FISHERY OCEANOGRAPHY--III

Ocean Temperature and Distribution of Pacific Salmon

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The research on the distribution and migration of the European eel, Anguilla anguilla, in the North Atlantic Ocean in the early part of this century became a classic study of fish and the ocean environment, many aspects of which remain unsolved today. The movement of this species during its life cycle is practically opposite that of the Pacific salmon, genus Oncorhynchus. Adult male and female eels migrate down rivers of western Europe and northern Africa into the ocean, where they spawn in the deep layers of the Sargasso Sea (in the southwestern North Atlantic Ocean, several thousand kilometers from the streams) and then die. The eggs hatch into larvae, which are passively transported for 2 years by ocean currents toward the European coast. Here the transparent larvae metamorphose into small, black eels that swim up the fresh-water streams to grow and mature into adults; the cycle is than repeated.

The Pacific salmon enter fresh-water streams along the coast of the northern North Pacific Ocean as adults; they spawn and die in the shallow streams. When the eggs hatch, the young salmon move downstream into the ocean, where some stocks are known to migrate long distances, yet return to their natal streams to repeat the cycle. The contrast between the salmon and the eel is rather amazing, and the opportunity to study the relations between the ocean environment and the Pacific salmon has presented a stimulating challenge.

The Pacific Salmon

Less than 30 years ago, the movements of Pacific salmon during the marine phase of their life cycle were relatively unknown. Less than 20 years ago, it was believed that pink salmon, O. gorbuscha, off the coast of southeastern Alaska rose from deep water to begin a shoreward migration; no evidence was found that they had come from the open sea when first noticed in coastal waters. At that time, the Japanese believed that the marine phase of their life cycle was spent in an unknown area of the North Pacific Ocean.

Even though no oceanic fishing for salmon was conducted, early estimates of an acceptable ocean environment were: depth, 0 to 200 m.; salinity, 30 to 35 ‰; and temperature, 0 to 20° C. The temperature range was probably based on summer stream and coastal temperatures, although evidence existed that adult salmon had migrated through streams where temperatures reached 27° C. Nevertheless, if no other factors were involved, a tolerance to surface temperatures of 20° C. would permit salmon to migrate as far south as lat. 30° N. across the entire ocean.

Studies of salmon on the high seas by the BCF Seattle Biological Laboratory began in 1955. Those were exciting times. Not since the studies of Charles H. Gilbert and his associates, conducted half a century ago off Alaska, was so much being discovered about the ocean distribution of Pacific salmon. Each day, during each set, the capture of additional salmon appeared critical, and little time could be spared for environmental research that competed with the fishing program. Nonetheless, some environmental observations were made aboard the charter fishing vessels.

Environmental Observations

For reasons to be explained fully later in this series, observations of temperature and salinity were made to depths of 1,000 m. at fishing stations to provide some indication of current patterns in this relatively little-known region of the North Pacific Ocean. These observations, made at night after the gill nets were set, posed little hindrance to the fishing program except for 1 or 2 hours of extra work for one or more of the crew. Only after several years of field work did we have instruments to make observations while

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the relatively slow (8- to 10-knot) vessels were en route to the next fishing location along predetermined cruise tracks.

We have observed that salmon are not found at 1,000 m. Why then did we require data at such depths, and were they really necessary? The lack of interest in environmental observations at depth during these early investigations had some basis in fact. It was known from the fishing efforts of the Japanese, as well as our own, that most salmon were caught in the upper half of a usually shallow 6-m. (20') gill net at night. This knowledge reinforced the belief that salmon basically were a surface fish, and that their distribution depended more or less upon surface conditions.

In fact, one early hypothesis concerning ocean distribution of salmon was that the extremely low surface temperatures--less than 0° C. in western North Pacific Ocean and northern Bering Sea during winter (due to ice formation in coastal areas and its subsequent advection eastward)--probably caused southward and eastward movement of salmon. This hypothesis implied that during winter the entire oceanic salmon population would be south and east of the Aleutian Islands, probably concentrated in the Gulf of Alaska. Winter fishing in the early 1960's, by BCF Seattle Biological Laboratory, however, showed that salmon were present as far west as long. 170° E., and even in the north-central Bering Sea.

