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REVIEW OF THE OCEANOGRAPHY OF THE NORTHERN PACIFIC

by
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PREFACE

The following brief review of the Oceanography of the Northern Pacific was prepared at the request of the U.S. Fish and Wildlife Service to assist the United States members of the Committee on Biology of the International Commission for the North Pacific Fisheries. A preliminary draft was completed in May, 1954, and copies were made available to interested agencies. The material has subsequently been revised and a Bibliography added. No attempt has been made to incorporate the voluminous Japanese data and literature.

The author wishes to acknowledge the courtesies extended by the U.S. Navy Hydrographic Office that provided a wealth of unpublished data from their files. Professional assistance in the preparation of this material from Dr. Howard R. Gould and Mr. Taivo Laevastu has added greatly to the content of the report.

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REVIEW OF THE OCEANOGRAPHY OF THE NORTHERN PACIFIC

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General Summary

In Figure 1 an attempt has been made to bring together the principal oceanographic characteristics of the Northern Pacific that may influence the distribution and abundance of fishes. Obviously such material is generalized and no attempt has been made to portray micro-environments. Furthermore, our knowledge of the oceanographic conditions is limited, particularly in the central and northern portions of the Pacific, so that in many cases the material must be considered only as estimates. This division of the Northern Pacific into a series of natural regions is based upon the characteristics enumerated below. In proposing such subdivision of the area, particular emphasis has been placed on the conditions at and near the surface. It is a fact that because of the continuity of flow, mixing, and seasonal shifts that no exact boundaries can exist, but for purposes of discussion it is convenient to be able to apply regional designations to areas with relatively homogeneous conditions.

The outstanding features of the whole region, that is, the ways in which it differs from the Northern Atlantic and Southern Ocean, are:

1. The virtual closure at Bering Strait in latitude 66°N. in contrast to the North Atlantic that continues relatively wide and unrestricted into the Polar Basin. The circumpolar continuity of the Southern Ocean around Antarctica and the relatively small percentage of land in southern latitudes have many consequences, but it may be said that in general the Northern Pacific is more similar to the Southern Ocean than it is to the Northern Atlantic.

2. As a consequence of enclosure of the Northern Pacific, the circulation of the surface waters tends to be latitudinal. In this it is similar to the Southern Ocean, but is different from the Northern Atlantic where the currents have conspicuous north and south components.

3. As a result of the current pattern and somewhat different climatic regimes, the surface salinities in the Northern Pacific are conspicuously lower than those in the Northern Atlantic and Southern Ocean.

4. Although winter cooling and the formation of sea ice occur in all three areas, the salinities of the surface waters of the Northern Pacific are so low that the density of the cooled water is less than that of water present at depths of several hundred meters. As a result, vertical circulation in the Northern Pacific is restricted to the formation of a relatively shallow intermediate layer. In the Northern Atlantic and Southern Ocean, both bottom and deep intermediate waters are formed in large amounts.

5. The striking differences in vertical circulation lead to a number of peculiarities in the Northern Pacific. Because all intermediate and deep water is produced in the south, and because the Northern Pacific is essentially a cul-de-sac, the waters have been removed from the surface for a much longer time than in the Northern Atlantic and Southern Ocean. As a result, the intermediate and deep waters of the Northern Pacifc are notably low in dissolved oxygen and high in plant nutrients (phosphate, nitrate, and silicate).

6. The Northern Pacific is a region of net dilution by precipitation and runoff. To conserve the balance of salt, the net outflow of the diluted surface waters must be balanced by the inflow of more saline intermediate and deep water. Because of the high nutrient content of these waters, the general level of nutrients in the water column is higher in the Northern Pacific than it is in the Northern Atlantic and Southern Ocean.

7. Although regional differences may obscure the general picture, the overall organic productivity of the Northern Pacific must, area for area, exceed that of the Northern Atlantic and Southern Ocean.

Characteristics of Natural Regions of the Northern Pacific

A. BOREAL ZONE

Low winter surface temperatures, (generally less than 5°C.).
Low surface salinity, (generally less that 33.5 $^0/_{00}$).
Counterclockwise circulations.
Moderate to high precipitation, (increases from west to east).
Generally high plant nutrient content in surface layers.
Winter ice cover in northern parts.
Includes extensive coastal and shallow water areas.

Characteristics of the Regions:

1. *Kamchata—Kurile coastal region*—Southerly flow of cold, dilute, nutrient-rich water. Mostly ice-covered in winter.
2. *Western gyral region*—Irregular currents but average counterclockwise circulation. Very high nutrient content. Strong mixing between Aleutian Islands. Includes part of Alaskan shelf.
3. *Alaskan coastal region*—Northerly flow of warm, dilute, medium nutrient-content water. Mostly ice-covered in winter. Shallow area having an irregular coast with many rivers.
4. *American coastal region*—Northerly flow north of about 50°N. and southerly in lower latitudes. Salinities low because of local precipitation and runoff. Temperatures relatively warm in northern part. Nutrients variable but usually moderate to high. Generally irregular coast.
5. *Alaskan gyral*—Subarctic water that turns northward and forms a counterclockwise gyral. Salinity moderate. Temperature relatively high. Divergence supplies nutrients so that content is generally high. Precipitation high. Deep area.

B. SUBARCTIC ZONE

Surface water originates by mixing of Oyashio and Kuroshio.
Winter surface temperatures generally between 5° and 10°C.
Surface salinities medium, (32.5$^0/_{00}$ – 34.5$^0/_{00}$).
Primarily west to east flow, turning southward in eastern region.
High precipitation, ($>$ 80 cm./year; increases from west to east, except off California coast).
Nutrients medium to high, (0.2 to 1.0 μg-at. P/L.).
No ice.
Upwelling along California coast.

Characteristics of the Regions:

6. *Subarctic region*—Surface waters formed by admixture of Boreal and Central water. Most active mixing at convergence of Oyashio and Kuroshio. Easterly flow with divergence when approaching American

coast, forming the Alaskan gyral and the southerly flow in the Transition region. Nutrients medium to high.

7. *Transition region*—General southerly flow of rather dilute waters.
8. *California region*—Adjacent to California coast upwelling results in low temperatures, high salinities and nutrient-rich water.

C. CENTRAL ZONE

9. *Central region*—Represents the major easterly flow of the North Pacific clockwise gyrals. Kuroshio introduces relatively warm saline water. Winter surface temperatures high, (above 10°C). Salinities high, (generally above $34^0/_{00}$). Precipitation moderate, decreases from west to east. Nutrients low, (0.2 μg-at. P/L. and less). No ice, no upwelling, no continental influence.

Description of Area

The North Pacific Ocean is roughly triangular in shape with the base on the equator and the apex at Bering Strait. Some of the major distances are given in Figure 2. Because of the wide range in latitude, all of the general charts used in this paper are based on Denoyer's semi-elliptical projection that is approximately an equal-area representation.

As shown in Figure 3, the North Pacific is, in general, roughly twice as wide as the North Atlantic up to 50°N., but in higher latitudes the Atlantic remains relatively wide, whereas the Pacific rapidly narrows to Bering Strait at 66°N. It may be noted that the Aleutian Islands are in about the same latitude as the North Sea, and that Bering Strait is comparable in latitude to Denmark Strait and the northern limits of the Baltic Sea. Furthermore, the Kurile Islands are in latitudes corresponding to Newfoundland and Nova Scotia. Such general relationships are important because certain conditions that depend primarily on latitude may be expected to be similar in the two northern oceans. A similar comparison with the South Pacific is made in Figure 3. It can be seen that there are no land masses in the South Pacific in latitudes south of about 55° except for the Antarctic Continent, which corresponds in size and position to the central part of the Arctic Basin. These two diagrams show the significant feature of the Northern Pacific—its virtual isolation from the Arctic Basin in latitude 66°N.

BATHYMETRY

Figure 4 shows the general bathymetry of the Northern Pacific. Outstanding features are the relatively deep basins on the landward side of the island arcs. In the southwest Bering Sea depths exceed 2,000 fathoms, and in the Sea of Okhotsk and the Sea of Japan they exceed 1,000 fathoms. The elevations from which rise the Aleutian Islands, the Kurile Islands, and the Japanese Islands greatly restrict the exchange of water, and sills are present in all cases. The continental shelf, approximately represented by the zone between the coast and the 100-fathom contour, is extremely large in the Bering Sea and is relatively extensive in the Sea of Okhotsk.

The greatest depths occur in the deep trenches that parallel the seaward slopes of the island arcs. Depths exceeding 4,000 fathoms are found in the Aleutian, Kurile, and Japan Trenches. Bering Strait, which is only 58 km. (31 miles) wide and with a maximum depth of 30 fathoms, provides a very limited access for the exchange of surface waters between Bering Sea and the Polar Basin. Surface currents and observations in Bering Strait indicate that the flow is almost always northward through the Strait.

A rough profile, Figure 5, extending from Kamchatka to the Alaskan Peninsula shows the approximate widths and depths in the various channels between the islands.

The bathymetry is based on information provided by the U.S. Navy Hydrographic Office.

BOTTOM SEDIMENTS

The nature of the terrigeneous deposits near land will vary depending on local sources. On the continental shelf bordering the coast of British Columbia and Alaska, glacial deposits are probably the most conspicuous except off the mouths of large rivers which have contributed fine-grained sediment. The striking feature about the deep-sea sediments is a broad band of diatom ooze extending from Japan into the Gulf of Alaska and the virtual absence of globigerina ooze. The most common deep-sea sediment is red clay. A comparison with the North Atlantic reveals several striking differences. First, there is no diatom ooze in the North Atlantic; second, the most common deep-sea sediment in the North Atlantic is globigerina ooze with red clay restricted to the deeper basins in the western part. As will be described later, the diatom ooze is believed to be related to the higher productivity of diatoms in the Northern Pacific. The absence of globigerina ooze can probably be attributed to the difference in the origin of the deep water in the two oceans (Refs. 56 and 72).

Climatology

WINDS

During the winter months the area is under the influence of the low pressure cell centered over Bering Sea (Fig. 6). The winds generally have a westerly component, blowing from the northwest in the western areas, from the west in the central areas, and gradually turning through southwest to south in the eastern areas. In the northern part of the Gulf of Alaska easterly winds prevail. The crossed arrows indicate regions of variable winds. The contours indicate the percentage frequency of winds of Force 4 and higher. It can be seen that the stormiest area is between 35° and 45°N. in mid-ocean.

During the summer months the winds tend to blow from the south or southwest except near the continental margins. Off the coast of America the winds turn toward the south, and in the area covered by the chart the northeast trades can be seen in the southeast area. The contours in Figure 7 indicate the percentage of the time that the winds are Force 3 and less, and are essentially the opposite of the contours shown in Figure 6. It may be seen that light winds are most common in the lower latitudes and in the Gulf of Alaska. The weight of the arrows is a measure of the stability of the wind direction.

