad Is., open to the sea in the southwestern portion of the bay: they are Kellett Channel, which is 8 miles wide and 40 to 45 meters deep, and Dewey Channel, which is 4 miles wide and 25 to 30 meters deep. Three very shallow lagoons are found along the southeastern boundary: Scammon, Black Warrior and Manuela. The San Benitos Islands lie approximately 15 miles west of Cedros Is. Ranger Bank, about 100 meters deep, lies 15 miles northwest of Cedros Is. There is little rainfall in this area and no rivers empty into the bay.

DESCRIPTION OF WATER MASSES[2]

For purposes of identification, seven water-mass sources are defined. The term "water-mass source" is a misnomer in some cases since some of the areas mentioned as source regions are not sources of water having definite reproducible characteristics, but rather areas where more or less permanent processes occur which result in water types which differ strikingly from neighboring water.

The seven water sources (Fig. 2) are:

1. California Current water, which is a water mass with very characteristic physical parameters. It is the source of low-salinity water for the bay. It is relatively cool, but not the coldest water in the bay; it has a high oxygen and PO_4-P content. It is present in large quantities and often dominates the bay waters.

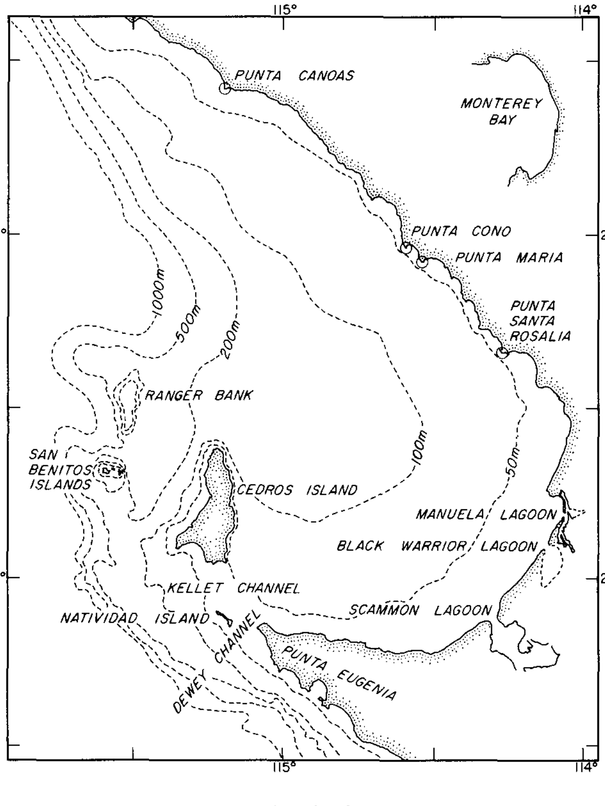

FIGURE 1. Geography of Sebastian Vizcaino Bay.

2. Upwelled water from the Punta Canoas region. Water of definite physical characteristics cannot be assigned to this region since upwelling is a process which brings to the surface layer whatever type of water happens to be present below the surface at a particular time. Usually the upwelling process, coastal

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[1] Contribution from the Scripps Institution of Oceanography.

[2] The water masses described in this report should not be confused with the major water masses as defined by Sverdrup in "The Oceans". They are used for convenience only in identifying and separating the local conditions found within, and in the immediate vicinity, of the Bay.

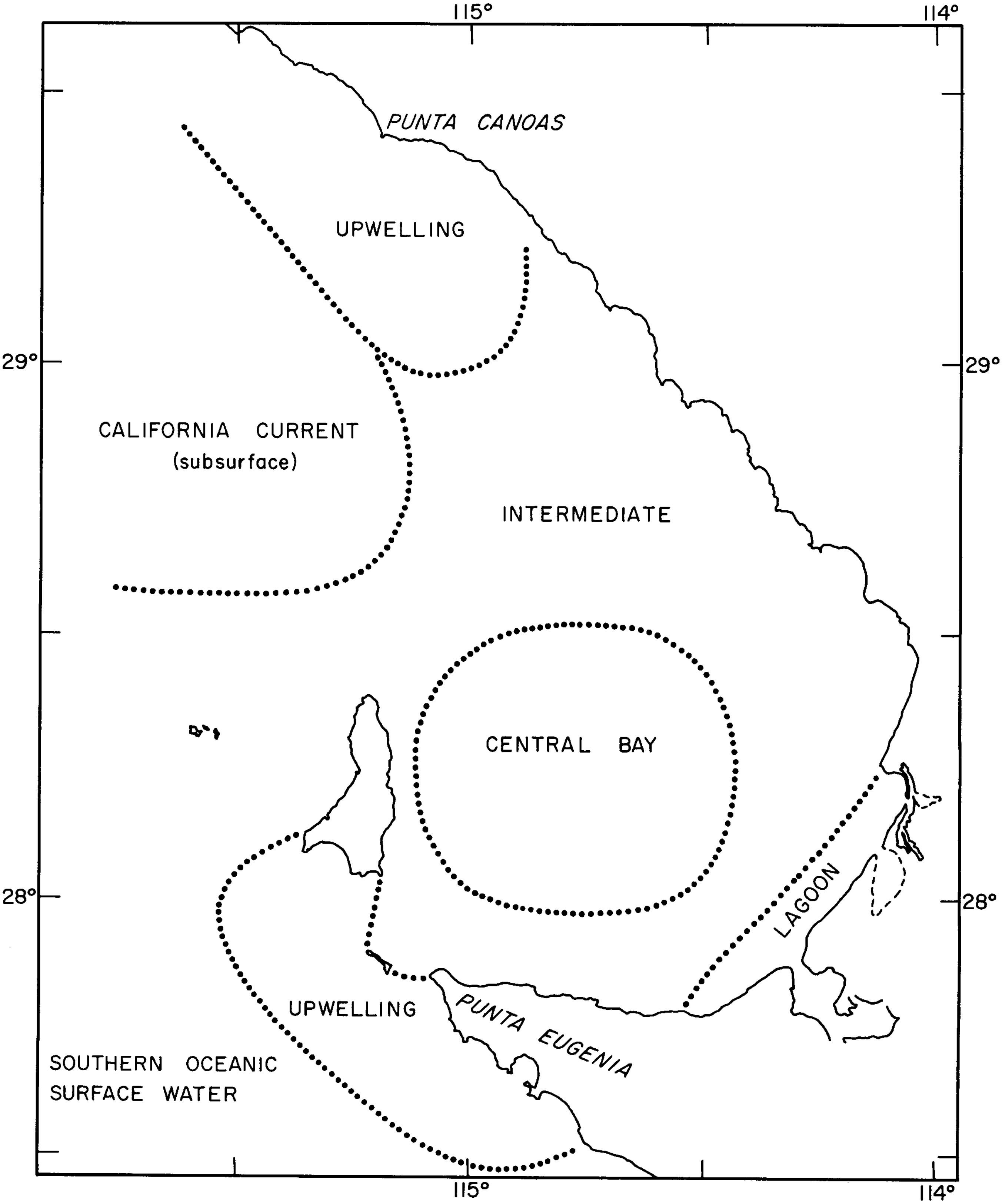

FIGURE 2. Water masses of Sebastian Vizcaino Bay.

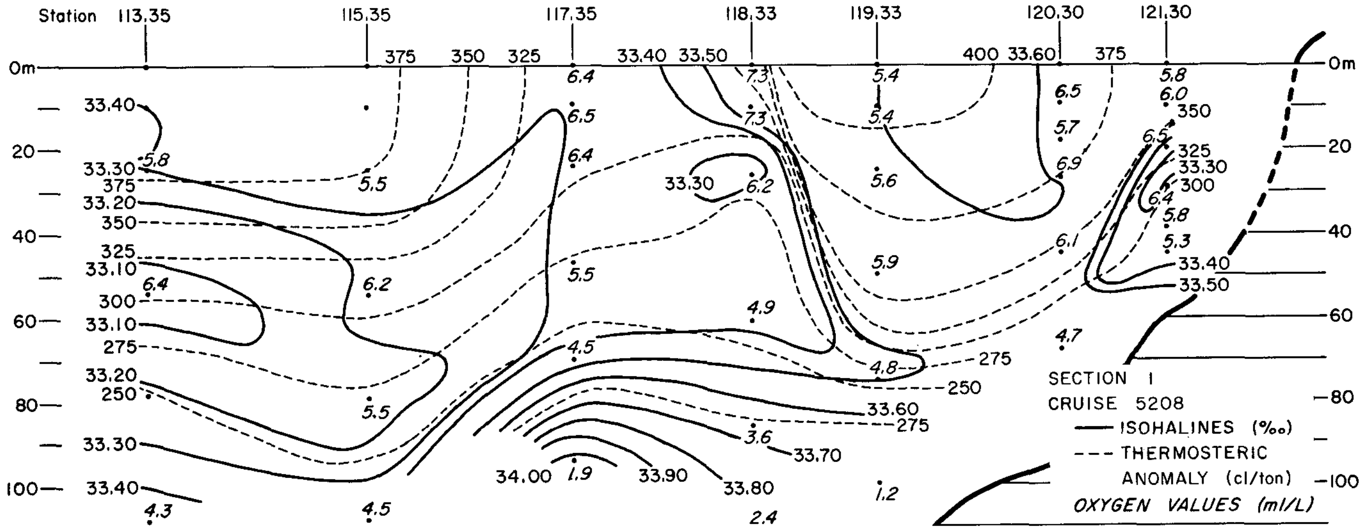

FIGURE 3. Section 1, Cruise 5208. Vertical section from the surface to 110 meters showing distribution of salinity (isohaline lines), thermosteric anomaly (lines of equal Δ' or δT) with oxygen values (ml/L) entered.

in this region, results in the coldest water because the vertical temperature gradient is normally negative. Whether or not this water will have a high or low salinity value depends upon what water is being upwelled. In the Punta Canoas area higher-salinity water is most frequently upwelled.

3. Central Bay water is also the result of a local condition and cannot be described as having definite characteristic values. There appears to be a permanent or semi-permanent clockwise rotating eddy in the bay. Its position and size vary considerably. It is definable because it is characteristically delineated from the

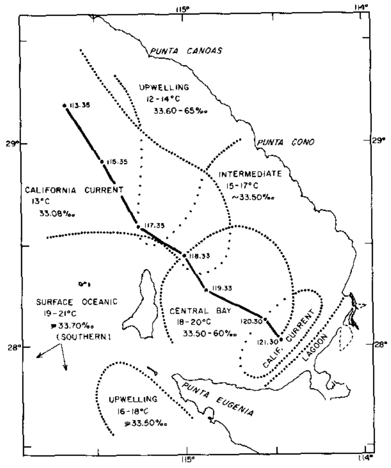

FIGURE 4. Cruise 5208. Block Diagram showing general characteristics and locations of water masses in August 1952 (5208).

surrounding water by a very sharp thermocline and oftentimes by "fronts" (Cromwell and Reid 1956). This pocket of water is usually found to be well mixed and relatively warm. It is usually warmer than the surrounding water indicating it is probably held for a longer time in the surface layers.

4. Lagoon water appears to be of minor importance in the regime of the bay, but it often has extremely different characteristic values. High temperatures and salinities are found. This water is probably mixed into the bay water somewhere along its southern periphery. It can be called a true source region since water of definite characteristics forms there.

5. Upwelled water from the Punta Eugenia area can be described in the same manner as the water from the Punta Canoas region. The main difference is in the importance of the two areas in relation to the bay. Punta Eugenia water is probably the least important of any of the water-mass sources described. Some of this water may enter through the southwestern channels and affect some of the southern coast of the bay, as evidenced by certain cold water algae found there (Dawson 1952).

6. Southern oceanic surface water is characterized by high temperatures and salinity. This water is found along the coast to the south of Punta Eugenia and influences the bay mainly during the late summer and fall months.

7. Water from the deep coastal salinity maximum is a subsurface mass (usually found at 200-300 meter depth) which is characterized by relatively high temperatures and salinities, a very low oxygen content and a relatively high phosphate content. It is actually an extension of Equatorial Pacific water northward along the coast. It enters the bay circulation from below by moving up over the continental slope and shelf.

In addition to the types of water just described other water is sometimes found which does not fit any of these classifications. This is, of course, to be expected when two or more of the above water types mix. We will call this intermediate water.

A general descriptive analysis of certain special cruises into the bay will be made in terms of the above-mentioned water-mass source regions.

SPECIAL CRUISE, AUGUST, 1952 (CR 5208)

In August, 1952, the first special CalCOFI cruise was made into Sebastian Vizcaino Bay. At this time low salinity California Current water was found within the upper 100 meters. (Fig. 3 and Fig. 4). This appears as a tongue of water to the west and northwest of the bay entrance, north of Cedros Island. Salinities as low as 33.08 $^{0}/_{00}$ and temperatures of about 13°C were observed in the core of the tongue at a depth of 50 to 55 meters immediately west of the bay entrance (Fig. 3). A patch of similar water is found along the southern shore at a depth of 20 meters or more. It may be a continuation of the present invasion or the remnants of an earlier invasion.

Punta Canoas upwelled water has a temperature range of 12 to 14°C and a salinity range from 33.60 to 33.65 $^{0}/_{00}$ in the surface layers. It is found as a crescent shaped ridge opening to the west, extending south from Punta Canoas, reaching to within 10 miles of Cedros Is. (Fig. 4 and 5). This water is found at the surface in the northern one-third of this distance only. It apparently upwells from depths of less than 100 meters. A relatively strong "front" is found between the California Current water and this upwelled water. The entrance of upwelled water into the bay circulation probably accounts for the depression of the bay temperatures as compared to the neighboring surface oceanic waters (Fig. 4).

Central bay water is restricted to a prominent clockwise rotating eddy occupying the main part of the bay east of Cedros Island (See the isobaths and isothermes of the $\Delta' = 300$ surface on Figure 6). The $\Delta' = 300$ surface has been chosen as a reference surface because it coincides closely with the core of the low salinity California current water in this region and usually delineates the bottom of the central bay eddy. A sharp thermocline separates this water from the colder less saline water below. The central bay

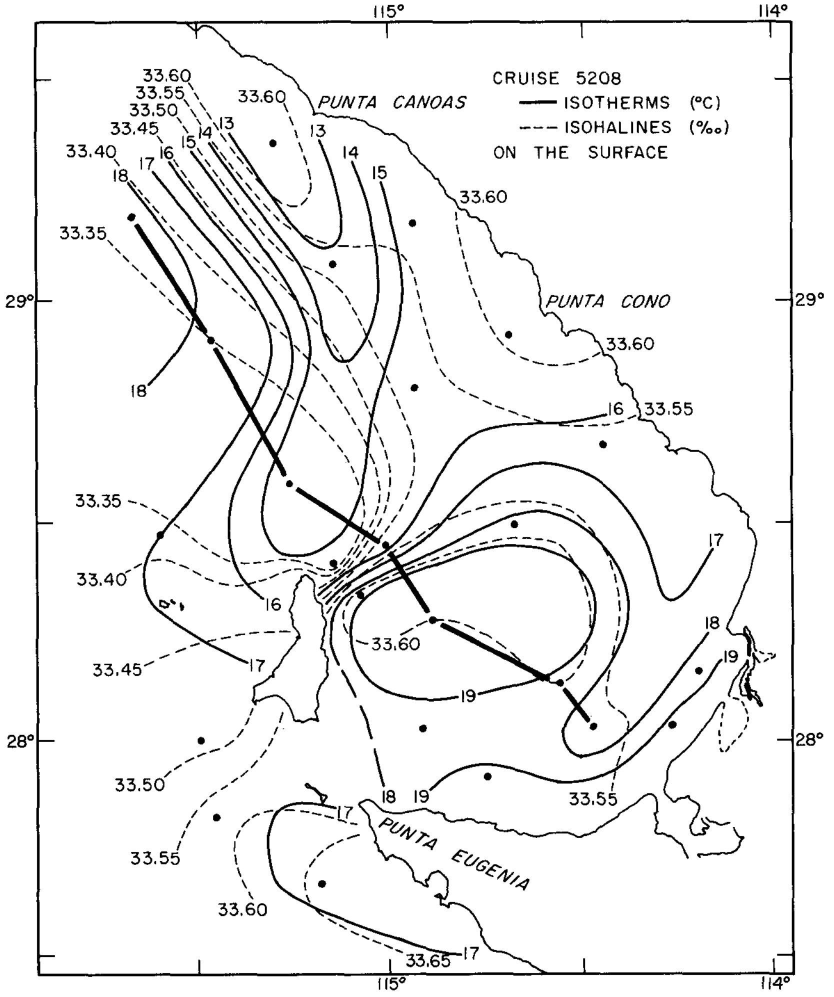

FIGURE 5. Cruise 5208. Surface temperature and salinity distribution (Isotherms in °C, isohalines in $^{0}/_{00}$).

water is well mixed from the surface to the thermocline, which has a maximum depth of 60 to 70 meters. The surface temperatures range from 18 to 20°C and the salinities from 33.50 to 33.60 $^{0}/_{00}$. A strong "front" is found along the northwestern boundary of the eddy. The southern end of the cold Punta Canoas upwelled water is found adjacent to the central water and helps to intensify the "front" (Fig. 5). Another weaker "front" can be traced between the central bay and the intermediate water found to the east and northeast. Along the southeastern edge of the eddy the intermediate and central water becomes homogeneous and the "front" disappears.

Lagoon water is found immediately offshore of the lagoons along the southeastern edge of the bay. We have little data but we do know the water is very warm and saline.

Upwelled water from the Punta Eugenia area had surface temperatures from 16 to 18°C and salinities of 33.50 $^{0}/_{00}$ or greater (Fig. 4). Apparently some of this water is carried into the bay on the incoming tide and gives evidence of being found along the northern shore of Punta Eugenia (Dawson, 1952).

Southern surface oceanic water is found southwest of the bay beyond the Punta Eugenia upwelled water with temperatures, at the surface, from 19 to 21°C or greater (Fig. 4). None of this water seems to have been in the bay at this time.

Intermediate water was found as a very shallow layer (less than 20 meters thick) immediately west of Punto Cono (Fig. 4 and 5). It extends along the eastern and southeastern shoreline of the bay where it blends with the central water. Temperatures range from 15 to 17°C and salinities are near 33.50 $^{0}/_{00}$. This water appears to be a mixture of California Current, Punta Canoas upwelled and central bay waters. The thermocline separating it from the cooler water below comes to the surface just southeast of Punta Canoas forming another front. This front between the upwelled and intermediate water becomes diffuse to the south.

Underlying most of the water in the bay is water from the deep coastal salinity maximum. This water may slide up the continental shelf south and west of Kellett and Dewey Channels and continue over the sill between Cedros Island and the San Benitos Is-

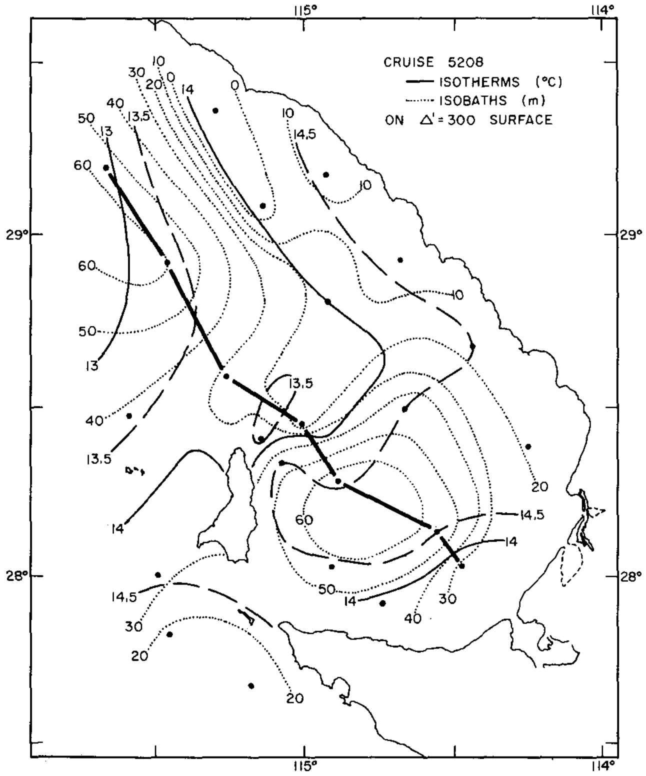

FIGURE 6. Cruise 5208. The depth of, and temperature distribution on, the thermosteric anomaly surface Δ' = 300. (Isobaths in meters, isotherms in °C.)

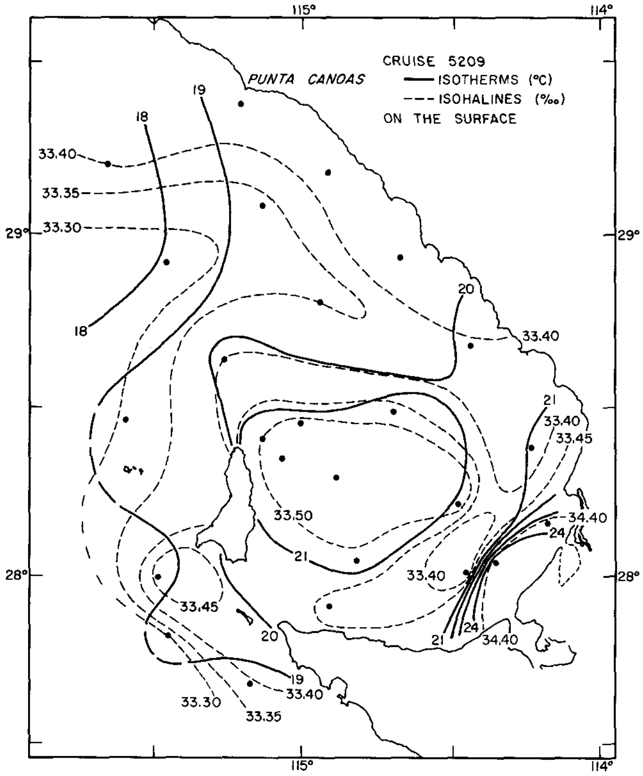

FIGURE 7. Cruise 5209. Surface temperature and salinity distribution. (Isotherms in °C, isohalines in ‰.)

lands and then around the northern end of Cedros Island into the bay (Fig. 1). The presence of this water is clearly seen at station 117.35 in Sect. 1. Evidently water of this type is often upwelled into the surface layers.

The weather situation at the time of this cruise should have resulted in a moderately strong flow of air from the northwest. This fits in well with the observed conditions, since evidence of coastal upwelling certainly was found.

COMPARISON WITH OTHER CRUISES

The special cruise made in August, 1952, (CR 5208) was followed by a second special cruise, the next month, September, 1952, (CR 5209) which is of interest since it gives some idea as to how conditions can change at least within four or five weeks.

A list of the most obvious changes are given below:

1. No upwelling was in evidence at either Punta Canoas or Punta Eugenia.
2. California Current water had invaded most of the bay as well as the area immediately outside the bay.
3. The central bay eddy shifted northward.
4. No strong fronts were found.
5. There was marked warming of the entire bay.

In general, these changes brought about more homogeneous conditions between the water masses in the bay. (Fig. 7) California Current water dominated the scene. The core of this relatively cool, low salinity water enters the bay midway between Punta Canoas and Cedros Island spreads to the east and southeast along the coast, then underruns and mixes with the central bay water along the southern and southeastern coast.

The central bay water has been diluted with California Current water. The average salinities dropped from 33.50 to 33.60 ‰ to 33.40 to 33.45 ‰, except at the very surface with salinities continuing at about 33.50 ‰. On the average the temperatures are about 2°C higher in the mixed layer than in August. With the cessation of upwelling off Punta Canoas and the spread of the central bay water northward, the surface fronts along the northern edge of the eddy appear to have been eliminated. (Compare Figures 5 and 7.)

Lagoon water is evident along the southern shore. It is very warm (23 to 24°C) and saline (34.20 to 34.40 ‰). This water apparently remains along the southern coastline.

Surface oceanic water outside the bay in the upper few meters is a degree or two warmer than in August, but it is otherwise not much changed.

The intermediate water of the August cruise is difficult to find. The region where it was found during August now has water with salinities from 0.20 to 0.35 ‰ lower and temperatures from 19 to 21° C, an average of 3 to 4° higher.