An explanation is possible concerning the position of salmon caught in gill nets that neither has been proved nor disproved: When salmon close to the surface approach the net, it is detected sonically. A natural avoidance reaction would be for the fish to swim upward toward the surface and, unless they jump out of the water (which is unlikely), they are caught in the upper portion of the net. If they swim downward, no air-water interface restricts their movements, and they are able to pass under the nets. (In studies with sunken gillnets, some salmon have been caught at depths in excess of 30 m., or about 100 ft.)

Surface Temperature & Salmon Distribution

Evidence obtained during late spring and summer in the mid-1950's indicated that surface temperatures were not as directly related to salmon distribution as subsurface temperatures. The southern limit of salmon in the central North Pacific Ocean (as determined by gill-net catches) was at about lat. 47° N. A sharp faunal division seemed to occur here; south of this latitude, only albacore (Thunnus alalunga) were caught (salmon and albacore were taken in same net at only one of hundreds of fishing locations). The surface temperature at this latitude during the fishing period was about 11° C.; we tended to consider this temperature as an upper threshold for salmon in the ocean. Salmon, however, were caught in water temperatures of 12° to 13° C.--at some locations temperatures were much lower than the earlier estimate of 20° C. If surface temperatures of 13° C. are not limiting, salmon should be found south of lat. 40° N. in midocean, but they have not been taken there. Although it is possible that the southern limit of salmon is dictated by the northward limit of the carnivorous albacore, this relationship has not been proved.

The investigations suggested, as long ago as 1956, that temperature distributions at depth were closely related to the distribution of salmon. The subject still has not been studied. Cold winter air at these latitudes cools the sea surface and causes the water to be more dense than that below; because of this change in density, some masses of water sink and others well up until the upper part of the water column has a uniform temperature, representative of minimum air temperatures.

Subsequent insolation (exposure to sun's rays) during spring and early summer warms the surface layer. As warm water is less dense than cold, no sinking occurs other than that due to turbulent mixing. A lens of warm water forms at the surface. Before diffusion can distribute this heat to sufficient depths and eradicate the lower temperatures formed during winter, fall cooling begins. Thus a temperature-minimum stratum is formed (temperatures below the depth of winter mixing are higher than those causing the winter turnover); this structure is a relatively permanent feature of the northern North Pacific Ocean.

Temperature-Minimum Stratum

Several important points are illustrated by the gill-net catches and temperatures along long. 155° W. during summer 1956 (fig. 1). It is obvious that the two largest catches (94 and 150 salmon) were made at the more northerly

