

OCEANOGRAPHIC CONDITIONS AND SALMON DISTRIBUTION SOUTH OF THE ALASKA PENINSULA AND ALEUTIAN ISLANDS, 1956

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ABSTRACT

Salmon fishing and related oceanographic cruises in the North Pacific prior to 1956 are summarized, and comparison is made between salmon catches and oceanographic features determined from data collected aboard the chartered fishing vessels *Mitkof*, *Celtic* and *Paragon* in the area south of the Alaska Peninsula and Aleutian Islands in the summer of 1956.

No immediate relationship between surface conditions and the presence or abundance of salmon in the eastern Pacific is indicated, but a subsurface temperature front at approximately lat. 48°N. coincided with the southern limit of summer catches. In the spring of 1956, however, salmon were caught by the vessels of the Japan Fisheries Agency and a Bureau of Commercial Fisheries vessel as far south as lat. 41°N.-42°N.

Since limited oceanographic information was obtained in 1956, data collected by various agencies in 1958 are utilized to show the extent and continuity of two oceanographic fronts in the area considered. A salinity front at lat. 42°N. coincides with the southern limit of spring catches, and a temperature front at approximately lat. 46°N. in the western Pacific, extending to lat. 48°N. in the eastern Pacific, coincides with the southern limit of summer catches.

Although very little is known concerning the high-seas migrations of salmon, it appears that northward of approximately lat. 48°N. in the eastern Pacific and lat. 46°N. in the western Pacific, the shallow surface layer north of the temperature frontal zone may cause salmon to remain near the surface, where they would be more susceptible to capture in surface nets during the summer, and does not necessarily imply that they are not present at depths to the southward during this period.

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INTRODUCTION

Prior to the development of the Japanese commercial high-seas salmon fishing in the North Pacific Ocean in 1952, very little was known about the marine habitat of the Pacific salmon (genus *Oncorhynchus*). Since 1955, the United States Bureau of Commercial Fisheries, serving as a research agency of the International North Pacific Fisheries Commission (INPFC), has been engaged in a study to determine the extent of intermingling of Asian and North American salmon in the North Pacific Ocean and the Bering Sea. One phase of this study is to determine the extent of oceanic salmon environment and the oceanographic conditions affecting their distribution and movements. Therefore, the purpose of this report is threefold:

1. To summarize various oceanic salmon fishing and related oceanographic cruises prior to 1956 that provide information on the distribution of salmon and the oceanic environment.

2. To present results of the fishing and oceanographic programs, carried out aboard chartered fishing vessels *Mitkof*, *Celtic* and *Paragon* southward of the Alaska Peninsula and Aleutian Islands in 1956, which show the southern limit of the salmon distribution in that summer.

3. To compare results of the above cruises and those conducted by the Japan Fisheries Agency in the spring of 1956, with oceanographic features that may determine the southern extent of salmon distribution in spring and in summer.

REVIEW OF SALMON FISHING AND OCEANOGRAPHIC CRUISES PRIOR TO 1956

An excellent review of the history of the Pacific salmon is presented in Bulletin No. 1 of the International North Pacific Fisheries Commission (INPFC, 1955). The following is a brief summary of studies on the marine environment of the salmon near the Aleutian Islands.

INVESTIGATIONS PRIOR TO 1952

Taguchi (1956) reported that for more than 10 years prior to 1941 the Japanese had fished for salmon off the east and west coasts of Kamchatka, U.S.S.R., and were aware that the salmon fed and matured in an unknown area in the North Pacific Ocean. They believed that the ocean currents controlled the migration routes of the salmon.

The results of coastal tagging experiments prior to 1952, summarized by Hartt (1959), indicated a wide range of salmon migrations across the North Pacific, but did not reveal the extent of the oceanic distribution of the salmon. Early oceanographic cruises, excluding those by the Japanese, provide only fragmentary environmental data in the North Pacific, and have been summarized by Fleming (1955). Data from Japanese cruises have been compiled by the Japan Agricultural Technical Association (1954).

The U.S. Bureau of Fisheries made the first investigation to obtain oceanographic observations in conjunction with a salmon fishing effort near the Aleutian Islands and in the Bering Sea during the spring and summer of 1939, 1940 and 1941. World War II interrupted this investigation before it was completed, and no specific relationships between the salmon and

environmental factors were determined. Barnaby (1952) reported the results of the fishing cruises, and the oceanographic data have been recovered and presented by Favorite and Pedersen (1959a) and Favorite *et al.* (1961). The area is essentially a coastal environment, and the study was concerned directly with the salmon runs into Bristol Bay streams.

INVESTIGATIONS DURING 1952 TO 1954

The Japanese commercial high-seas salmon fishing fleets which commenced gillnet operations in the western North Pacific Ocean and Bering Sea in 1952 proved that good catches of salmon could be made on the high seas. Data from these commercial operations are difficult to obtain, but reports by Taguchi and Hirose (1954), Taguchi (1955) and Taguchi and Shoji (1955) have shown relationships between salmon migrations and movements of water masses, particularly in the area south and west of the western Aleutian Islands. It was noted, however, that in some locations the direction and velocity of the currents were quite variable. Taguchi (1957) reported that the dichothermal water (layer of cold water at depth which occurs as a temperature minimum) showed the extent of the Oyashio Current, and also that the southern boundary of salmon catches occurred along the belt where the Kuroshio Current converges with the Oyashio.

The oceanographic cruises of the *Tenyo-maru* (Tokai Regional Fisheries Research Laboratory), during the period of operation of the Japanese high-seas salmon fleet in the summer of 1952 and 1953, were some of the first investigations directed toward an understanding of the oceanic environment of the salmon. Watanabe (1954), utilizing these and other historical oceanographic data, summarized the general oceanographic conditions in the North Pacific. He reported that the major fishing grounds were at the boundary of the cold, northern surface water and the warm water of southern origin, and that better salmon catches were made in areas of sharp horizontal temperature and salinity gradients associated with upwelling. Nakai and Honjo (1954), reporting on the biological observations of the *Tenyo-maru* cruise in the summer of 1952, noted that good salmon catches were associated with plankton concentrations found in the westward-flowing current south of the Aleutian Islands.

In 1953, the *John N. Cobb* (U.S. Fish and Wildlife Service) made an exploratory fishing cruise along the Aleutian Islands, but only surface observations were made (Schaefer and Fukuhara, 1954).

The *Oshoro-maru* (Faculty of Fisheries, Hokkaido

University), during student training cruises in the Aleutian area in the summer of 1953 and 1954, made combined oceanographic and exploratory salmon fishing studies. The results of the oceanographic studies, presented by Mishima and Nishizawa (1955), described the water structure in the western Aleutian area and showed that the area was characterized by an upper layer of cold, low salinity water and a lower layer of warm, saline water. They also noted that a warm, low salinity water mass flowed westward on the southern side of the Aleutian Islands, extending as far west as 165° East longitude.

INVESTIGATIONS BY THE INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION, 1955

The present marine investigations by the member nations of INPFC, Canada, Japan, and the United States, commenced in the summer of 1955. The *Tsukiyama-maru* (Japan Fisheries Agency) made a salmon fishing cruise in the Bering Sea and south of the Aleutian Islands, where limited oceanographic observations were made. During the same period the Bureau of Commercial Fisheries used the *John N. Cobb* and the chartered fishing vessels *Mitkof* and *Paragon* to make combined oceanographic and fishing cruises in the Gulf of Alaska and south of the Aleutian Islands. The results of the experimental fishing have been re-

ported by Powell and Peterson (1957). The limited oceanographic data (Favorite and Love, 1957) collected aboard the fishing vessels were inadequate to describe the oceanographic features in the area, but fortunately the fishing operation coincided with the international oceanographic program NORPAC, which provided an oceanographic survey of the North Pacific Ocean. The results of the oceanographic observations should appear shortly in atlas form.

The 1955 fishing operation directed by the American Section of the INPFC showed it was possible to catch salmon in gillnets in the eastern part of the North Pacific Ocean north of approximately lat. 47°N. An extensive experimental fishing and oceanographic program was planned by the American Section for the 1956 season.