Deep coastal salinity maximum water is found at Stations 117.35 and 118.35. In figures 8 and 9 this is

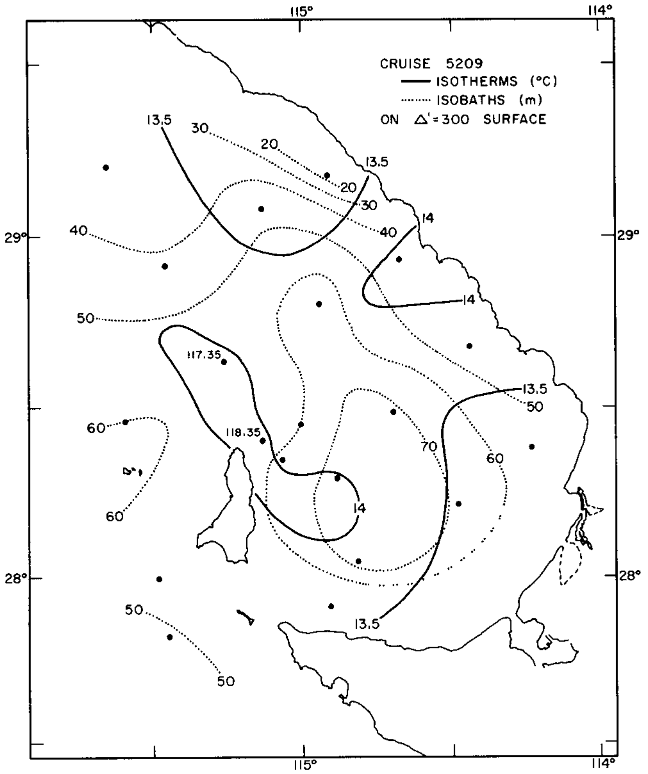

FIGURE 8. Cruise 5309. The depth of, and temperature distribution on, the thermosteric anomaly surface $\Delta' = 300$. (Isobaths in meters, isotherms in °C.)

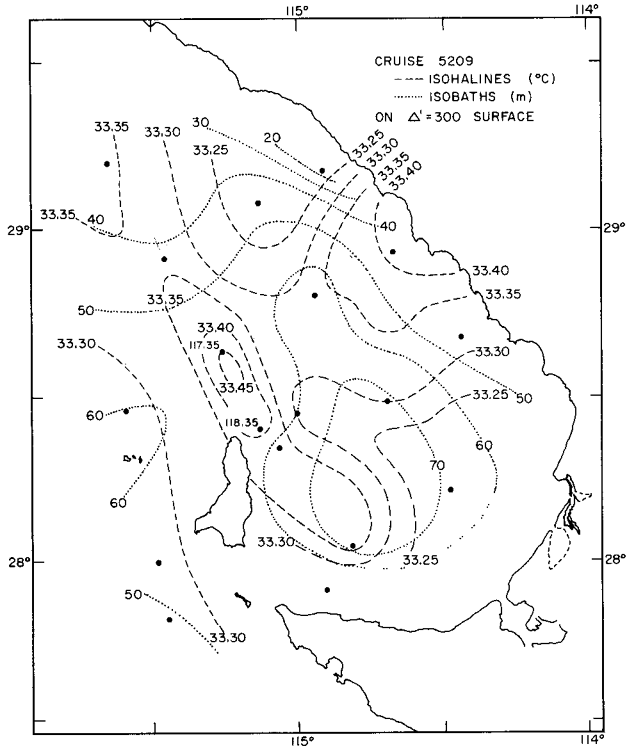

FIGURE 9. Cruise 5309. The depth of, and salinity distribution on, the thermosteric anomaly surface $\Delta' = 300$. (Isobaths in meters, isotherms in °C.)

clearly seen as a warmer, more saline zone on the $\Delta' = 300$ surface. This water is about 1°C warmer than during August.

The general meteorological conditions over the Pacific should have resulted in a relatively weak flow of air from the northwest. This could account for the absence of coastal upwelling at this time.

Reference has been made to surface oceanic water originating to the south and southwest as playing a part in the water-mass sequence in the bay. Neither cruise in 1952 offered any definite evidence of this. We were fortunate, however, in obtaining direct evidence during a special bay cruise in September, 1953, (CR 5309, see Fig. 10). At this time conditions were found to be similar to those in September, 1952, (CR 5209). No upwelling was in evidence at either Punta Canoas or Punta Eugenia. California Current water dominated the scene, being found along the entire northeastern shore of the bay to a depth of 50 meters. It was also found beneath the central bay water as a layer 10 meters or more thick. It could be traced as a subsurface layer 20 to 30 meters thick seaward from the northern half of the bay and as a thin sheet to the northern end of Cedros Island.

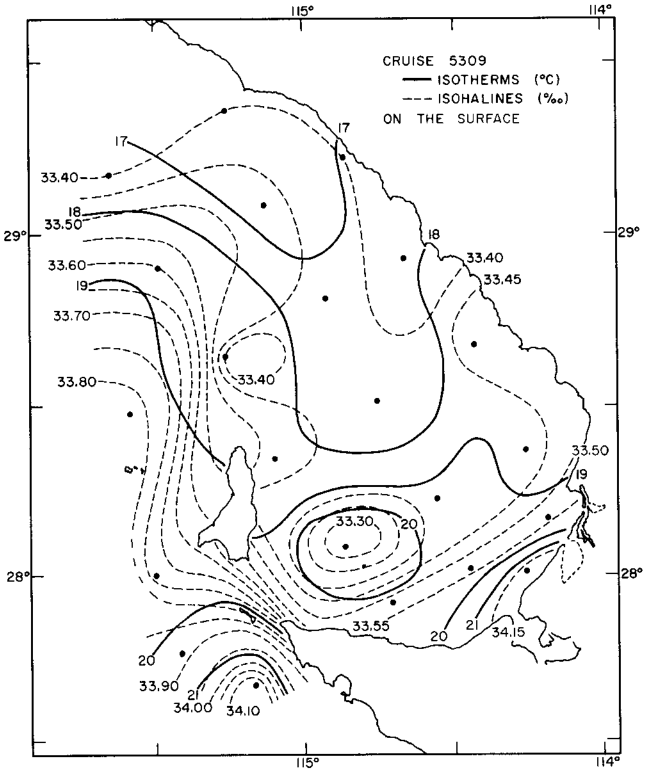

FIGURE 10. Cruise 5309. Surface temperature and salinity distribution. (Isotherms in °C, isohalines in ‰.)

The central bay water was diluted with California Current water. It had uniform salinity values of 33.35 to 33.40 ‰, and surface temperatures near 20°C. The eddy was displaced to the southern portion of the bay (Figure 10) as contrasted to September, 1952, when it was found to the north (Figure 7). A weak front can be found along its northern edge.

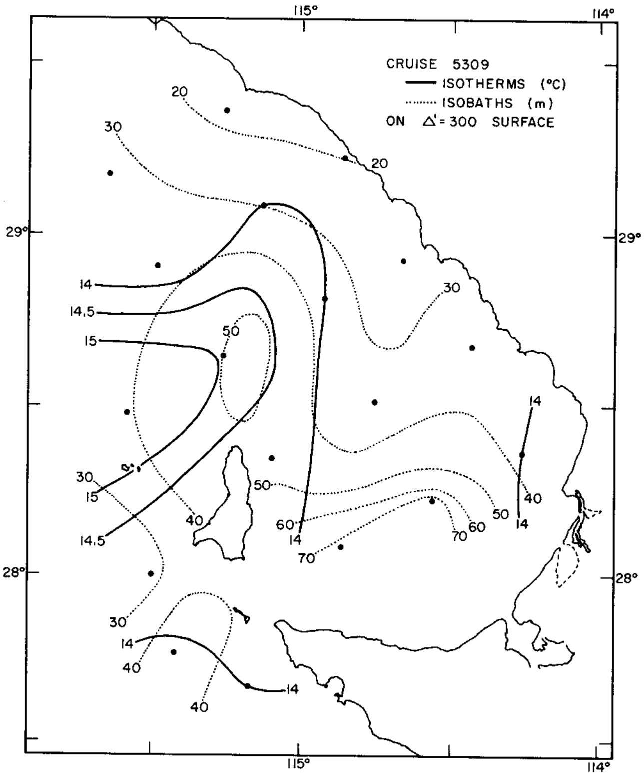

FIGURE 11. Cruise 5309. The depth of, and temperature distribution on, the thermosteric anomaly surface Δ' = 300. (Isobaths in meters, isotherms in °C.)

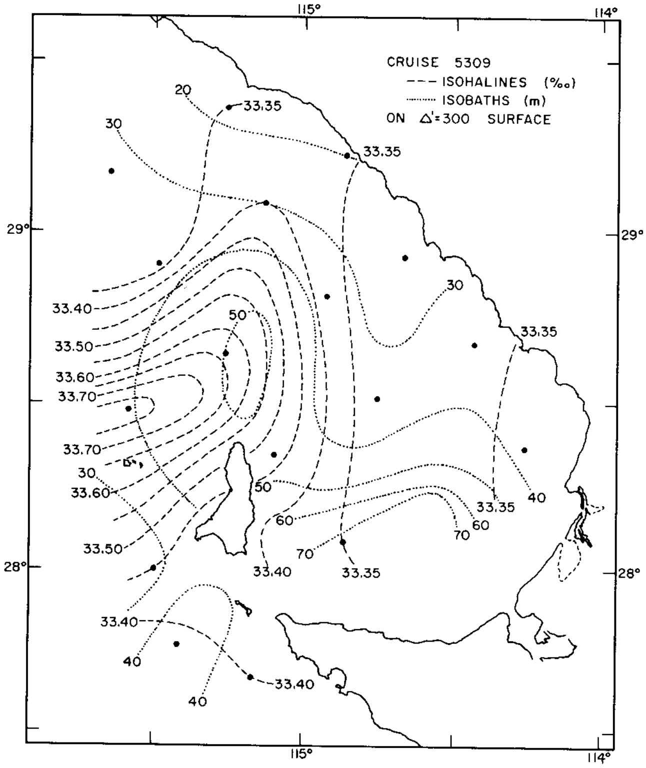

FIGURE 12. Cruise 5309. The depth of, and salinity distribution on, the thermosteric anomaly surface Δ' = 300. (Isobaths in meters, isohalines in ‰.)

As in the 1952 cruises, lagoon water was found along the southern shore line. Temperatures of at least 22°C and salinities greater than 34.00 ‰ are found.

The most interesting feature, however, is the southern surface oceanic water found immediately west of the channels and Cedros Island in the upper 30 to 50 meters. As can be clearly seen on Figures 11 and 12, this warm saline water extends into the bay around the northern end of Cedros Island. Invasion of the bay by water of this type and in this amount could certainly account for any sudden increase in the temperature and salinity values, especially in the surface layers.

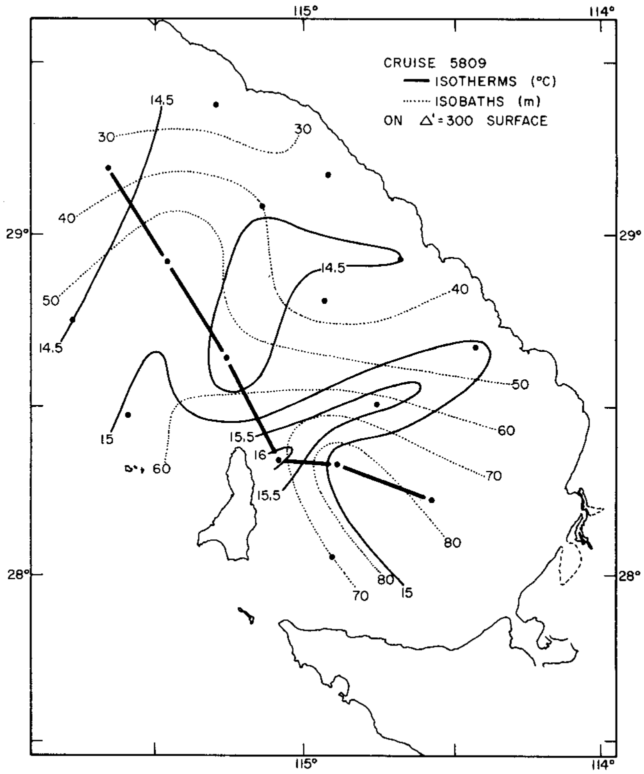

FIGURE 13. Cruise 5809. The depth of, and temperature distribution on, the thermosteric anomaly surface Δ' = 300. (Isobaths in meters, isotherms in °C.)

In September, 1958, (CR 5809), a good example of the influx of deep coastal salinity maximum water into the bay circulation is found (Figures 13, 14 and 15). This is of special interest since it shows this deeper water being injected into the upper (shallow) levels of the bay water and therefore being made available for rapid inclusion in the surface circulation. As is evident from the figures, this water is relatively warm and saline with an exceptionally low oxygen content.

Other special cruises have been made into the bay but the above mentioned cruises give examples and support the hypothesis that the sequence of events of the physical environment, both seasonally and year to year changes can, in part, be explained and described in terms of these water masses and processes.

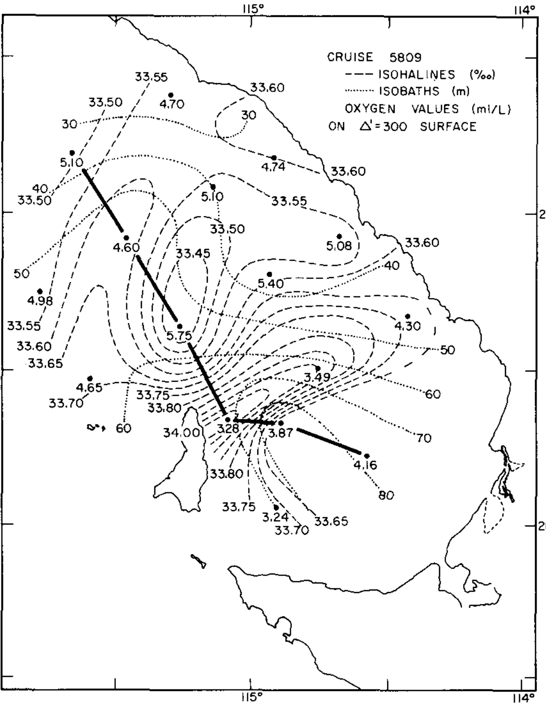

FIGURE 14. Cruise 5809. The depth of, salinity distribution and oxygen values on the thermosteric anomaly surface Δ' = 300. (Isobaths in meters, isohalines in ‰, oxygen values in ml/L.)

SEASONAL VARIATION

In discussing seasonal patterns at any particular point, we wish to delineate between variations which are easily predictable, such as the effect of incoming radiation from the sun and sky, and those which are not. The less predictable events which cause variations throughout the year are the replacement of one water mass by another, plus all the degrees of mixing which attend these changes. The changes we observe are a result of a combination of all these phenomena.

In the upper layers each water mass undergoes its own seasonal changes which can vary to some extent from year to year. These year by year variations can change the characteristics of a water mass, but these changes are not usually so great that the water mass loses its identity. Therefore, even though water mass characteristics may vary, they can still be distinguished from other water masses.

An examination of a monthly plot of surface temperatures for Station 120.30 in the bay, shows the coldest months to be March and April and the warmest, September and October (Fig. 16). This follows closely the 10 year averages for neighboring inshore oceanic stations not in the bay. These stations also show March-April as the coldest period and September-October, the warmest. The bay tends to be 1° or 2°C cooler than the oceanic water outside the bay most of the year. This is probably due to its proximity

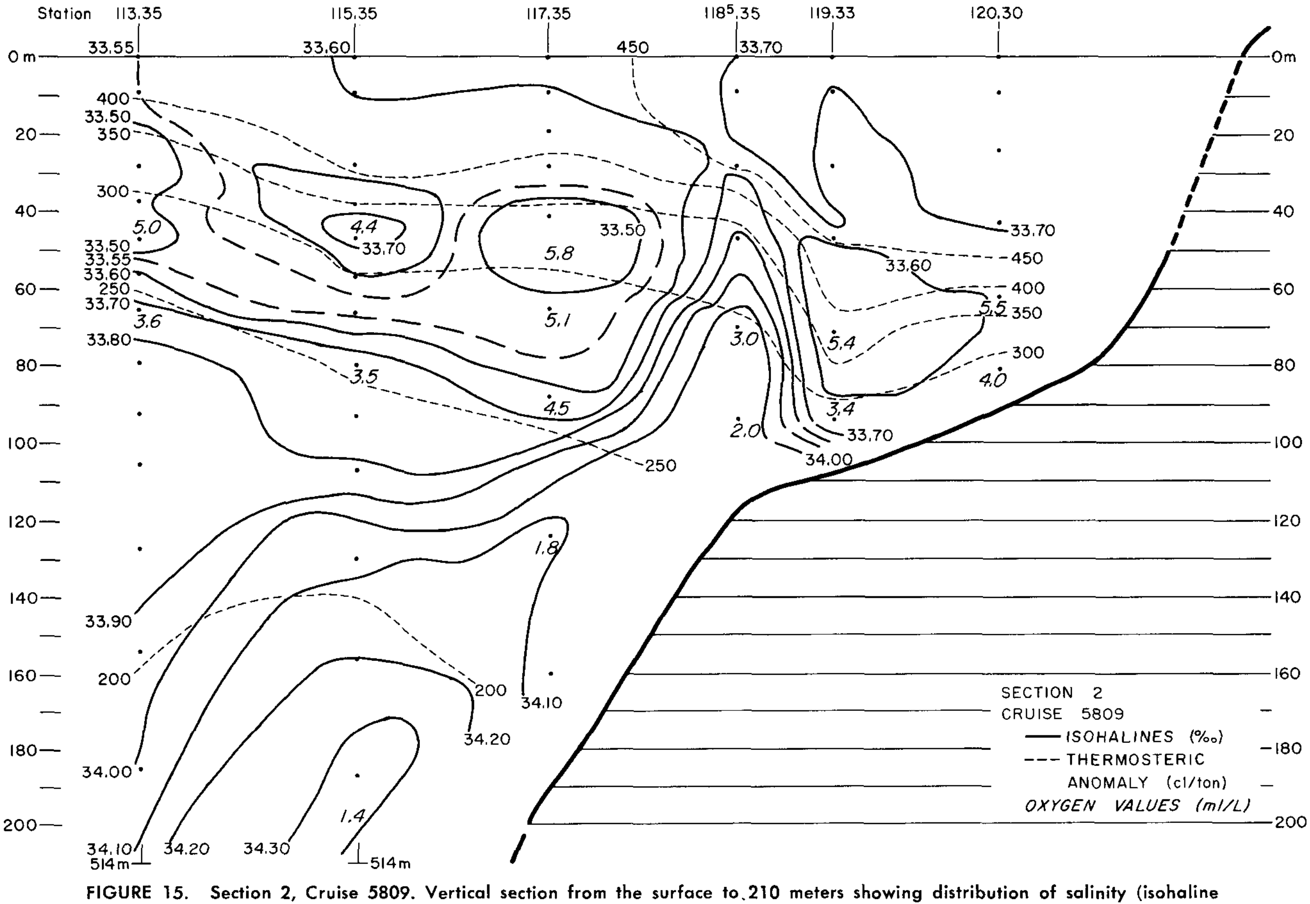

FIGURE 15. Section 2, Cruise 5809. Vertical section from the surface to 210 meters showing distribution of salinity (isohaline lines), thermosteric anomaly (lines of equal Δ' or δ_T) with oxygen values (ml/L) entered.

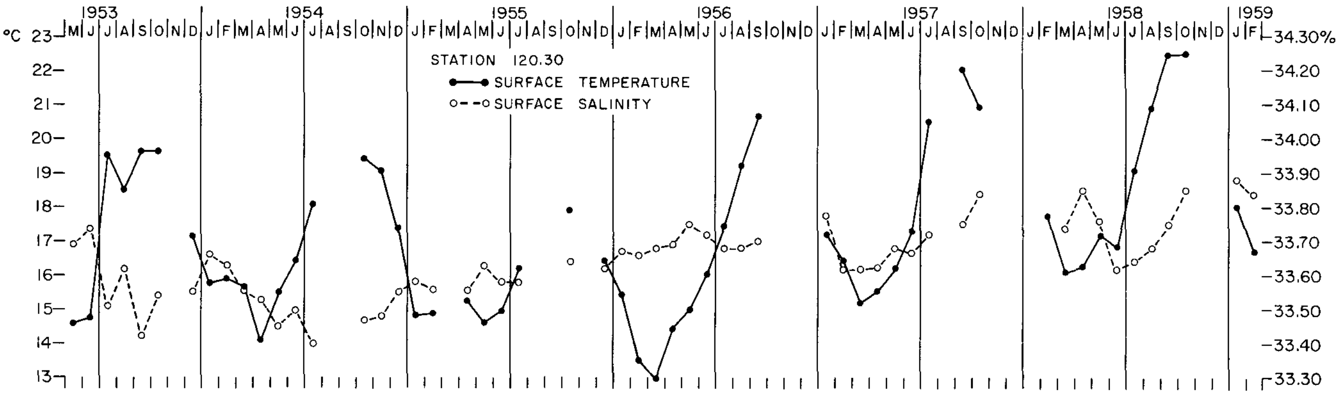

FIGURE 16. Plot of surface temperature and salinity values for each month observed from May 1953 to February 1959 for station 120.30.

to the coastal upwelling area near Punta Canoas. The annual temperature range for the surface layers in the bay is normally 5° to 7°C.

A plot of the salinities for each month does not show any such simple pattern on the average (Fig. 16). If we keep in mind the relative temperature and salinity conditions at any particular location and within a period of time of a few months, at most, so as to eliminate from the discussion longer trends, the presence of a more or less predictable cycle is found.

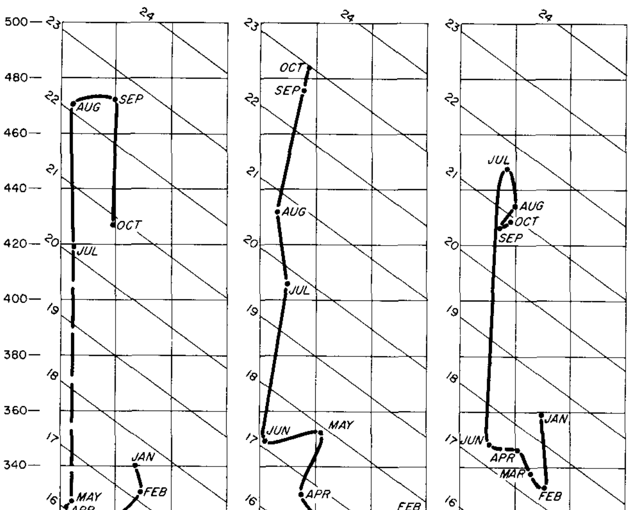

FIGURE 17. Monthly values of the surface temperature and salinity at station 119.33 plotted on a special chart used in the processing of hydrographic data (Klein, MS).

Figure 17 gives some examples of the surface temperature and salinity values plotted on a special chart developed by Klein (Klein, MS). Each point represents the observed value at station 119.33 for a given month. This station was chosen for the illustration since it is centrally located and is usually under the influence of the central bay eddy which in turn seems to reflect the characteristics of the water masses which are dominating the bay at any particular time. Considering the lower points on this graph to be relatively cold, the upper points relatively warm, the points farthest left as having relatively low salinity and the ones to the right relatively high salinity, we can regroup the data into a table showing the relative values, as defined above, from month to month (Fig. 18). This table also includes results from station 120.30. A pattern emerges which can be explained in terms of the water masses and processes defined as available for the bay.

In general, the bay waters are relatively cool from January through June. At the same time the salinity can be either high or low. The water is cold at this time because of two factors. The first is the predictable normal temperature pattern for all waters of similar latitude due to the incoming radiation. The second factor is the presence of coastal upwelling which tends to keep the water cold. Upwelling can and does occur at any time of the year but seems to be most persistent during this period. The salinity variation can be explained by the presence or absence of upwelling or California Current water, or both. With upwelling in progress, a source of higher salinity water is available. Although all upwelled water is not necessarily of high salinity, it usually appears to be in this area. With California Current water present, a readily available source of low-salinity water is found. Therefore these are the dominating factors controlling conditions in the bay from January through June.

