A SUMMARY OF BCF INVESTIGATIONS OF THE PHYSICAL-CHEMICAL OCEANIC ENVIRONMENT OF PACIFIC SALMON, 1955-68

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INTRODUCTION

When the International North Pacific Commission (INPFC) began its investigations in 1955 knowledge of the distribution, abundance, origin and movements of Pacific salmon on the high seas was almost non-existent (Jackson, 1963). Although some information concerning oceanographic conditions in the North Pacific Ocean was available, it was fragmentary (Fleming, 1955); and knowledge of relationships between oceanographic conditions and salmon were also almost non-existent, particularly in the eastern part of the ocean. Broad studies of the sea life of the salmon were commenced along six lines of research: study of seasonal movements as indicated by the fishery; tagging; marking of seaward migrants; differentiation of stocks by morphological, physiological or biological characteristics; special high seas fishing to study movements and the factors controlling them; and a study of oceanography, physical and chemical.

The purpose of this report is to summarize briefly the significant results of BCF physical-chemical oceanographic investigations. It should be pointed out that demands on vessel time for the collection of salmon in specific areas and during specific periods prohibited a systematic detailed, quasi-synoptic study of the ocean, and the small size of the vessels at times permitted only a minimum of observations. Nevertheless, invariably, when significant changes in ocean conditions were encountered changes in salmon catches occurred. This is considered good evidence that when better methods of observation and analysis of oceanographic conditions are available, when more of the biology of the salmon is known, and when more time at sea is spent investigating relationships between the two, considerably more facts will be forthcoming.
According to Davidson and Hutchinson (1938), the Pacific salmon were found along the North American coast from Monterey Bay, California to Kotzebue Sound, Bering Sea; along the Asian coast from the Anadyr River Siberia to the Tumen River, Korea, and Cape Inuboye, Honshu Island, Japan; and in isolated streams along the Arctic coast. Further, although transplants of this genus were attempted in various parts of the eastern coast of North America, east and west coasts of South America, western Europe, Australia, New Zealand and Hawaii, only in Chile, New Zealand and the northeast North American coast was some success attained. Although recently, extensive transplants have been made in the Great Lakes and in the Arctic along the northern Russian coastline, perhaps it is too early to judge the success or failure of this experiment. Thus, it can be said that the native distribution of the Pacific salmon is basically confined to the North Pacific Ocean.

Over 30 years ago, Moulton (1939) in the foreword of a symposium concerning the migration and conservation of salmon held in 1938, summarized the state of knowledge and the challenges inherent in a study of the salmon. "...In the problem of accounting for the migration of salmon one enters a field in which science and romance appear to meet. At least it has often been maintained that the nature fish moved by some strange super-human instinct, return after several years at sea to precisely the stream of their birth and there, in their first home, deposit and fertilize their eggs to begin a new generation. The method of science, however, is to look for explanations of phenomena in the general properties of the world about us, even though at first this seems to us almost or quite supernatural. During the past two or three decades these methods have been extensively used in attempts to account for the migration of salmon. Not only have the currents and the temperatures and the chemical constitutions of the waters in which they live been extensively surveyed,
but salmon of various ages in numbers running into tens of thousands have been marked. In spite of the fact that large numbers of these tagged or marked salmon have been recovered, as reported in this symposium, the story of what takes place in their migrations is yet far from being complete, and the explanations of them are as much open to question......".

At that time there were two opposing theories as to the marine environment of salmon: first, on entering the ocean, salmon remained throughout their lives at sea close to the mouth of their home stream; and second, the fish ranged widely, far beyond any conceivable influence of the home stream to which they predominantly returned. Which theory was correct was really indeterminate because most of the early marine tagging and environmental studies, which commenced in the 1920's, were limited to coastal waters.

In the eastern North Pacific, tagging studies by Gilbert (1924) and Gilbert and Rich (1927), showed that sockeye salmon returning to streams in Bristol Bay moved westward in great numbers over the continental shelf on the southern side of the Alaska Peninsula and northward at the first opportunity, through False Pass, into the Bering Sea. A chum salmon tagged during these experiments was recovered from the Kamchatka Peninsula which indicated an extensive oceanic migration of this species. Although in subsequent years a sockeye salmon was reported caught in middle of the Gulf of Alaska and a school of sockeye salmon reported several hundred miles offshore (Moulton, 1939), the movements of salmon during the marine phase of their life cycle was relatively unknown. Davidson and Hutchinson (1938) believed that salmon frequented waters of open sea as well as these of the immediate coast, and proposed that salmon were limited to waters with temperatures of 0° to 20° C., salinities of 30 to 35 o/oo, and depths of 0 to 200 m. As recently as 1952, a report on an extensive tagging program in coastal waters of southeastern Alaska indicated that there was no evidence that pink salmon came from the open sea when they first appeared in coastal waters, and it was hypothesized that they might simply rise from deep water.
In the western North Pacific Ocean, the Japanese conducted tagging studies during the 1920's near the Kurile Islands and Kamchatka Peninsula. They believed that the marine phase of the salmon's life cycle was spent in a then unknown area of the North Pacific Ocean (Taguchi, 1956). This assumption was given further credence by Japanese tagging studies conducted during the periods 1936-38 and 1941, which showed extensive oceanic migrations of sockeye salmon in the Bering Sea and western North Pacific Ocean. Hartt (1962) has summarized the results of other early tagging investigations in the eastern and western North Pacific Ocean. Oceanographic investigations in the northern part of the North Pacific Ocean have been summarized by Dodimead, Favorite, and Hirano (1963).