OCEANOGRAPHIC CONDITIONS AND SALMON CATCHES, SUMMER 1956, (MV MITKOF, MV CELTIC AND MV PARAGON)

Except for the rather gross effects of temperatures outside the lethal limits, we know little about the oceanographic properties or features which may affect the distribution of salmons. Often an investigator will select one property such as temperature or salinity

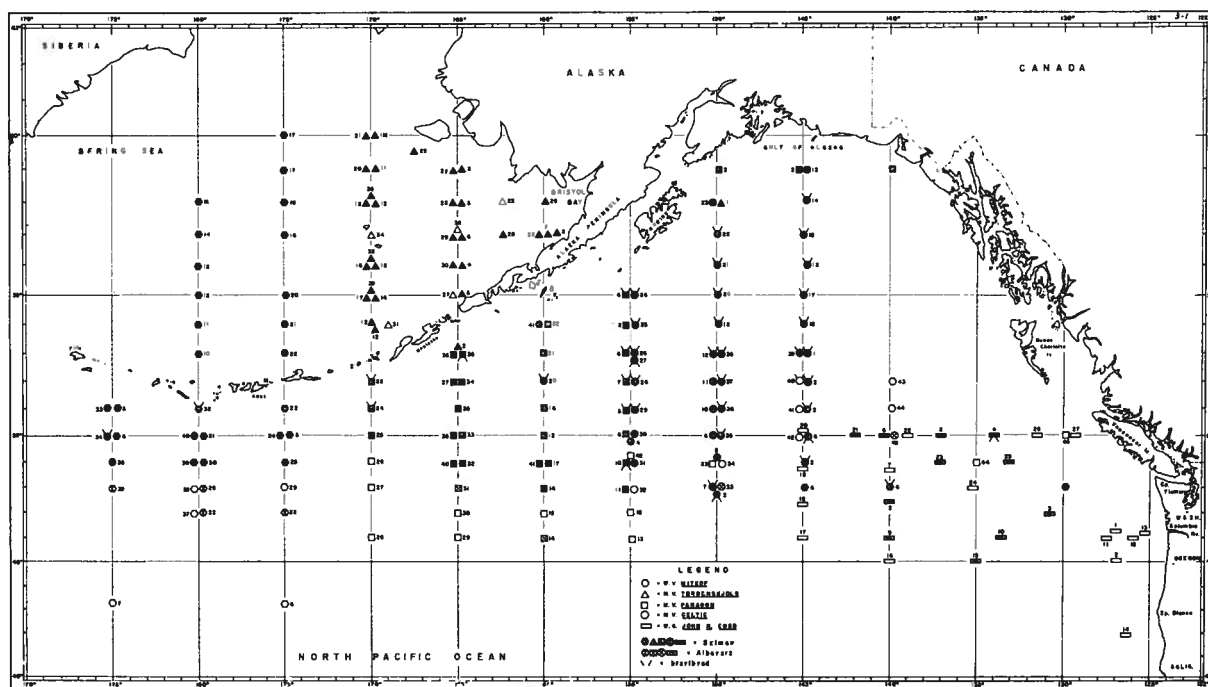


FIGURE 1. Locations of fishing sets and distribution of salmon, steelhead and albacore during the period May to September, 1956, as determined by the catches of the vessels *Mitkof*, *Tordenskjold*, *Paragon*, *Celtic* and *John N. Cobb*. Numbers indicate serial order of sets (from Hanavan and Tanonaka, 1959).

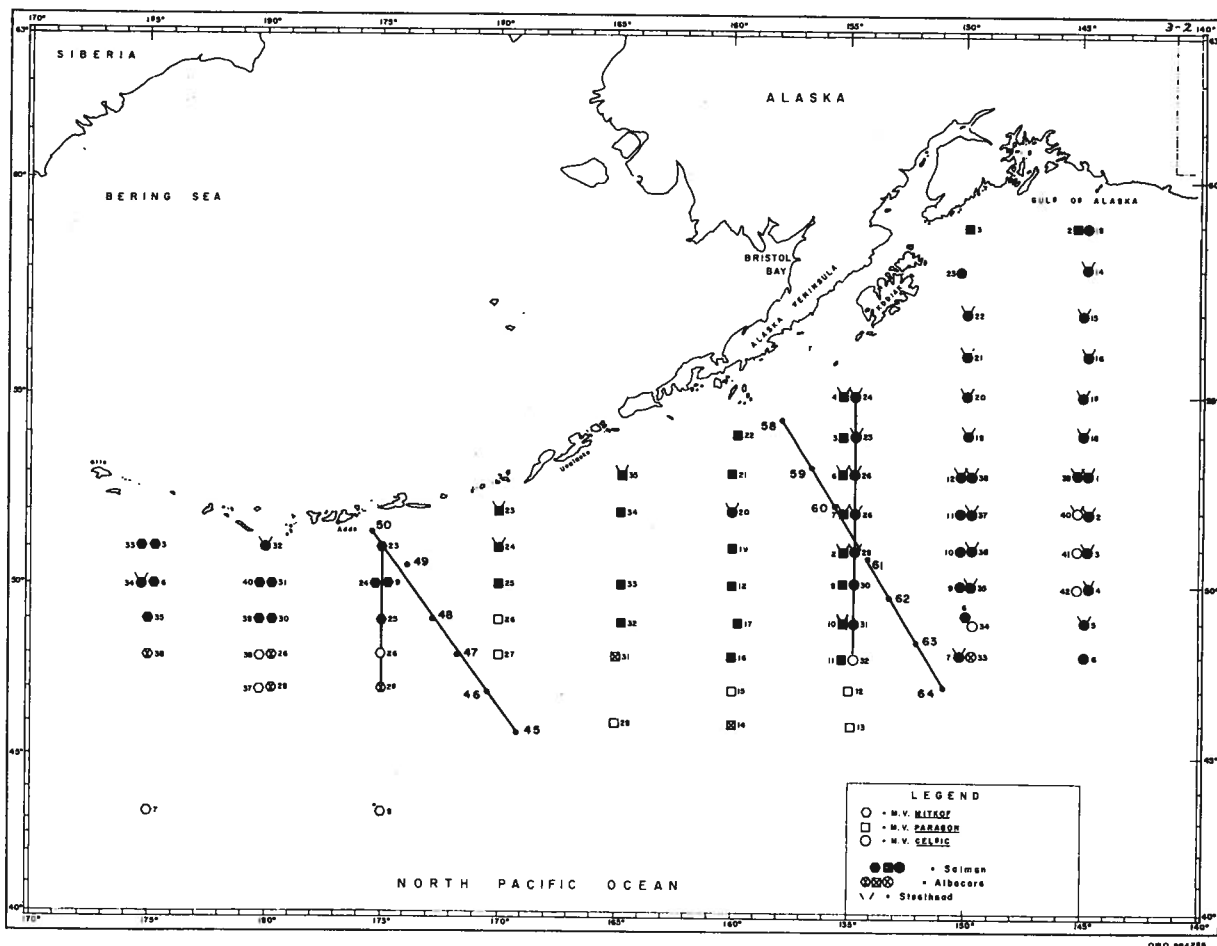


FIGURE 2. Oceanographic stations south of the Alaska Peninsula and Aleutian Islands, Summer 1956. The solid lines indicate locations of vertical sections described in the report. (New Glasgow stations 45 to 50 and 58 to 64 are indicated by small dots.)

and relate it to a biological phenomenon, but this tells only a small part of the story and may not hold true in another area or under different circumstances. Until we know more of the reaction of salmon to changes or extremes of temperature and salinity, we must consider the environment as a whole. For this reason, the oceanographic data obtained aboard the charter vessels have been treated in several different ways to show as specifically as possible different environments, that is, different water structures, that might be detected by the salmon. At this stage of our investigation perhaps some of these differences may appear unimportant, but they have been sought out and presented because they may prove valuable in planning future research.

SOURCES OF DATA

The locations at which fishing sets were made in the summer of 1956 by the *John N. Cobb* and four chartered fishing vessels *Mitkof*, *Paragon*, *Celtic* and

Tordenskjold, as presented by Havanan and Tanonaka (1959), are shown in Figure 1.

The *Cobb* made 27 fishing sets on and eastward of long. 145°W., resulting in a total catch of only 25 salmon. These sets, as well as those of the *Celtic*, *Mitkof* and *Paragon* eastward of long. 145°W. where no or only a few salmon were caught, are not considered in this report. Also excluded are the *Mitkof* and *Tordenskjold* Bering Sea sets, which will be discussed in a separate report.

The *Mitkof*, *Paragon* and *Celtic* stations provide a comparison of oceanographic conditions and salmon catches south of the Alaska Peninsula and the Aleutian Islands (Fig. 2).