The months of July and August tend to be somewhat warmer with low-salinity values continuing. Detailed weather data throughout the year would clarify the picture, but it is proposed that the upwelling process usually weakens at this time, owing to lighter winds. This, in addition to the normal increasing solar radiation, would allow more rapid warming of the mixed layer. The main source of water available to the bay would most likely be low-salinity California Current water. This would account for the relatively warm low-salinity water usually found at this time.

During the months of September through December the bay waters tend to be warmest and most saline, although the warm water is normally in the process of cooling later during this period, especially during December. The higher salinities are most likely the result of advection of water from the coastal regions

Relatively	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
LOW SALINITY	○	○	○	○	○	○	○	○	○				○	○	○	○	○	○	○	○	○			
HIGH SALINITY	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●			●	●	●	●
LOW TEMPERATURE	△	△	△	△	△	△							△	△	△	△	△	△						
HIGH TEMPERATURE							▲	▲	▲	▲	▲	▲							▲	▲	▲	▲	▲	▲

FIGURE 18. Tabulation showing the relative seasonal values obtained from Fig. 17. The data are repeated through a two-year period to show the pattern more clearly.

south of the bay. An example of this type of invasion was described earlier in this report (September 1953, CR 5309).

The cycle begins again with the onset of more wind and consequent upwelling in late December or early January along with normally cooler weather. This sequence is probably oversimplified and may be interrupted but the available data indicate the presence of a basic pattern. If this is the case, a combination of monitoring certain water masses and a good coverage of wind and weather for the bay may be sufficient to follow satisfactorily the changes in the physical environment.

ACKNOWLEDGMENT

The author is indebted to Mr. H. S. Shirley for the preparation of all the figures. This work was supported by the Marine Life Research Program of the Scripps Institution of Oceanography, a part of the California Cooperative Oceanic Fisheries Investigations.

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ON NONSEASONAL TEMPERATURE AND SALINITY VARIATIONS ALONG THE WEST COAST OF THE UNITED STATES AND CANADA

GUNNAR I. RODEN[1]

ABSTRACT

Power spectra of sea surface temperature and salinity anomalies are investigated for the frequency range between zero and six cycles per year. It is found that the power of these anomalies is concentrated at low frequencies and that high frequencies contribute almost nothing to it. The power spectra of temperature anomalies are similar for all 20 stations investigated here, but large regional differences exist in the salinity spectra. The coherence between sea and air temperature anomalies is moderate to good for well exposed stations, and there exists a direct relationship between them. The coherence between salinity and precipitation anomalies is good only for stations along the open coast where there is little river discharge, the anomalies being related inversely to each other. The coherence between salinity and river discharge anomalies is moderate to good for stations at the boundary between river and oceanic water and poor elsewhere. The coherence between surface temperature and salinity anomalies is moderate for light ship and island stations and poor along the continent. The relation between them is mostly an inverse one, as is characteristic of upwelling regions.

INTRODUCTION

For many years careful records have been kept of sea surface temperature and salinity at various stations along the west coast of the United States and Canada. If these records are plotted against time, seasonal as well as nonseasonal variations are obtained. The seasonal variations have been studied by McEwen (1912, 1919, 1929, 1938), and Pickard (1953) and the nonseasonal variations by Hubbs (1948), Reid (1960) and Roden (1958). The particular relation between temperatures and tides was investigated by Herlinveaux (1957), and between salinity and river discharge by Tully (1952).

In this paper the regular seasonal variation is eliminated by taking differences between the monthly mean and the long term mean of the same month. The resulting anomalies are then used to compute the average power contained in each record and also the power spectral density, coherence and phase as defined below. In performing the calculations it has been assumed that the anomaly records are stationary, at least in the wide sense, so that the functions derived depend only upon the sampling interval, and are independent of any origin in time.

The location of tide gage and lighthouse stations is shown on figure 1. Most of them are located in harbors and bays and only few of them are well exposed. Blunts Reef represents a light-ship, anchored a few miles off Cape Mendocino, in the heart of the upwelling region. For meteorological records the nearest meteorological station was chosen. In most cases the tide gage an meteorological stations are located within a radius of 20 km, but in a few instances stations further apart had to be combined. Where the nearest meteorological station was more than 50 km away, no comparisons between oceanographic and meteorological variables were made.

DATA

Sea surface temperatures and salinities were obtained from the U.S. Coast and Geodetic Survey (1956), the Fisheries Research Board of Canada (1958) and the Scripps Institution of Oceanography of the University of California (unpublished). At the Canadian stations the monthly means were computed from daily observations made one hour before the daytime high water. The individual temperature readings are estimated to be accurate within 0.2 C and the individual salinities, determined by a modified Mohr titration, are reported to have an accuracy of $\pm 0.06^0/_{00}$. At the United States stations the observations are made at a random hour during each week day, and in many cases the monthly means are computed from less than 20 daily values. The accuracy of individual temperature readings is estimated to be within 0.2 C except for stations in Southern California where the accuracy is somewhat greater, because better thermometers were used. The accuracy there is estimated to be within 0.05 C. The surface salinities up to July 1954 were obtained from density observations by hygrometer at all stations. The accuracy of a single hygrometer reading is not very great, and must very with the individual skill of the observer. In some cases the salinities so determined are probably accurate only within $0.3^0/_{00}$. Since July 1954 the salinities at La Jolla, Balboa, Hueneme, Pacific Grove, SE Farallon Island, and Blunts Reef Lightship are determined by a Knudsen titration, the accuracy of which is about $\pm 0.05^0/_{00}$.

Air Temperature and precipitation records were obtained from the U.S. Weather Bureau (1872-1949, 1950-1960, and 1916-1960) and the Canadian Department of Transport (personal communication). The monthly averages of air temperatures are computed from four equidistant daily readings at 0000, 0600, 1200 and 1800 GMT. The accuracy of an individual reading is estimated to be within 0.1 C. The accuracy of rainfall is estimated to be 1% of the total or about 0.3 cm, whichever is the greater.

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[1] Contribution from the Scripps Institution of Oceanography.

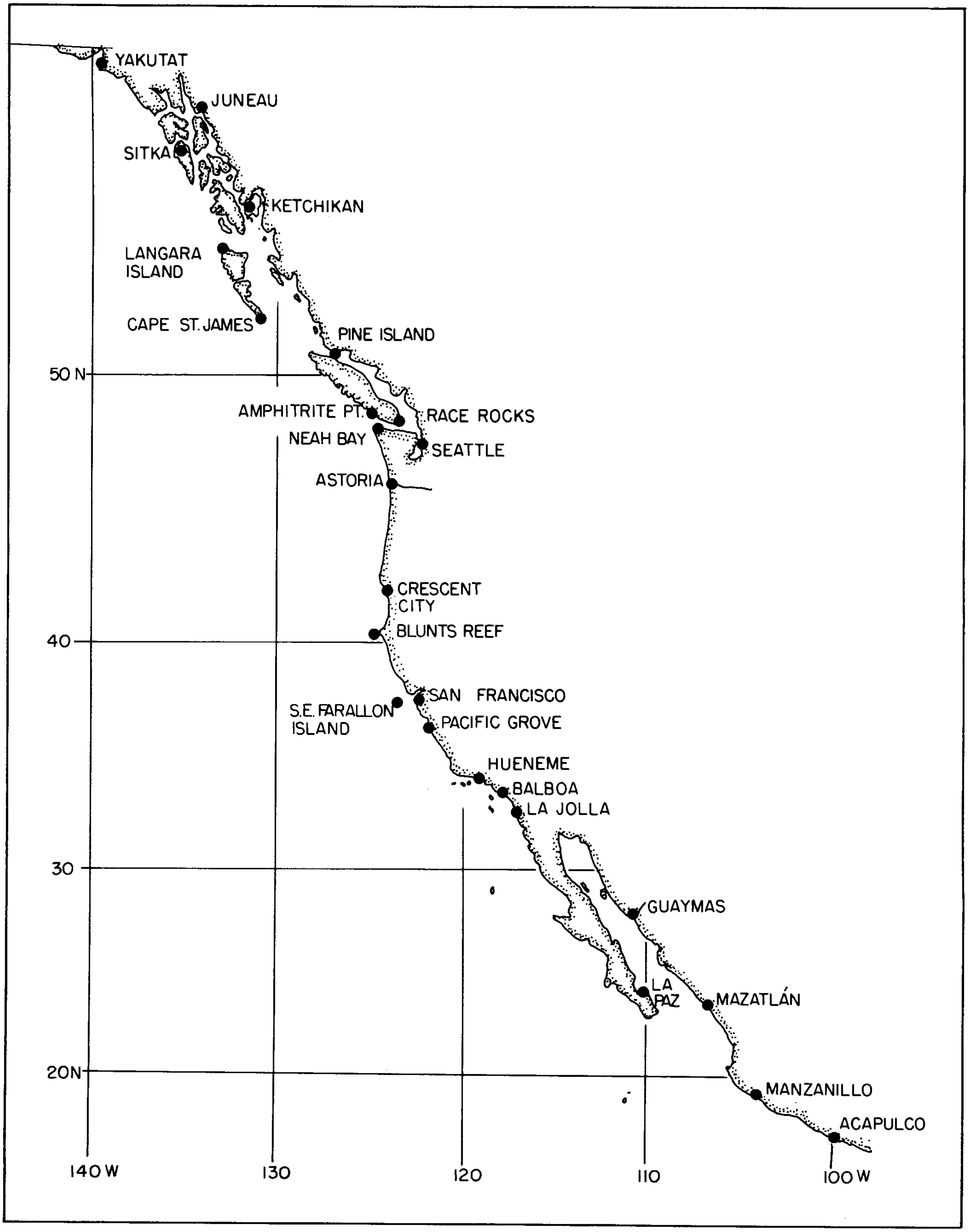


FIGURE 1. Location of stations where temperature and salinity observations are made.

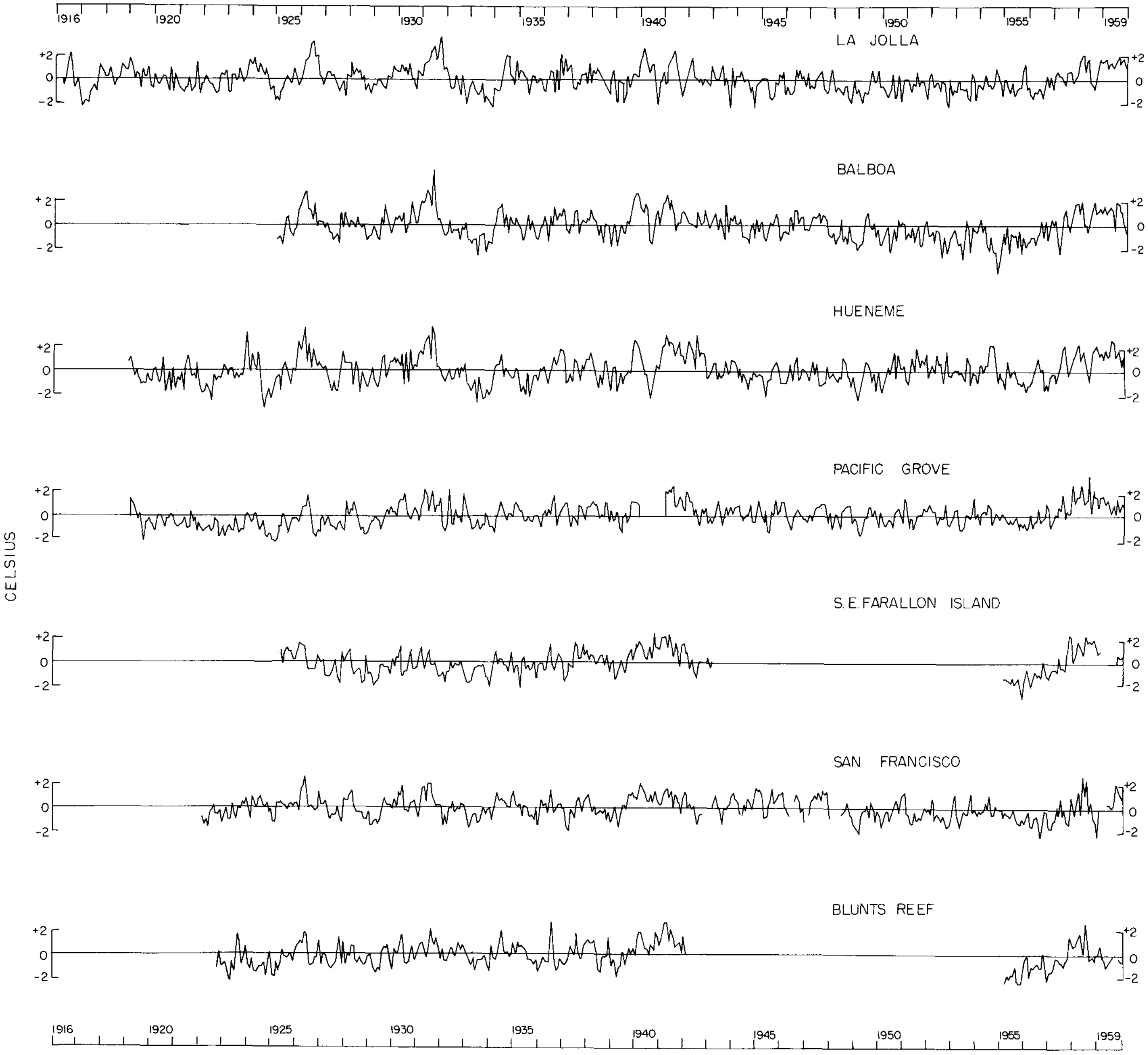


FIGURE 2. Sea surface temperature anomalies at California stations. .

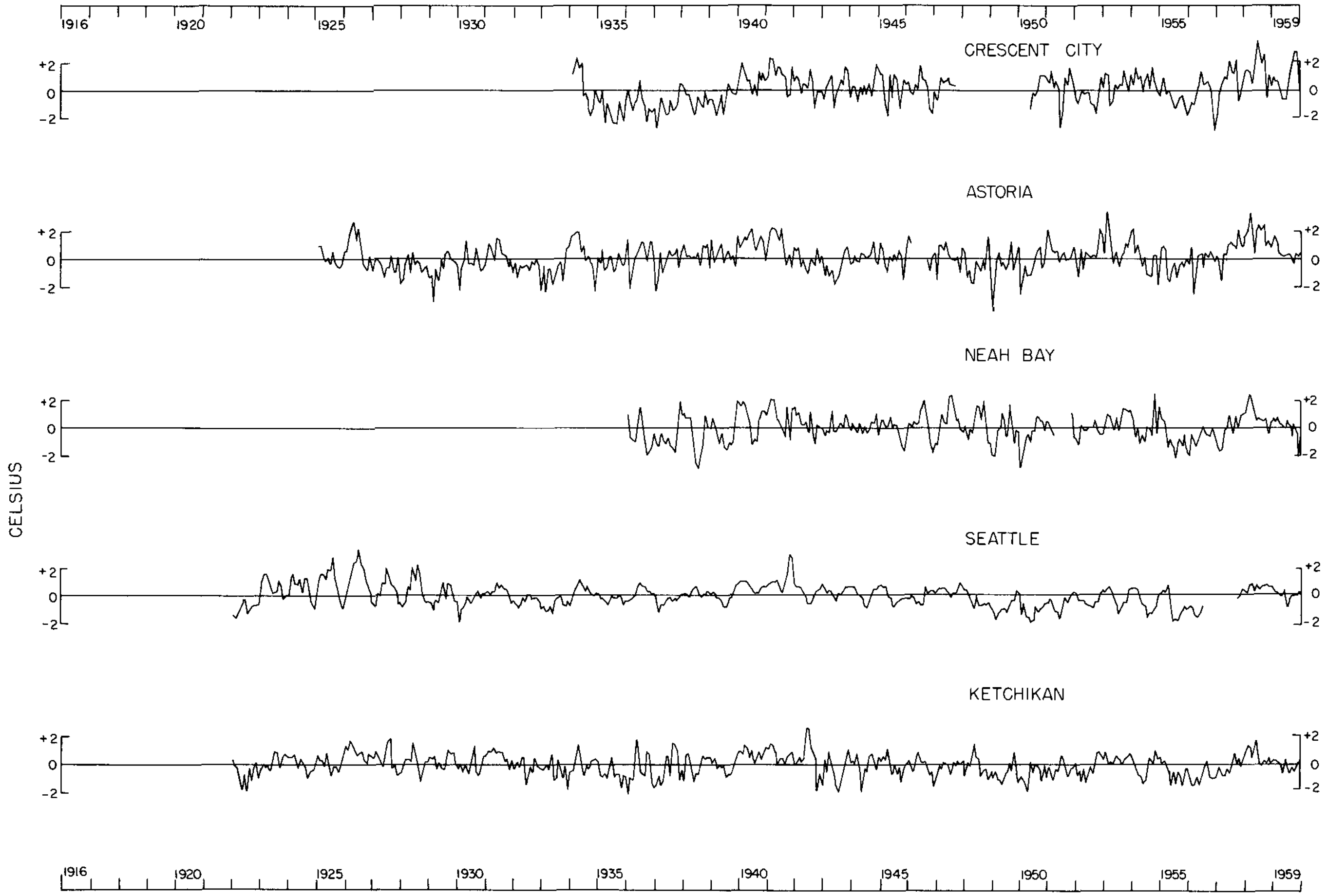


FIGURE 3. Sea surface temperature anomalies at Oregon and Washington stations and at Ketchikan, Alaska.

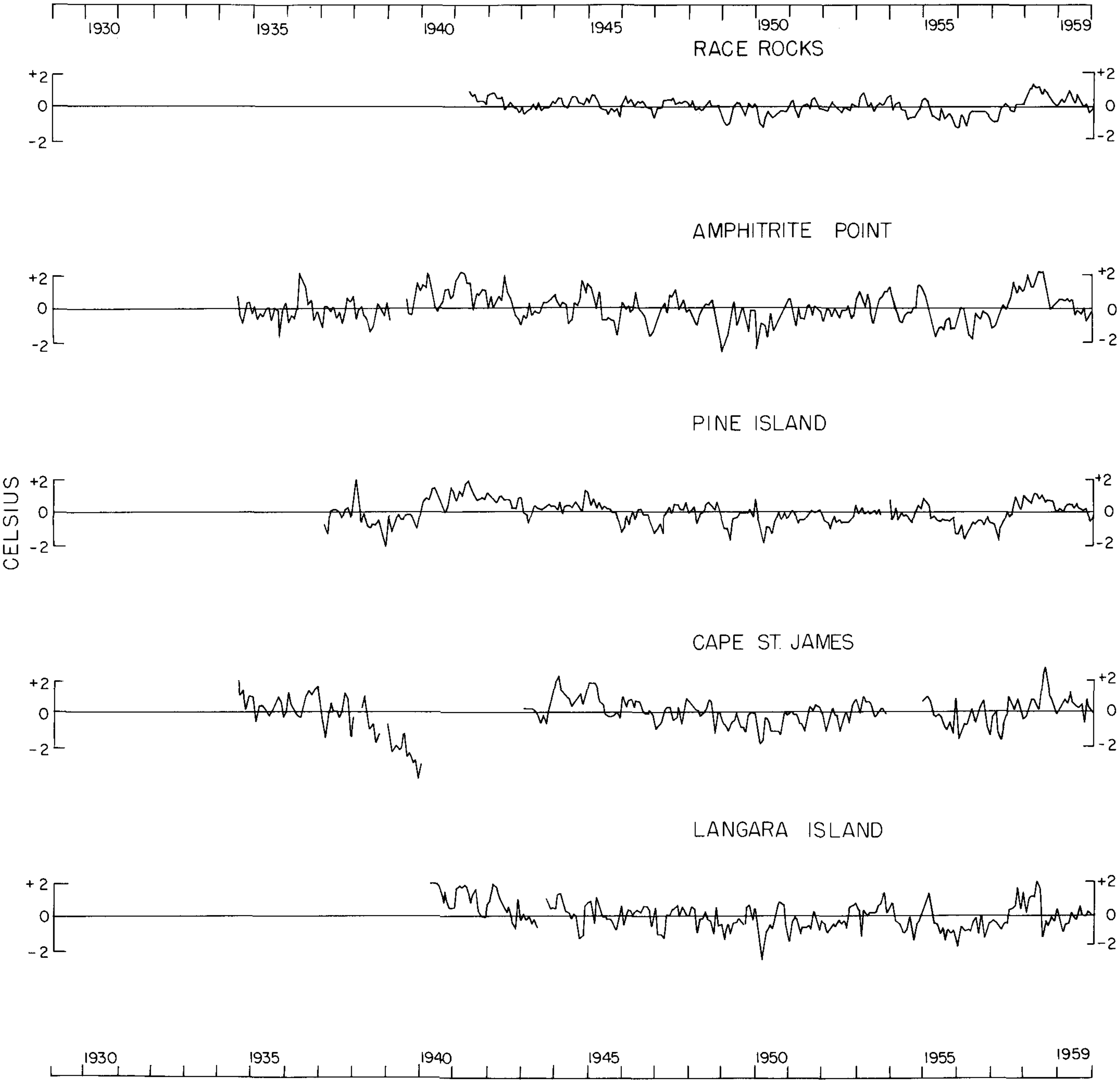


FIGURE 4. Sea surface temperature anomalies at British Columbia stations.

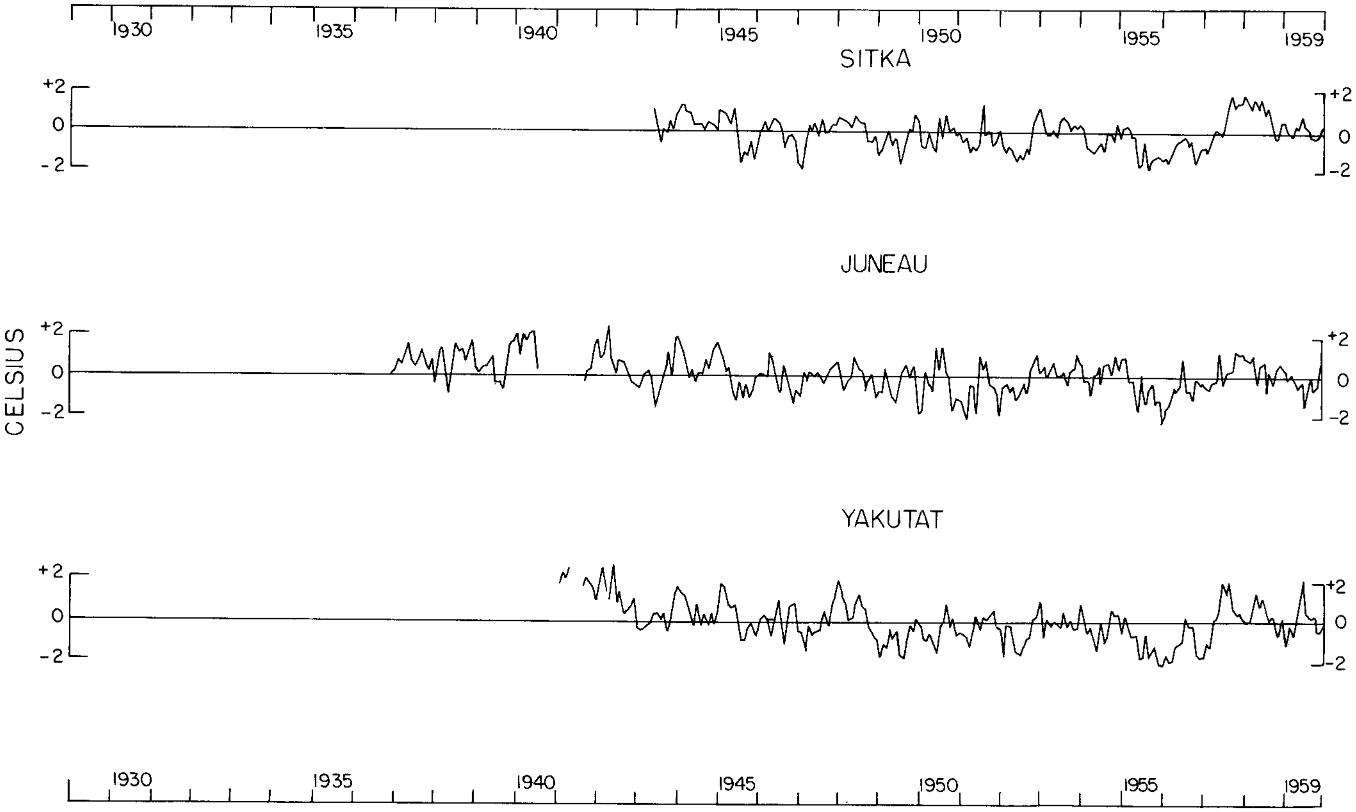


FIGURE 5. Sea surface temperature anomalies at Alaskan stations.