Figures 6 and 7 are based on data in the "Climatic Atlas of the Oceans" (Ref. 101).

PRECIPITATION

Precipitation is heaviest in a broad band extending from the vicinity of southern Japan toward the Gulf of Alaska. Within this band precipitation exceeds 80 cm. per year and reaches a maximum of more than 160 cm. per year near the American coast. The rainfall decreases toward the south with a minimum of less than 20 cm. per year off the coast of southern California. Northward from a line from Honshu to the Alaskan Peninsula, rainfall is between 40 and 80 cm. per year. North of approximately 40°N. the annual precipitation exceeds evaporation, and consequently the Northern Pacific is a region of net dilution (Ref. 45).

SEA ICE

The greatest extent of sea ice during the winter season is shown in Figure 6. The extreme limit of ice begins to retreat northward in March in the central portion of Bering Sea, but it is not until late May or June that there is any pronounced change. By June the ice limit has retreated to about 62°N., except for isolated patches along the coasts. By July, ice is limited to the Gulf of Anadyr and Bering Straits, and in August and September there is no ice remaining in Bering Sea and there is open water to the north of the Straits. In October, ice is again present in the Gulf of Anadyr and the northern portions of Bering Strait and it spreads southward rapidly until December, reaching its maximum coverage by February. The limit shown is for broken ice (Ref. 103).

COMPARISON WITH ATLANTIC

Winter winds are not as strong as in comparable latitudes in the North Atlantic. The same general situation prevails during the summer. During the winter there are conspicuous differences in ice distribution in the Pacific and Atlantic. In the western Atlantic, ice extends as far south as Nova Scotia in 42°N., whereas there is open water to the east of Iceland extending northward to Spitzbergen in 80° N. The southern range in the western Atlantic is comparable to that in the vicinity of Japan, and it is the absence of ice in the northeastern Atlantic that is the conspicuous difference. The mean limit of pack ice around Antarctica reaches its lowest latitudes in September and at that time lies between 55°S. and 65°S. During the southern summer the ice retreats to approximately 65° or 68°S. As a first approximation the occurrence of sea ice in the North Pacific is roughly comparable to its distribution in Antarctic waters.

Water Conditions

SURFACE TEMPERATURES AND SALINITIES

During the winter months, surface temperatures vary from approximately —2°C. in the ice fields to about 18°C. at 30°N. The general trend of the isotherms is from west to east, but all show a slight northerly trend in crossing from west to east, except near the continental margins where the influence of currents is most pronounced. A comparison of Figure 8 with the corresponding winter surface currents, Figure 15, reveals the effects of the Oyashio, the California Current, and the gyral in the Gulf of Alaska. During the summer the general trend of the isotherms does not differ greatly, but temperatures are from 5° to 20° higher than during the winter (Fig. 9). The smallest changes are in the vicinity of Bering Strait and the greatest changes are in the Sea of Japan and surrounding the northern islands of Japan.

The trend of isohalines is generally from west to east with conspicuous modifications that can be attributed to the effects of currents and to the dilution that occurs along the coast of Canada and in the Gulf of Alaska. In the lower latitudes there is relatively little difference between winter and summer salinities, but north of about 40°N. salinities are generally lower in summer than in winter (Fig. 10). During the summer the isohalines in Bering Sea show the effect of the northward flow on the American side and of southward flow along the coast of Siberia and Kamchatka (Fig. 11).

The temperature and salinity charts are based on data made available by the U.S. Navy Hydrographic Office.

COMPARISON WITH ATLANTIC

A comparison of the surface temperatures in winter shows relatively little difference in the western portions, but to the east of 40°W. in the Atlantic they are notably higher than in the Gulf of Alaska and Bering Sea. A similar situation prevails during the summer. A comparison of salinity conditions reveals that the entire area has much lower salinities than the North Atlantic, and in general the values for the North Pacific are $2\,^0/_{00}$ less. Between Spitzbergen and Norway, surface salinities often exceed $35\,^0/_{00}$, whereas in Bering Sea they rarely exceed $33\,^0/_{00}$.

VERTICAL CIRCULATION

A comparison of the vertical distribution of temperature and salinity in the North Pacific and North Atlantic reveals a major difference in the character of the vertical circulation. High salinity water carried northward in the Atlantic and cooled during the winter, sinks to the bottom and forms the water mass that fills a large part of the Atlantic Basin. Because of its low salinity, the waters of the Northern Pacific, even when reduced to approximately freezing temperatures, are still of only relatively low density and when these sink they spread out as an intermediate layer at depths of only a few hundred meters. Associated with this major difference in vertical circulation in the North Pacific and North Atlantic are vastly different distributions of dissolved oxygen, pH, phosphate, nitrate and other constituents. The deep waters of the North Pacific, even including those in the deep basin in Bering Sea, are waters of Antarctic origin and in comparison to the North Atlantic, are extremely low in dissolved oxygen and very high in phosphate and nitrate. The formation of deep water in the Atlantic is most active in the latitude of South Greenland (60°). Intermediate water is formed in the Atlantic where the cold waters of the Labrador Current converge with the Gulf Stream to the east of Newfoundland. Cold diluted intermediate water is formed in the Bering Sea along the coast of Siberia and Kamchatka and probably in the Sea of Okhotsk. A temperature and salinity profile in the northwestern part of the Pacific is shown in Figure 12. The phosphate content of the intermediate and deep water is particularly noteworthy, being roughly three times higher than that in the North Atlantic and twice as high as that in Antarctic waters.

These sections are based on *CARNEGIE* data and Russian observations (Refs. 25 and 69).

Figure 13 shows various characteristics of the temperature conditions in the vicinity of the Aleutian Islands (Ref. 65).

THICKNESS OF MIXED LAYER

Examination of bathythermograph data from the Northern Pacific shows that during the winter months the thickness of the surface mixed layer exceeds 100 meters in all areas except immediately adjacent to the California coast. In regions of strong winds and in latitudes near the lower limit of the area, the thickness of the mixed layer exceeds 150 meters. By May, spring warming is apparent over the entire area although gradients are small and still at considerable depth in the open ocean. Close to the continental coasts, a shallow mixed layer and a steep thermocline are already present. By midsummer (August), when surface heating has reached its maximum, the surface mixed layer rarely exceeds 30 meters and it is generally less than 20 meters. With the onset of cooling, the surface waters will become colder and the mixed layer will deepen. The combined effects of cooling and stronger winds will continue until winter conditions are attained.

It should be pointed out that during the winter, temperatures are characteristically uniform from top to bottom in the shallow waters of Bering Sea. Beneath the ice, water temperatures must approach the freezing point of sea water which is about —1.75°C. for the salinities present in the area. In the deeper parts of Bering Sea, this cold water does not penetrate to greater than about 100 meters because of the presence of high density water at these depths. Similar conditions probably prevail in the Sea of Okhotsk.

DISTRIBUTION OF PHOSPHATE

Figure 14 has been prepared from very scanty data from the available summer observations. Values to the north of about 45° are conspicuously high even during the summer months, indicating a high potential productivity. (Compare with Figure 1 and see discussion of regional characteristics).

The material shown in Figure 14 has been compiled from many sources including unpublished data (Ref. 115), and the results obtained in 1954 by the University of Washington in the Gulf of Alaska. Considering that the values shown are for the surface water and are chiefly for the summer months, the amounts of phosphate present are extremely large. It is only to the south of about 40°N. that low values characteristic of the subtropical oceans are encountered.

The generally high values for dissolved phosphate in the surface water must reflect the influence of the winter overturn and the intense mixing that occurs in such areas as the passes between the Aleutian Islands. The processes that maintain the high levels in the central part of the Gulf of Alaska are probably associated with the divergence of surface currents. The effects of upwelling are most conspicuous along the coast of the United States. Possibly upwelling, and certainly the mixing associated with the strong tidal currents, maintain the high values along the coast of British Columbia.

Because many of the data shown in Figure 14 were obtained during late summer, it is to be noted that depletion of nutrients cannot be a major factor in limiting plant productivity in the Northern Pacific. The lack of seasonal studies of the abundance of both plant and animal plankton is one of the greatest deficiencies in our knowledge of the region and must form a major part of any systematic program of investigation.

Water Movements

The principal features of the surface circulation are shown in Figures 15 and 16. In lower latitudes the main flow is from west to east, forming part of the large clockwise gyrals in the northern hemisphere. North of about 45° there are a series of counterclockwise gyrals, one in Okhotsk Sea and one in the Gulf of Alaska, and apparently a net counterclockwise flow in Bering Sea. In addition there are numerous areas of variable currents and smaller gyrals. The major difference between winter and summer is that the eastward-flowing currents extend into somewhat higher latitudes than they do during the winter months. This is particularly noticeable in the eastern Pacific.

The most conspicuous current is the Kuroshio, which leaves the coast of Japan in about latitude 35°, and as it flows eastward mixes at its northern border with the cold and low salinity water brought southward by the Oyashio. The Kuroshio flow gradually turns southward, but the mixed water continues toward the east, centered on about 40°N. When approaching the American coast, a part of this mixed water, further diluted by precipitation, is deflected northward to form the gyral in the Gulf of Alaska. Another part turns southward to form the California Current. It should be noted that the latitude at which this apparent split occurs is approximately 50°N. in summer and shifts southward to about 43°N. in winter. The Davidson Current flows northward close to the coast of America, but is present only during the winter months.

It can be seen that water from the Gulf of Alaska passes between the Aleutian Islands and flows northward, some of the water passing through Bering Strait. Little is known concerning details of the currents in Bering Sea, but there seems to be a general counterclockwise circulation. Examination of physical and chemical data indicates that there are zones of convergence in the northwestern part of Bering Sea and in the area of mixing between the Oyashio and the Kuroshio. There is some evidence for a zone of divergence in the central part of the Alaskan gyral. Upwelling is a major feature along the California coast and some effects of divergence are detectable as far north as Vancouver Island during the summer months. Turbulent mixing, associated with the strong tidal currents in coastal waters and in the narrow and shallow passes between the Aleutian Islands, the Kurile Islands and the Japanese Islands, must have local effects on the temperature and salinity conditions and also on the supply of plant nutrients in the surface layers.

Figures 15 and 16 are based on compilations of surface currents made available by the U.S. Navy Hydrographic Office.