In 1952 after the signing of the Convention, the Japanese commenced a commercial salmon-fishing operation in the western North Pacific Ocean, and Fukuhara (1953) reported sizable catches were made in the open ocean and in the vicinity of the Aleutian Islands. Although in subsequent years these commercial operations continued, no additional information concerning the distribution of salmon in the eastern North Pacific Ocean was forthcoming because the Japanese were prevented by Treaty from fishing east of long. 175° West, and principles of conservation prevented Canadian and American commercial interests from fishing in oceanic areas. However, extensive fishing and oceanographic programs were established by research teams in Japan, Canada and the United States in 1955 and information began to be accumulated and pieced together.
The distribution of BCF oceanographic stations in the early phases of the INPFC program is a general indication of the fishing operations which were designed to solve the Protocol problem. The fishing pattern was largely predetermined and oceanographic stations were generally limited to those locations where gillnet fishing was conducted.

Exploratory fishing in 1955 was conducted in the northern Gulf of Alaska, along lines 5° and 10° of longitude east and west of the abstention line (long. 175° W) southward of the Aleutian Islands to lat. 45° N (Fig. 1). Near lat. 49° N there was a sharp north-south separation between catches of salmon and albacore. No salmon were caught south of lat. 47° N and no albacore were caught north of lat. 48° N. At only one location (lat. 47° N, Long. 175° E) were salmon and albacore caught in the same net. Processing of serial oceanographic data at this time was tedious and time consuming and relationships between salmon distribution and environment were sought using surface temperatures because these were readily available. The wide distribution of salmon was somewhat surprising and field operations in 1956 were enlarged to cover the entire area north of approximately lat. 46° N from the Gulf of Alaska as far west as long. 175° E, and the southeastern part of the Bering Sea (Fig. 2). There was a clear demarcation between salmon and albacore catches at about lat. 48° N, and with only a few exceptions salmon were caught at all fishing stations north of lat. 48° N.

The entire emphasis of the 1957 program was shifted from a general distributional study to a statistical one in the central Subarctic Region which called for repetitive fishing at nine locations, lat. 50°, 53°, and 56° N at long. 165° W, 175° W and 175° E (Fig. 3). These locations lacked not only geographical continuity because of the Aleutian Island arc but also environmental continuity because at lat. 50° N the flow is eastward, immediately south of the
Aleutian Islands it is westward, and immediately north of the islands it is eastward. Thus, the plan was not particularly successful from an environmental standpoint.

Operations were confined generally to the area east and west of the Abstention Line, long. 175\(^\circ\) W, during the years 1958 to 1961 (Figs. 4 to 7) and fairly good coverage was obtained. Oceanographic observations were obtained, not only at and between fishing stations, but en route to and from the fishing area. Although only two charter vessels participated in the 1959 field work, the greatest geographical coverage was obtained. During the 4-year period, it was obvious that there was time for only superficial analysis of the oceanographic data before the field work commenced the following spring and it became necessary to curtail field work when the experimental fishing commenced year around observations. The crowded space, living conditions, working schedule, vibrations and motion aboard the small boats prevented any extensive chemical analyses or data processing at sea. Since this was before the development of inductive salinometers, STD's and machine processing, it is obvious from the number of oceanographic stations that extensive interpretation of data was not possible prior to the next field season.

It soon became obvious that in order to discover distributional patterns of adult salmon, the majority of which began migrating to natal streams prior to July, operations had to begin in early spring. Although one charter vessel commenced fishing as late as July in 1957, vessels chartered in 1958 commenced field operations as early as May; and field operations in 1959 commenced in April and terminated in September.
Ocean conditions and salmon distribution were observed to be different each spring. On the assumption that spring conditions were strongly influenced by the preceding winter, it was necessary to consider winter operations. Because of the frequent severe storms during the winter, we required large vessels, not only for reasons of safety, but also so that fishing could be conducted in rough seas. (The motions of the smaller vessels in moderate to rough seas prohibited work on deck). The MV Bertha Ann was chartered in February 1962 and we were able to conduct the first winter salmon distribution and oceanographic cruise in this part of the Subarctic Region (Fig. 8). Subsequently we were able to acquire a similar type vessel, the RV George B. Kelez. Both were surplus coastal cargo vessels (AKL type) and, because the main deck was only 2-3 meters above the water-line, these were easily adaptable to field work.

Although some fishing was accomplished aboard the Kelez in 1963 and 1964, time was required to install the oceanographic laboratory space and equipment that would permit shipboard analysis of data. Periodic testing of these facilities was done during cruises off the Washington coast during 1963 to 65; these cruises will be the subject of another report. Nevertheless, some oceanographic observations, such as bathythermograph lowerings, were obtained during the salmon cruises and serial data from hydrographic casts were obtained in winter and summer 1963 (Fig. 9). It was not until fall 1965 (Fig. 10) that we were ready to resume complete physical-chemical observations but only limited biological oceanographical observations aboard the Kelez in the Aleutian area on a year round basis. At this time, primary emphasis of fisheries programs was devoted to forecasting the size of the sockeye salmon run of Bristol Bay and the area south of Adak Island was selected as an index site. Thus, a large part of the field work from 1966 to 1968 was concentrated in the vicinity of long. 175° W (Figs. 11 to 13).
Physical and chemical data from all these cruises (Table 1) have been tabulated and are available in published form or as INPFC Documents. These data, and the extensive bathythermograph data obtained during field operations are also on file at the National Oceanographic Data Center.
Table 1.—List of oceanographic cruises sponsored or conducted by the BCF Biological Laboratory, Seattle, Washington.