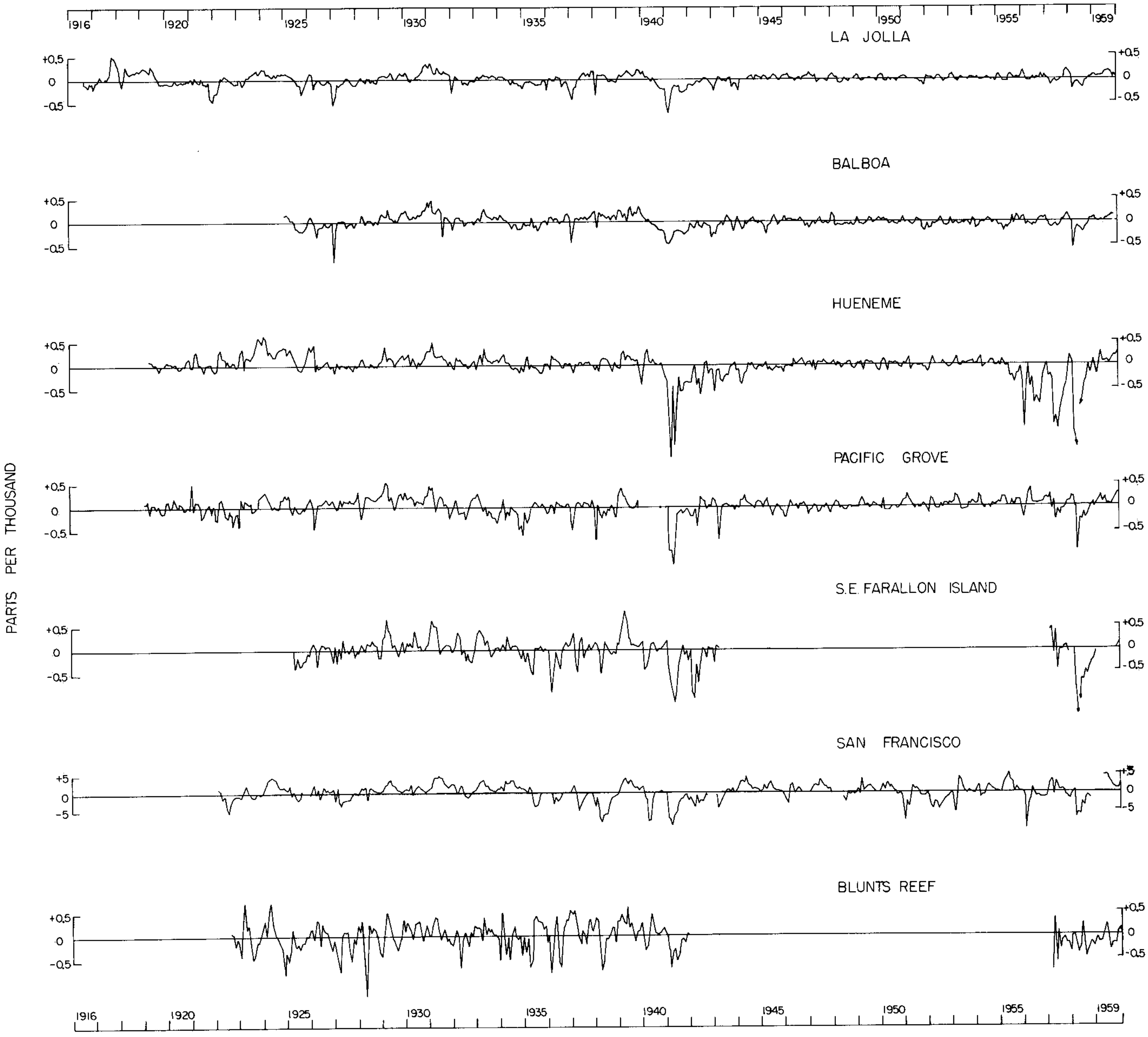


FIGURE 6. Salinity anomalies at California stations. The records for La Jolla, Balboa, Hueneme and Pacific Grove are questionable between 1944 and 1955.

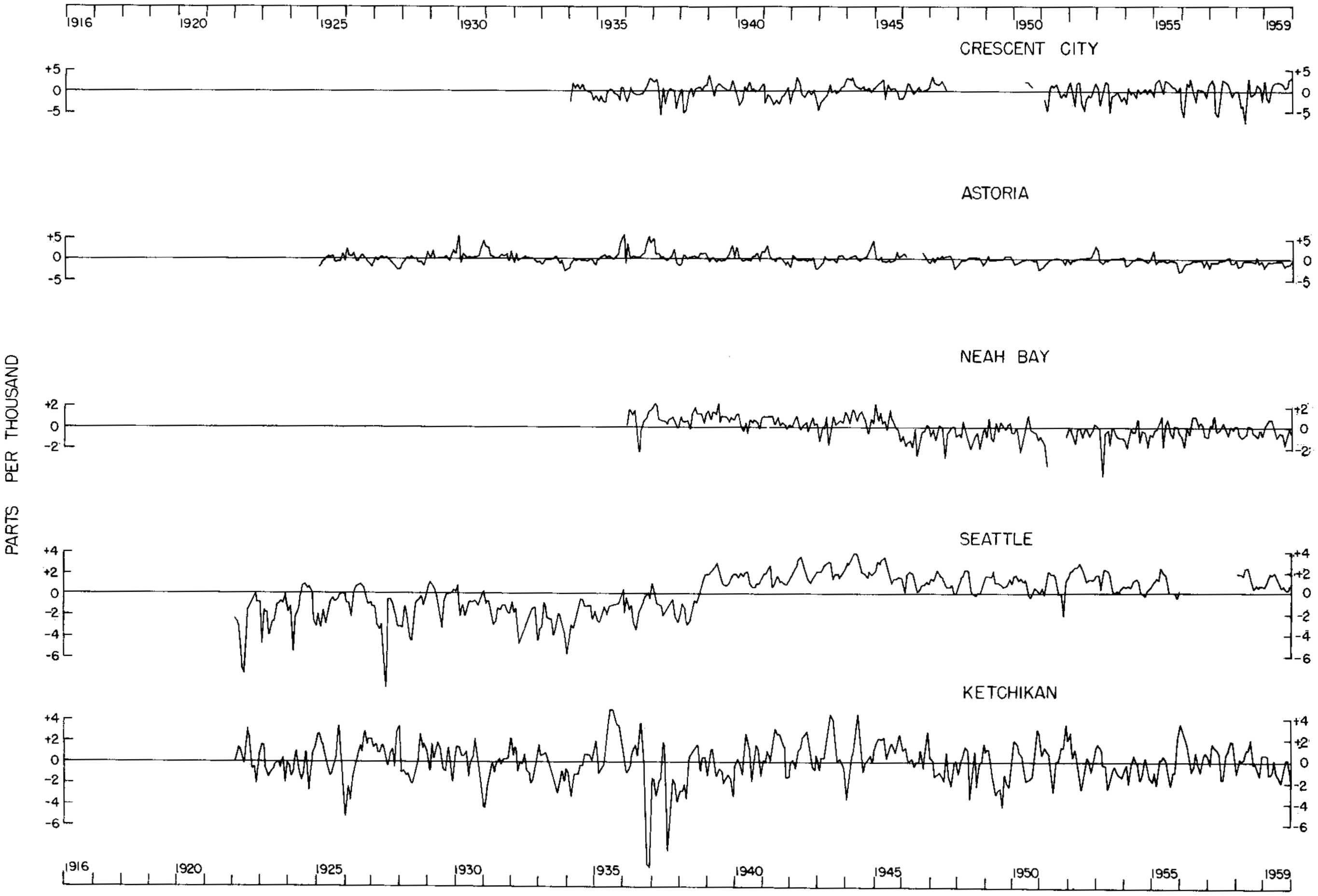


FIGURE 7. Salinity anomalies at Oregon and Washington stations and at Ketchikan, Alaska. The Seattle record is questionable.

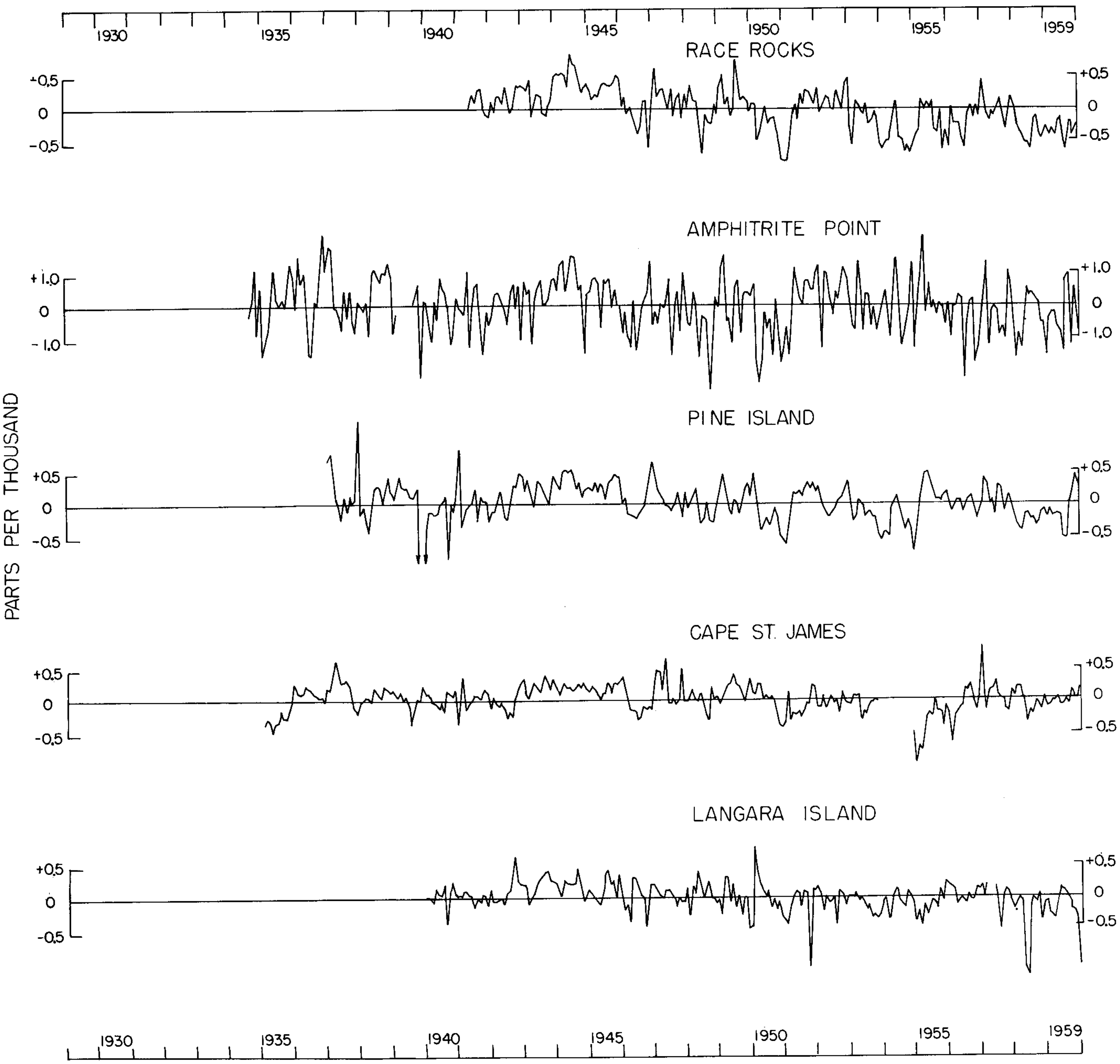


FIGURE 8. Salinity anomalies at British Columbia stations.

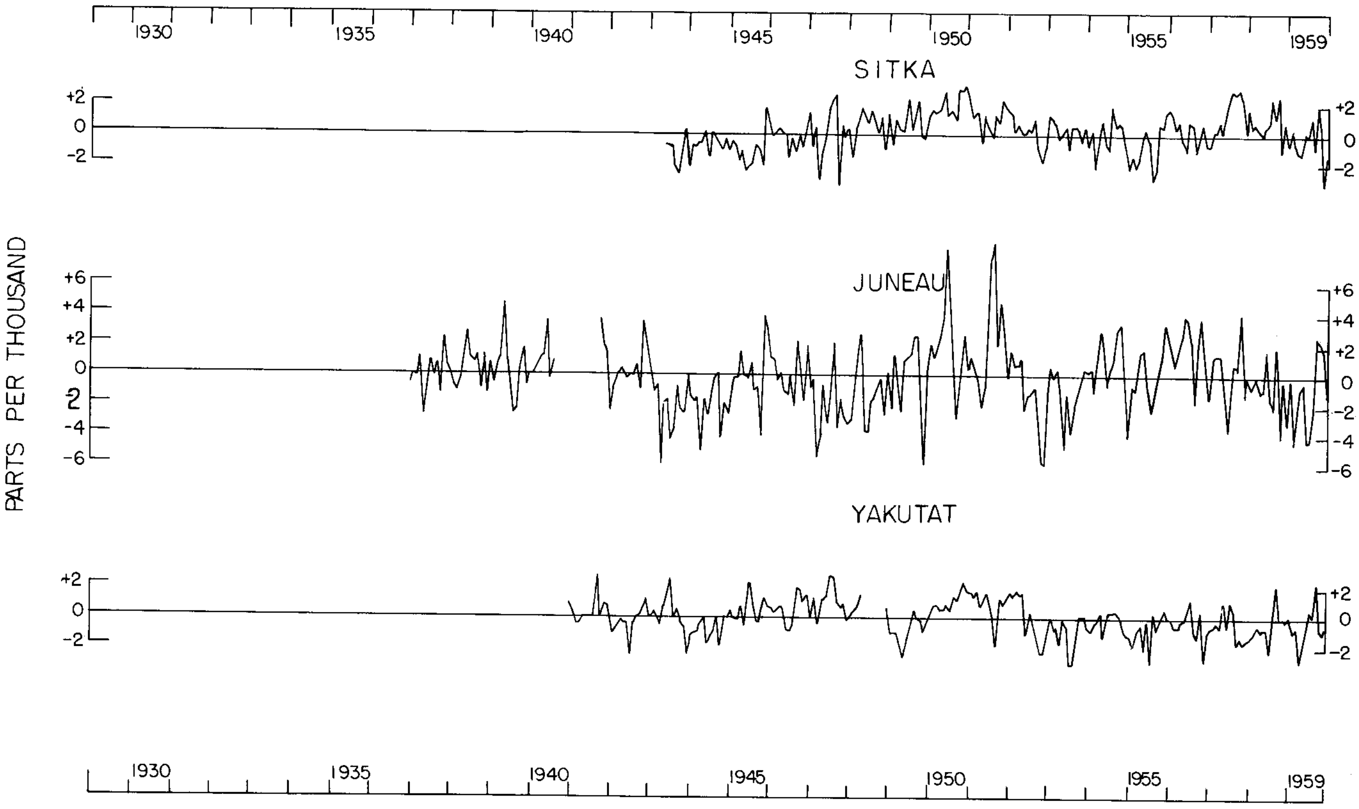


FIGURE 9. Salinity anomalies at Alaskan stations.

Runoff records were obtained from the U.S. Geological Survey (1958) and the Surface Water Branches in Menlo Park, California, and Sacramento, California. They are considered to be accurate within 5% of the individual flow.

The sea surface temperature records are shown in figures 2 to 5. Although the details of the records vary, a few preliminary results can be obtained from a visual inspection of them; (a) the magnitude of the anomalies is about the same for all stations, (b) the maximum amplitude of the anomalies appears to be 4C, (3) there are no obvious periodicities discernible, (d) the anomalies are similar over distances of several hundred kilometers and (e) for the majority of stations the mean of the record does not change appreciably, indicating stationary conditions.

The surface salinity records are shown in figures 6 to 9. A visual examination of them leads to the following preliminary conclusions: (a) the magnitude of the salinity anomalies varies greatly from one station to another, (b) the smallest anomalies are found at stations in Southern California where rainfall is scarce and at stations in straits where tidal mixing is considorable, (c) the largest anomalies occur at stations where there is considerable influence by both runoff and oceanic water, (d) there are no obvious periodicities. The salinity anomalies at La Jolla, Balboa, Hueneme and Pacific Grove show a sharp discontinuity in magnitude and general character about 1944. Although there was some reduction of the magnitude of other anomalies at this time (Isaacs 1960), no sharp discontinuities of the type shown here were observed.

The salinity determinations of the above mentioned stations were all done by the same observer, and it is possible that the discontinuity is due to a change in instrument, or to some other reason. Since the cause is not known, the records between 1944 and 1955 should be regarded with suspicion. Similarly the Seattle record suggests some radical change, and should be questioned.

The probability distribution of sea surface temperature and salinity anomalies is shown in figure 10. It is seen that the temperature anomalies are normally distributed, and that their probabilities vary very little from one station to another. The salinity anomalies are generally not normally distributed, and tend to be negatively skew. This is particularly the case where there is considerable influence of runoff (San Francisco).

The standard deviations and extreme ranges for each of the stations are given in Table 1. For sea surface temperature anomalies there is no dependence upon latitude; the anomalies appear, however, to be larger for stations situated in shallow bays and harbors than for those situated in straits and sounds, suggesting that tidal mixing may be important in reducing the amplitude of the temperature variation. For air temperature anomalies there is a slight dependence upon latitude, the anomalies being somewhat larger at high than at low latitudes. The salinity and precipitation anomalies are dependent upon the particular environment of the station and do not suggest a relation to latitude.

TABLE 1

Standard Deviations (σ) and Extreme Ranges (r) of Monthly Sea Surface Temperature (θ), Salinity (S), Air Temperature (A) and Precipitation (p) Anomalies

STATION*	σ_θ °C	σ_s °/oo	σ_A °C	σ_p cm	r_θ °C	r_s °/oo	r_A °C	r_p cm
La Jolla-San Diego	0.9	0.1	1.1	2.8	6	1	7	24
Balboa-Los Angeles	1.0	0.1	1.3	4.1	7	1	7	24
Hueneme-Sta. Barbara	1.1	0.2	1.2	4.4	7	3	7	34
Pacific Grove-Sta. Cruz	0.9	0.2	1.2	6.0	6	2	7	36
SE. Farallon Isl.-Pt. Reyes	0.9	0.3	. .	2.9	5	4	. .	24
San Francisco	0.8	2.3	1.0	3.9	5	13	7	33
Blunts Reef-Eureka	0.9	0.3	1.2	5.6	4	3	8	41
Crescent City	1.1	1.7	1.2	11.5	6	10	8	61
Astoria-North Head	1.0	1.1	1.2	. .	7	8	9	. .
Neah Bay-Tatoosh Isl.	1.0	1.0	1.2	7.3	5	7	10	43
Seattle	0.8	1.9	1.4	4.0	5	11	10	26
Race Rocks-Victoria**	0.5	0.3	1.2	3.4	3	2	10	21
Amphitrite Point**	0.9	0.8	. .		4	4		. .
Pine Island-Port Hardy**	0.5	0.2	1.3	5.8	4	4	8	37
Cape St. James**	0.8	0.2	. .	. .	7	2	.	
Langara Island-Masset**	0.8	0.2	1.5	4.2	4	2	11	24
Ketchikan	0.8	1.8	. .	13.5	4	14		65
Sitka	0.8	1.3	1.6	9.0	4	6	11	58
Juneau	0.8	2.3	2.0	8.4	4	11	10	42
Yakutat	1.0	1.1	1.9	13.1	5	5	11	107

* Where two names occur, the first refers to the oceanographic, the second to the meteorological station.

** Salinity determined by titration.

COMPUTATIONAL PROCEDURES

Let $\theta\ (t)$ and $A\ (t)$ denote anomalies of sea surface temperature and air temperature, respectively. Then the autocorrelations and crosscorrelations are defined by

$$(1)\qquad \begin{aligned} \phi_{\theta\theta}(\tau) &= <\theta(t)\theta(t+\tau)>; \\ \phi_{AA}(\tau) &= <A(\mathrm{t})A(t+\tau)>; \\ \phi_{\theta A}(\tau) &= <\theta(t)A(t+\tau)> \end{aligned}$$

provided the records are stationary. Here $< >$ denotes the time average over the entire record length, and τ is the time lag in months.

The power spectral densities and cross power spectral densities are obtained from a Fourier transform of the correlation functions

$$(2)\qquad \begin{aligned} E_{\theta\theta}(\omega) &= \frac{2}{\pi}\int_0^\infty \phi_{\theta\theta}(\tau)\cos\omega\tau d\tau; \\ E_{AA}(\omega) &= \frac{2}{\pi}\int_0^\infty \phi_{AA}(\tau)\cos\omega\tau d\tau; \\ E_{\theta A}(\omega) &= \frac{1}{\pi}\int_{-\infty}^\infty \phi_{\theta A}(\tau)e^{-i\omega\tau}d\tau \end{aligned}$$

Practical methods for evaluating the power spectra are given by Munk, Snodgrass and Tucker (1959).

The coherence between $\theta\ (t)$ and $A\ (t)$ is defined by

$$(3)\quad \mathrm{R}_{\theta A}(\omega) = \frac{E_{\theta A}(\omega)}{[E_{\theta\theta}(\omega)\ E_{AA}(\omega)]^{1/2}}$$

and must lie between the values zero and one. If $R = 1$ the coherence is perfect, if $R = 0$ there is no coherence between the two variables. The phase lag of θ (t) over A (t) is defined by

$$(4) \quad \Pi_{\theta A}(\omega) = \text{arc tan} \frac{E_{\theta A}(\omega) - E_{A\theta}(\omega)}{E_{\theta A}(\omega) + E_{A\theta}(\omega)}$$

provided that for a positive numerator $0 \leqq \pi \leqq 180$ and for a negative numerator $180 \leqq \pi \leqq 360$. If $\pi = 0$ degrees, the two variables are related directly to each other, if $\pi = 180$ degrees there exists an inverse relationship between them.

Similar relations can be established for any other pair of variables. The length of the records used varies from 163 months at Crescent City to 444 months at Ketchikan. The length of the record at each station, n, the number of lags used, m, and the resulting *degrees of freedon*, ν, defined by

$$(5) \quad \nu = \frac{2n}{m}$$

are given in Table 2. Also shown in this table are the 95% confidence limits for the power spectra, provided the variables are normally distributed.

TABLE 2

Total Length of Record (n), Number of Spectral Estimates Used (m), and Resulting Degrees of Freedom (ν). Also Given Are the 95 Percent Confidence Limits for the Power Spectra (P)

STATION	n month	m month	ν	P (unit)^2/c.p.y.
La Jolla-San Diego	504	24	42	0.67–1.62
Balboa-Los Angeles	348	24	29	0.63–1.81
Hueneme-Sta. Barbara	420	24	35	0.66–1.69
Pacific Grove-Sta. Cruz	480	24	40	0.67–1.64
SE. Farallon Isl.-Point Reyes	204	24	17	0.56–2.25
San Francisco	336	24	28	0.63–1.83
Blunts Reef-Eureka	228	24	19	0.58–2.13
Crescent City	163	24	14	0.53–2.54
Astoria-North Head	372	24	31	0.64–1.78
Neah Bay-Tatoosh Isl.	276	84	23	0.60–1.97
Seattle	408	24	34	0.65–1.71
Race Rocks-Victoria	192	24	16	0.56–2.73
Amphitrite Point	276	24	23	0.60–1.19
Pine Island-Port Hardy	174	24	15	0.55–2.40
Cape St. James	192	24	16	0.56–2.31
Langara Island-Masset	228	24	19	0.58–2.13
Ketchikan	444	24	37	0.66–1.67
Sitka	192	24	16	0.56–2.31
Juneau	204	24	17	0.56–2.25
Yakutat	216	24	18	0.57–2.19

It should be pointed out that the power spectral densities depend upon the amount of averaging done upon the original data (Munk 1960); if the monthly means were obtained from hourly readings, the power spectrum will be different from one where the monthly means were obtained from daily readings. In case of a simple Markov process the power is decreased by an increased amount of averaging.