Factors Affecting Productivity

The total amount of photosynthesis carried on by aquatic plants beneath a unit area of the sea surface depends upon a complex of biological and physical factors. Ketchum (Ref. 47) has summarized various ways in which photosynthesis and productivity can be estimated, and has shown that the total annual productivity can vary tremendously from one part of the ocean to another. In the following discussion, productivity will be expressed in terms of organic carbon.

Organic carbon, 1mg. = 2.3 mg. dry weight plankton
= 37 mg. wet weight plankton
= 0.024 mg. of phosphorus

Representative values for total plant productivity are as follows (Ketchum, Ref. 47):

Estimates of Total Organic Plant Production

Location	*Production*	*Reference*
English Channel	39- 101 g. C/m^2/6 mos.	Harvey, 1945
Long Island Sound	95-1000 g. C/m^2/year	Riley, 1941
Western Atlantic, 28°-38°N.	530 g. C/m^2/year	Riley, 1941
38°-41°N.	320 g. C/m^2/year	Riley, 1941
28°-41°N.	140- 530 g. C/m^2/year	Riley, 1941
3°-13°N.	278 g. C/m^2/year	Seiwell, 1935
Pacific, off S. Calif.	215- 430 g. C/m^2/year	Sverdrup & Fleming, 1941
Gulf of Maine	120 g. C/m^2/year	Redfield et al (1937)*
Barents Sea	170- 330 g. C/m^2/year	Kreps & Verjbinskaya, 1932
Helsingör Sound	44 g. C/m^2/year	Steemann-Nielsen (1937)

*Calculated for this table using the C:P ratio of 100:2.5.

Steeman-Nielsen (Ref. 83) has estimated that the average gross plant production in the oceans is 0.15 g. of carbon/m^2/day. This would correspond to a total production for all oceans of 1.5 x 10^{10} tons of carbon per year or roughly the same as that of land plants. This value is considerably less than earlier estimates by Riley (Ref. 73). The value of 0.15 g. of C/m^2/day is representative of the open ocean in middle and lower latitudes. In areas of upwelling, and in the higher latitudes during spring and summer months, the gross productivity can be expected to be much greater, possibly by an order of magnitude.

The following factors are considered in any analysis of plant productivity:

(a) Solar radiation. This varies with latitude, season, length of day, time of day, and sky conditions.

(b) State of the sea surface. Calm seas permit more light to penetrate the water than when the surface is roughened by the wind. In high latitudes the presence of ice is a major factor because of its limited transparency.

(c) Transparency of water. Combined effects of the solar radiation, state of the sea surface, and the transparency of the water, determine the compensation depth, that is, the depth to which light is sufficient to permit photosynthesis to equal or exceed the respiration of the plants.

(d) Availability and supply of nutrients. In short time intervals, the quantities of such substances as phosphate, nitrate, silicate and other limiting "plant nutrients" present in the euphotic zone may retard photosynthesis. Riley *et al* (Ref. 75) believe that photosynthesis is retarded when the concentration of phosphate drops below about 0.5 μg-atoms/L. (16.5 mgs. P or 47.5 mgs. PO_4 per cubic meter). No data are available on the other nutrients but there is usually a relatively constant ratio between the concentrations of phosphate and nitrate ($N:P = 15:1$ by atoms). Silicate varies independently of the other elements, being notably higher in the North Pacific and Antarctic than it is in the waters of the North Atlantic.

Over longer periods the effect of the nutrients must be considered as determined by the rates of regeneration in the surface layers, and more particularly by the rate of supply of the nutrients to the lighted surface layers.

The sinking of dead plants and animals, organic detritus, fecal material and the vertical diurnal migration of many plankton and nekton forms that feed near the surface, result in a loss of carbon, nitrogen, phosphorus, etc., from the surface layers. Riley (Ref. 73) has estimated that 90 per cent of the materials are regenerated in the upper 200 meters but that the remaining materials are in effect lost to the surface layers. When one considers the long-term aspects of productivity, it is apparent that it is processes that will return the plant nutrients from the deeper, nutrient-rich water that must control the total productivity of the oceans and the major regional differences in fertility.

The processes by which nutrients are returned to the surface layers are:

(a) Winter mixing. In higher latitudes (above about 40°), cooling of the surface waters in winter increases their density and they tend to sink and mix with underlying water. The winds contribute to this mixing and the result is to return nutrients to the surface where they are once more available for photosynthesis when light is sufficient.

(b) Turbulent diffusion through the thermocline. This must contribute to the fertility and differs from (a) in that it is a continuous but slow year-round process even in low latitudes.

(c) Mass displacement. The processes of cooling and freezing that lead to the formation of intermediate and deep waters must affect the oceanic fertility by upward displacement of nutrient-rich water. This upward displacement can occur in regions remote from the areas where such waters sink from the surface.

(d) Upwelling. Directly or indirectly, winds can produce divergences in the surface currents that result in upward movement of nutrient-rich waters that are carried along and spread horizontally by the currents. Well-known regions of upwelling are of relatively limited area, being restricted to coastal bands (as off California, Peru, and Southwest Africa) and to zones between diverging currents (Equatorial Pacific).

(e) Type of water exchange. In certain portions of the oceans, it is possible to distinguish between two general types of vertical circulation and water exchange. In one type there is a net inflow of surface water and a net outflow of deep water. Because such surface waters are low in nutrients, regions of this type are low in nutrients and the productivity is relatively small. The Mediterranean Sea is a classical example of this type. In more general terms, the same situation prevails in the North Atlantic. In the second type there is a net outflow of surface waters and an inflow of deep water. Because the deep water is rich in nutrients, their over-all level is high and this type of water exchange results in relatively large regional productivity. Puget Sound is an example of such an area and a similar situation is characteristic of the North Pacific and Bering Sea. Combined effects of divergence and tidal mixing and the consequent water exchange probably account for the relatively high phosphate content in the surface waters adjacent to the coasts of British Columbia and in the Gulf of Alaska.

Steemann-Nielsen (Ref. 83) has estimated that the total productivity of the ocean is 1.5 x 10^{10} metric tons of carbon per year. This requires 3.6 x 10^8 metric tons of phosphorus. If only 10 per cent of this sinks below 200 meters each year, a minimum amount of 3.6 x 10^7 tons must be returned to the surface layers by the processes outlined above. It is obvious that combinations of factors lead to great regional differences.

Stability is a term used to indicate the rapidity with which density increases with depth. A water mass of uniform density is said to have indifferent stability, and vertical turbulence created by winds or by currents will extend throughout the depth of the layer. Where there is an abrupt increase in density with depth, mixing is greatly impeded. Both temperature and salinity affect the density but, in open ocean areas, temperature usually has the dominant influence. The surface mixed layer is a zone of indifferent or low stability and the thermocline and/or halocline is a layer of high stability. It has been generally recognized that diatom production is adversely affected where water is turbulent, and Sverdrup (Ref. 90) has indicated an objective way of relating the biological conditions to the thickness of the wind-stirred layer. He has defined a "critical depth" in terms of light intensity. He has suggested that the mixed surface layer must be less than this critical depth if the phytoplankton is to increase. He has tested this relationship for conditions at Weather Ship M (66°N. 2°E.) and has obtained satisfactory agreement. The introduction of this concept that diatoms can only prosper when the water is stabilized at fairly shallow depths appears to satisfy several relationships that are known to exist. In the first place, it may account for the fact that the spring blooming of phytoplankton usually begins at an earlier date near shore than it does in the open ocean in comparable latitudes. This situation can be accounted for by the stabilizing effect of fresh water runoff and the more rapid heating, and hence, further stabilization that occurs near the surface. The use of this concept may also account for the fact that in the open ocean the spring phytoplankton blooms seem to occur at roughly similar dates over a wide range of latitude. It is known from temperature observations made with bathythermographs that in the northern hemisphere, evidence of surface heating and the development of a shallow mixed layer and seasonal thermocline first appear during April, and it is generally during this month that diatom populations increase most rapidly. There are relatively few data on seasonal phytoplankton populations in the open ocean. Sverdrup presents some data for Station M, and Corlett (Ref. 14) has presented three years of observations from two weather ships in the North Atlantic, one located at approximately 60°N. and one at 53°N. In all cases the most rapid increase in diatom populations occurred in late March or during April. Hart (Ref. 37) has presented a wealth of information concerning phytoplankton populations in Antarctic waters. He has divided his observations into three latitudinal bands, a northern region extending 300 miles southward from the Antarctic convergence (average latitude of convergence, 53°S.), an intermediate region extending from the southern limit of the northern region to the Antarctic Circle, and a southern region between the Antarctic Circle and Antarctica. In the lower latitude region the most rapid development of diatoms occurs in October or November (corresponding to April or May), and the most rapid increase in the intermediate zone is in December, and in the highest latitudes in January (corresponding to June and July, respectively). The delay in spring blooming in these latitudes can probably be attributed to the influence of the ice which retreats poleward during these months.

There are no seasonal studies of diatom populations in the open waters of the North Pacific except near Japan and off the California and Oregon coasts. Cupp (Ref. 16) has reported on phytoplankton collections made at Scotch Cap over a period of five years. Although probably affected by proximity to land, these observations indicate maximum rates of increase in March.

Examination of data mentioned above shows that, in most cases, peak phytoplankton populations occur one month later than the month of maximum rate of increase. It is noticeable that the interval during which diatom populations remain relatively high in a given latitude tend to become shorter the higher the latitude. This is most clearly demonstrated by Hart's data from the Antarctic. Except in the highest latitudes the diatom populations tend to show two or more maxima during the growing season. To summarize the factors that appear to control the seasonal variations in phytoplankton, the principal physical factors seem to be: availability of nutrients in the surface layers, development of stability so that there is a shallow surface layer less than the critical depth, and in high latitudes the retreat of the ice.

No mention has been made of the influence of zooplankton grazing upon diatom production. In low latitudes it is probably true that there is essentially a balance between phytoplankton production and grazing throughout the year. In higher latitudes the development of phytoplankton during the spring is limited by increased grazing and later variations in grazing may explain the series of maxima that are usually shown by phytoplankton populations (Fleming, Ref. 26). In mid-latitudes these may be due to development of several generations of zooplankton. In high latitudes where the growing season is very short, phytoplankton populations develop rapidly and are presumably followed by a rapid increase in zooplankton, and probably the latter represent only a single generation.

Practically nothing is known of the seasonal variations in plankton populations in the Northern Pacific. There is a vital need for studies similar to those of Corlett (Ref. 14), Halldal (Ref. 35) on phytoplankton and Jaschnov (Ref. 46) and Kielhorn (Ref. 48) on zooplankton. These surveys are based primarily on systematic collections made from weather ships in the North Atlantic.