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<tr>
<th>Vessel</th>
<th>Cruise period</th>
<th>Data reference</th>
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<tr>
<td><strong>John N Cobb</strong></td>
<td>July - September</td>
<td>Favorite and Love (1957)</td>
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<tr>
<td><strong>Paragon</strong></td>
<td>August - September</td>
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<tr>
<td><strong>Mikof</strong></td>
<td>August - October</td>
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<tr>
<td><strong>Celtic</strong></td>
<td>July - September</td>
<td>Love (1959)</td>
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<tr>
<td><strong>Mikof</strong></td>
<td>May - September</td>
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<tr>
<td><strong>Paragon</strong></td>
<td>July - September</td>
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<td><strong>Tordenskjold</strong></td>
<td>May - September</td>
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<td><strong>Attu</strong></td>
<td>May - September</td>
<td>Favorite and Pederson (1959)</td>
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<td><strong>Paragon</strong></td>
<td>July - September</td>
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<tr>
<td><strong>Pioneer</strong></td>
<td>June - September</td>
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<tr>
<td><strong>Attu</strong></td>
<td>May - August</td>
<td>Favorite and Pederson (1959)</td>
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<td><strong>Pioneer</strong></td>
<td>May - August</td>
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<tr>
<td><strong>Pioneer</strong></td>
<td>April - August</td>
<td>Favorite, Callaway and Hebard (1961)</td>
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<tr>
<td><strong>Tordenskjold</strong></td>
<td>May - September</td>
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<tr>
<td><strong>Paragon</strong></td>
<td>May - July</td>
<td>Morse (1964)</td>
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<tr>
<td><strong>Pioneer</strong></td>
<td>May - August</td>
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<tr>
<td><strong>Marine View</strong></td>
<td>May - August</td>
<td>Morse (1964)</td>
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<td><strong>Paragon</strong></td>
<td>May - August</td>
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<tr>
<td><strong>Bertha Ann</strong></td>
<td>February - April</td>
<td>Favorite, Morse, Haselwood, and Preston (1964)</td>
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<tr>
<th>Vessel</th>
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<th>Data Reference</th>
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<tr>
<td>George B. Kelez</td>
<td>February - March</td>
<td>Ingraham (1964)</td>
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<td></td>
<td>July - September</td>
<td>Van Dyke (1966)</td>
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<td></td>
<td>1963</td>
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<tr>
<td>George B. Kelez</td>
<td>October - November</td>
<td>Ingraham (1969)</td>
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<td></td>
<td>1966</td>
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<tr>
<td>George B. Kelez</td>
<td>February - March</td>
<td>Ingraham and Fisk (1969)</td>
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<tr>
<td>Paragon</td>
<td>June</td>
<td>Larrance (1969)</td>
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<tr>
<td>George B. Kelez</td>
<td>July - September</td>
<td>Ingraham and Fisk (1969)</td>
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<td>1967</td>
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<tr>
<td>George B. Kelez</td>
<td>January - March</td>
<td>Ingraham and Fisk (1969)</td>
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<td>June - August</td>
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<td>1968</td>
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<tr>
<td>George B. Kelez</td>
<td>February - March</td>
<td>Ingraham and Fisk (1969)</td>
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<td>April - June</td>
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<tr>
<td>Miller Freeman</td>
<td>July - August</td>
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1/ Oceanographic observations, North Pacific Ocean, October 2 - November 8, 1965. RV George B. Kelez, BCF, Bio. Lab., Seattle, Washington (Processed.).


3/ Atomic Energy Study - Stations not shown — see McAlister, W. B., C. Mahnken, R. C. Clark, Jr., W. J. Ingraham, J. Larrance and D. Day. MS. 1968. Final report, oceanography and marine ecology in the vicinity of Amchitka Island. Battelle Memorial Institute, Columbus, Ohio. 146 pp. (Processed.)
PHYSICAL–CHEMICAL ENVIRONMENT OF SALMON

The results of field work in 1955 resolved two significant conditions: salmon were caught in surface gill nets at all fishing locations from northern Vancouver Island across the Gulf of Alaska to Unalaska Island, and catches at the more western and southern fishing locations revealed an apparent southward limit of salmon at about lat. 47°N (Powell and Peterson, 1957). Because salmon were believed to remain near the sea surface, there was an immediate tendency to accept the surface isotherm near lat. 47°N, 11° C., as an environmental boundary (INPFC, 1955 – p. 60). However, analysis of water properties below the surface in the area in which sockeye salmon were caught showed that this area was characterized by a subsurface temperature-minimum stratum at approximately 100 m. depth in which the temperature was equivalent to that existing in the winter months at the surface in this area, approximately 3° C. It was noted that this stratum provided a year round constant temperature environment to salmon in the Gulf of Alaska (Favorite, 1957). Because this temperature was generally considered a lower threshold for most salmon, and the fact that temperatures in this stratum decreased westward reaching values less than 0° C. in the vicinity of the Kurile Islands, some speculation existed as to whether Asian salmon migrated from the western to the eastern Subarctic Region during winter.