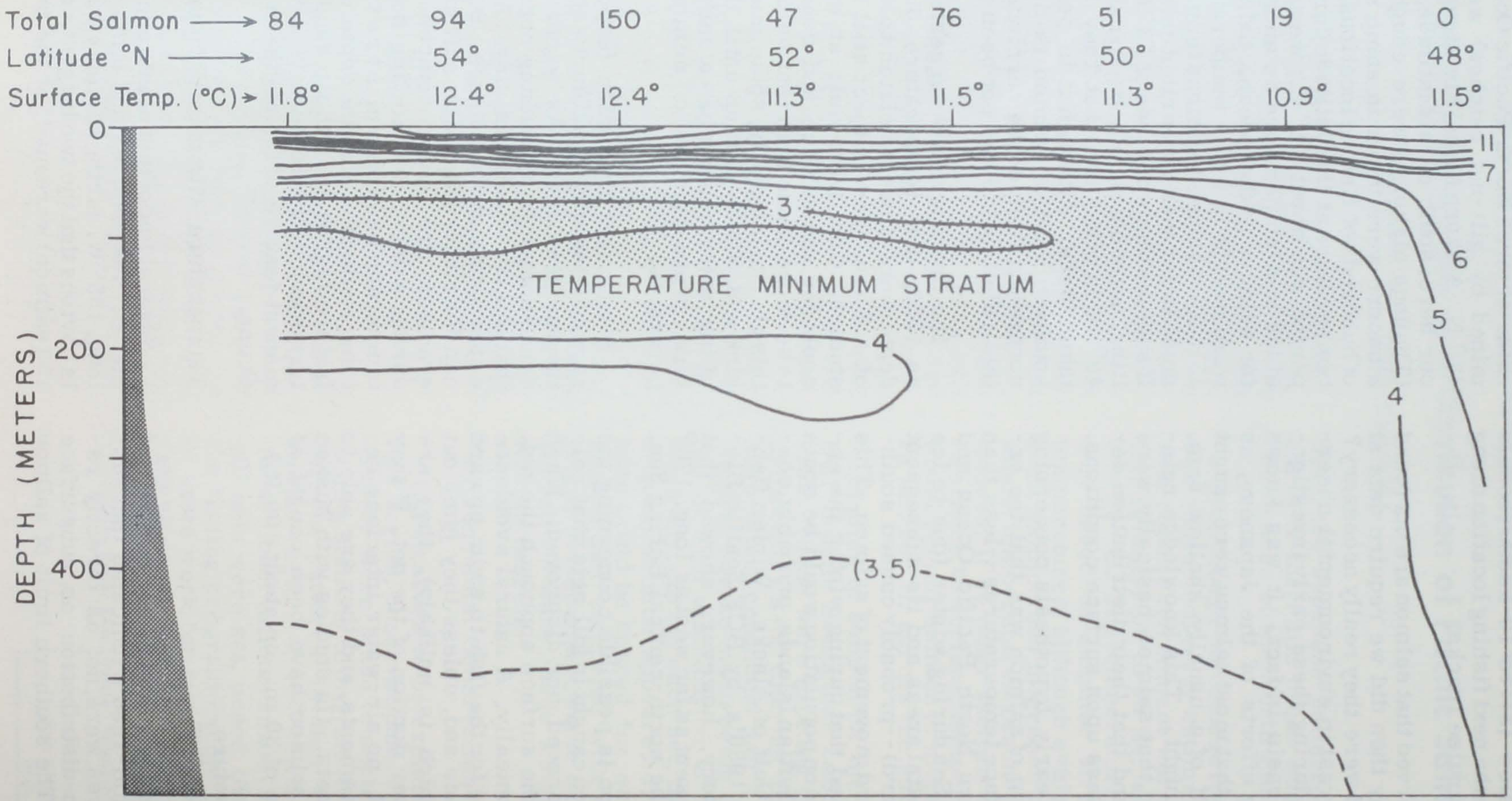

Fig. 1 - Vertical temperature distribution and surface gill-net catches along long. 155° W., summer 1956. Temperature minimum stratum shown by shading.