It is generally agreed that shallow waters tend to be more productive than adjacent deep water areas. Two factors probably contribute to this situation. In the first place, organic material sinking from the surface is trapped by the bottom where it may be eaten by bottom-living organisms or mineralized by the bacteria. It is therefore more readily available to return to the euphotic zone by processes of turbulent mixing and may be available for plant development several times during a season. The second factor, which is believed important, is the quantity of living organisms on the sea floor. These organisms always represent the bulk of the living material in the water column and consequently could act as a reservoir of the essential elements, returning them to the water as products of metabolism. Riley (Ref. 73) has presented data obtained by Harvey (Ref. 39) in the English Channel that indicate that on the average, the bottom invertebrates represent about 65 per cent of the total biomass in the water column, which in this case is 70 meters deep. The biomass of the bottom-living invertebrates will presumably depend on the character of the bottom; and if the suggestions made above are correct, it would follow that the regional productivity in shallow water will depend to some extent upon the character of the underlying bottom. Rocky or firm bottoms that favor the development of invertebrates should be associated with regions of higher productivity than those with shifting sandy bottoms that are generally unfavorable for invertebrates.

Long-Term Temperature Trends

In recent years there has been an increasing interest in the changes in fishery yields in the North Atlantic and the apparent correlation of these with long-term trends in surface water temperatures. Representatve temperature data for the Northern Pacific are presented in Figure 17. The localities selected were determined primarily by the length of the period for which data were available rather than by the desirability of the location. Gross correlations between annual surface temperatures and mean sea levels are suggested by the comparative data in Figures 17 and 18 (Ref. 52). In order to be able to compare temperature trends with those in the North Atlantic, two sets of data are shown in Figure 18, one for the Faroe Island region and one for St. Andrews, New Brunswick (Refs. 81 and 44). Although in relatively protected inshore waters, data for Departure Bay, British Columbia, are presented in Figure 19 because of the great length of time for which temperature data are available (Ref. 96).

State of Oceanographic Knowledge

Figure 20 shows the tracks followed by major oceanographic expeditions in the Northern Pacific. No attempt has been made to show the detailed work conducted by the Japanese in the vicinity of their country, nor the numerous cruises conducted by the Scripps Institution of Oceanography off the coast of California and Oregon. Although the chart may give the impression of reasonable coverage, it should be emphasized that many of the major expeditions shown here were limited in scope. Most of them obtained temperature and salinity observations at various depths, but only a few made analyses for plant nutrients and very few obtained any information on the distribution of plankton. Results of the cruises indicated as NH (Northern Holiday) and Ba (Trans-Pac), conducted by the Scripps Institution of Oceanography, have not yet been published. These data when available will provide valuable information in areas otherwise virtually unknown. It should also be pointed out that with the exception of cruises Ba, NH and some of the Canadian investigations (POG) and those of the International Fisheries Commission (IF), all the data are limited to the summer months. For this reason it is virtually impossible to determine the nature of the seasonal cycles, particularly those at depth.

During August 1954, the University of Washington vessel *BROWN BEAR* made a survey of the Gulf of Alaska. Phosphate data from this cruise are incorporated in Figure 14.

During the period of late July to early September 1955, it is expected that an international program of observations will be carried out by various Japanese, Canadian and U.S. activities to obtain simultaneous observations in an area extending from Japan to the United States, and in the Bering Sea. This program is referred to as NORPAC.

The following United States agencies are currently engaged in offshore oceanographic programs in the Northern Pacific:

The U.S. Fish and Wildlife Service is actively engaged in oceanographic surveys in the central part of the Pacific. This program is centered in the Pacific Oceanic Fisheries Investigations with laboratories in Honolulu. During the past several years most of their efforts have been devoted to studies in lower latitudes, but during the winters of 1953-54 and 1954-55, cruises were made to as far as about 40°N. Their work involves physical oceanography, plant nutrients, zooplankton observations and experimental fishing (Refs. 5, 15, 79, 85).

The U.S. Coast and Geodetic Survey, as a part of their program of hydrographic surveying along the coastal waters of United States and Alaska, has made numerous measurements of currents, temperatures and salinities. Observations of this type are now being obtained in survey areas in and near Bering Sea.

The U.S. Navy, through the Naval Electronics Laboratory at San Diego, has conducted oceanographic cruises in the Northern Pacific, but except for several papers dealing with submarine geology their data are not yet published.

The Department of Oceanography, University of Washington, is currently engaged in both inshore and offshore oceanographic surveys. The offshore work to date has been in the areas shown in Figure 20. Participation in NORPAC is planned.

Scripps Institution of Oceanography has conducted two extensive cruises previously mentioned, namely, Trans-Pac and Northern Holiday, and is making monthly observations off the coast of California and Oregon. They will participate in the co-operative program in late summer, 1955.

The Hancock Foundation of the University of Southern California has an ocean-going research vessel, but it is not believed that they have conducted any work in the Northern Pacific.

Other activities, such as the Hopkins Marine Station of Stanford University and various state fisheries agencies, have participated to a limited extent in oceanographic programs.

Extensive studies were made by the International Fisheries Commission during the period 1927 to 1929 (Refs. 93, 94, 95).

Work by Canadian oceanographers, namely the Pacific Oceanographic Group at Nanaimo, and the Institute of Oceanography at the University of British Columbia, has been limited to inshore investigations and offshore surveys in the area shown in Figure 20 (Ref. 97). Participation in NORPAC is planned.

No attempt has been made to indicate the intensive studies conducted by the Japanese. However, most of their work has been limited to the waters near Japan and there are only scattered observations extending as far north as Bering Sea.

The only modern Russian investigations that have been examined are those in the Bering Sea. These surveys, conducted in 1932-33, include physical, chemical, and biological studies (Refs. 70,71). Only the physical and chemical data have been located.

In the files of the U.S. Navy Hydrographic Office are numerous unpublished Japanese observations as well as data collected by U.S. naval vessels. One of the most valuable sets of observations is the file of bathythermograph records which has been compiled during the last twelve years. In addition there are some unpublished observations of physical properties collected by U.S. naval vessels.

General Plan for Future Work

It should be obvious from the preceding material that our knowledge of the oceanography of the Northern Pacific is fragmentary. The principal deficiencies are: (a) in proper seasonal coverage, (b) in observations of factors affecting biological productivity, and (c) in plankton studies. In any program intended to establish the regional and time variations in the abundance of fishes and in any studies to determine the influence of oceanographic factors on migrations, spawning, productivity, etc., emphasis should first be placed upon extensive regional surveys rather than upon intensive local studies. Furthermore, the achievements attained by the Pacific Oceanic Fisheries Investigations are indicative of the value of simultaneous and co-ordinated studies in both oceanography and fisheries. It should also be emphasized that general regional surveys should be planned so that the work can be conducted over a period of at least five years. These should provide opportunities to cover the area in considerable detail and to establish the general features of year-to-year variations which, in middle and higher latitudes, may be very large. As such general surveys are made, emphasis can be shifted towards those regions or phenomena that appear to be critical and added emphasis can be placed upon coastal areas.

The limited amount of data available for the Northern Pacific reflects the stormy conditions that prevail during the winter months. In order to conduct the necessary program, vessels engaged for this purpose must be large enough to permit working under adverse conditions and should probably be strengthened to withstand operations in broken ice. A vessel well suited to this type of work is the *DISCOVERY II* that has operated for the past twenty years in the southern oceans, carrying out a general survey of the region under the direction of the Discovery Committee. The *DISCOVERY II* is 234 feet long with a displacement of 2100 tons. This vessel is larger than any of the oceanographic vessels available in the United States with the exception of those operated by the U.S. Navy Hydrographic Office. In any year-round operations in the Northern Pacific, it would be unwise to attempt extensive surveys without a vessel of the general type of the *DISCOVERY II,* which has proved by many years of very successful work that she is capable of operating under conditions comparable to those in the Northern Pacific.

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A bibliography is attached which includes many of the references to the oceanography of the Northern Pacific but does not contain any of the extensive Japanese publications. In addition, a number of references are included that are of general interest although the results reported are not for the Northern Pacific. Only those references bearing directly on the subjects are cited in the text. Grier (Ref. 34) is an excellent source of both Japanese and other references prior to 1941, and the majority of the works listed in the bibliography are of a later date. Schott (Ref. 78) and the various Atlases (Refs. 101, 102, 103, 104 and 105) are excellent sources of information on the entire Pacific.

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ADDENDA

ASSOCIATION D'OCEANOGRAPHIE PHYSIQUE. UNION GEOD. ET GEOPHYS. INTERN. Monthly and annual mean heights of sea-level, up to and including the year 1936. Publ. Scientifique No. 5, 255 pp. 1940.

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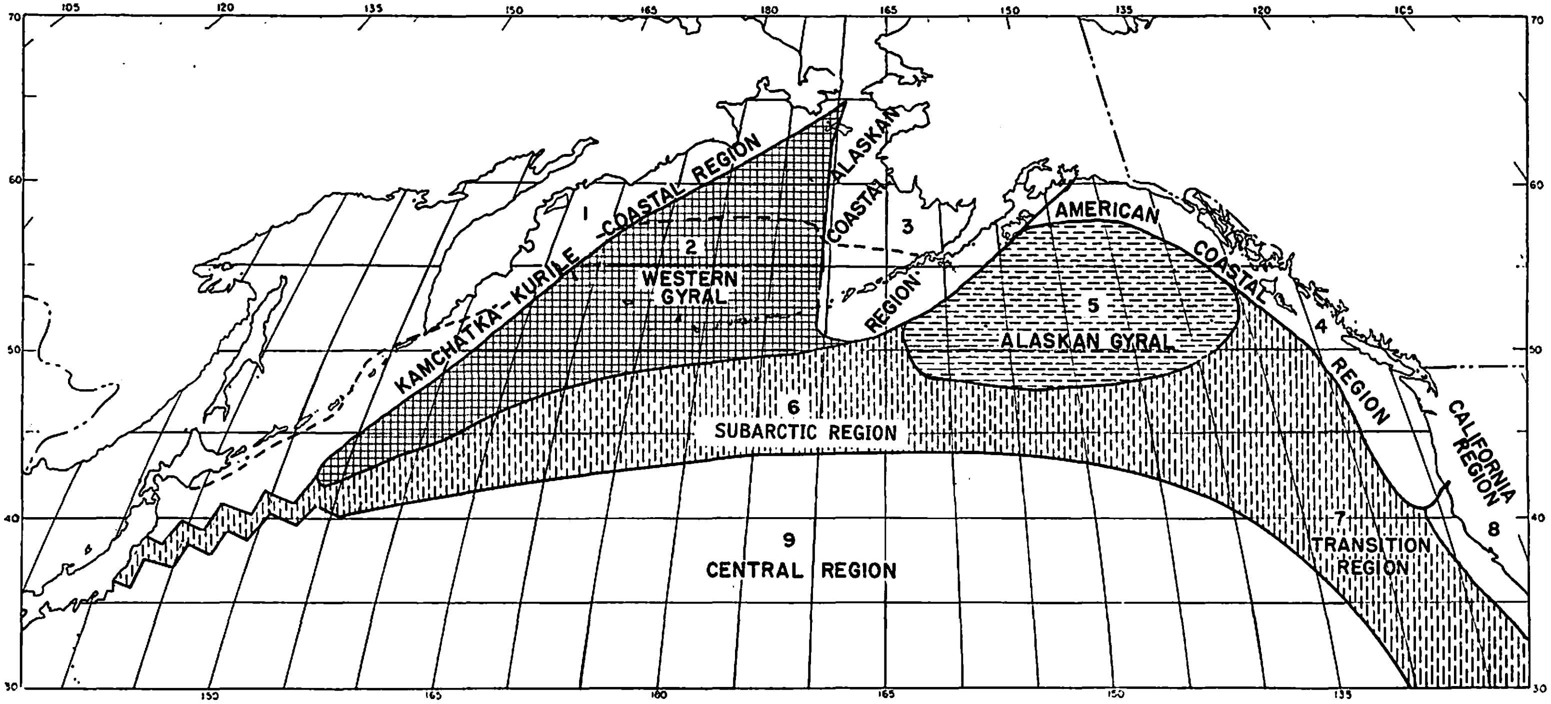


FIGURE 1. Natural Regions of the Northern Pacific Ocean.