The computations of the power spectra, coherence and phase were performed on a IBM 709 electronic calculator at the Western Data Processing Center in Los Angeles.

POWER SPECTRA OF TEMPERATURE AND SALINITY ANOMALIES

The power spectra of sea surface temperature anomalies are shown in figure 11 for the frequency range between zero and 6 cycles per year (c.p.y.). It is seen that most of the power is concentrated at low frequencies, mainly between 0 and 1.5 c.p.y. and that the high frequency end of the spectrum contains relatively little power. This suggests that there is very little contamination from frequencies beyond 6. c.p.y. in the spectra shown here. Most of the spectra indicate an exponential decrease of the power with frequency, suggesting a Markov type process, for which prediction is not very effective (Roden and Groves 1960). The spectra for Neah Bay, Washington, and Seattle, Washington, show peaks near 1 c.p.y., which, when real, would indicate an annual periodicity. The peaks are, however, barely significant (upon applying the confidence limits shown in Table 2), and the periodicity is therefore not well established.

The power spectra of surface salinity anomalies are shown in figures 12 and 13. Most of the power is concentrated between 0 and 2 c.p.y., and for the majority of stations the spectra do not contain any power for frequencies higher than about 4 c.p.y. There is a large variation from station to station of the power contained in each spectrum; the Canadian stations located on small islands and the Californian island stations contain a hundred times less power than those along the mainland coast, excepting the Southern California stations. There are no significant peaks, or periodicities, contained in spectra of the salinity anomalies.

COHERENCE AND PHASE BETWEEN SEA SURFACE AND AIR TEMPERATURE ANOMALIES

The coherence (Fig 14) between sea and air temperature anomalies is moderate to good for stations along the open coast and for island stations, and is relatively poor for stations located considerable distances from the open coast along inland sounds. Thus for Blunts Reef, Neah Bay and Yakutat the coherence varies around 0.7 whereas for Seattle and Juneau it is only 0.4 or less. The maximum values of coherence vary around 0.9, indicating that in the most favorable cases about 80% of the anomalies can be related to each other. The phase (Fig. 15) between sea and air temperature anomalies varies around zero degrees and is at most stations independent of frequency, which suggests a direct relation between sea and air temperature anomalies, for all frequencies between 0 and 6 c.p.y. The considerable scatter at Juneau together with the low coherence indicates the absence of any significant relationship there.

The ratio of the power of sea surface to air temperature anomalies is shown in Table 3. For the Californian stations and Yakutat the ratio is somewhat larger at low than at high frequencies suggesting that a certain time is required for the anomalies to respond to each other. For Neah Bay and Langara Island there is no simple dependence upon frequency.

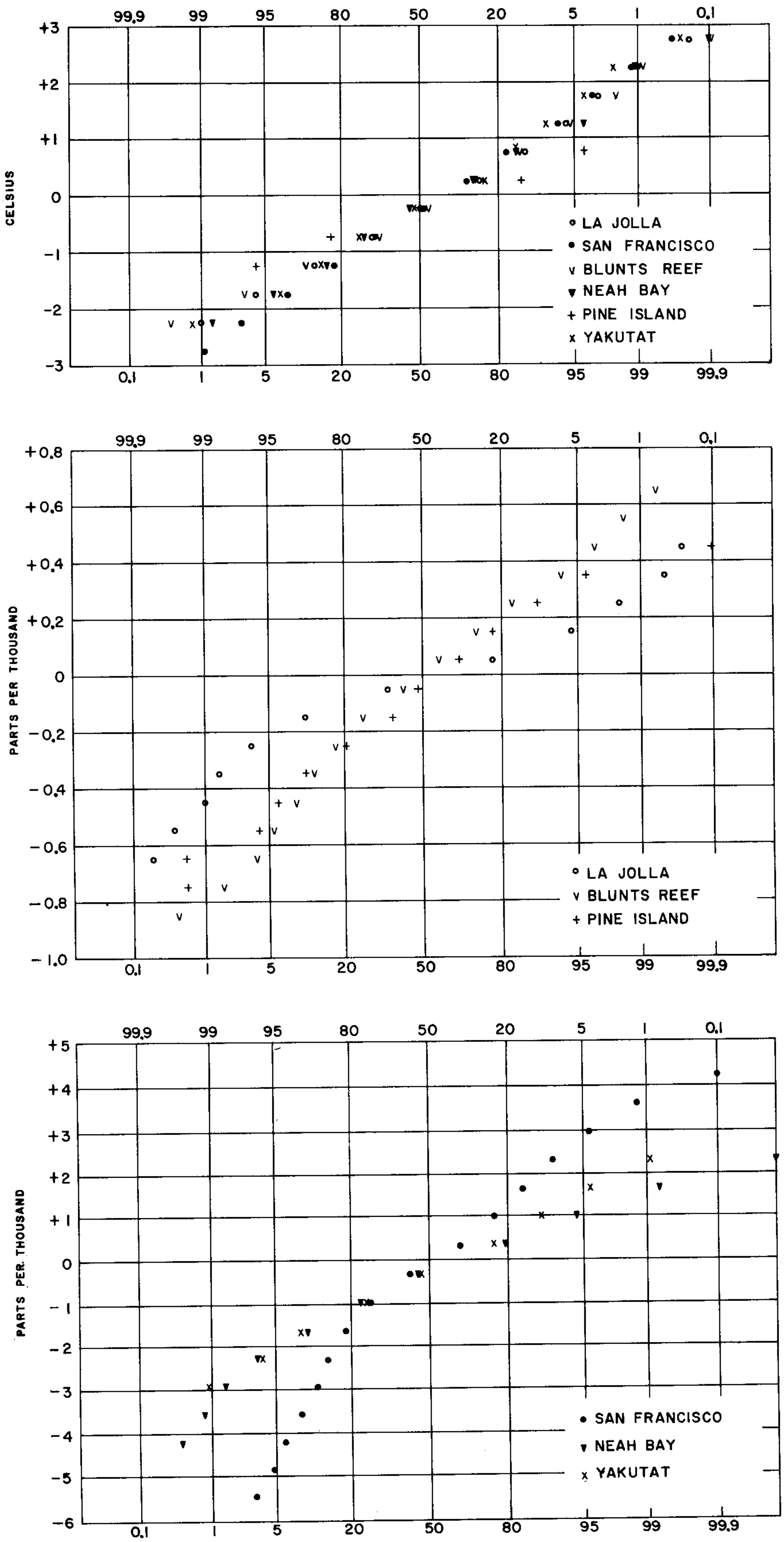
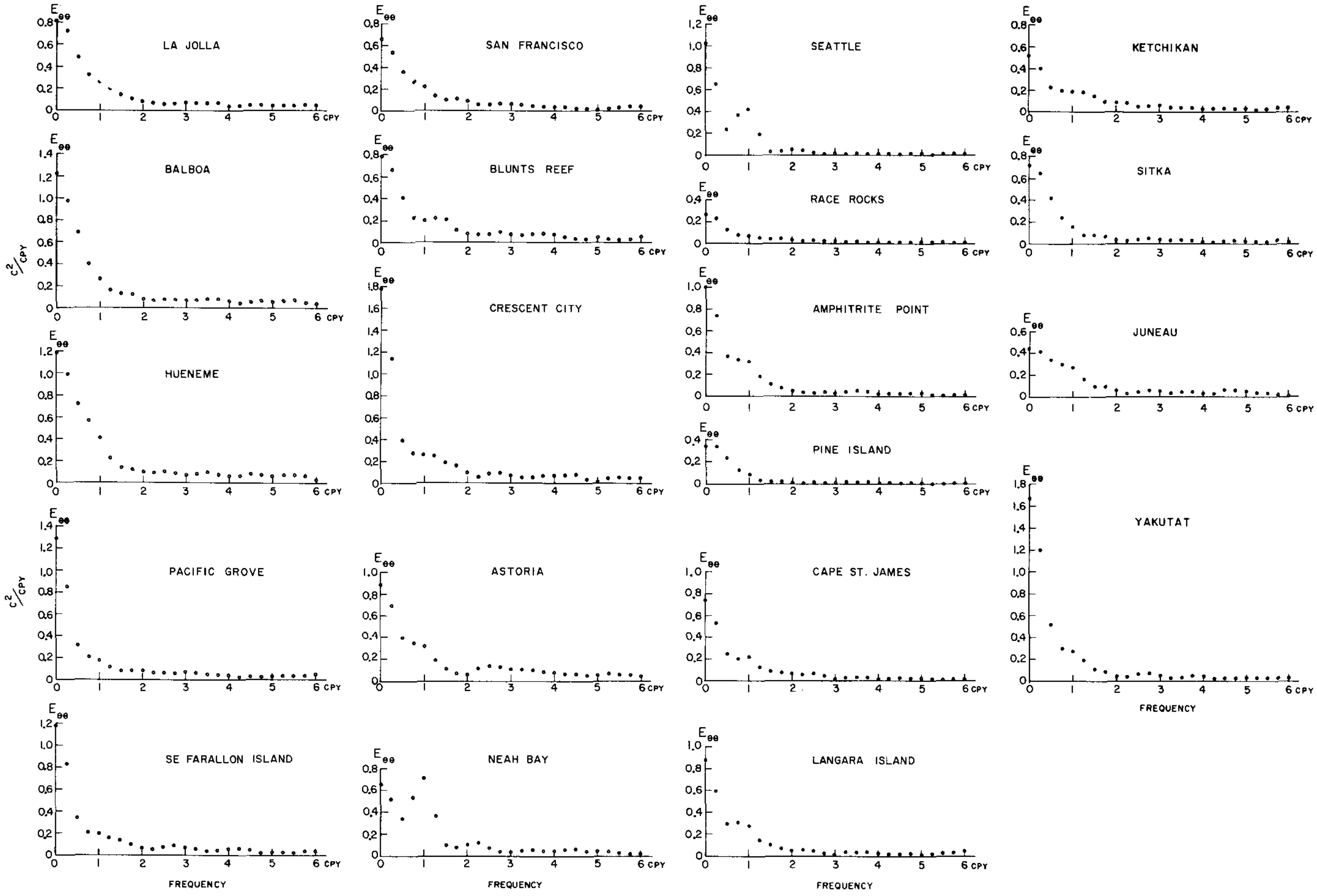


FIGURE 10. Probability distribution of sea surface temperature and salinity anomalies.



LA JOLLA

SAN FRANCISCO

SEATTLE

KETCHIKAN

BALBOA

BLUNTS REEF

RACE ROCKS

SITKA

HUENEME

CRESCENT CITY

AMPHITRITE POINT

JUNEAU

PINE ISLAND

YAKUTAT

PACIFIC GROVE

ASTORIA

CAPE ST. JAMES

SE FARALLON ISLAND

NEAH BAY

LANGARA ISLAND

FIGURE 11. Power spectra of sea surface temperature anomalies.

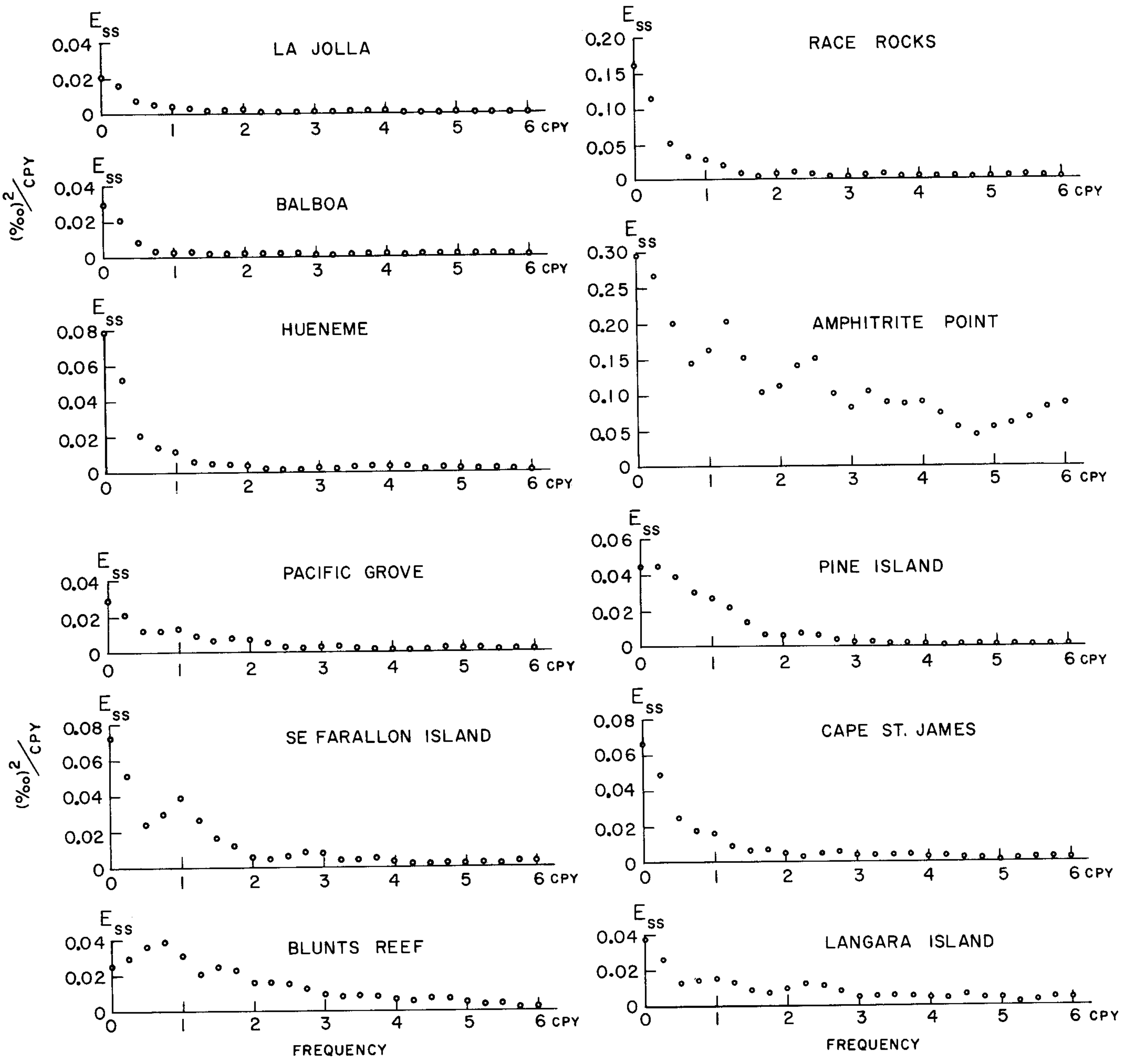


FIGURE 12. Power spectra of salinity anomalies.

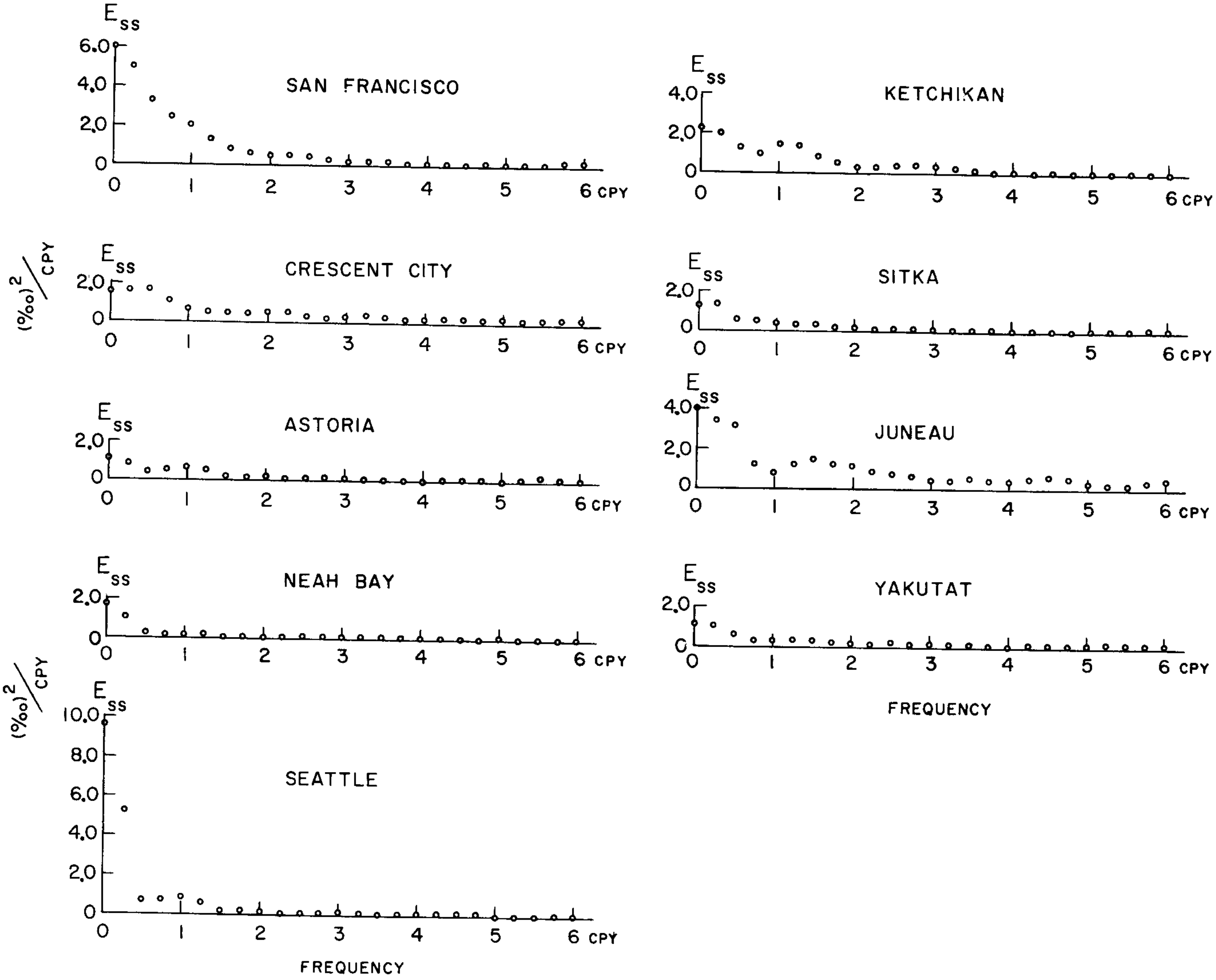


FIGURE 13. Power spectra of salinity anomalies.

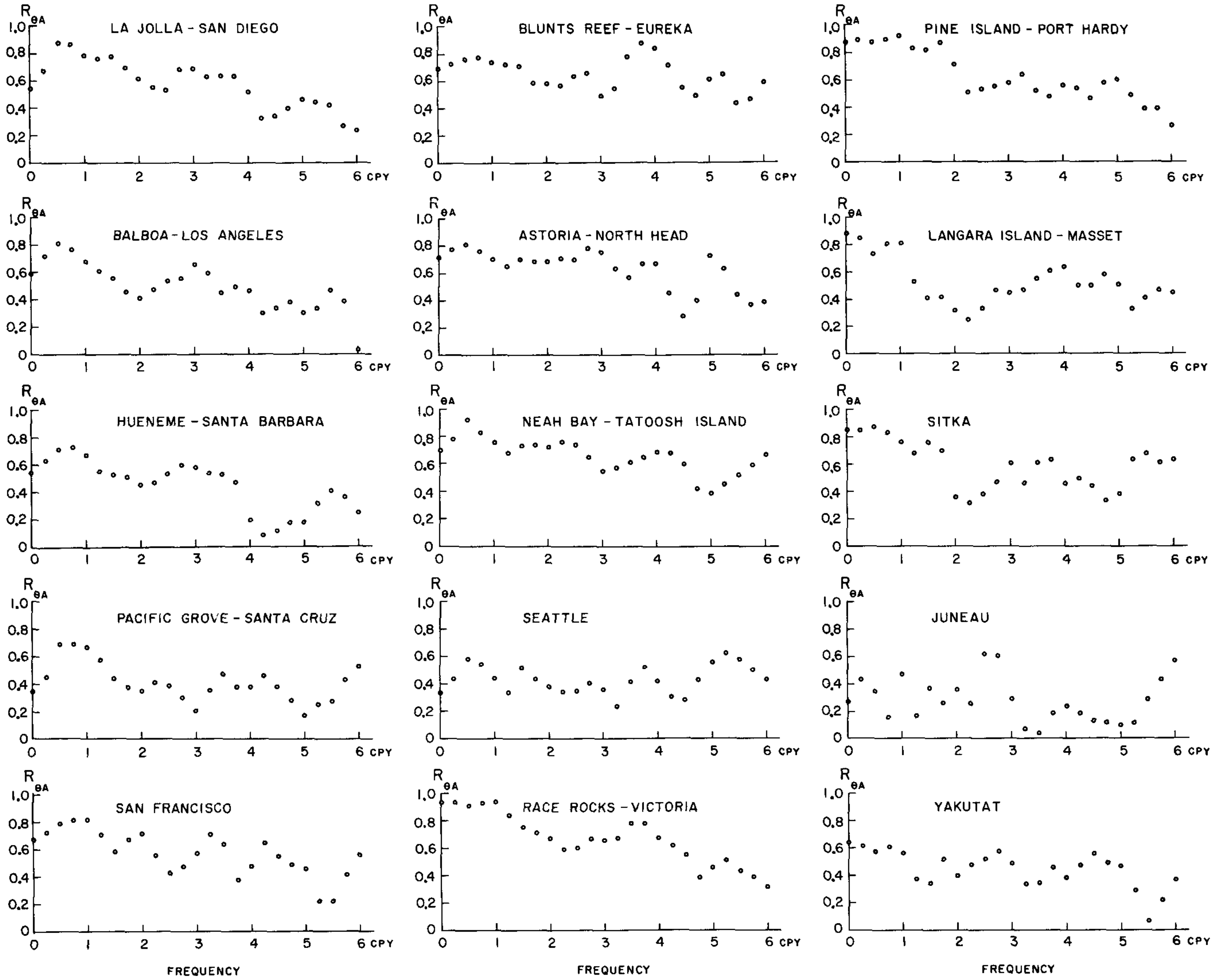


FIGURE 14. Coherence between sea surface temperature and air temperature anomalies.

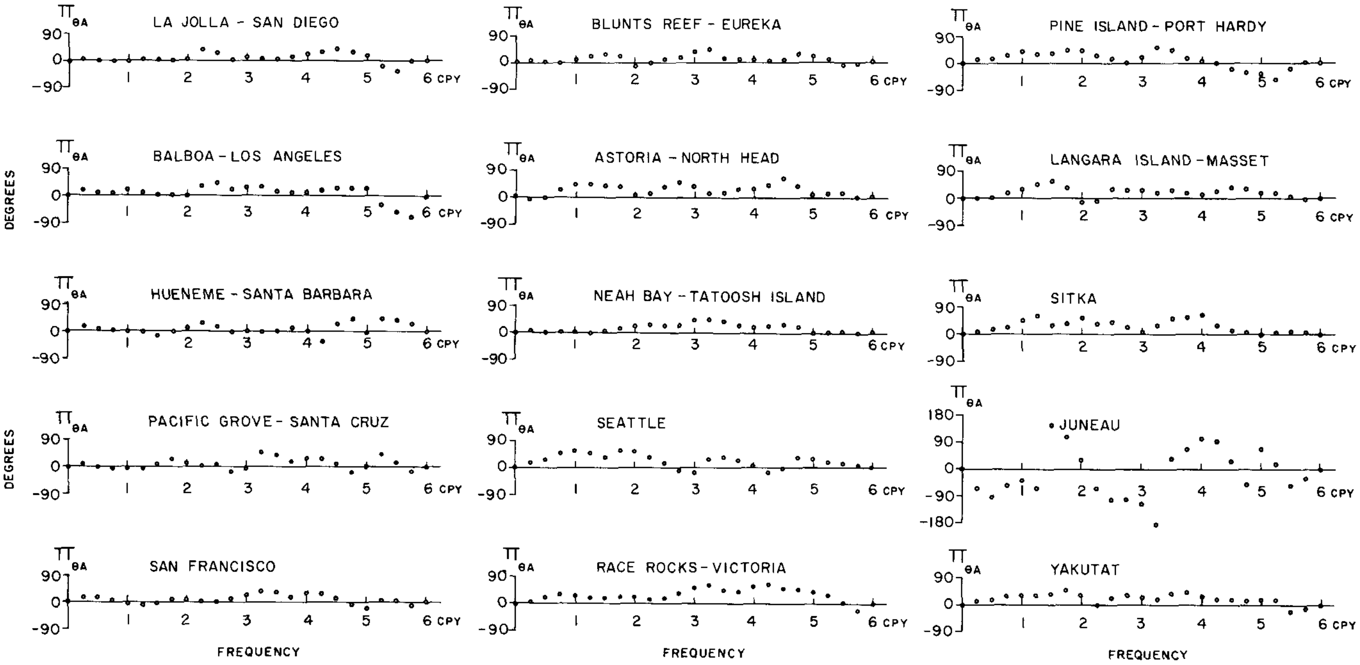


FIGURE 15. Phase between sea surface temperature and air temperature anomalies.