The success of the 1955 field season provided the stimulus for a greatly expanded program in 1956. Field operations were extended into the Bering Sea and an interesting relationship between salmon and the environment was obtained from data along long. 170°W in June. North of lat. 57°N, and thus over the shallow continental shelf of Bristol Bay, temperatures throughout the water column were less than 3° C.; and only one sockeye salmon was caught at each of three sets in this area; however, seaward of the shelf, at lat. 56°N, where temperatures were nearly 6° C. at the surface and greater than 4° C. at
depth, over 900 sockeye salmon were caught (Favorite, 1957). This implied that sockeye salmon might concentrate for a short period off the shelf until seasonal warming created a favorable regime for the onshore migration to river systems in Bristol Bay.

The north-south lines of stations south of the Alaskan Peninsula and eastern Aleutian Islands provided valuable information on the southern extent of the salmon environment. Although the wide spacing of oceanographic observations (over 100 km.) did not reveal any significant fronts at the surface, the distributions of temperature and salinity at the surface clearly reflected divergences in the flow south of the Aleutian Islands, near long. 170°W; one branch turning northward into the Bering Sea, another continuing westward along the southside of the islands, and a third turning eastward and recirculating around the Gulf of Alaska. It was felt that this divergence might have some effect on salmon distribution, but no particular pattern was evidenced in the salmon catches in this area. (Favorite and Hanavan, 1963 - p. 63). However it should be pointed out that not only were the stations in poor locations relative to the flow, but the east-west spacing of the lines of stations was about 350 km. and thus little relationship could be expected. Nevertheless, the vertical water structure clearly indicated several different environments.

Although the origin of the cold temperature-minimum stratum in the Gulf of Alaska and south of the eastern Aleutian Islands was still in doubt (INPFC, 1957 p. 83), the southern boundary of the stratum was an excellent indication of the southern limit of salmon during summer (Favorite 1957; Favorite and Hanavan, 1963). Four areas with significantly different oceanographic conditions were defined: Gulf of Alaska, south of Aleutian Islands (between long. 179°W and 170°E), west of long. 170°E to the Asian continent, and the Bering Sea.
Data accumulated in 1956 also permitted identification of four specific water masses south of the Aleutian Islands using temperature-salinity relationships below the surface layer. These were identified as: (1) water originating off the Asian coast, (2) water formed in the central part of the Gulf of Alaska, (3) water flowing westward along the Aleutian chain, and (4) water of an intermediate or transition nature between Subarctic and Pacific Central Water (Favorite and Hanavan, 1963). No salmon were caught in the transition zone which existed southward of the other three.

Further investigations of relations between these water masses and salmon distribution was delayed until 1958 because experimental fishing in 1957 was largely confined to the 9 locations indicated in the section on the scope of oceanographic studies. However, extensive bathythermograph lowerings while the vessels moved along N-S cruise tracks provided an indication of temperature changes associated with the flow along the south side of the Aleutian islands (INPFC, 1959, p. 81-84; Calloway, 1963), and provided the first indication of the continuity of a significant westward flow of warm water along the south side of the Aleutian Islands. An investigation of historical data showed that the influence of this warm water could extend as far west as long. 165°E. South of this warm intrusion, cold water intruded eastward from the Asian coast into the central Aleutian area. The relative identity of sockeye salmon, as determined by meristic characters, caught in these two water masses in 1957 indicated that the former was a preferred environment for North American sockeye salmon and the latter for Asian sockeye salmon. It was hypothesized that the westward terminus of the warm water flowing westward along the south side of the Aleutian Islands was partially effective in separating these two stocks (INPFC, 1959, p. 85-87). Further conclusive evidence of a separation of sockeye stocks in this area was subsequently provided as a result of an analysis of salmon tagging studies by Kondo, Hirano, Nakayama and Miyake (1965 - p. 53-55).
Particular emphasis was placed upon obtaining more knowledge of salmon distribution in the vicinity of the Aleutian Islands during the 1958 field season and this prevented any further investigation of the southern boundary of the environment. We were able to show that the position of the warm water with respect to the western Aleutian Islands was quite variable. Whereas in 1957 it was contained southward of Attu Island, there was a marked northward intrusion into the Bering Sea east of Attu Island in 1958.

A better description of the four water masses identified in 1956 south of the central Aleutian Islands, between long. 170°W and 170°E, was obtained in 1958, and a model of vertical water structure was presented for use in ascertaining the particular environment in which salmon were caught (Favorite, 1960—water mass (1) was now identified by a cold trough with a deep (200–300 m. depth) temperature-minimum stratum formed during winter in the western part of the ocean and advected eastward; water mass (2) was characterized by a warm ridge with a shallow (100 m. depth) temperature-minimum stratum formed locally during winter and was basically a shear zone between the westward flow to north and eastward flow to the south; water mass (3) was identified by a warm trough and high westward flow; and water mass (4) although erroneously identified as central Pacific water, was basically a transition zone between Subarctic and Subtropic Water. The distribution of fishing stations was not designed to investigate relationships between salmon and water masses and no specific correlation was apparent in the catch.

Perhaps the most significant aspect of the 1958 field season was the extensive oceanographic coverage obtained by all agencies. It was apparent from the results of the 1957 field work that our knowledge of oceanographic conditions would be greatly enhanced by investigating the continuity of features across the ocean and considerable effort was expended by members of the INPFC Subcommittee on Oceanography, not only to obtain as broad a coverage as possible,
but also to encourage other agencies to conduct oceanographic cruises in the Subarctic Region. Excellent coverage, far superior to that obtained by the 1955 NORPAC cooperative effort, was obtained in the northern part of the ocean. An oceanographic atlas was compiled (Dodimead and Favorite, 1961) which revealed a remarkable continuity of surface and subsurface oceanographic features across the ocean. These data were also used to define southern limit of salmon distributions during summer and winter in relation to oceanographic features (Favorite and Hanavan, 1963).