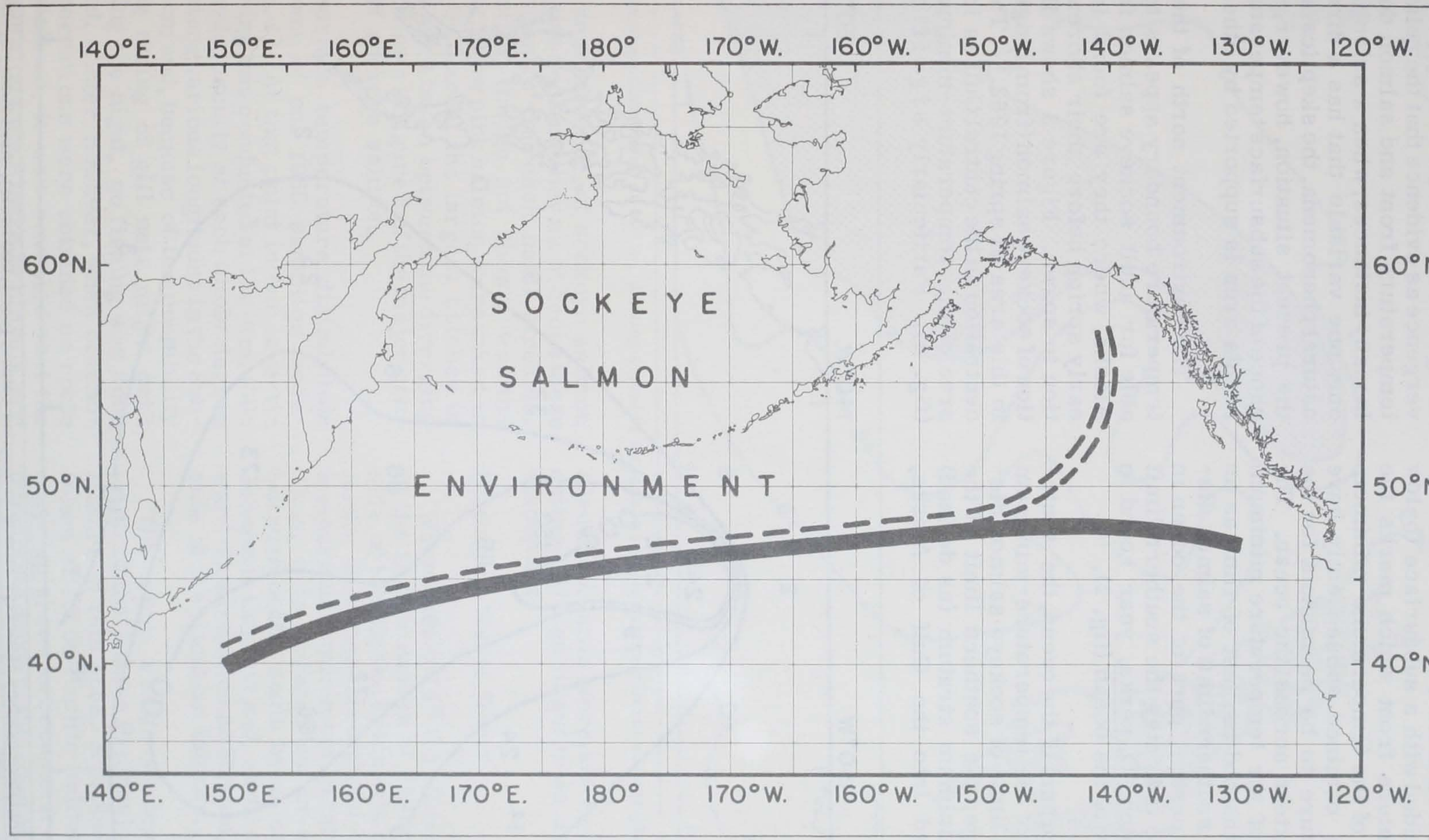

Fig. 2 - Approximate positions of southern boundary of temperature-minimum stratum of 4.0° C. (shown by dashed bar), and the southern boundary of sockeye salmon distribution as determined by gill-net catches (shown by solid bar).

stations and in water of maximum surface temperature--12.4° C.; also, that the southern limit of salmon catch (lat. 49° N. at this longitude) coincided with a subsurface (below 50 m.) temperature front which marks the southern limit of the temperature-minimum stratum. Data obtained subsequently have shown this feature to be permanent for the region and to extend across the ocean. The southern limit of the temperature minimum stratum has withstood the test of time as an indicator of the southern limit of salmon distribution in the central part of the ocean in summer; it also indicates the southern limit of sockeye salmon, O. nerka, year round in the central part of the ocean (fig. 2).

In the eastern part of the ocean, the southern boundaries of the temperature-minimum stratum and the limit of sockeye salmon distribution diverge; the southern limit of the temperature-minimum stratum (as defined) turns northward into the Gulf of Alaska, whereas the southern limit of sockeye salmon distribution continues eastward toward the Oregon coast. Skeptics may point to this divergence as evidence that the relation between temperature front and salmon does not hold. In many instances, when a scientist measures only one variable that has a direct effect on natural phenomena, the skeptics are right. In the present situation, however, the significance of the subsurface temperature boundary in this area is supported by other data.