Personnel of the Department of Oceanography, University of Washington, Seattle, Washington, under the direction of Dr. Richard H. Fleming, carried out the oceanographic program aboard the charter vessels. Love (1957, 1959) has described the oceanographic

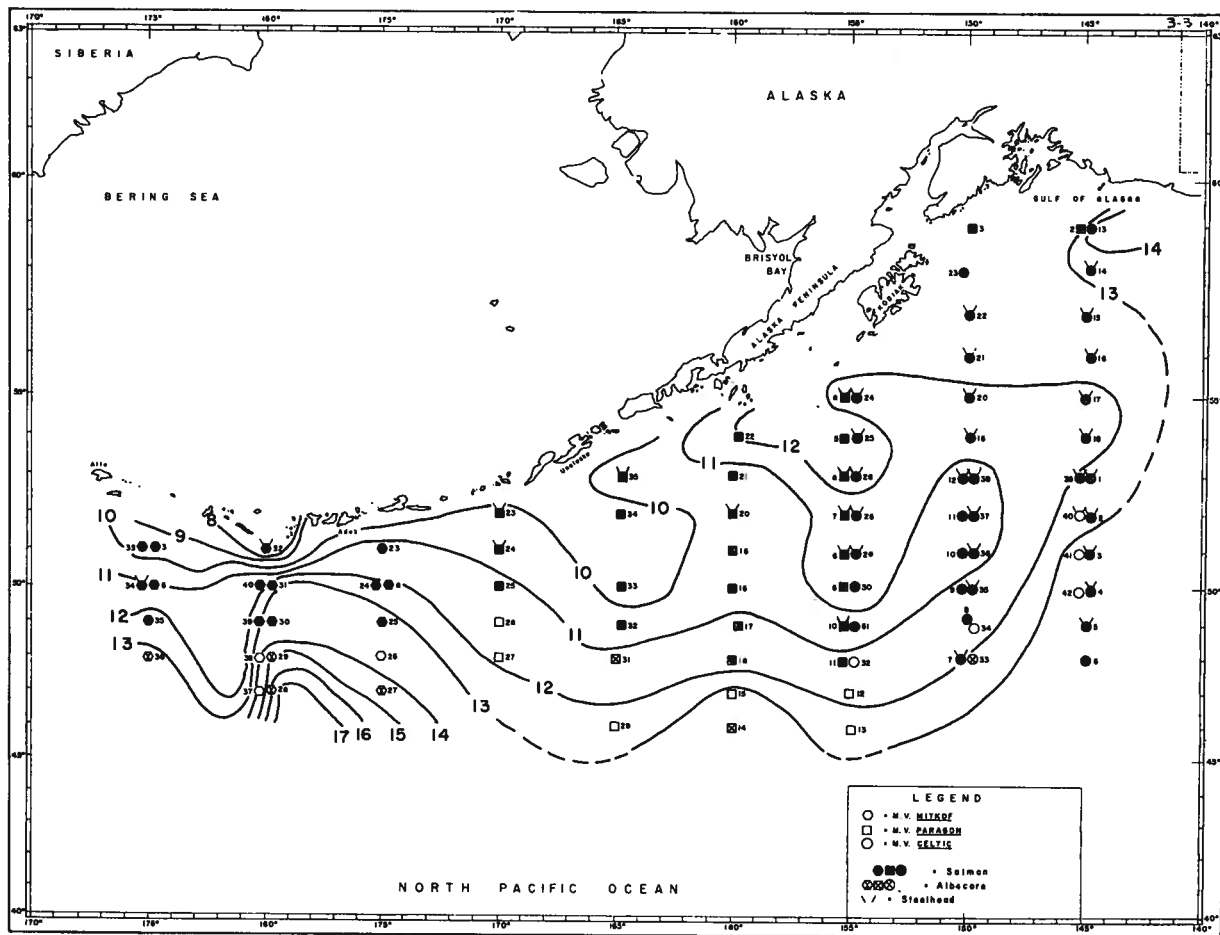


FIGURE 3. Surface temperature ($^{\circ}\text{C}$.), Summer 1956, showing the absence of any sharp gradients except at 180° .

procedures used aboard the vessels and has tabulated the physical and chemical data. To augment the presentations of horizontal and vertical sections of water properties constructed from these data, additional information from the 1956 summer cruise of the HMCS *New Glasgow* (Pacific Oceanographic Group, 1957) have been utilized. The locations of these stations are shown also in Figure 2.

It should be noted that the presence or absence of salmon has been determined from surface gillnet catches, and that by August the majority of the maturing salmon have left the oceanic environment and are approaching or have entered the streams to spawn. The results of the Canadian exploratory cruises eastward of the area discussed in this report have been published (Manzer, 1958).

SURFACE CONDITIONS IN RELATION TO SALMON DISTRIBUTION

Salmon have often been considered predominantly a surface fish; thus, relationships between oceanographic

conditions and salmon distribution were sought in the surface layer. One might assume from the locations of salmon catches shown in Figure 1 that the absence of salmon in gillnet catches south of lat. 48°N . would be associated with sharp gradients of surface water properties indicating the presence of another water mass with different physical and chemical properties that could be detected by salmon. This is not indicated by our data which show a gradual transition in surface water properties in contrast to an abrupt change in properties at greater depth.

In order to present as complete a picture as possible of the surface conditions, *Oshoro-maru* (Hokkaido University, 1957) and *New Glasgow* data have been used in contouring the surface temperature and salinity distributions. The locations of these stations are not shown because fishing sets were not made.

Surface temperature. The July-August surface temperatures have been combined to show the summer temperature distribution in the fishing area (Fig. 3). Sharp gradients occur only at long. 180° where the

intrusion of warm water ($13^{\circ}\text{C}.$ to $17^{\circ}\text{C}.$) from the south is apparent. South of lat. $50^{\circ}\text{N}.$ between long. $145^{\circ}\text{W}.$ and $175^{\circ}\text{W}.$, the surface temperature gradient is approximately $1^{\circ}\text{C}.$ per 60 miles. This does not appear to constitute an effective environmental boundary for the southern distribution of salmon, particularly in view of the fact that at *Mitkof* station 25 salmon were caught in surface temperatures greater than $13.5^{\circ}\text{C}.$ Using this temperature as an upper threshold, salmon should have been caught as far south as lat. $45^{\circ}\text{N}.$ between long. $145^{\circ}\text{W}.$ and $165^{\circ}\text{W}.$

Figure 1 also reveals a slight northward shift in the southern limit of catches along long. $145^{\circ}\text{W}.$, $150^{\circ}\text{W}.$ and $155^{\circ}\text{W}.$ as the season progressed (as indicated by the higher set numbers). This apparent northward movement of the salmon was not accompanied by an appreciable change in the surface temperature except at long. $145^{\circ}\text{W}.$ where the divergence of the Subarctic Current greatly complicates the circulation off the North American coast. Tables 1 and 2 compare salmon catches and surface

conditions at repeated sets on long. $150^{\circ}\text{W}.$ and $155^{\circ}\text{W}.$ A rise of only $1^{\circ}\text{C}.$, generally from $10^{\circ}\text{C}.$ to $11^{\circ}\text{C}.$, was associated with no catches of salmon in August at stations where salmon had been caught in July. Since salmon were caught at 16 other fishing sets where temperatures were greater than $12^{\circ}\text{C}.$, one cannot say that surface temperatures were a control-

TABLE 1. Comparison of salmon catches and surface conditions at repeated sets at lat. $48^{\circ}\text{N}.$ to $50^{\circ}\text{N}.$ on long. $150^{\circ}\text{W}.$, Summer 1956.

Station	Latitude	Date	Surface temperature ($^{\circ}\text{C}.$)	Surface salinity (‰)	Total salmon catch
<i>Celtic</i> 7	$48^{\circ}\text{N}.$	July 21	11.10	32.67	39
" 33	$48^{\circ}\text{N}.$	August 30	12.28	32.56	0
<i>Celtic</i> 8	$49^{\circ}\text{N}.$	July 22	10.26	32.57	78
" 34	$49^{\circ}\text{N}.$	August 31	11.26	32.55	0
<i>Celtic</i> 9	$50^{\circ}\text{N}.$	July 23	10.30	32.60	39
" 35	$50^{\circ}\text{N}.$	Sept. 1	11.46	32.87	6