Field work in 1959 consisted basically of fishing stations at 111 km. (60 mile) intervals along north-south cruise tracks at 5° intervals of longitude from approximately long. 170°E to 160°W from as far north as lat. 60°30'N, and south to lat. 47°N. Data obtained permitted an excellent description of the westward flow along the south side of the Aleutian Islands and water mass (3), or the warm trough, was first given the name, Alaskan Stream (Favorite, 1967b). Evidence was presented that the flow extended as far westward as long. 165°E near lat. 50°N where it diverged sending one branch into the Bering Sea and the other south and then eastward into the Subarctic Current. A westward flow of 85 cm/sec (1.7 kts) was found south of Adak Island which was commensurate with, not only speeds of salmon migrations in this area, but also the general direction of movement as determined by gillnet and purse seine sets. The fact that sockeye salmon tagged in this current system as far west as Attu Island returned to Bristol Bay gave sound evidence that the provisional abstention line established at long. 175°W in this area did not protect this North American stock.
Other interesting relations between salmon catches and the environment south of the Aleutian Islands were also revealed in 1959. The eastward flowing current that existed south of the Alaskan Stream and previously identified as water mass (1) was given the name Oyashio Extension; and it was shown that the ridge structure which separated the two opposing current systems was very narrow in this area. Average fork lengths of sockeye salmon caught at locations south of the Aleutian Islands along long 175°E in May showed a difference of about 60 mm. between salmon caught in the westward flowing Alaskan Stream and those caught in the eastward flowing Oyashio Extension current system; pink salmon catches increased from none to 102 (Favorite, 1959).

A comparison of the boundaries of the discrete water masses defined using 1956 data with water of similar characteristics in 1959 showed that considerable changes in the boundaries of these four environments could occur (Favorite and Hebard, 1961). Large numbers of sockeye salmon were found in August (and thus probably immature salmon) south of the Alaskan Peninsula and eastern Aleutian Islands in the surface water above the ridge structure. The largest amount of planktonic food organisms was also found in this area.

Up to this time our field work was conducted in late spring and summer. Salmon catches south of the Aleutian Islands and in the Gulf of Alaska showed little indication of a preferential environment by species and one was forced to conclude that separation on the high seas might only be by stocks or places of origin. Since racial studies were only beginning to develop techniques for such identifications it was difficult to ascertain specific relationships between salmon and the environment. Although we had shown that pink salmon along long 175°E were absent from the more northern waters in May 1959, we were unprepared to find the sharp separation of sockeye and pink salmon in the Gulf of Alaska revealed by Canadian long-line catches in April and early May 1962 (INPFC, 1964 - pp. 30-43). Large catches of sockeye salmon were not
found in the peripheral coastal waters through which the salmon must pass to reach native streams. The sockeye salmon were concentrated in the central part of the Gulf, and the distribution corresponded very closely with the water mass associated with the oceanographic feature described previously as the ridge area (Favorite, 1967). An indication of a similar distribution of immature sockeye in August 1959 has also been discussed previously, but the salmon in the Gulf of Alaska were largely mature salmon.

Demands for distributional studies and large samples for racial analyses dominated our vessel deployment in 1960 and 1961. Although we continued to monitor oceanographic conditions at fishing stations and completed some further plankton studies, major emphasis was devoted to analyses of previous data and an extensive review of past and present oceanographic investigations which was compiled jointly with A. J. Dodimead (Canada) and T. Hirano (Japan) (Dodimead et al., 1963). In this work, the concept of water masses was subjugated to that of a domain concept in which one or more oceanographic parameters are used to define the boundaries of specific environments.

The domain concept, although quite a general descriptive tool, provided the needed description of dominant oceanographic features of Subarctic Region. This avoided the inherent controversies of delimiting boundaries of finite features in three dimensions using what were still considered only fragmentary data. There was some reluctance to accept the southern boundary (rather than the northern one) of the Transitional Domain (whose extent was basically identical to the previously described transitional water mass) as the southern boundary of the Subarctic Region, not only because of the high temperatures in the Transitional Domain, but also because of the absence of a shallow temperature-minimum stratum. But the choice provided a single descriptive term for the salmon environment and was accepted.
One shortcoming of the joint report on oceanography, and a serious gap in our knowledge of salmon distribution, was the absence of data in the central and western Subarctic Region during winter. This was largely due to the fact that not only were our charter vessels too small to endure the weather and to permit work in this area characterized by severe winter storms but Japanese fishing and research vessels were also not considered safe enough to conduct operations in this area. However, we chartered the MV Bertha Ann and conducted the first winter oceanographic and salmon fishing cruise south of Adak Island (long. 175°W) during the period February 14 to March 6, 1962 (Favorite, Morse, Haselwood and Preston, 1964).