The environment north of the subsurface temperature boundary appears to be preferable for adult sockeye salmon in the Gulf of Alaska, where they are found in winter and early spring before their shoreward migration to spawn. Figure 3 shows the distribution of sockeye salmon (from longline catches) in this area in spring 1962.[1/] The large concentration in the central Gulf is in the general area of the temperature-minimum stratum (fig. 4). Particularly significant is the

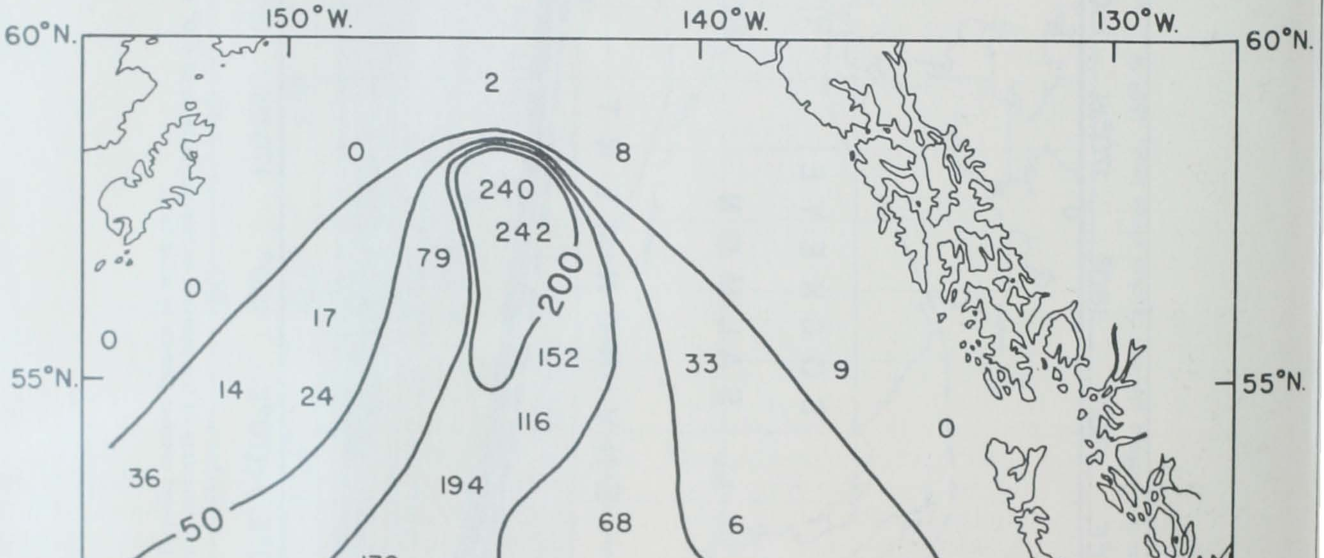

Fig. 3 - Relative numbers of sockeye salmon in longline catches (per 1,000 hooks), April 9-May 6, 1962.

1/Fisheries Research Board of Canada. 1964. Progress in 1962 in Canadian research on problems raised by the Protcol. Int. N. Pac. Fish. Comm., Annu. Rep. 1962: 30-53.