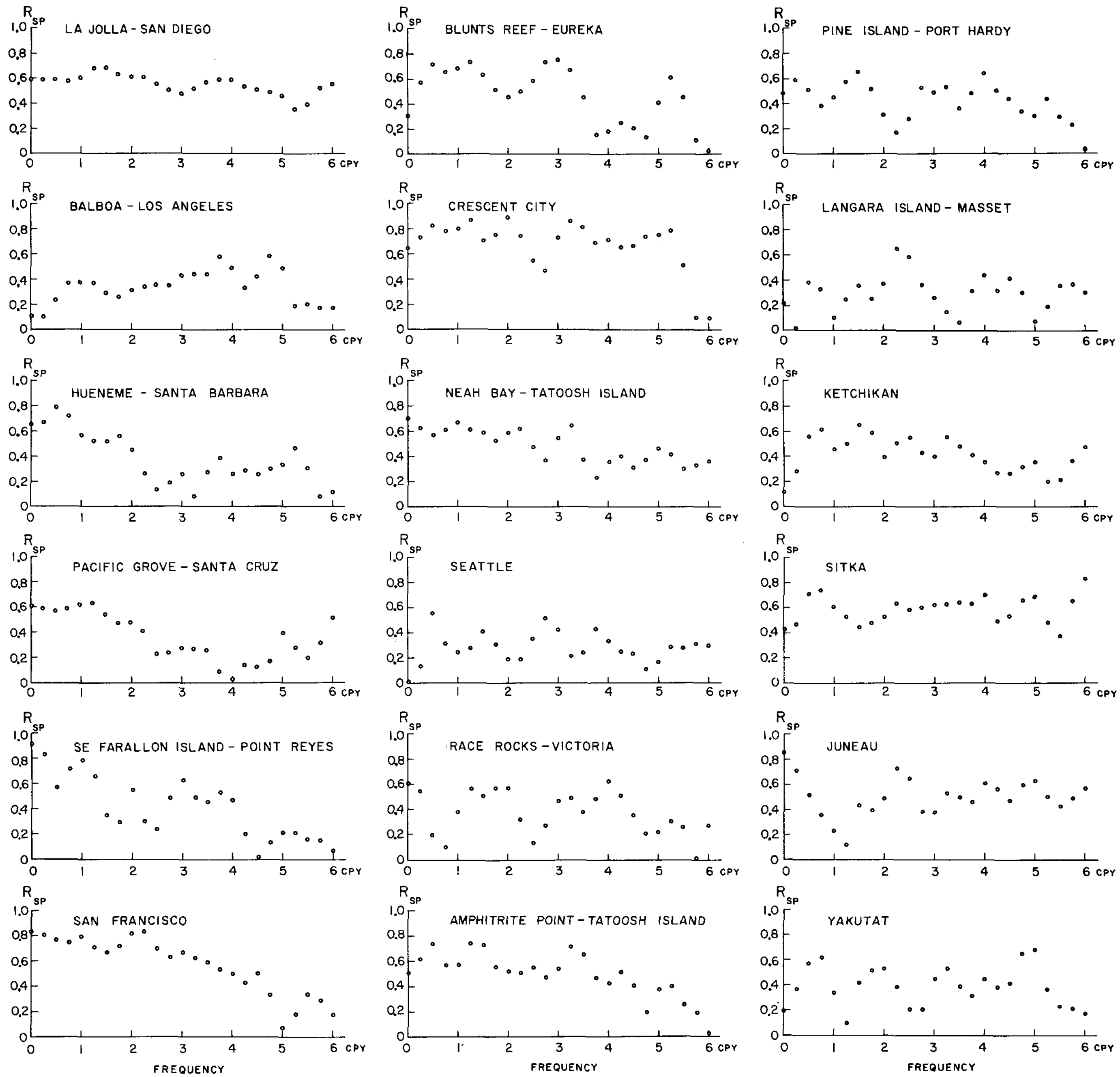


FIGURE 16. Coherence between salinity and precipitation anomalies.

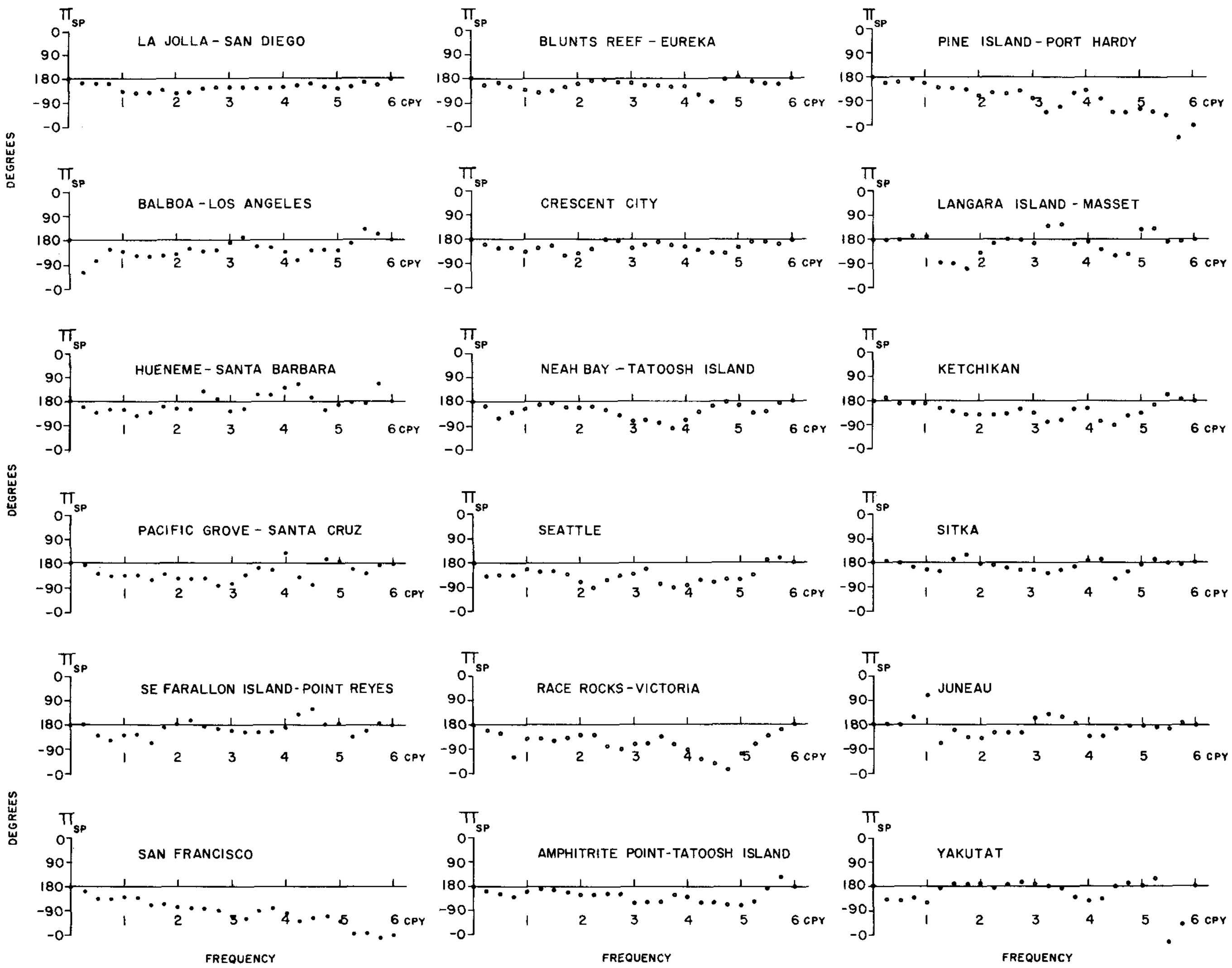


FIGURE 17. Phase between salinity and precipitation anomalies.

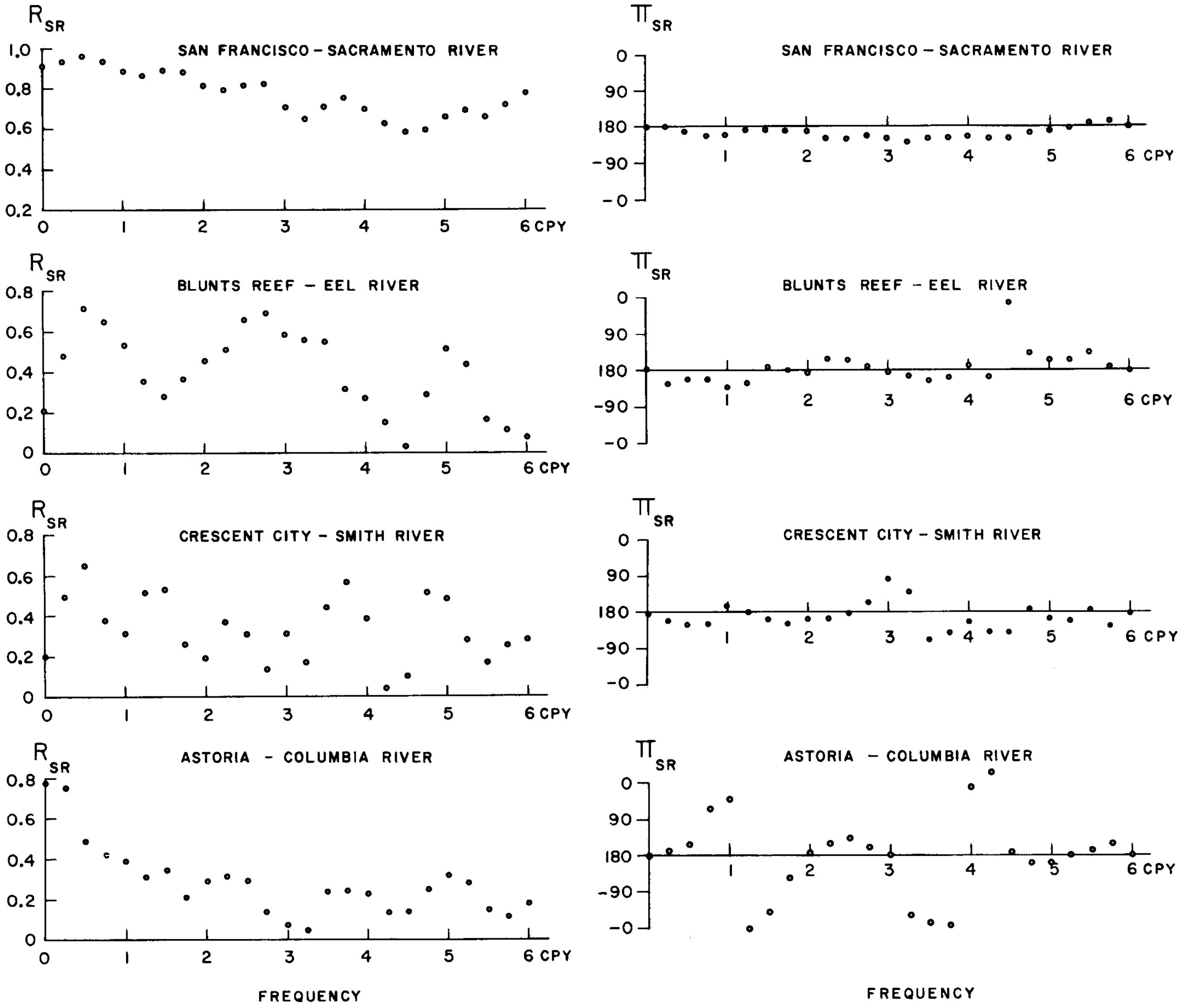


FIGURE 18. Coherence and phase between salinity and river discharge anomalies.

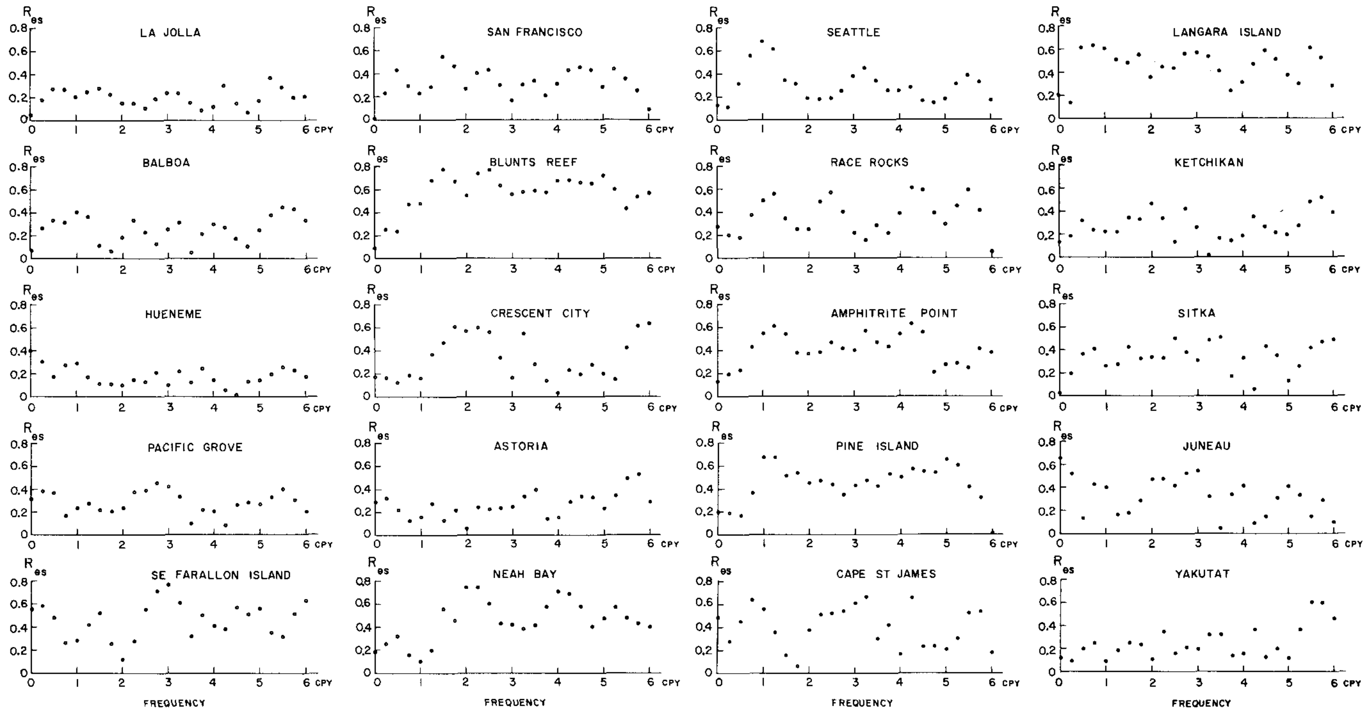


FIGURE 19. Coherence between sea surface temperature and salinity anomalies.

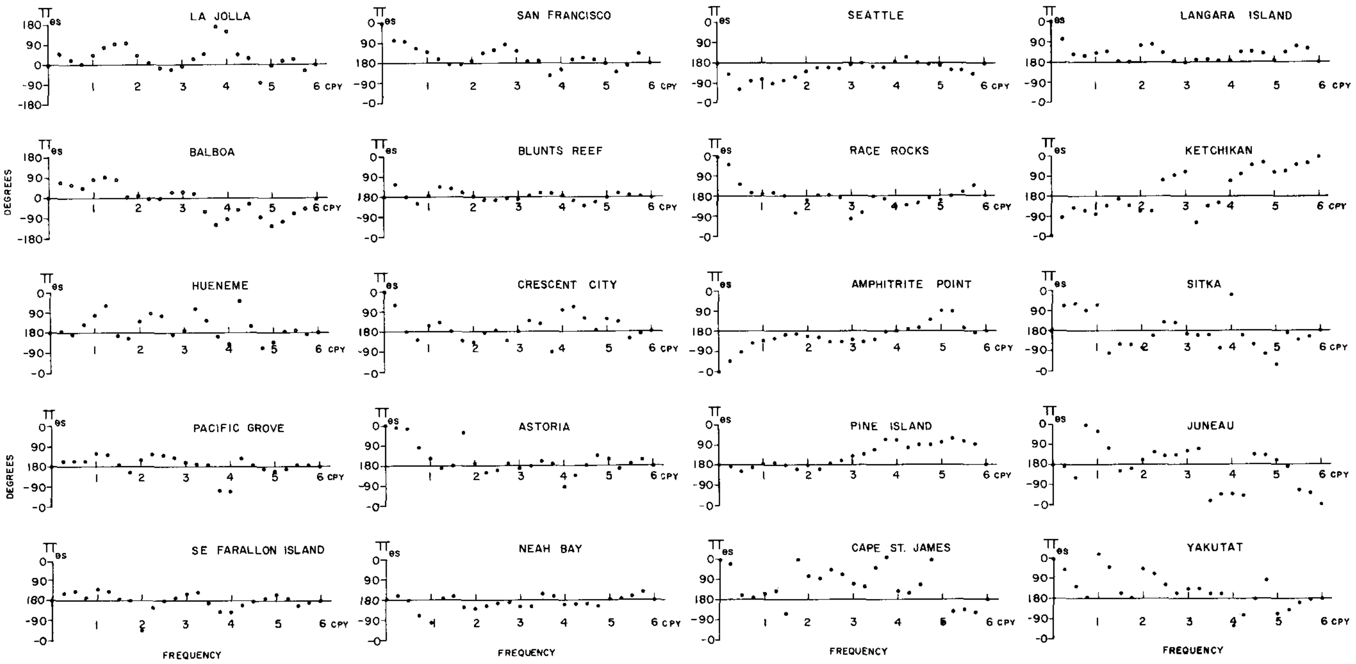


FIGURE 20. Phase between sea surface temperature and salinity anomalies.

TABLE 3

The Ratio $E_{\theta\theta}/E_{AA}$ As a Function of Frequency

f c.p.y.	La Jolla	San Francisco	Blunts Reef	Neah Bay	Langara Isl.	Yakutat
0	0.70	0.73	1.01	0.45	0.36	0.65
1	0.84	0.69	0.67	1.39	0.68	0.30
2	0.67	0.64	0.57	0.54	0.25	0.10
3	0.44	0.70	0.42	0.28	0.11	0.14
4	0.40	0.50	0.47	0.39	0.15	0.16
5	0.50	0.50	0.31	0.83	0.13	0.10
6	0.56	0.50	0.37	0.50	0.45	0.06

COHERENCE AND PHASE BETWEEN SALINITY AND PRECIPITATION ANOMALIES

The coherence (Fig. 16) between salinity and precipitation anomalies varies widely from station to station, because of the very local character of rainfall. For La Jolla, Crescent City, Neah Bay, Amphitrite Point and Sitka the coherence is relatively high and does not vary much with frequency. About 40% to 60% of the salinity anomalies at these stations can be related to anomalies in precipitation. At San Francisco and SE Farallon Island the coherence is high at low frequencies (0 to 3 c.p.y.) and low at high frequencies, which suggests that short period salinity variations are related to some other factor than rainfall. At Blunts Reef the coherence scatters widely, which is probably due to the influence of upwelling, in addition to precipitation, upon the surface salinity. The phase (Fig. 17) between the anomalies is generally 180 degrees, which shows that salinity and precipitation anomalies are related inversely to each other. At San Francisco and a few other places there is a phase drift from 180 degrees at low frequencies to 0 degrees at high frequencies; this is, however, not significant in view of the low values of coherence at higher frequencies.

COHERENCE AND PHASE BETWEEN SALINITY AND RUNOFF ANOMALIES

At stations located near rivers, the variation in the discharge of the river can be expected to have considerable influence upon the surface salinity. This is particularly true of stations located near the boundary of oceanic and river water. In figure 18 are shown the coherence and phase between the salinity anomalies at Fort Point, San Francisco and the discharge of the Sacramento River at Verona, and other cases. It is seen that about 70% of the San Francisco salinity anomalies can be accounted for in terms of anomalies of river discharge. The relatively low coherence between the salinity anomalies at Astoria and the discharge of the Columbia River at The Dalles is not surprising in view of the fact that Astoria is located right at the river and is seldom influenced by oceanic water. The coherence between the Blunts Reef salinity and the Eel River discharge at Scotia is moderate, and is better at certain frequencies than at others, which is probably due to the additional influence of upwelling upon the salinity. In the best cases about 50% of the salinity anomaly can be related to discharge anomalies. The coherence between the Crescent City salinity anomalies and the discharge of the Smith River near Crescent City is not particularly good. The phase between salinity and runoff anomalies is 180 degrees where the coherence is high.

COHERENCE AND PHASE BETWEEN SEA SURFACE TEMPERATURE AND SALINITY ANOMALIES

The coherence between surface temperature and salinity anomalies (Fig. 19) is moderate for stations on islands and on well exposed capes and points, and relatively poor elsewhere. The best coherence is found for Blunts Reef Lightship, where for frequencies between 1.5 and 6 c.p.y. about 50% of the variations can be related to each other. The phase (Fig. 20) is 180 degrees indicating that an inverse relation exists between the anomalies. This is not surprising, since in summer low temperatures are associated with high salinities, owing to upwelling, and in winter relatively high temperatures are connected with low salinities due to abundant precipitation. A similar but poorer relation is also found at SE Farallon Island. Several northern stations, particularly Race Rocks, B.C., and Seattle, Washington, show an oscillation of the coherence with frequency; the cause for this remarkable feature is not known. The phase between temperature and salinity anomalies scatters about 180 degrees at many stations which suggests that high temperatures are associated with low salinities and vice versa; this is not an unexpected result in view of the extensive upwelling occuring during summer months.

CONCLUSION

The following results were obtained from a statistical analysis of the various oceanographic and meteorological records:

(1) At most well exposed stations air temperature anomalies can be used as an indicator of sea surface temperature anomalies. The relation between these anomalies is direct and instantaneous.

(2) At most stations not affected by river discharge local precipitation anomalies can be used as an indicator of salinity anomalies. The relation between these anomalies is an inverse one.

(3) The relation between river discharge and salinity anomalies is good at stations located at the boundary between oceanic and river water. It is not good upstream. The anomalies are related inversely to each other.

(4) Temperatures and salinity anomalies at most coastal stations are not related to each other. At island stations and on lightships there is a moderate and inverse relation between these anomalies. The inverse relation between temperature and salinity anomalies is characteristic of upwelling regions off the west coast of the United States.

(5) Sea surface and air temperature anomalies occur more or less simultaneously over very large areas. Salinity and precipitation anomalies are very local phenomena.

ACKNOWLEDGMENTS

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The computations were carried out at the Western Data Processing Center of the University of California in Los Angeles.

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THE USE OF A COMMON REFERENCE PERIOD FOR EVALUATING CLIMATIC COHERENCE IN TEMPERATURE AND SALINITY RECORDS FROM ALASKA TO CALIFORNIA

MARGARET K. ROBINSON[1]

INTRODUCTION

One of the major aims of the California Cooperative Oceanic Fisheries Investigations has been to correlate fluctuations in fish catches with fluctuations in the oceanic environment. Toward this end, it has been necessary to evaluate the scale of variability of ocean temperature and salinity for periods of a month, season, year, decade and longer.

The area of interest has expanded from Southern California waters to include the area from Cape San Lucas to the Gulf of Alaska. When the widescale warming in the eastern North Pacific took place between 1957 and 1959, our horizons were again expanded to include the western North Pacific in search of cause and effect relationships which might explain these large-scale changes (Sette and Isaacs, 1960).