As far as environmental investigations were concerned, we hoped to answer several important questions. First, was the Alaskan Stream present during winter? Uda (1963) believed that this warm westerly flow south of the Aleutians developed near the end of the Alaskan Peninsula in spring and summer and extended to western end of the Aleutian Island chain by August. Second could salmon be caught in this area during winter? And third, what would be the southern limit of salmon distribution? A strong westward flow having temperatures greater than 4°C between 50 and 100 m. depth was found south of Adak confirming the Alaskan Stream as a year round feature. Thus, it was established as a significant current system of the North Pacific Ocean. One or more of the five major salmon species were caught at one or more stations between Adak Island and lat. 45°N along long. 175°W. South of lat. 45°N Transition Water was encountered, and it extended to lat. 42°N where the Subarctic-Subtropic Boundary occurred. No salmon were caught south of lat. 45°N (Favorite and Morse, 1964). Comparison of vertical temperature structure between winter and the previous summer along this longitude indicated that seasonal cooling occurred only within the upper 50 m. in the area between Adak Island and lat. 41°N even though a pronounced change in vertical
distribution occurred at lat. 45°N. This suggested that features below this layer were relatively permanent and might provide some orientation to salmon during a 1-3 year residence in the ocean—provided (1) they move this deep in the water column or (2) they are influenced by an item, such as a food organism, that is associated with the lower layer.

The successful cruise of the MV Bertha Ann resulted in acquisition of a similar type vessel, RV George B. Kelez, and salmon distribution cruises continued. However, although much more research was required in regard to environmental relationships, we required laboratory space and electronic devices that would permit processing and analysis of data at sea and more freedom to select fishing locations on the basis of oceanographic conditions. Although some modern oceanographic facilities were developed aboard the Kelez during 1963 and 1964, it was obvious prior to this time that we not only required an enormous field program, but also a much larger analytical staff if we were to be responsible for ascertaining annual environmental changes throughout the Subarctic Region and their effect on salmon, which migrated from the central part of the region to both eastern and western shores. Having described the basic salmon environment (Dodimead et al., 1963), we were found with the problems of defining in time and space what features or continuity of flow influenced salmon movements and how to ascertain or forecast these conditions with sufficient rapidity and accuracy to permit research vessels and industry to utilize this information. Because funds were limited alternative solutions were sought.
FORECASTING PHYSICAL-CHEMICAL CONDITIONS

A major breakthrough in the rapid estimation or forecasting of oceanographic conditions was accomplished by Fofonoff (1962), who provided a method of obtaining theoretical wind-driven transports for the North Pacific Ocean based entirely upon mean monthly atmospheric pressure at sea level. Comparison between these transports and those computed from shipboard observations was made for conditions during summer 1958 (year the best oceanographic coverage of the North Pacific Ocean had been obtained) and the results were in good agreement (Favorite, 1961a; Favorite and Morse, 1963). Comparison between these theoretical wind-stress transports and calculated geostrophic volume transports during summer 1959 in the Alaskan Stream also showed good agreement (Favorite, 1967) even though boundary conditions and bottom topography were not considered. The advantages of estimating environmental conditions using wind-stress transports are that these transports not only are independent of costly and often inadequate oceanographic measurements, but also that they can be calculated on a monthly basis with little delay in real time from meteorological data. Mean values of winter and summer wind-stress transports for the decade 1950 to 1959 were compared and a noticeable increase in Alaskan Stream transport during winter was noted (Favorite, McAlister, Ingraham and Day, 1967).
Wind-stress transport in the Gulf of Alaska was also found to be much greater during winter than summer even though geostrophic volume transports show a relatively constant value year round. Comparison of wind-stress transports and connected sea-level measurements in the Gulf of Alaska indicate that winter intensification can exist, but the readjustment of mass in the water column is too slow to show the effects of this periodic force. Thus, previous descriptions of flow in this area based upon serial oceanographic data reflect only a quasi-steady state and current speeds based upon this method may be much too low in winter and too high in summer (Favorite, 1968). Thus, the wind-stress method of estimating transports may actually prove to be more accurate than that which uses oceanographic data when the former are derived in a more rigorous manner. We are presently trying to improve this method.

One immediate application of knowledge of transport in specific areas is the possibility that variations in the intensity of the Alaskan Stream may be directly related to not only the percentage of Bristol Bay sockeye salmon migrating westward of the abstention line, but the distance they move westward of it (Favorite et al., 1967 – pp. 95-96).

Another alternative to the problem of predicting flow which was considered was a drifting telemetry buoy program. A program of this kind would provide information on the gross environmental changes in the Subarctic Region, as well as the basis for improvement of forecasts from wind-stress transports, particularly in the area of boundary currents such as the Alaskan Stream. We conducted an extensive drift bottle study during the winter cruise of the RV George B. Kelez in the central Subarctic Region in 1962-64 that indicated objects released south of the Aleutian Islands between lat. 49° and 42° N were recovered on the North American coast between Kodiak Island and Oregon (Favorite,
1964a); and a drifting telemetry buoy program to augment shipboard studies was suggested to the INPFC (Favorite, 1964b). In order to obtain further support a specific joint proposal was made during a meeting in Tokyo in March 1964 under the auspices of the United States-Japan Cooperative Science Program to track a telemetry buoy across the Pacific Ocean (Robinson, 1964). Even though considerable interest in such a program was shown by Japanese and American scientists, this was only one of many proposals from one of a variety of scientific committees which were established under this program, and no action was taken.

Nevertheless, tests of drifting telemetry buoys were conducted off the Washington coast from May to July, 1964 (Favorite, Fisk and Ingraham, 1965), and an experiment was suggested in which buoys would be released at periodic intervals in the vicinity of the Kurile Islands and frequent determination of positions would be made by aircraft, ships, and eventually even satellite (Favorite, 1966; Favorite and McAlister, 1966). Successful data telemetry tests were carried out in summer 1967, and a description of the experimental buoy has been presented (McAlister, 1969). Attempts to establish a satellite communication link has been hampered by lack of adequate funding and failure of a NIMBUS satellite (McAlister, Ingraham, Day and Larrance, 1969).
Field studies in the central Subarctic Region in 1965 indicated that during fall, immature sockeye salmon south of Attu Island were found predominantly in the area of low flow over the ridge structure rather than in the westward flowing Alaskan Stream to the north, or the eastward flowing subarctic Current to the south (Ingraham, 1966).