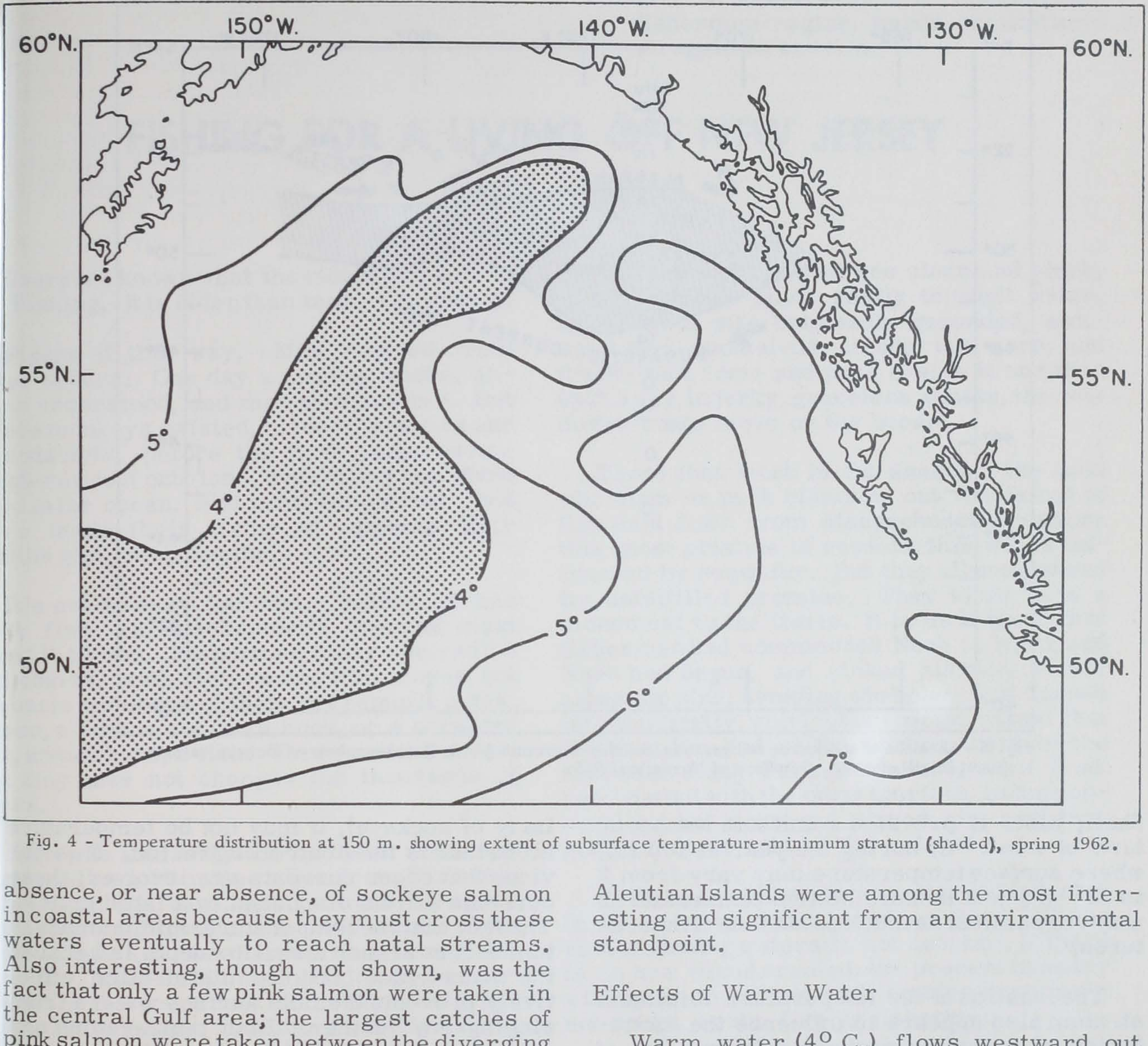

Fig. 4 - Temperature distribution at 150 m. showing extent of subsurface temperature-minimum stratum (shaded), spring 1962.

absence, or near absence, of sockeye salmon in coastal areas because they must cross these waters eventually to reach natal streams. Also interesting, though not shown, was the fact that only a few pink salmon were taken in the central Gulf area; the largest catches of pink salmon were taken between the diverging boundaries shown in figure 2 of the major concentration of sockeye salmon.

The subsurface temperature distribution indicates some of our 1965 sampling inadequacies (fig. 1). At that point in our investigations, fishing was conducted at 110-km. (60-mile) intervals, usually at each whole degree of latitude along various longitudes in the Subarctic Region; and, because of the possibility that the long string of gill nets might drift ashore during the night, no fishing was done close to land. Later, however, when oceanographic observations were obtained en route to fishing stations, it was revealed that the inshore areas along the Alaska Peninsula and Aleutian Islands were among the most interesting and significant from an environmental standpoint.

Effects of Warm Water

Warm water (4° C.) flows westward out of the Gulf of Alaska at depth along the south side of the Alaska Peninsula and Aleutian Islands; it forms a northern boundary to the temperature-minimum stratum in the Gulf. Thus, it is isolated as an offshore feature bounded on the south by an eastward-flowing Subarctic Current and, on the north, by a westward-flowing Alaskan Stream, along the south side of the Aleutian Islands.