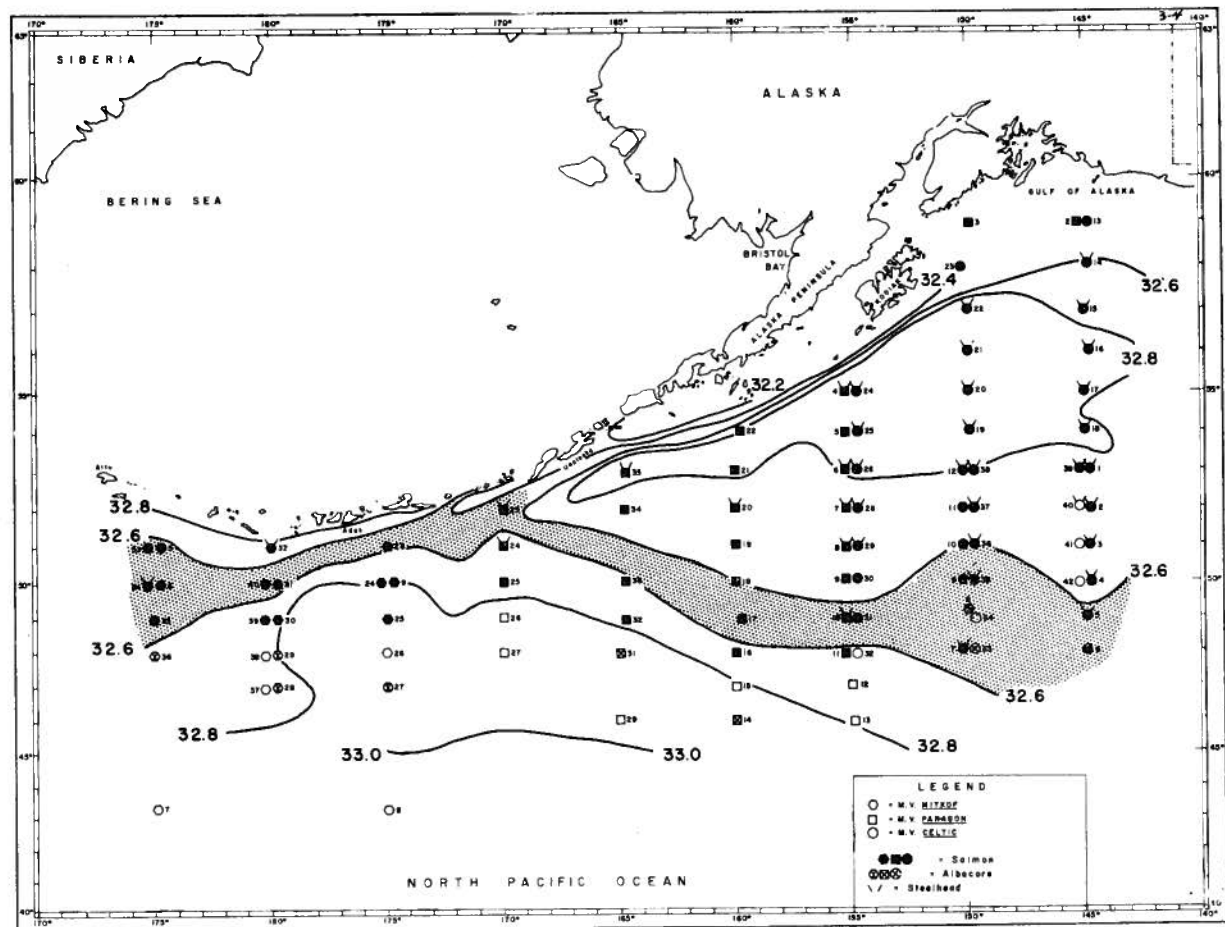


FIGURE 4. Surface salinity, Summer 1956, showing broad band of minimum salinity ($32.6^{\circ}/_{00}$).

TABLE 2. Comparison of salmon catches and surface conditions at repeated sets at lat. 48° N. to 50° N. on long. 155° W., Summer 1956.

Station	Latitude	Date	Surface temperature (°C.)	Surface salinity (‰)	Total salmon catch
Paragon 12 (not repeated)	47° N.	July 28	11.60	32.74	0
Paragon 11	48° N.	July 27	10.98	32.68	3
Celtic 32	48° N.	August 28	11.49	32.65	0
Paragon 10	49° N.	July 26	9.70	32.58	36
Celtic 31	49° N.	August 26	10.90	32.58	19
Paragon 9	50° N.	July 25	9.14	32.69	40
Celtic 30	50° N.	August 23	11.32	32.72	51

ling factor in determining the southward limit of the salmon in this area.

Surface salinity. The surface salinity distribution presented in Figure 4 shows a broad band of minimum salinity (32.6 ‰) extending from long. 175°E. eastward along the Aleutian Islands to long. 170°W., where it trends southeastward to the coast of North America. This band of lower salinity water, which indicates a region of convergence, was not noticeably present in the previous summer. It is believed to be a remnant of the previous summer's runoff from the Alaskan coast, and in the process of recirculating around the Gulf of Alaska gyral. The position of this band between long. 160°W. and 145°W. corresponds generally to the southern limit of the salmon catches. This relationship, however, is not readily apparent westward of long. 160°W. where catches were made south of the narrow band of minimum salinity which extended to long. 175°E. The salinity distribution provides an indication of the convergence of two current systems, but salmon were caught north, south, and within the band of minimum salinity, and no precise relationship between surface salinity and the southern limit of salmon distribution is evident.

Thus, although the sharp gradients of surface properties in the western Pacific where the cold, dilute, southward flowing Oyashio Current converges with the warm, saline, northward flowing Kuroshio Current provide indication of a major fishing ground, the surface gradients in the eastern Pacific are slight. In summer the surface temperature gradients, although influenced by vertical movement of cold water, are chiefly the result of latitudinal heating. The salinity gradients are determined by the amount of dilute coastal water recirculated counter-clockwise around the Gulf of Alaska gyral. It is apparent that neither surface temperature nor surface salinity are closely

related to the absence or abundance of salmon as determined by gillnet catches.

VERTICAL SECTIONS OF TEMPERATURE AND SALINITY IN RELATION TO SALMON DISTRIBUTION

Though surface conditions do not reveal the presence of any sharp gradients of temperature or salinity at the southern limit of salmon catches, the subsurface water structure does appear to show a direct relationship.

Two representative vertical sections of temperature and salinity have been selected for discussion—one southward of the Alaska Peninsula and the other southward of the Aleutian Islands.

Section on longitude 155°W. The vertical water structure on long. 155°W. constructed from data at Celtic stations 24 to 32 is shown in Figure 5. A similar water structure was found on long. 145°W., 150°W., 160°W. and 165°W.

At lat. 56°N., the characteristic downward slope of isolines near the continental shelf is implied by dashed lines. The temperature minimum (less than 3.5°C.) at 75 to 100 meters, typical of a water column in the Gulf of Alaska, is clearly evident between stations 24 to 31. Between stations 31 and 32, however, the almost vertical 4° and 5° isotherms indicate the presence of water of a southern origin. Salmon catches, at the respective stations, tabulated at the top of the figure, show that no salmon were caught in the surface gillnets at station 32.

As noted previously, surface temperatures do not indicate the presence of an abrupt change in temperature at depth. Nor can one say that the absence of salmon at station 32 was caused by higher surface temperatures because the large catches of 94 and 150 salmon at stations 25 and 26 were made in surface temperatures over 1°C. higher than the unproductive set at station 32.

The vertical salinity distribution also shows relatively uniform horizontal values between stations 24 to 30, but at stations 30 and 31 the isolines trend downward in the frontal zone.

Section on longitude 175°W. The other vertical section selected for discussion, on long. 175°W., is representative of the structure on long. 170°W., 180° and 175°E. Data from *New Glasgow* station 50 at lat. 51°31'N. and *Mitkof* stations 23 to 27 are presented in Figure 6. *New Glasgow* station 50 is not indicated, but has been utilized to show the southern extent of the coastal water as indicated by the 4°C. isotherm extending below 250 meters. Water characteristic

of the Gulf of Alaska is greatly compressed latitudinally and is present at *Mitkof* station 23. Between *Mitkof* stations 23 and 27 an intrusion from the west of water with a temperature minimum (less than 3.5°C.) below 150 meters is evident. The origin and extent of this water are discussed in the following section,

Temperature-Salinity Relationships. Southward of this intrusion, at station 27 where no salmon were caught, the sharp downward trend of the 4° and 5° isotherms (similar to the temperature structure at long. 155°W.) shows the subsurface front at lat. 47°N.

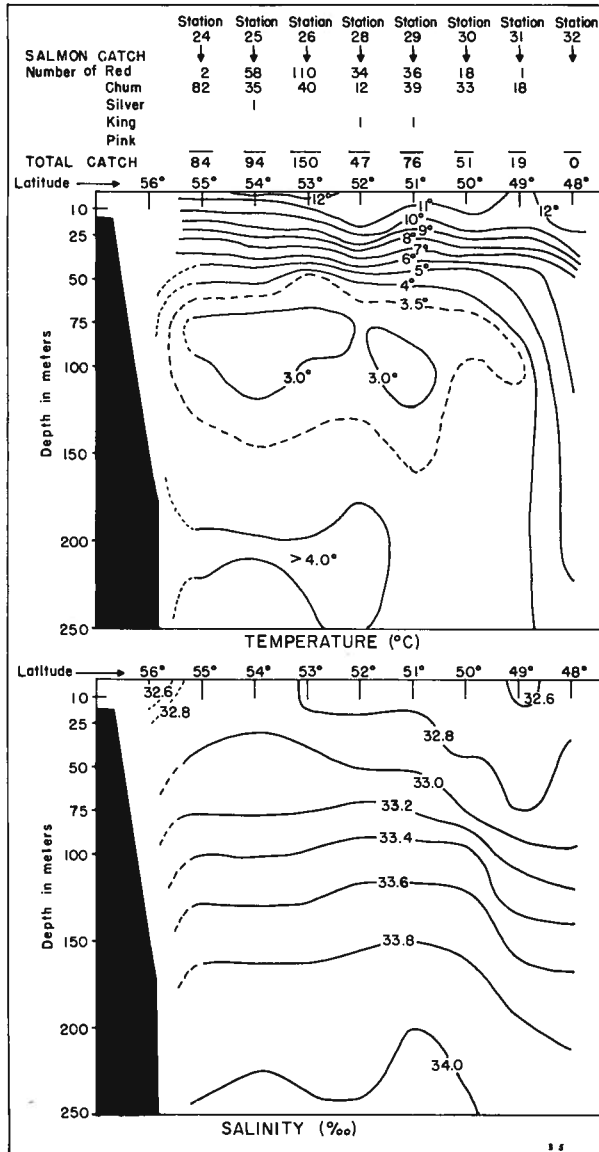


FIGURE 5. Comparison of salmon catches and vertical water structure on long. 155°W. (*Celtic* stations 24 to 32), showing temperature front associated with no salmon catches at lat. 48°N. (Alaska Peninsula shown in black).