The ultimate aim in studying climatic records is to make prediction of climatic events possible.

One of the most useful groups of data which have shed light on the climatic changes of the ocean is that of the daily temperature and salinity observations at shore stations between La Jolla, California, and Yakutat, Alaska. (U.S. Coast and Geodetic Survey, 1956, 1958; SIO Ref. 60-30, 1960; Fish. Res. Bd. of Canada, 1947-1960.)

There are two important reasons why these shore station data are so valuable: First, there is a very high positive correlation between air temperatures at adjacent meterological stations and sea-surface temperatures at shore stations (Hubbs, 1948; Tully, 1938); Second, it has been possible to correlate sea-surface temperature anomalies up to 150 miles offshore with sea-surface temperature anomalies at nearby shore stations, and thus indirectly with air temperatures along the Pacific coast (Reid, Roden, Wyllie, 1958; Robinson, 1957).

Therefore it has been possible to extrapolate physical conditions in the California Current region for periods where observations in the open ocean were unavailable, and to use these probable values to extend our understanding of the relation between the occurrence and behavior of marine organisms with changes in their physical environment.

There are 24 shore stations along the Pacific coast with almost continuous data. The periods over which the data have been taken, however, vary from 13 years at Santa Monica to 44 years at La Jolla. While it may be preferable to use the entire length of record when studying variability at individual stations, it is impossible to properly evaluate differences among stations without using a common base of reference.

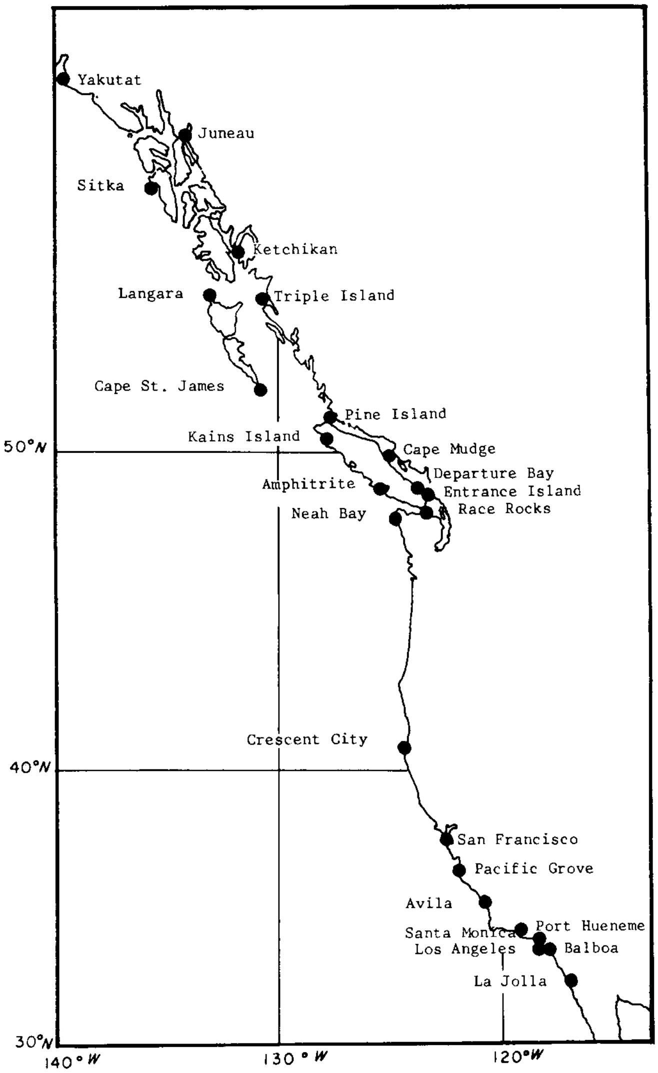

FIGURE 1. Shore Station Locations.

Temperature and salinity anomaly charts were therefore prepared, using means from the period 1949-1958 as a common reference base, for twenty-four Canadian and American shore stations whose locations are shown in figure 1. Before the publication of the charts, Japanese, Canadian and American oceanographers agreed to use the period 1950-1959 as a common base of reference, not only for shore stations' data but also for open ocean data in the North Pacific. Therefore, in order to make the charts which had already been completed more useful, and to relate

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[1] Contribution from the Scripps Institution of Oceanography.

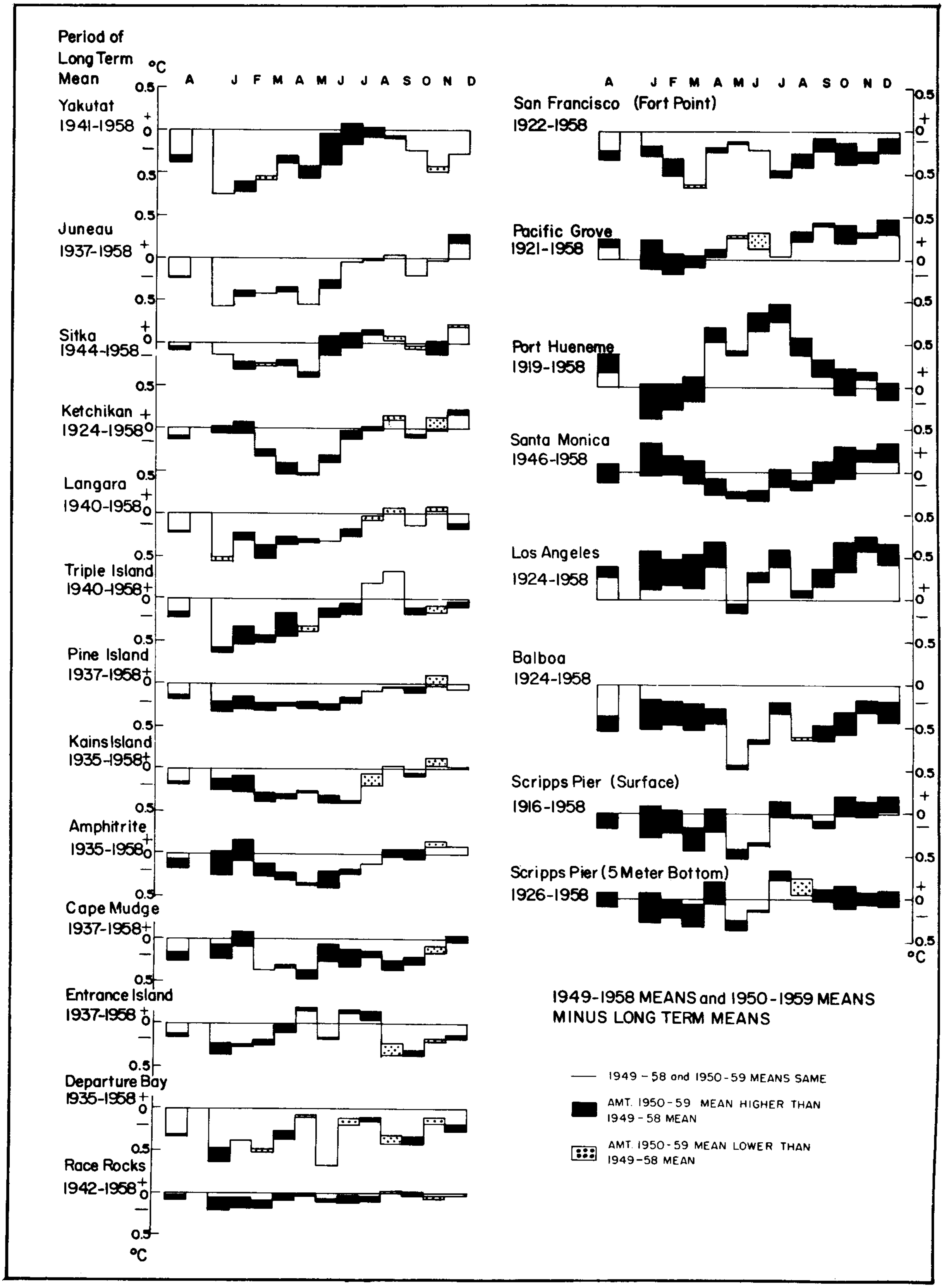

FIGURE 2. Relation of 10-year temperature means to long period means.

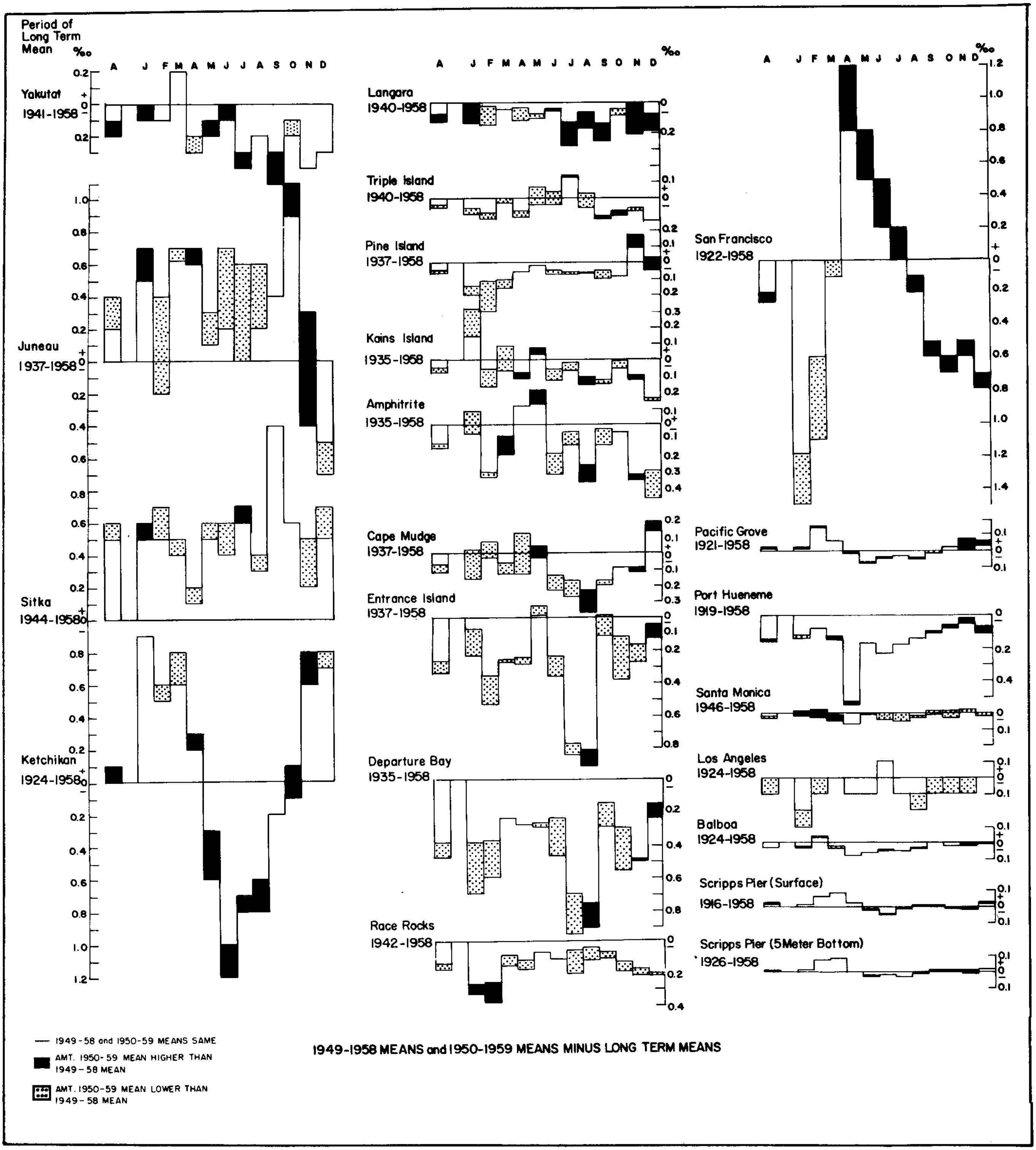

FIGURE 3. Relation of 10-year salinity means to long period means.

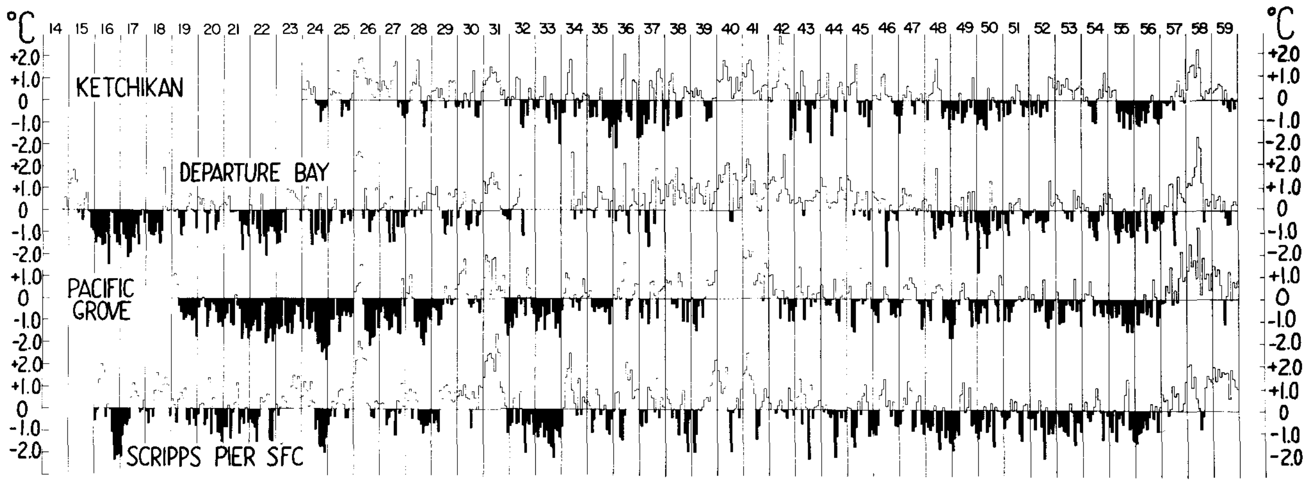

FIGURE 4. Chronological Temperature Anomalies based on 1950-1959 reference period.

them to the 1950-1959 reference period, changes and additions were made in the charts prior to publication, permitting an evaluation of the effect of altering the base period, as well as meeting the original objectives.

The relation of the 1949-1958 and the 1950-1959 ten-year monthly and annual means to each other and to the long-term means for each of twenty stations is shown for temperature in figure 2, and for salinity in figure 3. Four stations were omitted because data were incomplete for the period of reference.

The chronological temperature anomaly charts for all 20 stations were not redrawn based on the 1950-1959 reference period. Instead, only four key stations, each typical of the nearby area, were redrawn. Stations selected were Ketchikan, Alaska; Departure Bay, Vancouver Island, B.C.; Pacific Grove and La Jolla, California. Figure 4 presents the temperature anomalies based on the 1950-1959 reference period for these stations.

The chronological temperature and salinity charts based on the 1949-1958 reference base and anomaly charts for individual stations plotted by months for all years are included in SIO Ref. 60-30 (1960). Both 1949-1958 and 1950-1959 reference period means are given on the individual station charts.

The following points will be discussed in reference to the anomaly charts published in SIO Ref. 60-30 (1960) and to figures 2, 3 and 4. Station-to-station coherence, for the purpose of this discussion, is defined as the agreement in sign of temperature (or salinity) anomalies when computed from the same base of reference. 1. Sampling error for monthly temperature and salinity means and their respective anomalies. 2. The relation of the 1949-1958 and the 1950-1959 reference periods to each other and to the long-term means at each station. 3. The extent of station-to-station temperature coherence; visible evidence of coherence; statistical evidence of coherence; the relation of incidence of coherence to time of year; comparison of coherence computed for 20 stations with that computed for 4 key stations; prediction of coherence; and relation of magnitude of anomalies to incidence of coherence. 4. Evidence of persistence of higher- or lower-than average temperatures, and the relation of persistence to coherence. 5. Salinity coherence as shown in SIO Ref. 60-30 (1960). 6. The relation of temperature anomalies to salinity anomalies.

DISCUSSION

Sampling error in shore station data: In order to evaluate the reliability of the monthly temperature and salinity means and the anomalies derived from them at the shore stations, it is necessary to examine variability and the standard error of the means (σ_m). The standard deviations of temperature at shore stations within single months vary from 0.2°C. in winter to 2.0°C. in summer and σ_m from 0.04°C. to 0.37°C.

For the Southern California stations the standard deviations of salinity within individual months are very low, because there is little rainfall and runoff. Here σ_m is usually less than $0.01^0/_{00}$. However, at the Alaskan and British Columbian stations there is excess precipitation and runoff with resulting extreme ranges in salinity. San Francisco falls in this class also, because of the tremendous river runoff which empties into San Francisco Bay. Sample standard deviations of salinity for individual months at these northern stations range from $0.16^0/_{00}$ to $5.00^0/_{00}$. The standard error of the means, based on these values, ranges from $0.03^0/_{00}$ to $0.91^0/_{00}$. At both northern and southern stations the anomalies from month to month and from year to year exceed the possible sampling error.

The relation between the 1949-1958 and the 1950-1959 reference periods to each other and to the long-term means at each station is shown in figures 2 and 3. For both figures base period anomalies were computed at each station by subtracting the long-period means from the 1949-1958 monthly and annual means, and also from the 1950-1959 means.

Relation between ten-year and long-term means: The 1949-1958 temperature means (Fig. 2) were lower than the long-term means at three of the northern stations in all months. At other northern stations the period from July to December included several positive anomalies. The negative anomalies for the same months were smaller than in the first six months. At three southern stations—Pacific Grove, Port Hueneme and Los Angeles—the anomalies were predominantly positive, while at the remaining southern stations the anomalies were predominantly negative. There are marked differences between anomalies at Port Hueneme, Santa Monica, Los Angeles and Balboa. The long-period record at the latter two stations covers the same years, so it would appear that the marked differences at these two nearby stations are due to local effects, which may be the construction of Los Angeles harbor and/or the modifications to the harbor at Newport. On the other hand, there may have been real differences in the circulation at these two localities.

The 1950-1959 means are, in general, higher than the 1949-1958 means, but they, too, are lower than the long-term means. These differences are greater at the southern stations than at the northern stations. With the exception of Port Hueneme and Los Angeles, the 1950-1959 means agree more closely with the long-term means than did the 1949-1958 means.

It is important to note that the differences between the ten-year temperature means and the long-term means never exceed 0.5°C.[2] Thus, the change in the common reference period principally effects those months and years with small deviations. The spectacularly different years (e.g.—1931, 1933, 1941, 1958) would still stand out regardless of the base of reference.

Unlike the relatively systematic temperature relation discussed above, the salinity relation between the ten-year reference period means and the long-period means is random and confused. Figure 3 shows that the patterns of the anomalies, even for stations where long-term records are of the same length, seem to have little relation to each other. Port Hueneme, generally little affected by runoff, had such low salinities following a very heavy rainfall in April, 1958, that the 1949-1958 April mean salinity was very much lower than the long-term mean. The ten-year mean is so low, in fact, that the April values in the Port Hueneme salinity anomaly charts are all positive except for 1958.

There is also a random and confused relation between the salinity means of the two ten-year periods at all stations north of and including San Francisco. For example, the 1950-1959 mean salinities are lower than the 1949-1958 means 60% of the time; however, the differences occur irregularly in time and randomly from Yakutat to San Francisco. Differences south of San Francisco are so small that no trend can be detected.

Temperature Coherence: Station-to-station coherence as defined on page 124 is visibly evident in the chronological temperature anomaly charts. The most complete evidence of station-to-station coherence is published in SIO Ref. 60-30 (1960), where both temperature and salinity chronological anomaly charts for 20 stations are available. Figure 4, based on the 1950-1959 reference period at Ketchikan, Departure Bay, Pacific Grove and La Jolla, is similar to the charts for all 20 stations based on the 1949-1958 reference period in all major features. Inspection reveals the strikingly widespread north-to-south and station-to-station agreement in the well-known warm years (1926, 1931, 1941, 1957-1959) and in the cold years (1933, 1950, 1955, 1956). Another visible climatic feature which emerges from both the temperature charts of SIO Ref. 60-30 (1960) and figure 4, is that changes from positive to negative anomalies, or vice versa, do not occur at the same time from north to south. Note, for example, that the warm period of 1957-1959 ended earlier in the north and persisted through 1959 in the south.

A quantitative expression of the station-to-station coherence of temperature anomalies was obtained by determining the percentage of the total number of stations having temperature anomalies of the same sign, either positive or negative. This was done for the 20 stations used in SIO Ref. 60-30 (1960), (Table 1) and for the four stations in figure 4 (Table 2). Note in Table 1 that the number of stations with temperature data ranges from 10 in 1935 to 20 in 1946 and subsequently, and in Table 2 that data were not collected at Pacific Grove in 1940. Percentages for 1935-1959 appear in Table 1 only where there is a 95% probability that the coherence could not have happened by chance. This requires that the sign of the anomalies must be the same at 80% of the stations when based on 10 stations, and at 70% of the stations when based on 20. The percentages in Table 2 are included for comparative purposes even though agreement at 3 out of 4 stations (75%) is not significant at the 95% probability level. Table 1, based on the larger number of stations, is, consequently, the best estimate of coherence. Bold face percentages in both tables indicate that at the majority of the stations the anomalies were positive. A —, with no percentage listed above, indicates that coherence was not statistically significant, and the monthly anomaly was positive at the majority of the stations. Blank spaces indicate the majority of monthly anomalies were negative and coherence was not statistically significant.

The effect of the shift of base reference period on the percentages of positive and negative anomalies occurs when the anomalies are small, for statistical evidence shows that 50% of the changes in the two ten-year means were 0.1°C. or less and never exceeded 0.5°C. In a previous reference to figure 2, it was noted that means for both ten-year periods were generally lower than the long-term means at most stations, although those of the 1950-1959 period were closer to the long-term mean. The use of either ten-year base reference period not only produces the expected result of nearly equal numbers of positive and negative anomalies within the individual ten-year reference periods, but also results in larger numbers of positive anomalies in the years 1935-1949. It is worth noting that there is a surprising similarity in percentages of positive monthly and annual temperature anomalies. Using the 1949-1958 base reference period, Table 1 shows that 64% of the monthly anomalies and 68% of the annual anomalies were positive at the majority

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[2] 75% of the differences between the means of the two ten-year periods at the northern stations were 0.1°C. or less and exceeded 0.25°C. only twice. At the southern stations, only 27% of the differences were as small as 0.1°C. or less, and 26% exceeded 0.25°C.

TABLE 1

SIGNIFICANT PERCENTAGES OF TEMPERATURE COHERENCE BASED ON 10-20 STATIONS

No. of Stations	Year	Month												Annual Anomalies
		1	2	3	4	5	6	7	8	9	10	11	12	
10	1935	—	—	90			—				80	100	80	
11	1936	**82**	—	—	82	**82**	—	—	—	—	**91**	**82**	—	**82**
15	1937	73	87	**80**		—	**80**	—		**73**	**73**	**86**	**73**	—
14	1938	**86**	—	**86**	—	—	—		—	—	—			—
14	1939	**86**				—	—	—	—	—	—	**86**	**100**	—
16	1940	**100**	**100**	**94**	**94**	**94**	**75**	—	—	**94**	**94**	—	**94**	**83**
17	1941	**94**	**100**	**94**	**100**	**94**	**94**	**82**	**88**	—	**82**	**100**	**94**	**100**
18	1942	**95**	**95**	**95**	**95**	**72**	**83**	**89**	—	—	**83**			**95**
18	1943	—	**72**	**72**	**83**		—		**72**	—	**95**	**95**	**95**	**78**
19	1944	**95**	**90**	**90**	—	**74**	—		—	—	**84**	**89**	—	**84**
19	1945	**95**	**90**	**74**	—	—					—	90	79	—
20	1946	**75**	—	**70**	—	**85**	**95**	**75**		—		90	90	**70**
20	1947	70	—	**100**	**85**	**90**	**90**	**70**	—	—	**80**		90	**95**
20	1948	**85**		—		**70**	**75**	—	—			90	100	
20	1949	100	100		70	**80**	—			—	80	**70**	85	95
20	1950	100	100	70	70	100		**75**		—			—	80
20	1951	—		85	—			**80**	—		—	—	80	
20	1952				75		95	80	90	95	**90**	—	**70**	85
20	1953	**90**	**75**	—	—			**80**		—	—	**70**	—	**70**
20	1954	**100**	**85**	**80**	70	75				—		**80**	—	—
20	1955	**70**	**70**	—	85	90	95	95	75	90	100	100	100	100
20	1956	80	90	100	90	70	90	80		80	75	100	80	100
20	1957			—		**75**	**85**	**80**	**75**	**90**	**95**	**95**	**90**	**95**
20	1958	**100**	**100**	**100**	**100**	**100**	**90**	**70**	**85**	**75**	—	—	**85**	**100**
20	1959	**90**	**95**	**95**	**100**	**85**	**85**	**90**	—	—	**75**		**75**	**95**
No. of years	sig.	20	15	17	14	16	13	13	6	7	15	16	18	17

Bold type—Positive anomalies at majority of stations—percentage significant.
Dash—Positive anomalies at majority of stations—percentage not significant.
Light type—Negative anomalies at majority of stations—percentage significant.
Blank—Negative anomalies at majority of stations—percentage not significant.