The warm water at depth immediately south of the Alaska Peninsula is a permanent feature of this area. It probably has a significant effect on Pacific halibut (Hippoglossus stenolepis) stocks because it occurs at the approximate depth of the edge of the Continental

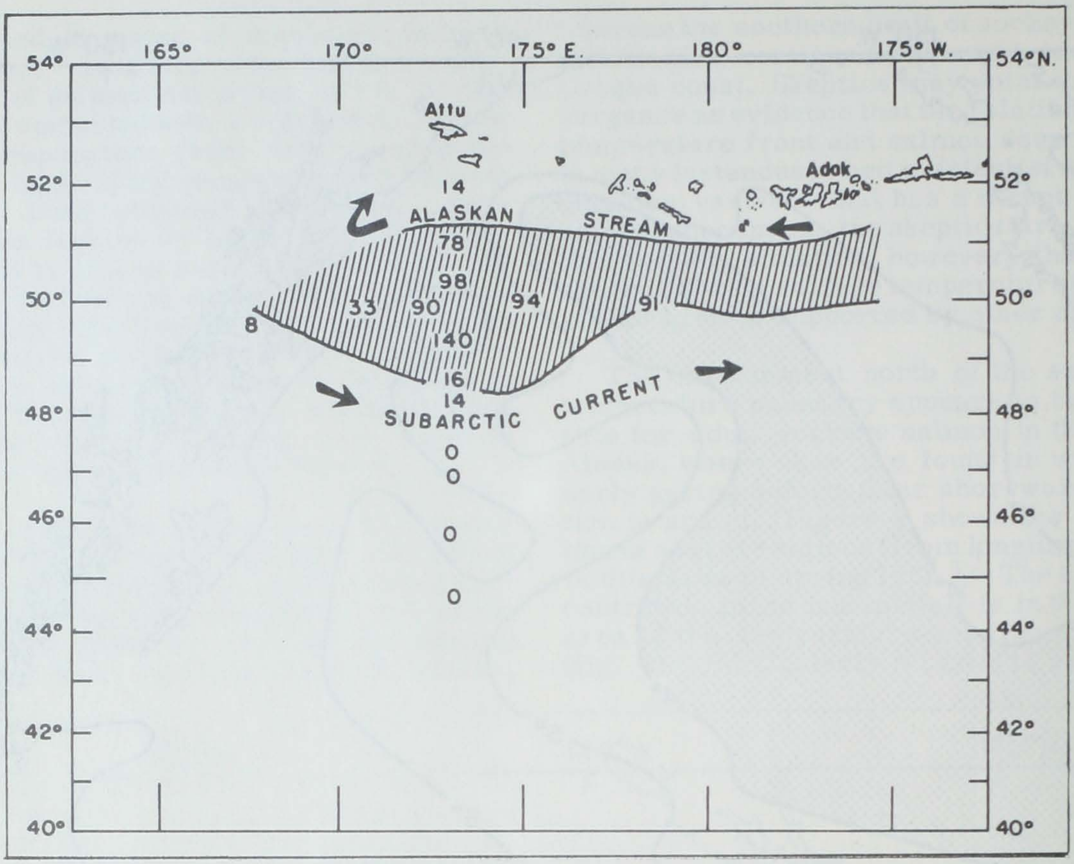

Fig. 5 - Location of subsurface temperature-minimum stratum (shaded) and numbers of sockeye salmon caught in gill-net sets, October and November 1965.

Shelf; also, it provides a uniform temperature of 4 to 5° C. during the year at 100 m., where surface temperature may vary from 2 to 12° C., and inshore bottom temperatures may vary almost as much as surface temperatures.

The location of the temperature-minimum stratum also appears to influence the distribution of maturing sockeye salmon south of the Aleutian Islands in fall. Data obtained in October and November 1965 show that large numbers were caught in surface gill nets in the general area of this stratum (fig. 5).

I have been careful not to imply a cause-and-effect relationship. Although the subsurface temperature distribution is a guide to determining salmon distribution (particularly of sockeye), it may not be temperature alone that is the controlling factor. It is obvious that ocean currents are involved; these currents will be discussed in a later article. The fact that the temperature-minimum stratum occurs at such a shallow depth is because the subsurface salinity distribution effectively prevents the cold surface waters from sinking any further. Both temperature and salinity determine density, which in turn governs flow. Furthermore, this plateau-like feature has cold water (approximately 3.0° C.) normally found only below 600 m. south of about lat. 48° N. in eastern part of ocean. It exists year round at depths usually less than 100 m. and has interesting biological and chemical aspects that have received only limited attention. Much research remains to be done.