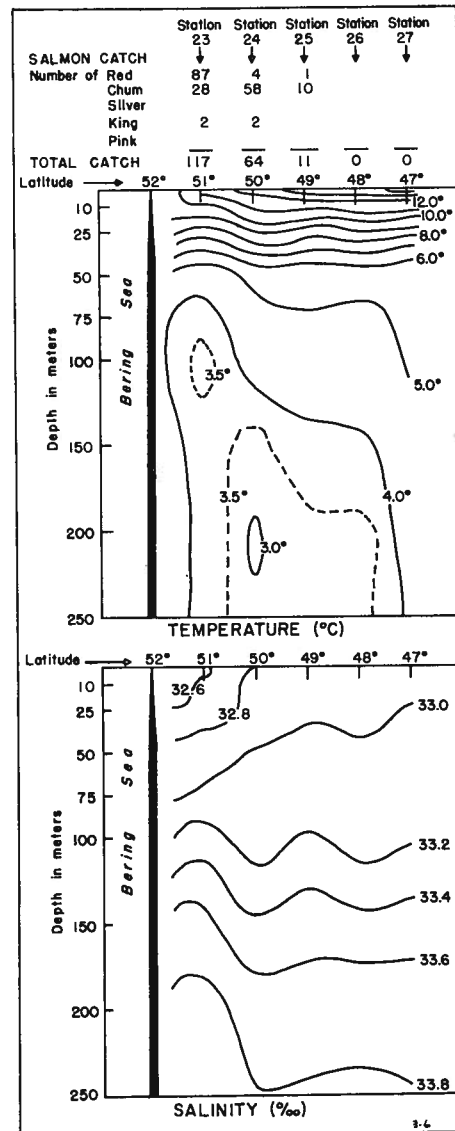


FIGURE 6. Comparison of salmon catches and vertical water structure on long. 175°W. (*Mitkof* stations 23 to 27), showing front at lat. 47°N. (Aleutian Ridge shown in black).

The salinity profile shows the surface dilution along the south side of the Aleutian Islands. Southward of the temperature minimum (3.5°C.) at station 23 the isohalines trend downward; however, the intruded water at stations 24 to 26 has resulted in a different salinity structure than shown at long. 155°W.

Temperature-salinity relationships presented in the following section are utilized to associate these water structures with recognized water masses and to show the geographic extent of the four types.

TEMPERATURE-SALINITY RELATIONSHIPS

Sverdrup *et al.* (1942) utilized temperature-salinity relationships to identify water masses in the North Pacific Ocean. They defined Pacific Subarctic Water as water in which no salinity minimum is present and note that use of the term should be confined to the area north of lat. 45°N. The Pacific Central and Pacific Equatorial Water masses are also defined, both of which are characterized by the presence of a salinity minimum at depth, the latter water mass being considerably more saline for any given temperature.

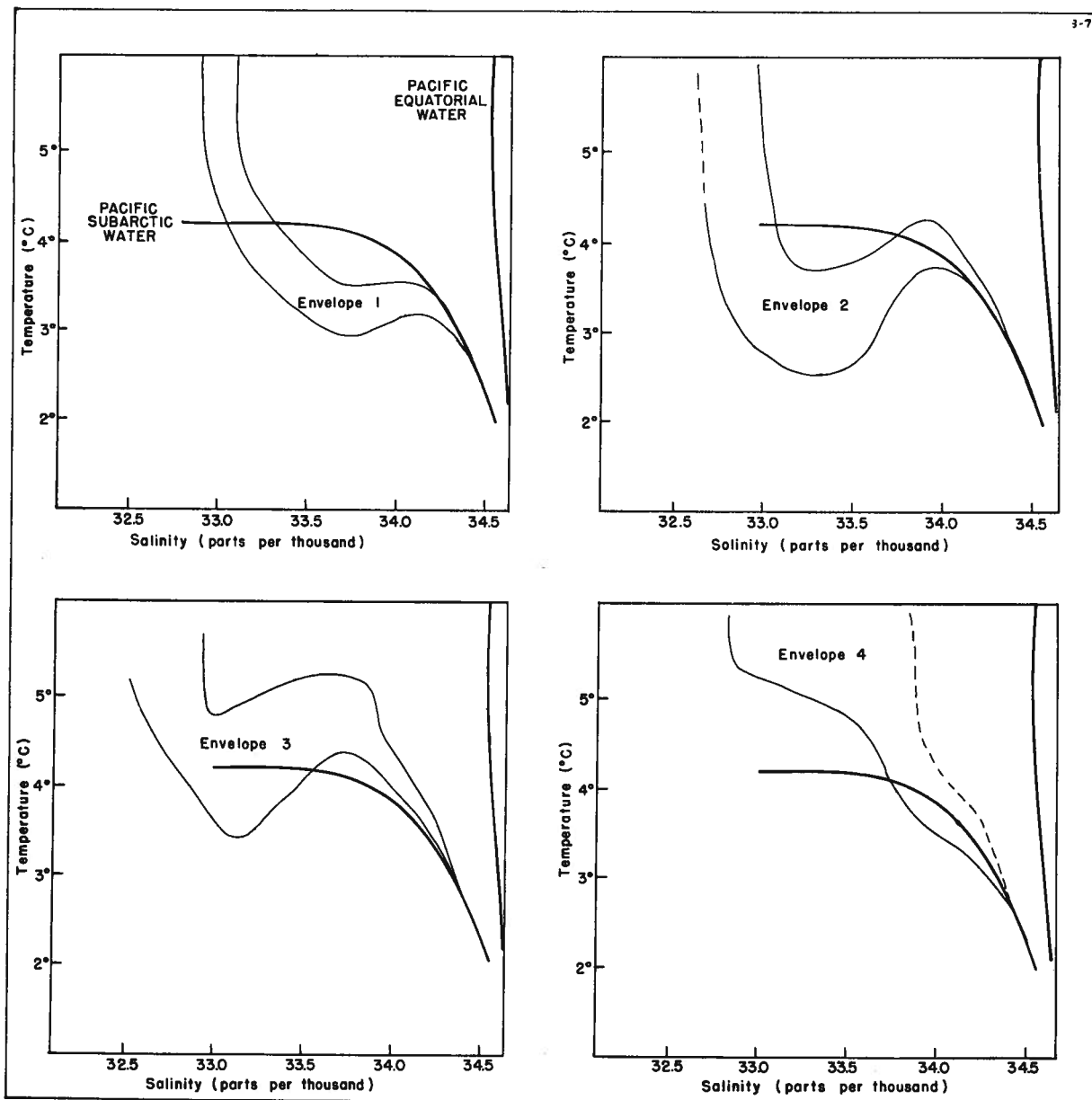


FIGURE 7. Temperature-salinity envelopes determined from *Mitkof*, *Celtic* and *Paragon* station data, showing three types of Subarctic Water (envelopes 1, 2 and 3) and Transition Water (envelope 4).

The extensive 1956 observations permit a more thorough examination of the water properties in the Subarctic Region than was possible for previous years. Values of temperature and the corresponding salinity within the ranges of 0°C. to 6°C. and 33‰ to 34.5‰ were plotted for each of the charter vessel stations shown in Figure 2. Individual station temperature-salinity curves have been enclosed within four envelopes. Values in the specified ranges exist at depth and have been selected as criteria of identification because they are relatively permanent compared to the transient surface values.

The envelopes are presented in Figure 7 and their relationships to the Pacific Subarctic and Pacific Equatorial curves can be inferred by the relative position of the envelopes between the two recognized curves.

The curves within envelope 1 are recognized by a slight temperature minimum accompanying salinities greater than 33.5‰ and usually occurring at 33.7‰ to 33.8‰. The temperature minimum occurs at

200 to 300 meters depth. The water identified by this envelope is believed to originate off the Asian coast where in winter the low surface temperatures and the presence of ice permit an extensive vertical overturn of the water column and result in a temperature minimum of about 0°C. at the above depths. The minimum temperature is gradually increased as a result of mixing and diffusion during the movement of this water mass eastward from the Oyashio region and reaches the 2°C. range in the central Pacific.