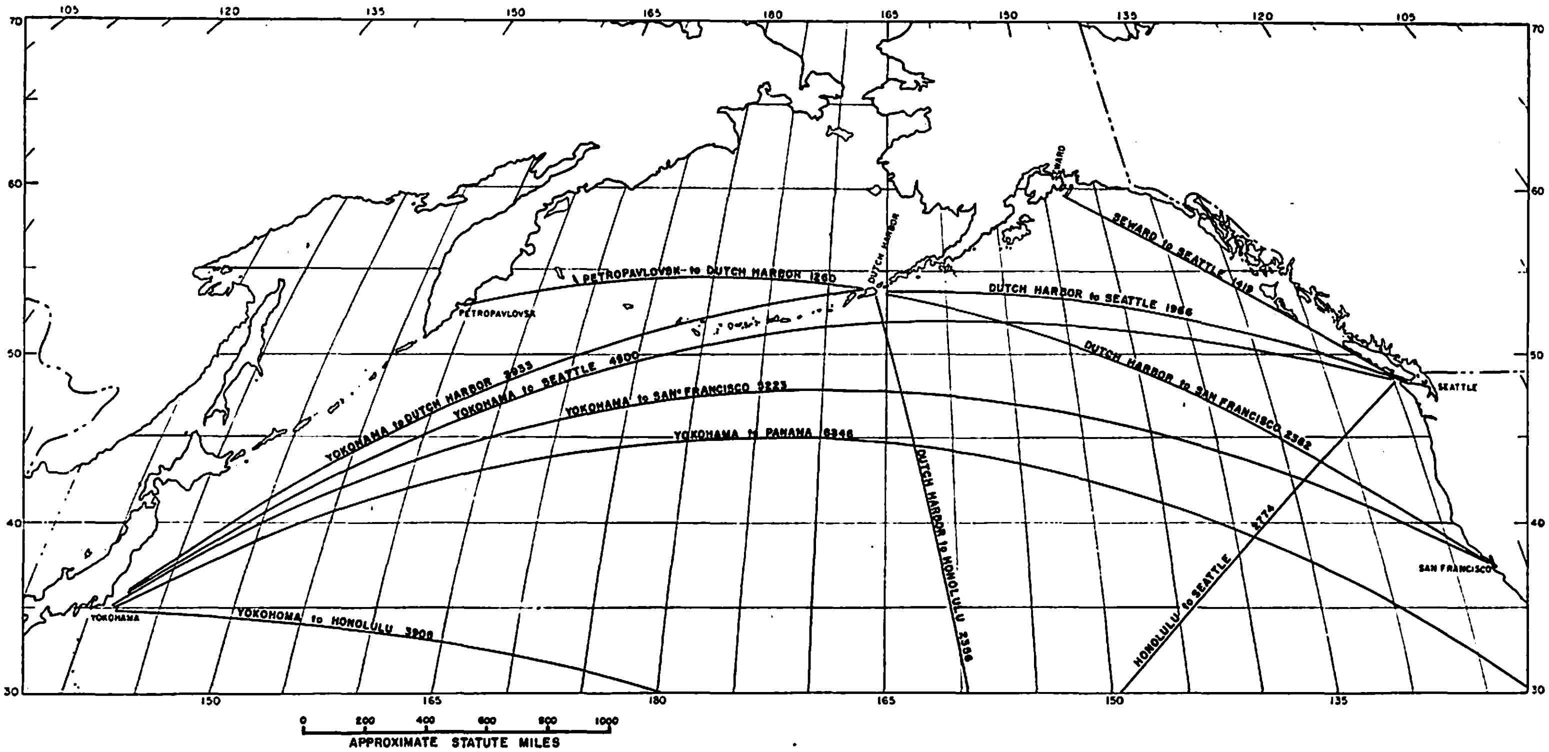


FIGURE 2. Distances of the Northern Pacific Ocean.

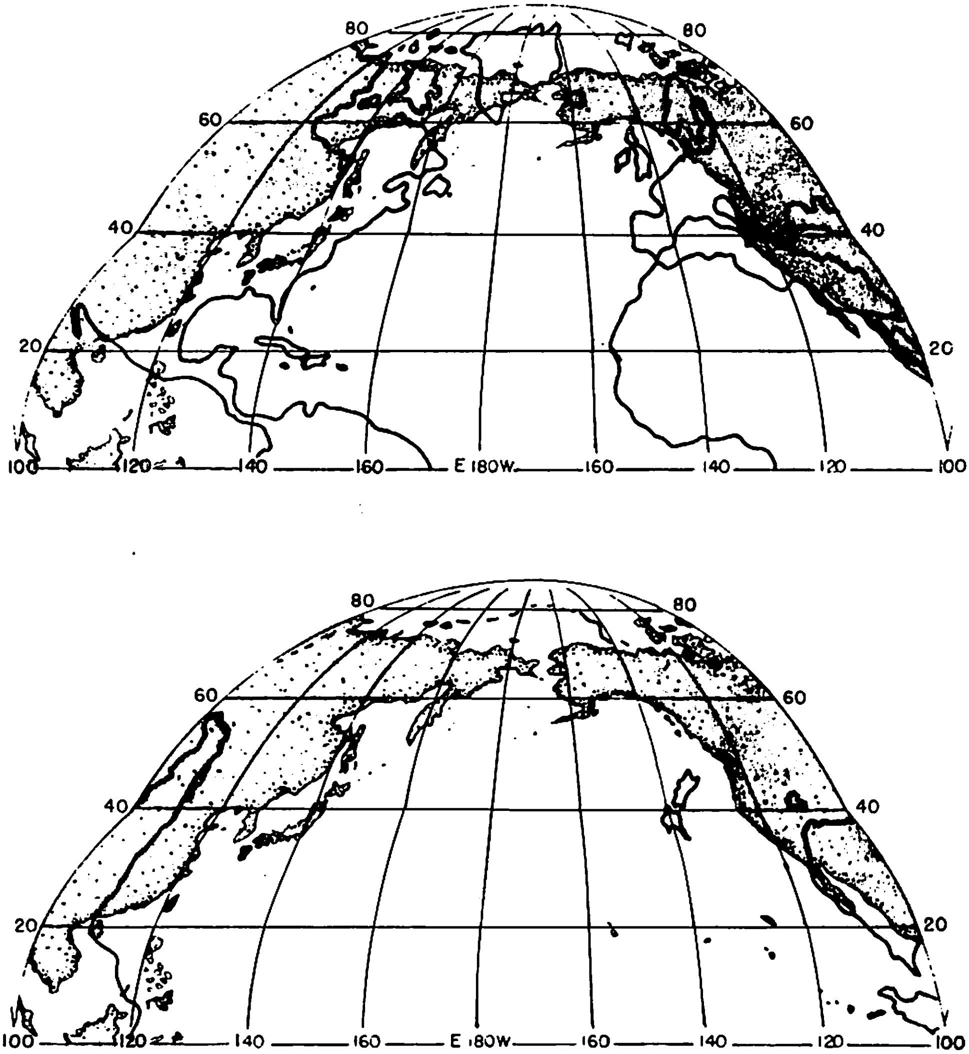


Figure 3. Comparison of North Pacific with North Atlantic and South Pacific Oceans.