The first oceanographic observations in the western Subarctic Region during winter were obtained during the cruise of the RV George B. Kelez in February and March 1966 (Fig. 11). The geostrophic current pattern south of Attu Island clearly indicated the terminus of westward flow in the Alaskan Stream to occur near long. 165°E and that the Komandorskiy Ridge influenced current patterns in this area (Favorite et al., 1967). Further discussion on flow in this area has been presented by McAlister, Favorite and Ingraham (1969).

Subsequent field work in 1966-68 has been more or less concentrated south of the Aleutian Islands, particularly south of Adak Island (the location of an indexing site for Bristol Bay sockeye salmon). We have been able to show the variability of oceanographic conditions in this area (Ingraham and Favorite, 1968; McAlister, Ingraham, Day and Larrance, 1969; McAlister et al., 1969).

Installation of an electronic remote sensing device S-T-D (Salinity-temperature-depth) aboard RV's George B. Kelez and Miller Freeman, has permitted a great reduction in the spacing of oceanographic stations and more precise definitions of oceanographic features in this part of the Subarctic Region. Five areas were defined that we believe to affect the distribution and movements of salmon in the central Subarctic Region south of the Aleutian Islands: (1) Oyashio extension, (2) Ridge, (3) Alaskan Stream, (4) Transition, and (5) Subarctic Current Areas.
(McAlister et al., 1969). The new feature, Subarctic Current Area, was defined as the area associated with the southern extent of the temperature-minimum stratum where the abrupt presence of warm water at depth results in a narrow band of higher than average eastward geostrophic velocity in the Subarctic Current System.

If we consider these five areas in detail it is realized that three are not necessarily identified at the surface where the salmon are being caught in gill nets. The Oyashio extension is identified by cold water, usually less than 3.6° C., at depths of 200-400 m. (and is actually part of the Subarctic Current system but not necessarily in main axis of geostrophic flow); the Ridge area by the isohaline configuration below the layer of seasonal overturn, 100-200 m; and the Transition area by temperatures of 4-9° C at 200 m. Only the Alaskan Stream and Subarctic Current areas are evident at the surface and then not by any visual or surface observation, but only through knowledge of water structures obtained by oceanographic casts to depths of at least 300-500 m.

These features certainly characterize the oceanographic conditions in this area and, although they have been used to ascertain relationships to salmon distribution patterns, care must be exercised in establishing specific relationships until we know more details about surface and subsurface flow.
It is impossible to determine actual flow in the ocean except by
direct measurements, and even these techniques are not perfected at the present
time; although drifting telemetry buoys would provide this information. This
is indeed unfortunate because knowledge of the direction and magnitude of flow
is of paramount importance when trying to establish relationships between the
environment and migrating salmon. Some indication of circulation has been
derived from the distributions of temperature and salinity, but one must be
cautious because, depending upon the type of mixing that occurs, erroneous
interpretations are possible. In fact, there are areas in the Subarctic Region
where surface values of temperature and salinity indicate entirely different
surface flows (Favorite, 1961b).

In the absence of direct measurements, relative geostrophic currents
provide a method of estimating flow and this method has been extensively, if
not almost exclusively used in INPFC studies by all contributors. A synthesis
of the extensive data available provides a general picture of circulation that
belies the year to year and season to season complexity that exists, and thus
is of only general use.

There is evidence that the surface flow in some areas, particularly
near the Aleutian Islands, is quite different from the flow at, or deeper than,
300 m.; and without experimentation, it is impossible to tell which system has
the most influence on the movements of salmon. For example, during feeding
periods salmon may respond to surface conditions, but they may use the subsurface
conditions to remain oriented to water masses that have continuity to areas close
to natal streams—provided (1) salmon descend to these depths, or (2) they are
influenced by an item, such as a food organism, that is associated with these
depths.
OCEANOGRAPHIC TERMINOLOGY, CENTRAL SUBARCTIC REGION

Our INPFC investigations have greatly expanded existing knowledge of the oceanic environment of the Pacific salmon, and established relationships between salmon distribution and the environment that strongly suggest salmon are influenced at certain times and areas by oceanographic conditions. It would be helpful if national sections used a common terminology when reporting oceanographic features in future reports. The following terms are used in describing our research activities.

The central Subarctic Pacific Region south of the Aleutian Islands can be divided into three major areas. The northernmost is the Alaskan Stream Area, a narrow intense westward flow bounded on the north by the Alaskan Peninsula and the Aleutian Chain. Immediately south of the Alaskan Stream lies an area of weak, variable currents called the Ridge Area because of characteristic ridging in the subsurface salinity structure. South of the Ridge Area begins the general filamentous eastward flow which covers a major portion of the Subarctic and Subtropical Regions of the North Pacific Ocean. The portion of this flow which lies within the Subarctic Region is the Subarctic Current.

North-south flows across the Ridge Area can result in the formation of gyres which may fragment the circulation into two or more partially closed subsystems. Two commonly reported gyres are the Alaskan Gyre usually centered south of the Alaskan Peninsula, and the Western Subarctic Gyre located near the western extremity of the Aleutian Chain. Besides these two semi-permanent gyres it is probable that others of varying permanence and effectiveness in separating flow systems are present from time to time. All of these features, except the Ridge Area, are presented in INPFC Bulletin No. 13 as parts of the Upper Zone Domains.
Within the broad eastward flow, referred to above as the Subarctic Current, there are four subareas which are believed to have biological significance:

1. The Recirculation Area, a new term, is applied to the location where warm, less saline Alaskan Stream water crosses the intervening Ridge Area by one of several possible processes and is subsequently carried eastward in the northernmost filament of the Subarctic Current.