The curves within envelope 2 are identified by a pronounced temperature minimum accompanying salinities less than 33.5‰ and usually occurring at 33.0‰. The minimum temperature occurs at 70 to 100 meters depth in the Gulf of Alaska where winter surface temperatures of 2-4°C. and mixing permit a winter overturn down to the depth of the halocline. Tully (1957) has discussed the formation of this minimum temperature, and Doe (1955) denoted the area having these characteristics to be the Mid-Gulf region. Although Doe's data were limited to the Gulf of Alaska

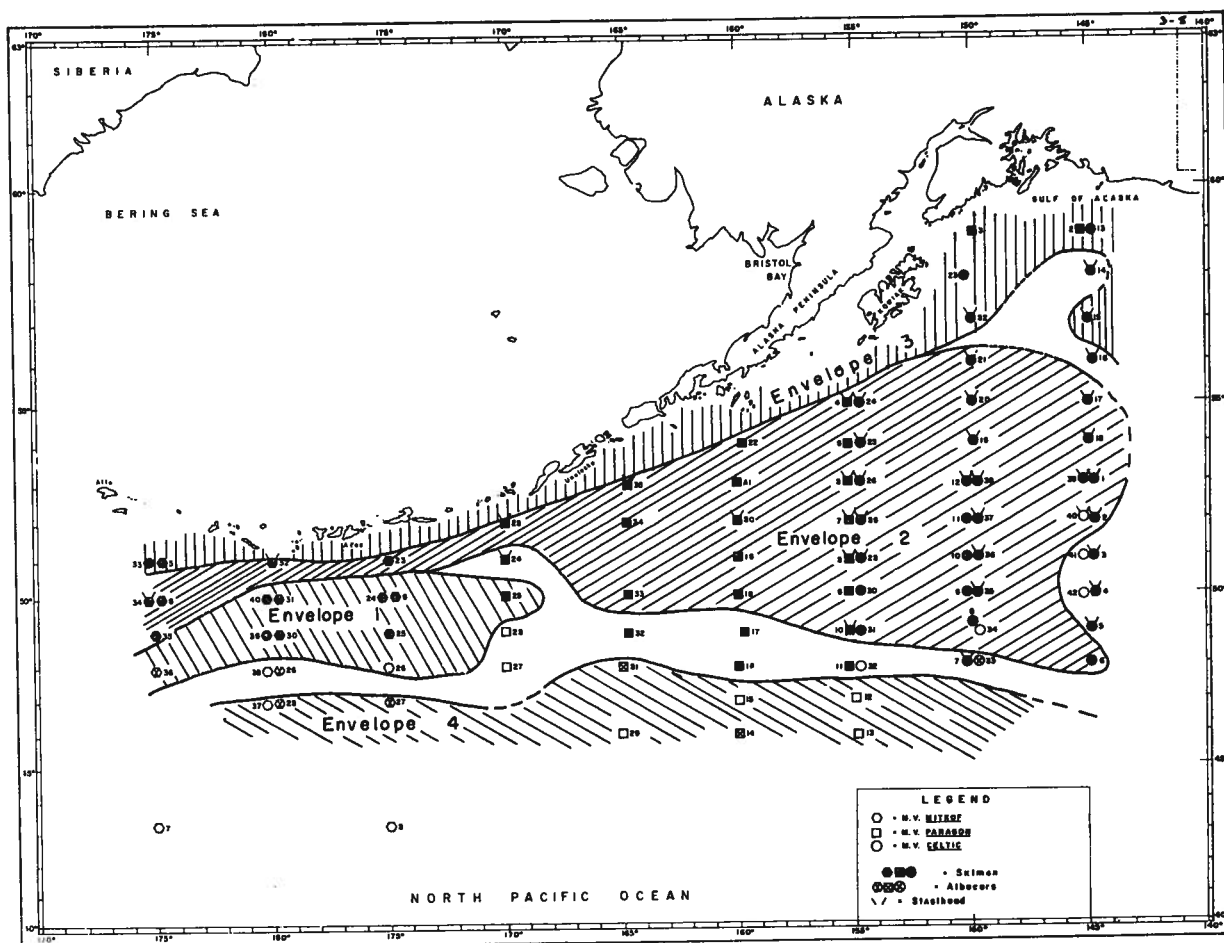


FIGURE 8. Geographical extent of water masses identified by temperature-salinity envelopes 1 to 4.

Alaska, it appears that a curve of this type is also present along the Aleutian Chain.

The curves within envelope 3 result from the mixing of waters characteristic of envelopes 1, 2 and 4, and water off the North American coast. They are associated with the westward flow of the Alaska current along the Aleutian Chain.

The curves within envelope 4 are characterized by warm, saline water and the absence of either a temperature or salinity minimum which identify it as a Transition Water mass between the Subarctic and Pacific Central Water. If one considers the so-called "polar front" to be the southern boundary of Subarctic Water, it would be indicated by stations having this characteristic curve. Oxygen-salinity relationships discussed later in this report also show a marked change at stations identified by envelope 4.

The geographical extent of the stations identified by the four envelopes are shown in Figure 8. There are some stations at which lateral mixing has prevented the T-S curves from falling within one of the characteristic groups.

The southern extent of salmon catches between long. 145°W. and 165°W. coincides very closely with the area of mixing between envelopes 2 and 4. No salmon were caught at stations identified by envelope 4.

Westward of long. 165°W., where no clear relationship existed between the catches and the surface temperature or salinity, it is apparent that all catches were made at stations identified by envelopes 1, 2, or 3. Thus, all catches were made in water identified as Subarctic, and none were made in the Transition Water mass identified by envelope 4.

Vertical section of silicate distribution near longitude 150°W. Only temperature and salinity observations were made aboard the *Mitkof*, *Celtic* and *Paragon*, but other chemical constituents, which show further differences in the environments north and south of the subsurface temperature front, were analyzed aboard the *New Glasgow*.

New Glasgow stations 58 to 64 are shown in Figure 2. Although values of phosphate, silicate, nitrate and pH were obtained, only the silicates show any appreciable change north and south of the front. Figure 9 shows a vertical section of silicates from the surface to 200 meters. In the upper 30 meters, from the Alaska Peninsula to lat. 48°N., the values range between 25 and 30 microgram-atoms per liter, but immediately south of lat. 48°N. the values decrease to less than 20, and are less than 10 microgram-atoms per liter at lat.

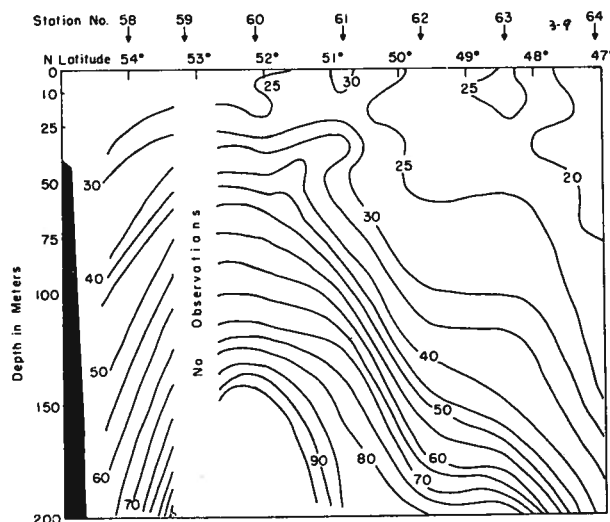


FIGURE 9. Vertical silicate distribution ($\mu\text{g. at./l.}$) (*New Glasgow* stations 58 to 66), showing the change in horizontal concentrations at approximately lat. 50°N. (Alaska Peninsula shown in black).

45°N. Below 50 meters the 25 microgram-atom per liter isoline dips sharply downward in a manner similar to the 4°C. and 5°C. isotherms in Figure 6.

OXYGEN-SALINITY RELATIONSHIPS

Additional evidence of a different environment north and south of the frontal zone can be shown by oxygen-salinity relationships at *New Glasgow* stations 58 to 64 and 50 to 45 (Fig. 2). The relatively saturated oxygen values in the surface layer do not show any significant differences, but at depth, oxygen-salinity relationships (Fig. 10) show that from the Alaska Peninsula to lat. 49°39'N. (stations 58-62) the relationships are quite similar and markedly different from those at stations 63 and 64, which are south of the temperature front.