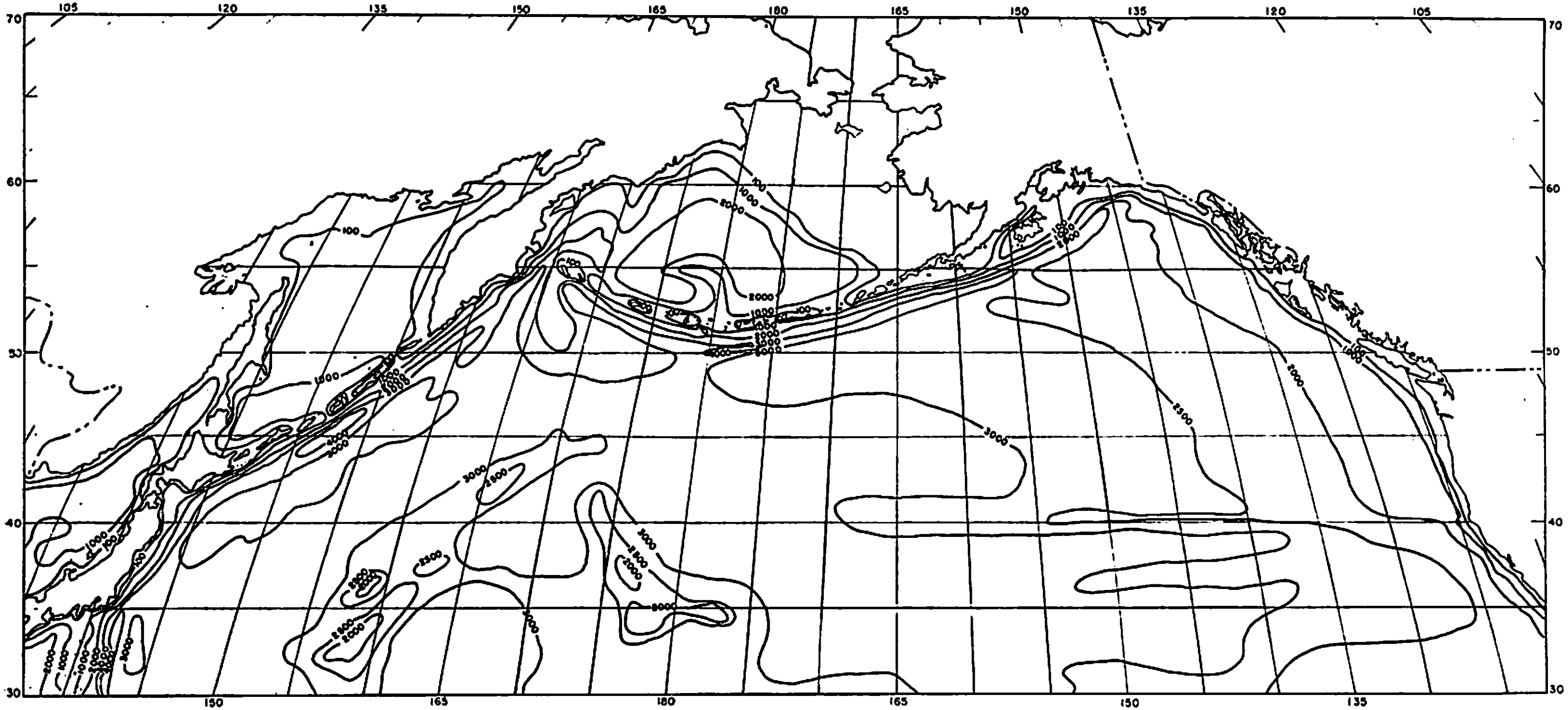


FIGURE 4. Generalized Bathymetry (Fathoms)

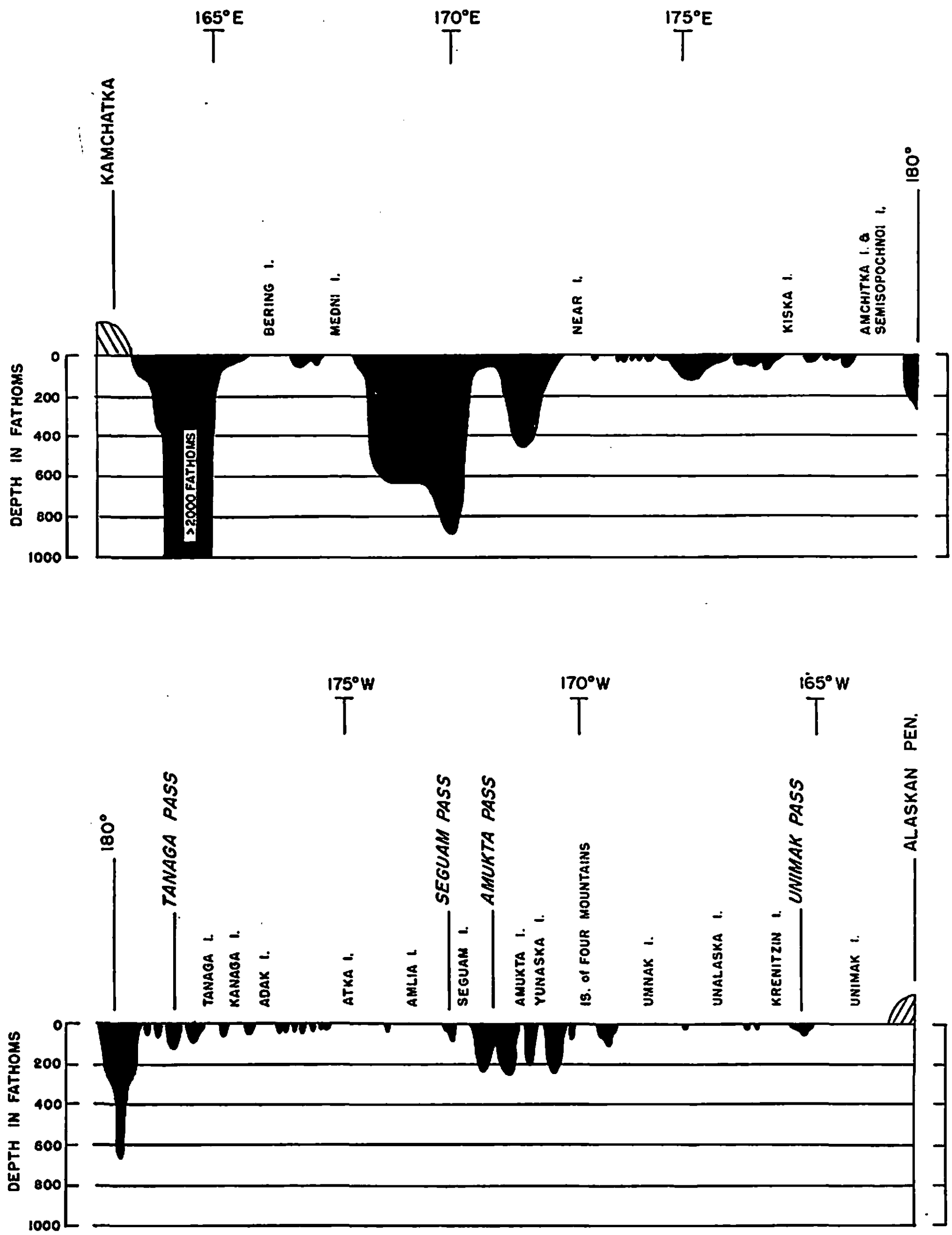


FIGURE 5. Depths in Passes between Kamchatka and Alaska.

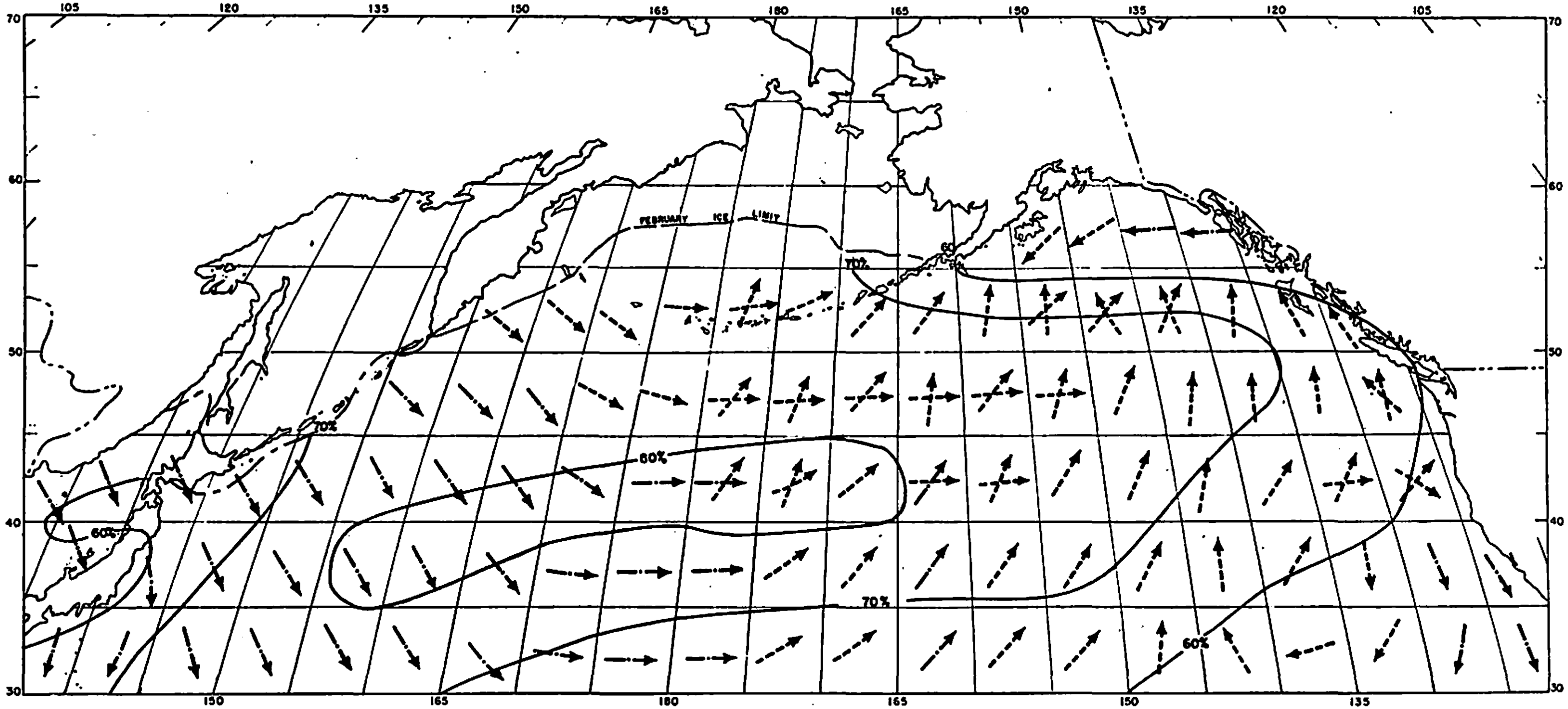


FIGURE 6. Predominant Surface Winds—February.