TABLE 2

PERCENTAGE OF TEMPERATURE COHERENCE BASED ON FOUR KEY STATIONS

No. of Stations	Year	Month												Annual Anomalies
		1	2	3	4	5	6	7	8	9	10	11	12	
4	1935	**100**	**75**	100	100			—	75		75	100	75	75
4	1936		75		75	**75**	**75**	75	75		**100**	**100**	**75**	**75**
4	1937	100	75	75	100	75	**100**	**100**	75	**75**	**75**	**100**	**75**	
4	1938	**75**	**75**	**100**	—	**75**	75		**75**	**75**	—	—	—	**75**
4	1939	**100**	—	—	**75**	—	**75**	**75**	**75**	**75**	**75**	**100**	**100**	**75**
3	1940	**100**	**100**	**100**	**100**	**100**	—			**100**	**100**	—	**100**	**100**
4	1941	**100**	**100**	**100**	**100**	**100**	**100**	**75**	**75**	**75**	**75**	**100**	**100**	**100**
4	1942	**100**		**100**	**75**	**100**	**75**	**75**	—	**75**	**75**		75	**75**
4	1943		**100**	**75**	**75**	—	**75**					**100**	**100**	**75**
4	1944	**100**	**75**	**75**	—	—	75		75	—	**75**	**75**	75	**75**
4	1945	**100**	**100**	—	75	—		75		75	**100**	75	75	**75**
4	1946	—	—	—	—	**75**	**100**	**75**	—	—	75	100	100	75
4	1947	75	75	**100**	**100**	**100**	**100**			—	**75**	—	75	**75**
4	1948	—	100	—	—	**75**	**75**	—	—	75	100	100	100	75
4	1949	100	100	75	75	**75**	**75**	75		**75**	100	—	100	100
4	1950	100	100	100	75	100	—	**75**	—		100	75	75	100
4	1951	100	100	100		75		—	**75**	75			75	100
4	1952	75	75	75	100	—	100	75	75	100	—	—	—	75
4	1953	**75**	—	—	—	75	75	—	75	**75**	—	—	—	—
4	1954	**75**	**75**	**75**	75	75	75	75	—	—	75	—	—	75
4	1955	—	—	—	75	100	100	100		75	100	100	100	100
4	1956	100	100	100	75		100	75		—		100	75	100
4	1957	75	75	**75**		**75**	**75**		—	**75**	**100**	**100**	**75**	**100**
4	1958	**100**	**100**	**100**	**100**	**100**	**100**	**75**	**75**	**75**	**100**	**100**	**100**	**100**
4	1959	**100**	**100**	**100**	**100**	—		**75**		75	**100**	**75**	**75**	**100**
No. of years	100%	14	11	11	8	7	8	2	0	2	10	12	9	10
No. of years	75-100%	20	20	18	18	17	19	15	11	16	19	16	21	23

Bold type—Positive anomalies at majority of stations—percentage significant.
Dash—Positive anomalies at majority of stations—percentage not significant.
Light type—Negative anomalies at majority of stations—percentage significant.
Blank—Negative anomalies at majority of stations—percentage not significant.

of the stations. Table 2, using the 1950-1959 base reference period, shows 57% positive monthly anomalies and 56% positive annual anomalies.

The bottom row of numbers in Table 1 represents the total number of years in which significant coherence occurs in a given month; hence, coherence is best in December and January, and poorest in August and September. Turning to Table 2, the row of figures next to the bottom represents the number of years in which there is complete agreement in the sign of the anomalies at all stations. The results are too conservative, so the second row of figures is given for 75-100% coherence. Now the results are too liberal an estimate of coherence, pointing up the difficulty in dealing statistically with only four stations.

One of the major purposes in studying long-period records is to develop relations which will make the prediction of climatic events possible. In Table 1, 1935-1959 station-to-station coherence was significant at the 95% probability level in 170 of the 300 months (57%). However, analysis of data from 20 stations is time consuming and data are not received immediately from all stations. Therefore, a detailed comparison was made of the results using all 20 stations and those based on four key stations in order to determine how good an estimate of coherence could be made on the basis of the four stations alone (Table 3).

Table 3's consideration of four key station coherence at 100%, 75%, and 50%, shows the extent to which accurate coastwise prediction would have failed. With four-out-of-four (100%) coherence, prediction coastwise would have been right in 82 out of 94 months; however, such a conservative prediction would have failed to anticipate 88 additional cases of coastwise coherence which actually occurred. With three-out-of-four (75%) coherence, predictions for coastwise coherence would have been correct for only half of the time, or 58 months. Fifteen of the remaining months would have been assigned incorrect signs for their respective anomalies: during these months anomaly signs at the majority of the stations were actually opposite those at three of the four key stations. With two-out-of-four (50%) coherence and the probability of any coherence reduced to chance, there were 90 instances where no coastwise coherence would have been predicted; yet, in 28 of these months significant coherence did occur among the 20 stations.

TABLE 3

COMPARISON OF COHERENCE COMPUTED FOR 10-20 STATIONS AND THAT COMPUTED FOR 4 STATIONS

Coherence 4 Stations	Coherence All Stations	No. Monthly Anomalies	Sub-Total	No. Annual Anomalies
100%	Significant, same sign	82		9
100%	Not significant, same sign	11		1
100%	Not significant, diff. sign	1		
			94	
75%	Significant, same sign	58		6
75%	Not significant, same sign	43		5
75%	Significant, diff. sign	1		1
75%	Not significant, diff. sign	14		1
			116	
50%	Significant	29		1
50%	Not significant	61		1
			90	
	Totals	300	300	25

Two questions arise concerning the absence of any significant coastwise coherence during about half of the months of the past 25 years. Are the northern and southern parts of our coasts in different climatic regimes? Or, recognizing that there are local effects which differentiate stations near the more typical four key stations, is the conspicuous absence of coherence related to the size of anomalies during those periods when local effects might be masking widespread climatic effects?

TABLE 4

AGREEMENT IN SIGN OF ANOMALIES AT FOUR KEY STATIONS

Coherence 4 Stations		No. Monthly Anomalies	Sub-Total	No. Annual Anomalies
100%		94		10
			94	
75%	La Jolla differed	35		3
75%	Ketchikan differed	28		8
75%	Departure Bay differed	28		1
75%	Pacific Grove differed	25		1
			116	
50%	Ketchikan-Departure Bay alike Pacific Grove-La Jolla alike	45		2
50%	Ketchikan-Pacific Grove alike Departure Bay-La Jolla alike	24		0
50%	Ketchikan-La Jolla alike Departure Bay-Pacific Grove alike	21		0
			90	
	Totals	300	300	25

For purposes of examining the first question, a tabulation of the precise way in which coherence occurred among the four stations was constructed (Table 4). In 31% of the months, all four stations had the same anomaly sign. In 39% of the months, one of the four had a different sign. Though La Jolla differed most frequently, the differences, percentagewise, were not significant among the four stations. In the remaining 30% of the months, there is coherence between different pairs of stations. The two northern stations (Ketchikan and Departure Bay) have similar but opposite anomaly signs to those of the two southern stations (Pacific Grove and La Jolla), twice as frequently as either of the other two possible combinations. (Note: Table 7 gives additional evidence of somewhat higher frequency of coherence when we separate the complete group of 20 stations into northern and southern components.) It is of utmost importance to note, however, that coherence among all four stations results twice again as frequently as when the northern pair is not coherent with the southern pair. The previously noted north to south time lag in climatic events partly accounts for those periods which show no coherence.

Relation of magnitude of anomalies to coherence: In order to investigate the second question, the mean absolute value of anomalies for all 20 stations, disregarding their signs, was computed. Correlograms (Fig. 5) were constructed for the relationship between the annual, February and August mean absolute anomalies and coherence at the stations covered in Table 1. Regretfully, the correlograms failed to demonstrate any linear relationship between the anomalies and the coherence. It was of interest to note, however, that when the magnitude of the mean anomaly was greater than 1.0°C., the coherence was statistically significant. Unfortunately, this occurred only twice in the past 25 years for annual anomalies, five times for February anomalies, and not at all for August, the largest mean absolute anomaly for August being only 0.85°C.

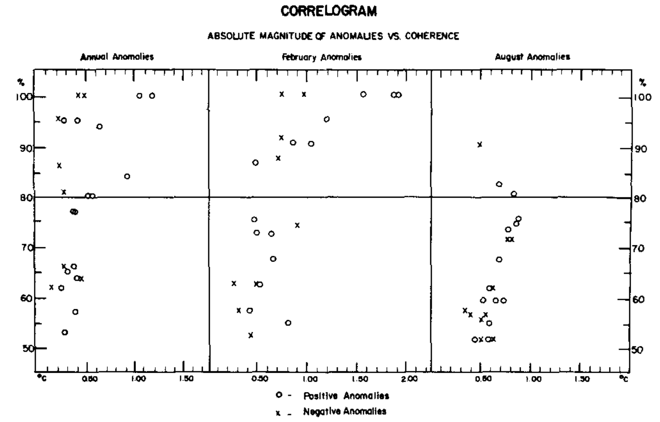

FIGURE 5. Correlogram. Absolute Magnitude of Anamolies vs. Coherence.

Because two of the four key stations are located at major scientific institutions and would be first to receive notice of major climatic changes, La Jolla and Departure Bay records were examined further for a possible relationship of the magnitude of their respective monthly anomalies to the incidence of 100% coherence at all four stations (Tables 5 and 6). Investigation disclosed that anomalies at La Jolla and Departure Bay were greater than 1.0°C. during 37% of those months with 100% coherence at all four stations. Unfortunately, however, there was nearly as large a percentage (29%) of the months with 100% coherence at all four stations when the La Jolla and Departure Bay anomalies were 1.0°C. or less.[3] Though about one-fourth of the 300 months in the past 25 years La Jolla had anomalies greater than 1.0°C., in only 9% of those 300 months did anamolies greater than 1.0°C. concur with 100% coherence at the four key stations. The same was approximately true at Departure Bay. Therefore, if the magnitude of anomalies at either station is useful in prediction at all, it is only that they might serve to alert us to possible widespread coherence.

TABLE 5

RELATIONSHIP OF MAGNITUDE OF MONTHLY TEMPERATURE ANOMALIES AT LA JOLLA TO COHERENCE AT FOUR KEY STATIONS

(La Jolla Monthly Anomalies)

Size of Anomalies	No. monthly Anomalies	Sub-Total	No. Months Coherence was 100%	Sub-Total
0.0°C-1.0°C	215	215	62	62
1.0° -1.5°	53	85	18	32
1.6° -2.0°	24		10	
2.1° -2.5°	7		3	
2.6° -3.0°	1		1	
Totals	300	300	94	94

TABLE 6

RELATIONSHIP OF MAGNITUDE OF MONTHLY TEMPERATURE ANOMALIES AT DEPARTURE BAY TO COHERENCE AT FOUR KEY STATIONS

(Departure Bay Monthly Anomalies)

Size of Anomalies	No. monthly Anomalies	Sub-Total	No. Months Coherence was 100%	Sub-Total
0.0°C-1.0°C	225	225	66	66
1.1° -1.5°	50	75	19	28
1.6° -2.0°	14		4	
2.1° -2.5°	6		3	
2.6° -3.0°	4		1	
3.1° -3.5°	1		1	
Totals	300	300	94	94

Persistence: The relationship of persistence to coherence, though suspected, has never been so conclusively evident as that revealed in Tables 1 and 2, figure 4, and SIO Ref. 60-30 (1960). Using auto-correlation computations, Roden and Groves (1960) had reported a significant tendency toward the persistence of temperature anomaly signs over periods of five months in an ocean area just off the Washington coast. But, Tables 1 and 2 and figure 4 show that when coherence is highly significant along the entire coast, persistence in the sign of the anomalies is apparent over even longer periods. For example, note that during the 1955-1956 period when significant coherence occurred coastwise, negative anomalies persisted for a period of 16 months without a break; and during 1957-1958, positive anomalies persisted for a period of 17 months. In fact, during the winter of 1958 there was a five-month period when positive anomalies persisted at all 20 stations. Because present records are too short, auto-correlation computation methods would fail to reveal the probabilities of reoccurrence of persistence over periods as long as 16 or 17 months.

Salinity Coherence: Coastwise station-to-station coherence in salinity anomalies was shown to be very poor in the chronological salinity charts published

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[3] The fact that these percentages apply to both stations appears to be fortuitous. In less than 1% of the 300 months did both stations have anomalies greater than 1.0° C. with the same signs at the same time.

in SIO Ref. 60-30 (1960). It did not seem worthwhile to re-draw these charts on the 1950-1959 reference base even for the four key stations. Some of the features, however, are of general interest as noted below.

There is little resemblance between the northern and southern stations, but over smaller areas salinity coherence is good. For example, the southern salinity anomaly charts for La Jolla and Balboa are similar, as are the northern charts for Departure Bay and Entrance Island. Yet at three British Columbian stations, the salinity anomalies differ considerably from those for Departure Bay and Entrance Island: at Langara, Pine Island and Race Rocks, mixing is so intense and rapid that the effects of precipitation and runoff are minimized and variability from month to month and from year to year is lessened to such a point that the range of the anomalies is only slightly greater than that found for the southern stations.

Salinity coherence, extracted from the charts in SIO Ref. 60-30 (1960), is summarized in Table 7 for three periods—annual, February and August anomalies—and in three groups—all stations, northern stations and southern stations. Coherence for the corresponding temperature anomalies is included in this table for contrast.

TABLE 7

NUMBER OF YEARS STATION-TO-STATION COHERENCE WAS SIGNIFICANT FOR SALINITY AND CORRESPONDING TEMPERATURE ANOMALIES

1935-1959 (25 years)

	Salinity	Temperature
ALL STATIONS (10-20)		
Annual Anomalies	7 (28%)	17 (68%)
February Anomalies	6 (24%)	15 (60%)
August Anomalies	9 (36%)	6 (24%)
NORTH STATIONS (4-13)		
Annual Anomalies	9 (36%)	15 (60%)
February Anomalies	11 (44%)	17 (68%)
August Anomalies	12 (48%)	8 (32%)
SOUTH STATIONS (5-7)		
Annual Anomalies	5 (20%)	14 (56%)
February Anomalies	6 (24%)	19 (76%)
August Anomalies	9 (36%)	8 (32%)

The table shows that while temperature coherence in August is least frequent, salinity coherence in August, even though it occurs only slightly oftener than August temperature coherence, is most frequent. Salinity coherence is also more frequent at the northern stations than at the southern stations or for the two combined. In the north, though coherence is almost as frequent in February as in August and though in both months it occurs more frequently than in the annual anomalies, even here salinity coherence occurs less than 50% of the time.

Relation Between Temperature and Salinity Anomalies: The temperature and salinity anomalies were examined to see if there was any relation between them during the exceptionally warm years of 1931, 1941 and 1957-1958, or during the exceptionally cold years of 1933 and 1955-1956. It was found that the warm years of 1941 and 1957-1958 were accompanied by low salinities (high precipitation) at most of the stations from north to south. This was not true, however, at the southern stations during 1931. Ketchikan, the only northern station with salinity observations at that time, showed very low salinities in the winter of 1930-1931 accompanying its higher than average temperatures.

In the cold years, there was no consistency in the temperature-salinity anomaly relationship from station to station, nor from one cold year to another.

CONCLUSIONS

The use of a common reference period has given us considerable new information about coastwise coherence in the northeastern Pacific. We can now accept station-to-station agreement or local station disagreement with more confidence. Large-scale climatic events and associated coherence were already well known, but now there is evidence that significant coastwise coherence in monthly temperature anomalies occurred during 57% of the months for the past 25 years and that coherence was highest in winter and lowest in August and September. Furthermore, in 17 of the 25 years there was significant coherence in annual temperature anomalies.

In comparison with the possibilities for coastwise prediction based on 20 stations, prediction based on four key stations would be either too conservative using the criteria of 100% coherence, or too liberal using the criteria of 75% coherence.

Coastwise, no linear relation between coherence and absolute magnitude of mean temperature anomalies exists, except for the occasional instances when mean anomalies exceeded 1.0°C. Respective mean anomalies for La Jolla and Departure Bay did exceed 1.0°C. more frequently, but these occasions were rarely concurrent with significant coastwise coherence. Thus, prediction of coherence on the basis of magnitude of anomalies at one of the major oceanographic institutions would have little probability of success.

There is evidence of a positive correlation between station-to-station coherence and persistence in time of positive and negative anomalies.

Coastwise coherence for salinity anomalies is generally poor. However, it is somewhat better in summer than in winter and also in the north if the sample stations are divided into north and south groups.

No clearcut relation exists between the signs of temperature anomalies and the signs of salinity anomalies.

Therefore, predictions of climatic events have low probability of success at present if based on statistics from past records of shore station temperatures and salinities. Namias (1960) and others are currently working toward clarification of the interaction of the atmosphere and the ocean. Perhaps when a better understanding of these physical inter-relationships is gained and when a major break-through toward successful long-range weather forecasting is made, we may be able to use these results in successfully predicting ocean temperatures.

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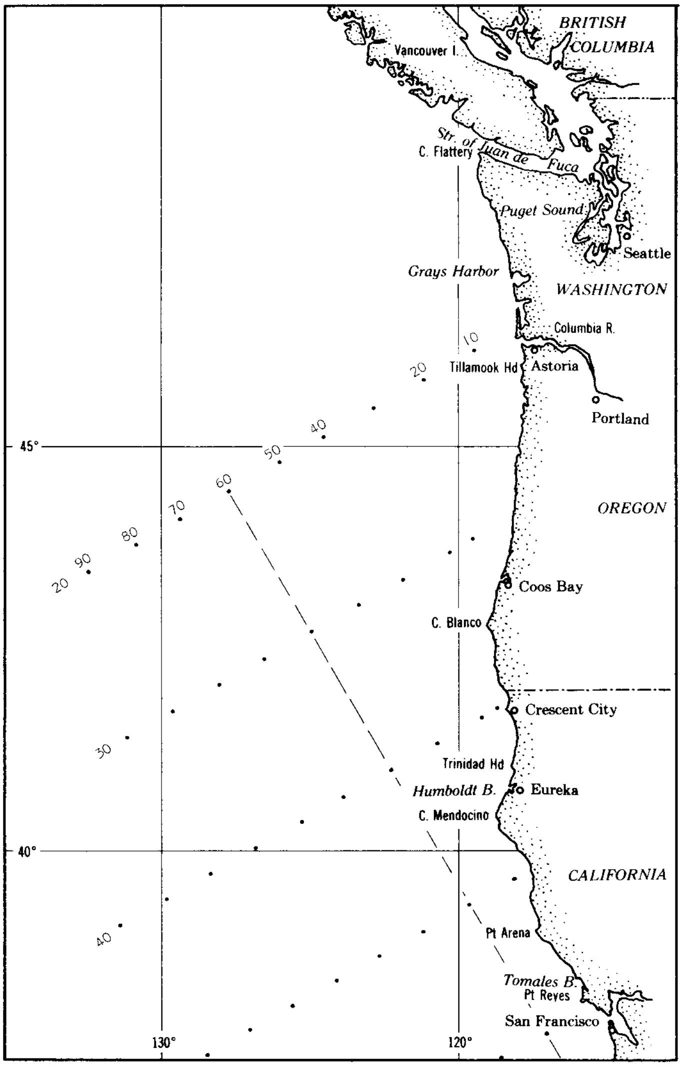

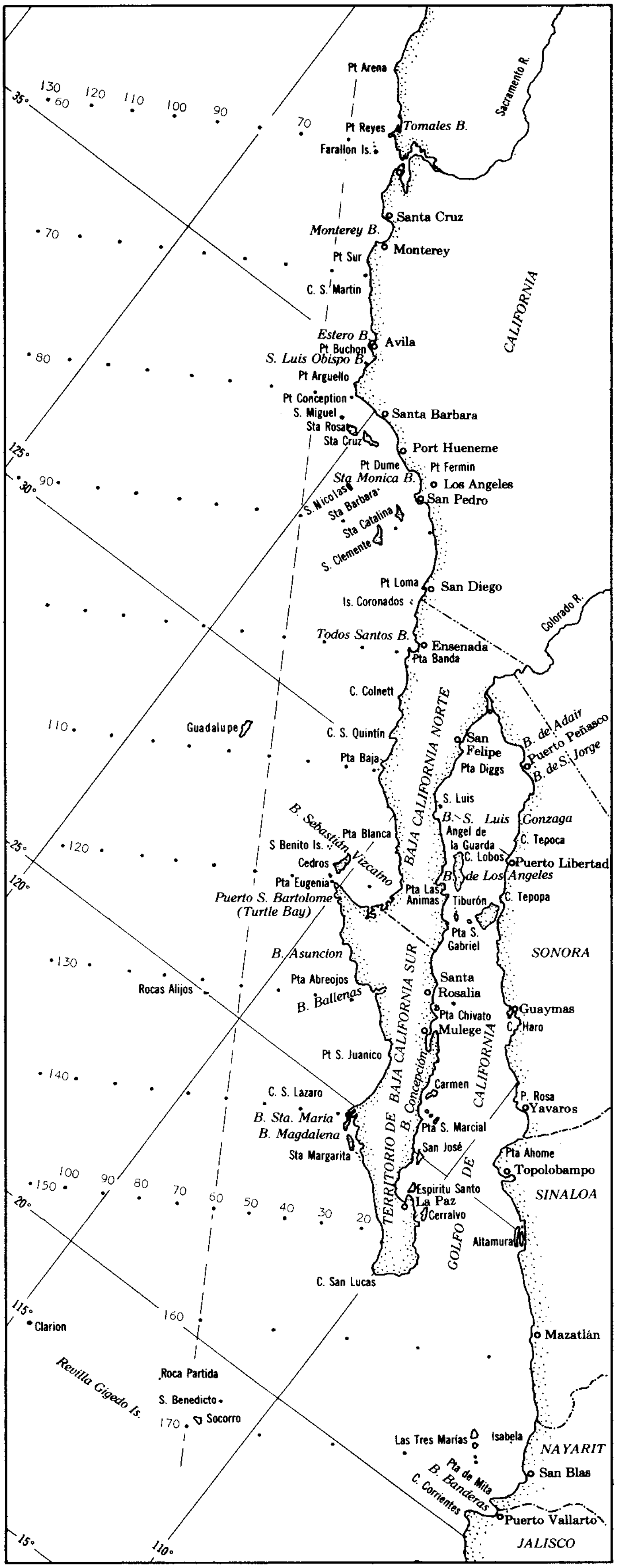

These maps are designed to show essential details of the area most intensively studied by the California Cooperative Oceanic Fisheries Investigations. This is approximately the same area as is shown in red on the front cover. Geographical place names are those most commonly used in the various publications emerging from the research. The cardinal station lines extending southwestward from the coast are shown. They are 120 miles apart. Additional lines are utilized as needed and can be as closely spaced as 12 miles apart and still have individual numbers. The stations along the lines are numbered with respect to the station 60 line, the numbers increasing to the west and decreasing to the east. Most of them are 40 miles apart, and are numbered in groups of 10. This permits adding stations as close as 4 miles apart as needed. An example of the usual identification is 120.65. This station is on line 120, 20 nautical miles southwest of station 60.

The projection of the front cover is Lambert's Azimuthal Equal Area Projection. The detail maps are a Mercator projection. Art work by George Mattson, U. S. Bureau of Commercial Fisheries.