The oxygen-salinity relationships at stations 50 and 49 (north of front at approximately long. 155°W.) are very similar to those at stations 58 to 62 (north of front at approximately long. 175°W.), indicating an east-west continuity of water properties. The values at stations 48 to 46 must be considered as transitional ones, but at station 45 (south of front at approximately long. 173°W.), the relationships are almost identical to those at stations 63 and 64 (south of front at approximately long. 173°W.). Although the separation of the two environments is not as sharp at long. 173°W. as at long. 155°W. because of oxygen-salinity relationships in the water intruded from the west (noted in the discussion of the vertical sections at long. 175°W.), the latitudes at which a change in oxygen-salinity relationships occurs coincide with the latitudes of the

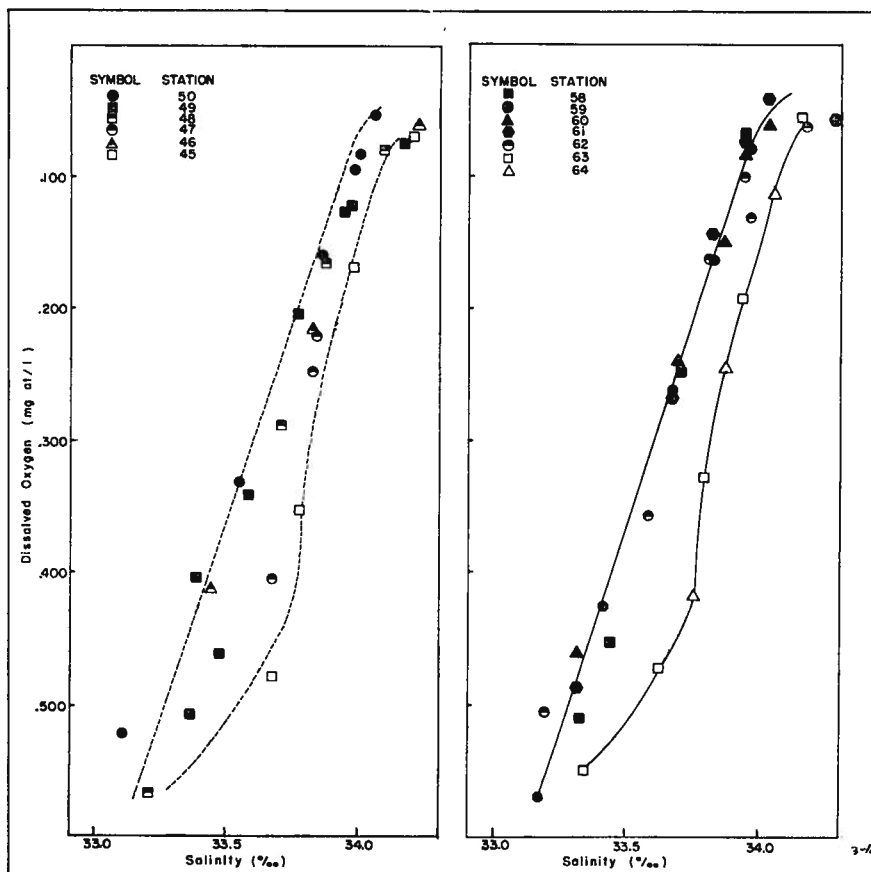


FIGURE 10. Oxygen-salinity relationships for *New Glasgow* stations, showing a marked change in relationships north of temperature front (dark symbols) and south of front (open symbols) at long. 169°W. to 175°W. and long. 151°W. to 158°W. (see Figure 2 for station locations).

temperature fronts at these approximate longitudes as shown previously by *Mitkof* and *Celtic* data.

SUMMARY OF *MITKOF*, *PARAGON* AND *CELTIC* DATA

Before comparing the results of our fishing cruises to those of the Japan Fisheries Agency, and considering the maximum southern extent of the salmon distribution, it would be advantageous to summarize the relationships between the salmon distribution and oceanographic conditions revealed thus far.

The results of the experimental fishing in July and August, 1956, aboard the chartered vessels *Mitkof*, *Paragon* and *Celtic* have shown that immature salmon were caught north of approximately lat. 48°N. from long. 145°W. to the westward limit of the area of investigation, long. 175°E.

Above lat. 48°N., the catches as reported by Hanavan and Tanonaka (1959) varied from one to over one hundred salmon. The largest catches were made south of the Aleutian Islands at *Mitkof* stations 32 and

33 (Figure 1) where 197 and 323 salmon were caught. At station 32, 162 of these were red salmon (*Oncorhynchus nerka*) and at station 33, 235 were red salmon. These represent about one-fourth of the total red salmon catch at the 131 fishing sets made by these vessels. Future observations adjacent to and along the Aleutian Islands are required to determine relationships between the environment and these unusually large red salmon catches.

The uncertainty of a depth of "no net motion" and the boundary conditions imposed by the land areas compromise the usual method of ascertaining surface currents by the dynamic topography. Because realistic velocities cannot be ascertained, surface currents have not been discussed. The intrusion of dilute surface water flowing westward along the Alaska Peninsula, the interaction of water north and south of the Aleutian passes, and the fast-moving violent Aleutian storms all affect the surface conditions overlying the basic subsurface features. These features, however, are relatively permanent, slow-moving, and

indicative of local areas that may serve as a guide to the migrating salmon.

The southern limit of the salmon catches in the area during the summer coincided with the subsurface temperature front separating Subarctic Water, as determined by subsurface temperature-salinity relationships, from Transition Water. Although the envelopes as presented clearly define subwater masses in the Subarctic Region, no attempt has been made to name them as Oyashio, Deep or Coastal because there is not sufficient data for a permanent classification.

Oxygen-salinity relationships and silicate distribution have been utilized to show that the subsurface environment north of the front is relatively uniform and significantly different from the environment to the south. This boundary at lat. 48°N., however, can only define the southern limit of the salmon distribution during the summer.

SOUTHERN EXTENT OF SALMON DISTRIBUTION

In the spring of 1956, two other investigations obtained data that show a further southward extent of salmon distribution. These were the Japan Fisheries Agency studying the salmon distribution south of lat. 46°N., and the Pacific Oceanic Fisheries Investigations, Honolulu, Hawaii, investigating the distribution of albacore tuna, *Germa alalunga* (Bonnaterre).

SALMON CATCHES BY THE JAPANESE FISHERIES AGENCY—SPRING, SUMMER 1956

The results of a Japan Fisheries Agency salmon fishing operation in 1956 show that lat. 48°N. was not the ultimate southern limit of the salmon distribution in the spring of 1956 in the western and central Pacific. Maeda (1959) reported the results of this excellent study on the salmon fishing grounds between lat. 40°N. and 46°N. and long. 155°E. and 175°W. during

TABLE 3. Southern limit of salmon catches between long. 155° E. and 175° W., Spring 1956 (Maeda, 1959).

Species	Period	Latitude
Red salmon (<i>Oncorhynchus nerka</i>)	Early May	43° N.
	Late May	45° N.
	Early June	46° N.
Chum salmon (<i>O. keta</i>)	Early May	42° N.
	Late May	45° N.
	Early June	46° N.
Pink salmon (<i>O. gorbuscha</i>)	Late May	46° N.
Silver salmon (<i>O. kisutch</i>)	Early May	42° N.

May, June and July, 1956. He compared the salmon catches with water temperature, transparency and sea surface currents, and noted that salmon migrating south of lat. 46°N. become concentrated around a cold water mass near long. 167°E. as the water temperature rises and that the waters south of lat. 46°N. are the best fishing areas in spring. The southern limits of the salmon catches have been reproduced in Table 3 and show that salmon were caught as far south as lat. 42°N. in May, but by June none were caught south of lat. 46°N.

SALMON CATCHES BY PACIFIC OCEANIC FISHERY INVESTIGATIONS—SPRING 1956

The southern limit of salmon catches eastward of the Japanese fishing area is indicated by a total catch of four pink salmon by the United States Fish and Wildlife Service vessel *Charles H. Gilbert* at lat. 41°28'N., long. 165°18'W. and lat. 41°30'N., long. 164°33'W. on April 22 and 23, 1956 (Otsu, 1956). These salmon were caught at the northernmost part of the *Gilbert* cruise, and none were captured south of this latitude.

OCEANOGRAPHIC CONDITIONS 1958

Since hydrographic casts were not made aboard the Japanese vessels or the *Gilbert*, the oceanographic features near lat. 40°N. in 1956 are not known. It can, however, be shown by previous and more recent data that the subsurface features that have been discussed are relatively permanent. Thus, the extensive oceanographic cruises in the North Pacific in 1958 afford a good indication of the continuity of oceanographic features across the ocean, and permit comparison of

TABLE 4. Sources of 1958 oceanographic data utilized in Figure 11.

Vessel	Agency
M.V. <i>Pioneer</i>	Bureau of Commercial Fisheries Biological Laboratory, Seattle, Washington (Favorite and Pedersen, 1959b).
R.V. <i>Hugh M. Smith</i>	Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii ¹ .
C.N.A.V. <i>Whitethroat</i>	Pacific Oceanographic Group, Fisheries Research Board of Canada, Nanaimo, British Columbia (Pacific Oceanographic Group, 1958).
R.V. <i>Ryofu-maru</i>	Japan Meteorological Agency, Tokyo, Japan ¹ .
R.V. <i>Soyo-maru</i>	Tokai Regional Fisheries Research Laboratory, Tokyo, Japan (Tokai Regional Fisheries Research Laboratory, 1959).