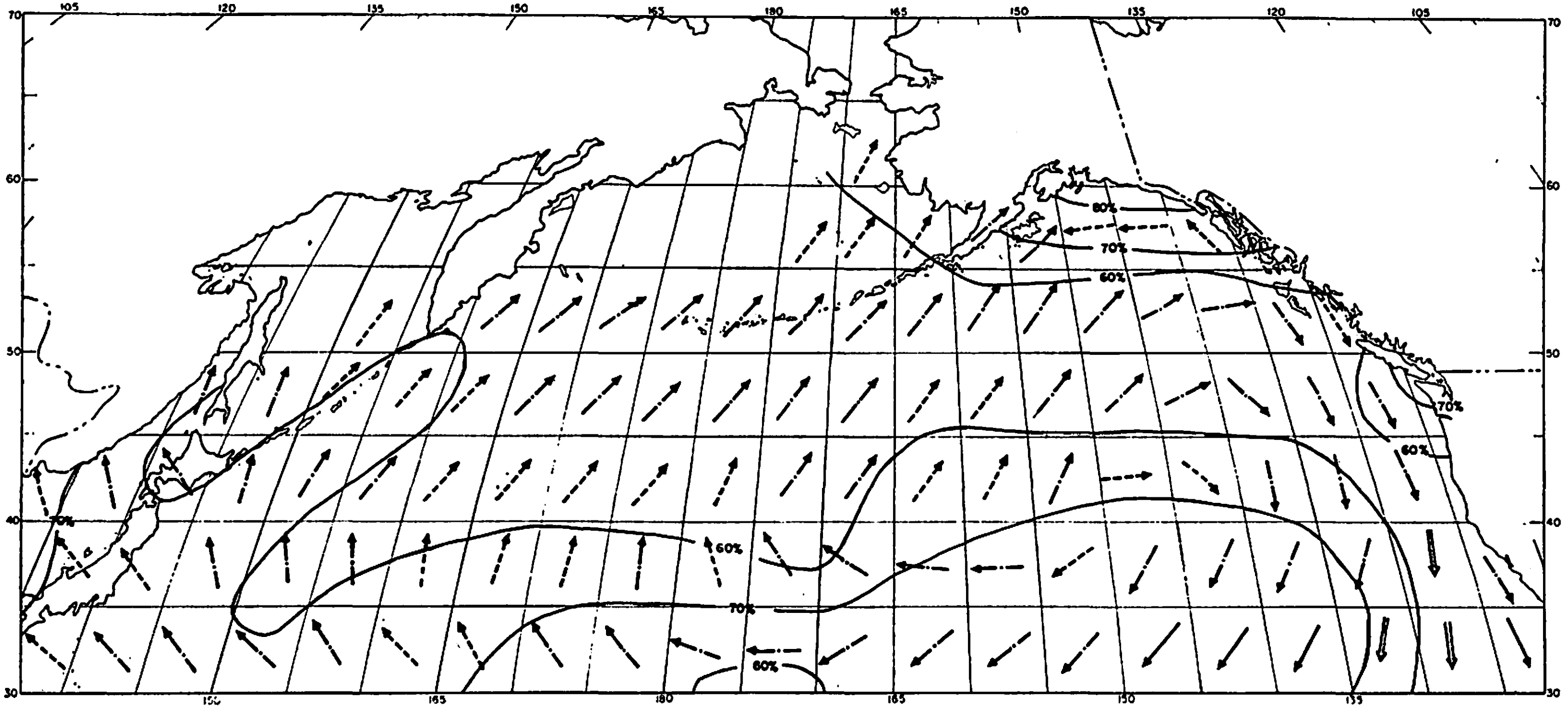


FIGURE 7. Predominant Surface Winds—August.

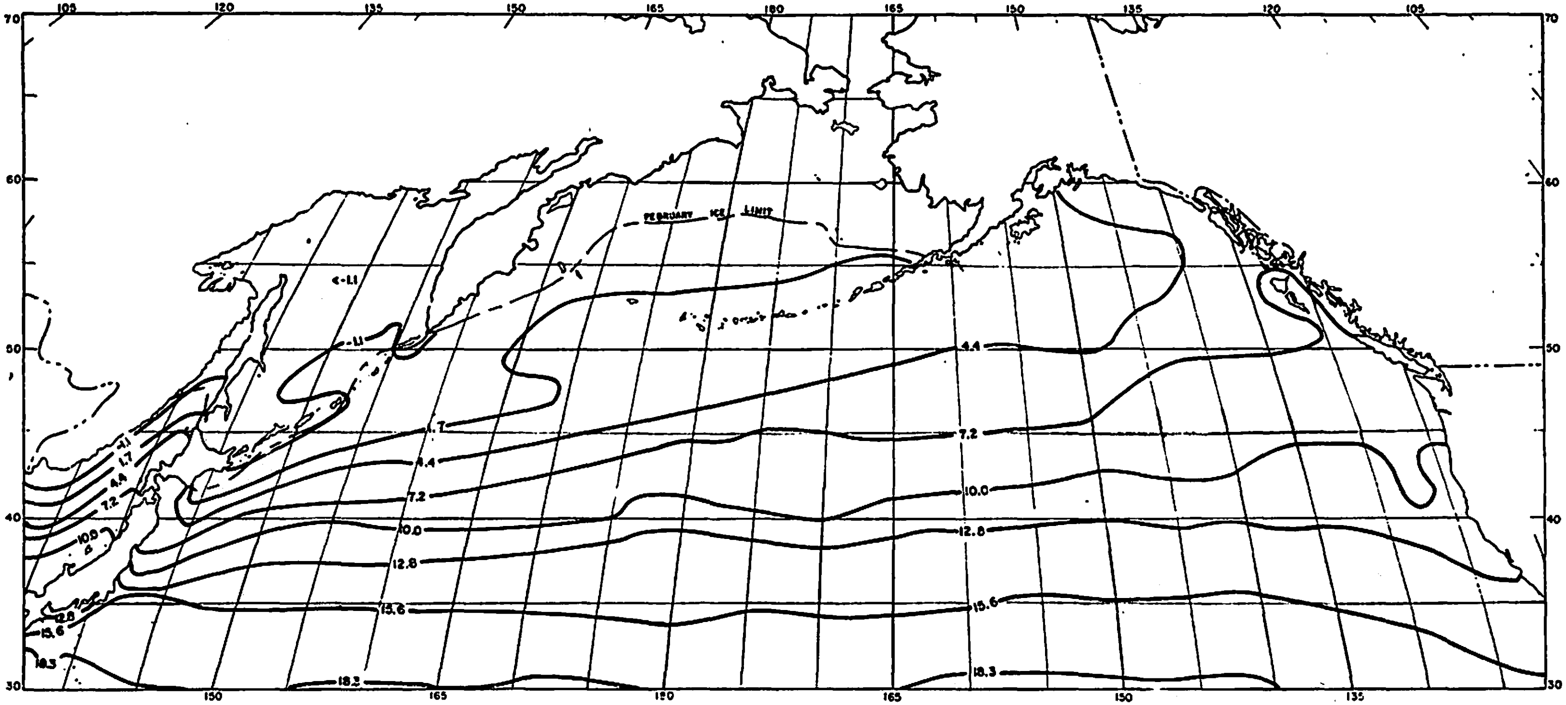


FIGURE 8. Surface Temperature—February.

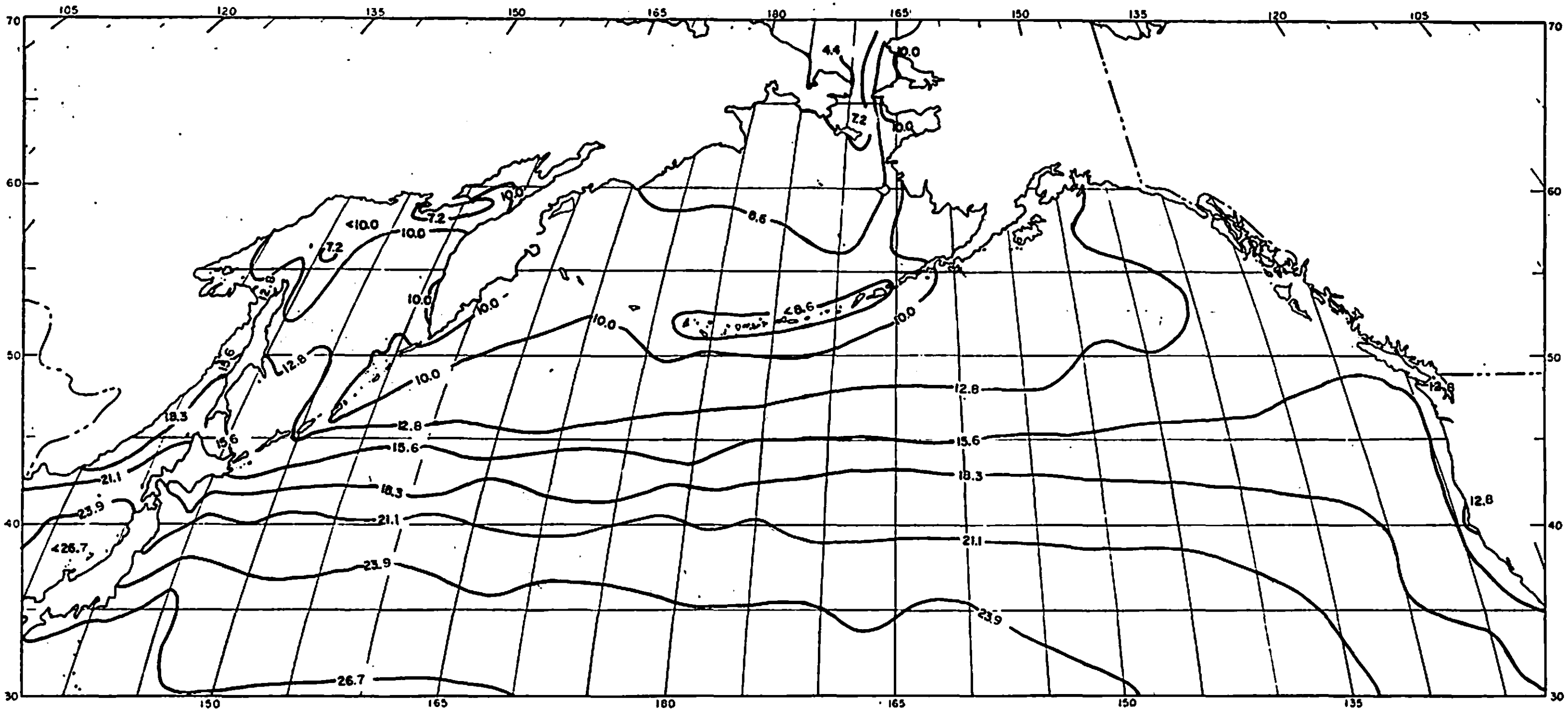


FIGURE 9. Surface Temperature—August.