2. One or more filaments of the Subarctic Current typically transport at depth a distinctive core of cold Western Subarctic Water. Although the location of this feature has been formerly denoted the Oyashio Extension Area, a more proper term is the Western Subarctic Intrusion Area.

3. The area where the temperature structure slopes sharply downward to the south in the water column, generally resulting in the highest eastward geostrophic velocities found in the Subarctic Region, has been called the Subarctic Current Area.

4. Extending southward from this subsurface temperature discontinuity to the southern boundary of the Subarctic Region is the Transition Area. This area, containing distinctly higher temperatures than the waters to the north, and the absence of a temperature-minimum or salinity-minimum stratum at depth, represents a transition between the Subarctic Region and the warmer and more saline Subtropical Region to the south.

Only one of these subareas, the Transition Area, has been identified in the Upper Zone Domains. The other three are considered useful in describing oceanographic conditions during fishing operations and have continuity beyond the central Subarctic Region.
Research associated with ascertaining relationships between these areas and the time and space distribution of salmon is continuing. More experimental fishing should be conducted at locations where sharp fronts exist at the boundaries of these areas, and there is good indication that continuous records of surface temperature and salinity along north-south cruise tracks can aid in locating these fronts. Cruise plans of this type conflict with those designed to obtain the general distributional pattern of salmon over a large area, but it is suggested that both approaches be considered.

FUTURE STUDIES

The exact relation between salmon distribution and physical-chemical oceanographic features has not been established. Some studies; such as Royce, Smith, and Hartt [1968]; have shown, however, that oceanographic features have a definite influence on salmon, and routine oceanographic observations should continue to be an integral part of field studies of salmon distribution. Much research remains to be accomplished, particularly in the Bering Sea, it is important that a significant part of the oceanographic effort be devoted to forecasting environmental conditions.

Since the beginning of the research program when small, modestly equipped charter vessels ventured forth into the comparatively unknown reaches of the Subarctic Region, we have gradually improved our research platforms, equipment, and techniques to the point where they are equal or better than any existing in the world today. Analyses of oceanographic data that previously required special training and extensive time to complete are now performed almost instantaneously aboard ship by modern machine methods and the results can be utilized to plan daily fishing operations. So we have reached our first plateau—we have general
knowledge of oceanographic features, and the laborious task of obtaining serial observations by Nansen bottle and the computations associated with subsequent tabulation and presentation of data is no longer necessary. The fishery biologist can obtain, almost by the push of a button, a visual presentation of the vertical distribution of salinity and temperature, as well as some indication of geostrophic currents. From this information and general guideline established by oceanographers as a result of previous studies, intelligent selection of fishing locations can be made, and environmental relationships ascertained.

But we have accomplished only half of the task. It is not enough to be able to recognize specific oceanographic features when they are encountered at sea, we must be able to predict their existence and location otherwise we are still in the searching phase. Modern science has provided us with observations that were only dreamed of a decade ago. Satellites provide daily pictures of cloud cover denoting the area and intensity of storms at sea that effect environmental conditions as well as ocean circulation patterns. And even though it appears that drifting oceanographic buoys will not become a reality in the near future, moored buoys exist now just south of the central Subarctic Region, and expansion of the moored buoy program is anticipated.

During the early years of our research, we were entirely dependent upon our vessels to obtain any information on sea surface temperatures in our operating area, and awaited with intense interest the first reports to ascertain general thermal conditions. Now surface temperature distribution charts are available for 5-day intervals from the U.S. Naval Fleet Numerical Weather Central at Monterey. These reflect not only our data, which are radioed directly to the Central, but data from all reporting ships in the area. The data are machine processed and promptly distributed. These charts, those of sea level pressure from which we determine wind-stress transports, in addition to charts of other meteorological parameters provide additional data that aid in the forecast of environmental conditions.
Forecasts of general circulation in the Subarctic Region and of specific flows such as the intensity of the Alaskan Stream past Adak Island, the recirculation in the Gulf of Alaska gyre, and the east-west extents of the Western Subarctic and Gulf of Alaska gyres, are all pertinent to maximum utilization of research vessels at sea, and to possible solutions of the Protocol problem.
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Figure 1.— Oceanographic stations, 1955
Figure 2.— Oceanographic Stations, 1956
Figure 4.—Oceanographic stations, 1958
Figure 5.—Oceanographic stations, 1959
Figure 6.—Oceanographic stations, 1960
Figure 7.—Oceanographic stations, 1961
Figure 8.—Oceanographic stations, 1962
Figure 9.--Oceanographic stations, 1963
Figure 10.—Oceanographic stations, 1965
Figure 11.--Oceanographic stations, 1966

Legend:
- 0 - 3 MILES BETWEEN STATIONS
- 3 - 10 MILES BETWEEN STATIONS
- STATIONS GREATER THAN 10 MILES APART
- NUMBERS INDICATE TOTAL NUMBER OF STATIONS IN PARTICULAR AREA
Figure 12.—Oceanographic stations, 1967
Figure 13a.—Oceanographic stations, April-May 1968
Figure 13b.—Oceanographic stations, July-August 1968