¹ Unpublished.

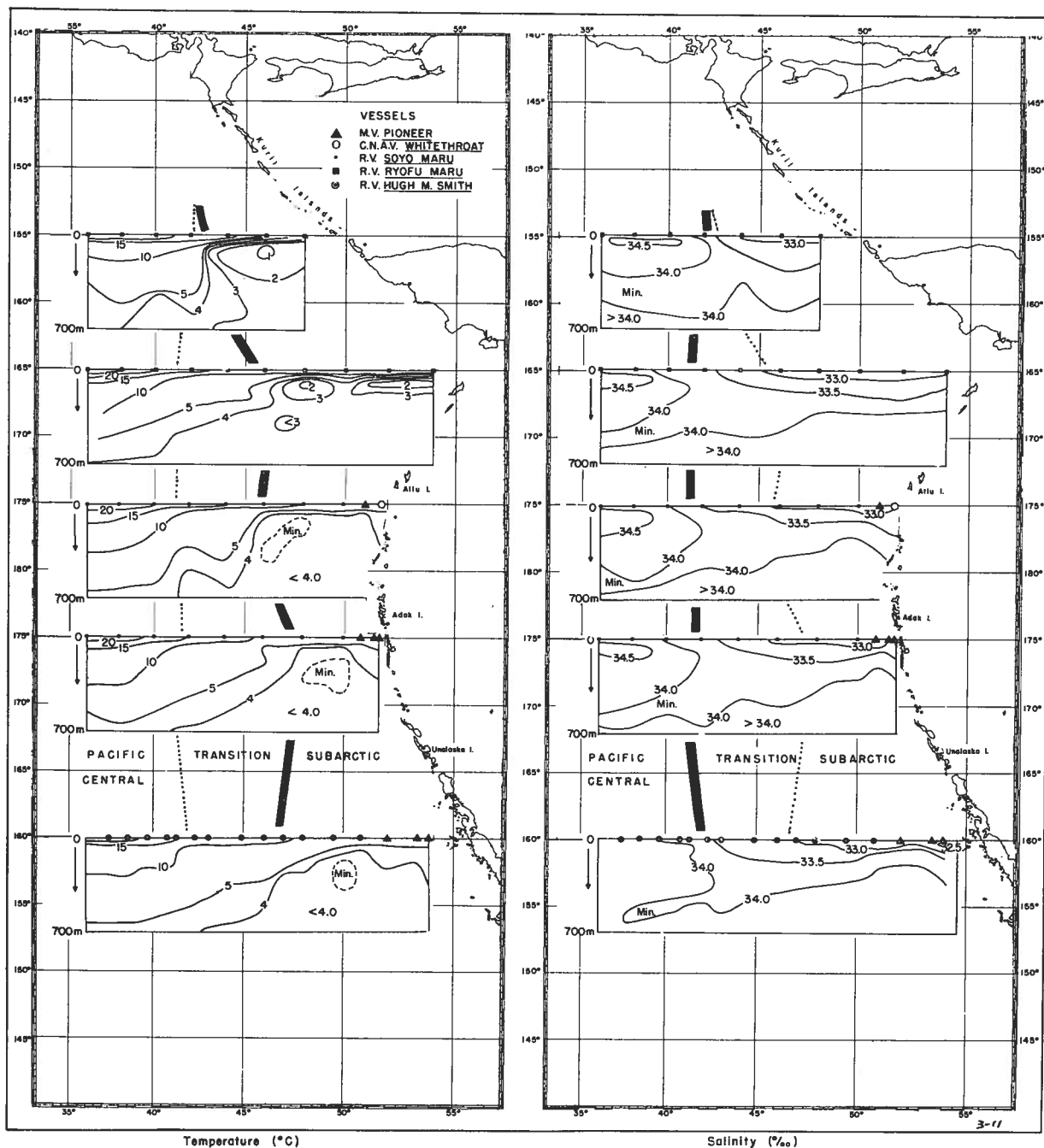


FIGURE 11. Vertical sections of temperature and salinity along long. 160°W., 175°W., 175°E., 165°E. and 155°E., Summer 1958, showing the extent of the Subarctic, Transition and Central Pacific Regions. Discontinuous black line inserted between the temperature sections shows proposed southern limit of salmon during summer; similar line between salinity sections shows proposed maximum southern limit of salmon. (Temperature contour interval: 0° to 5°C.—1°C.; 5° to 25°C.—5°C. Salinity contour interval: 0.5⁰/₀₀.)

the fishing results to oceanographic features. Sources of these oceanographic data are presented in Table 4. Figure 11 shows vertical profiles of temperature and salinity to a depth of 700 meters on long. 160°W. and 175°W., and 175°E., 165°E. and 155°E. Al-

though the detail permitted by the 1956 oceanographic data in the northeastern Pacific cannot be shown the significant features are clearly seen.

The discontinuous black line inserted between the

vertical sections of temperature indicate the approximate position of the temperature front associated with the 4°C. isotherm previously discussed. The crowding of the isotherms near the surface northward of this front shows the very shallow surface layer characteristic of the Subarctic Region. It should be noted that at long. 160°W. the front occurs at lat. 47°N., whereas in 1956 it was at lat. 48°N. This has been caused by a further eastward intrusion of water characteristic of envelope 1 discussed previously, which cannot be identified in this gross presentation. At long. 165°E. and 175°E., the front occurs at lat. 46°N. where Maeda (1959) reported large salmon catches in June, 1956.

The solid bars inserted between the vertical salinity sections show the northward extent of the salinity minimum characteristic of central Pacific water. The vertical 34‰ salinity isohaline denoting the salinity front occurs at lat. 41°N. to 42°N. and corresponds to the southern limit of salmon catches reported by the *Gilbert* and Japanese vessels in April and May in 1956.

The area between the temperature and salinity fronts is considered to be the Transition Region. In the western Pacific the fronts coincide and form a sharp environmental boundary, whereas in the central Pacific they are about 300 miles apart.

DISCUSSION AND CONCLUSIONS

Neither the oceanic extent of the distribution of salmons nor the factors which control their movements during the years they spend in the ocean are known. Comparisons of oceanographic conditions and salmon catch data from the *Mitkof*, *Celtic* and *Paragon* have shown that in the eastern North Pacific Ocean north of lat. 45°N. surface conditions did not indicate the presence or abundance of salmon.

Salmon catches at lat. 42°N. in the western North Pacific in May reported by Maeda (1959) and the April catch by the *Gilbert* at lat. 41°30'N., long. 165°W. indicate that the Transition Region, identified by the absence of either a temperature or salinity minimum, may constitute a preferable environment for salmon in spring, even possibly at depth in summer for immature salmon. The salinity front at approximately lat. 42°N., as defined by the almost vertical 34‰ isohaline, may denote the maximum southern limit of salmon distribution in midocean. Although there is an apparent northward movement of salmon in late May to lat. 45°N. and 46°N. in the western Pacific there is no evidence to show that the salmon were not present at depth southward of these latitudes and merely avoided the warm surface layer. In fact, Hashimoto and

Maniwa (1959), using echo-sounding equipment in the western Pacific, have shown that salmon do not necessarily migrate to the surface at night (thus making them susceptible to capture in gillnets) and in some instances remain at 30 to 50 meters depth.

The southern limit of gillnet catches in summer at lat. 46°N. in the western Pacific reported by Maeda (1959) and at lat. 48°N. in the eastern Pacific shown by Hanavan and Tanonaka (1959) occurred at the sub-surface temperature front which separates Subarctic Water, as identified at depth by a temperature minimum (<4.0°C.) rather than by surface dilution, from Transition Water. Northward of this front and thus in the Subarctic Region, the 4°C. isotherm forms a very shallow surface layer across the North Pacific. The shallow surface layer may confine food organisms nearer to the surface. Maeda *et al.* (1957) have shown that plankton concentrated near the surface by a thermocline has a close relationship to the migration of salmon. Then too, this layer is characterized by low salinity values reflecting dilution by runoff from coastal areas that may aid the salmon in their migrations. Either of these conditions could explain the presence of salmon in the northern area.

Lack of information concerning spawning and feeding migrations prevents making any specific conclusions as to the actual cause of a northward migration in spring—whether avoidance of the warmer surface temperatures to the south or the consequences of spawning or feeding migrations would cause the salmon to enter a different environment in which they may be forced closer to the surface. This would make them more susceptible to capture in the surface gillnets, and would account in part for the sudden appearance in spring of salmon near the temperature front and explain the apparent absence of salmon southward of the front in summer.

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