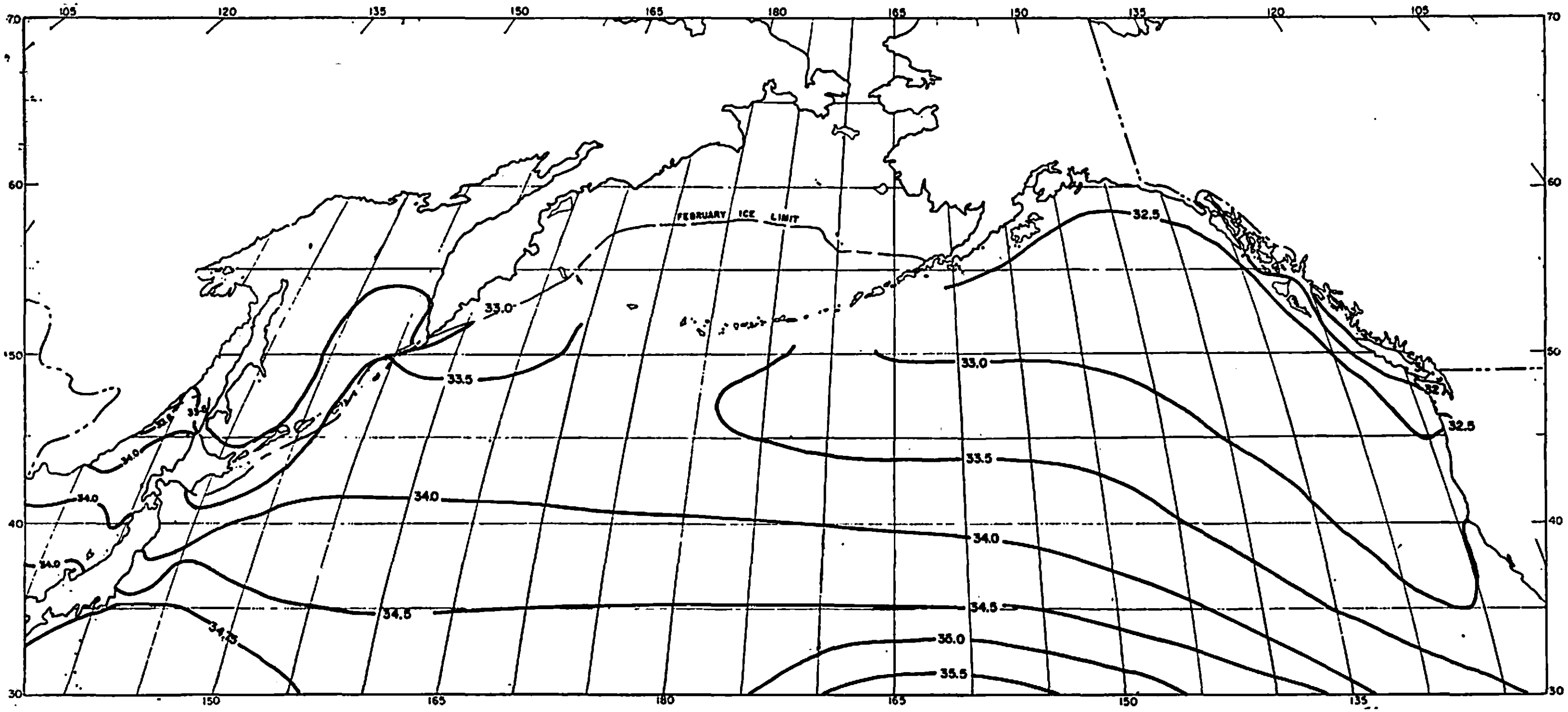


Figure 10. Surface Salinity—February.

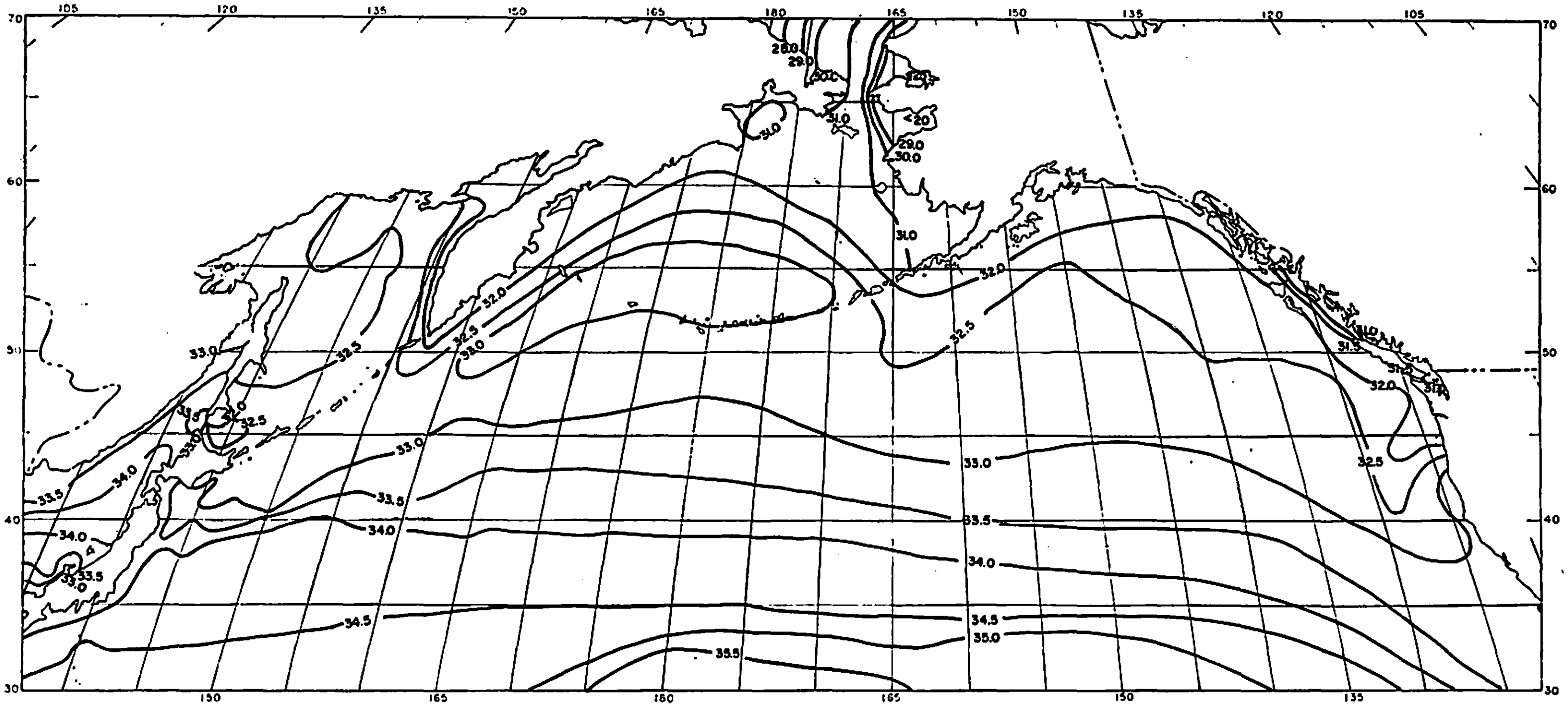
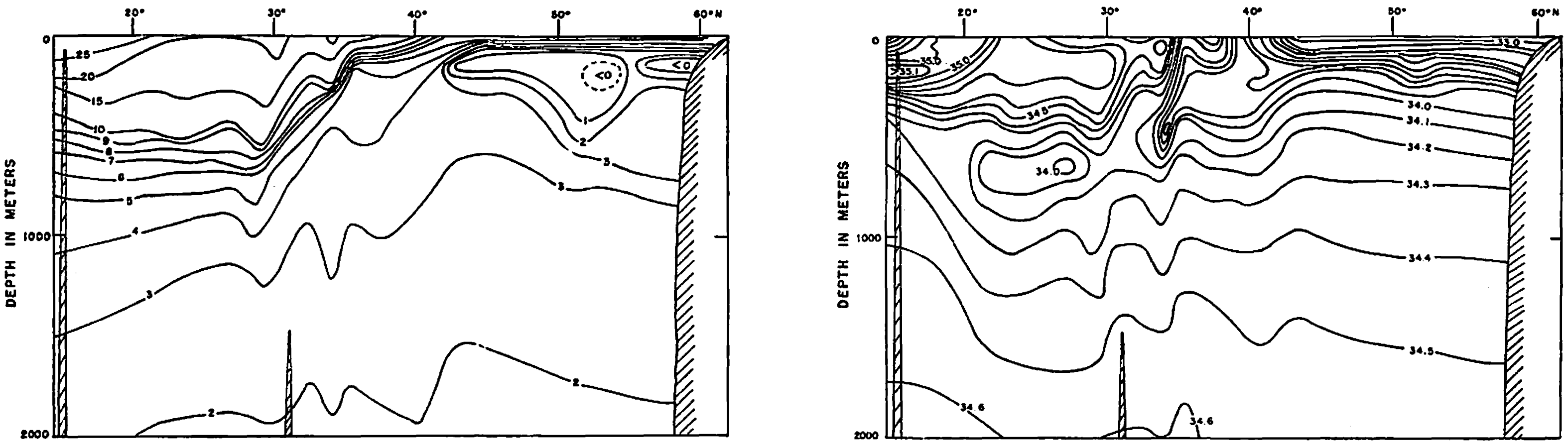
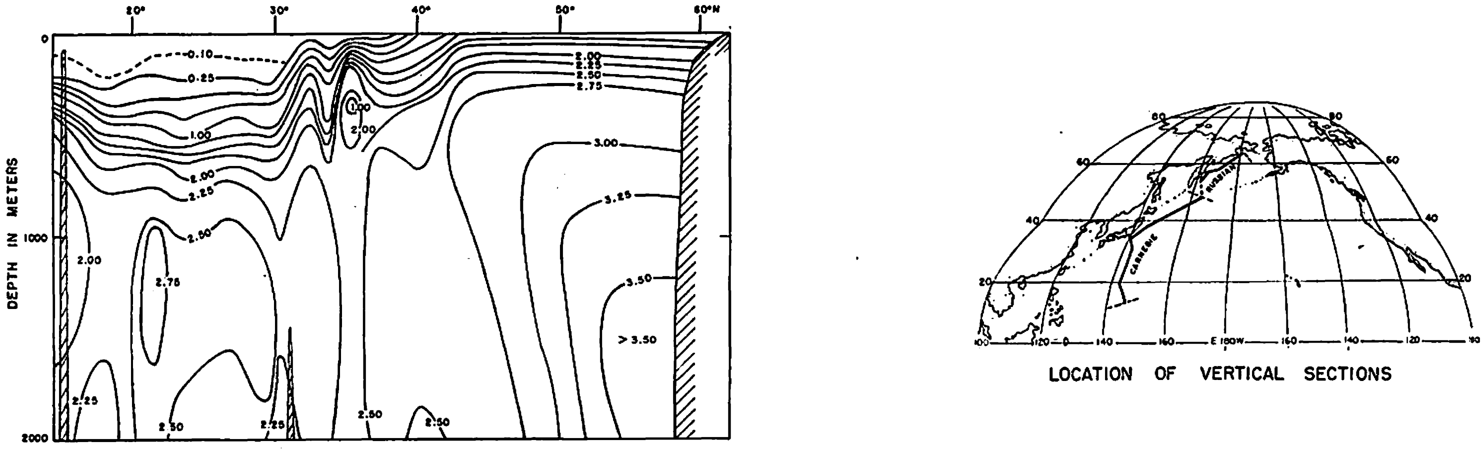


FIGURE 11. Surface Salinity—August.



TEMPERATURE

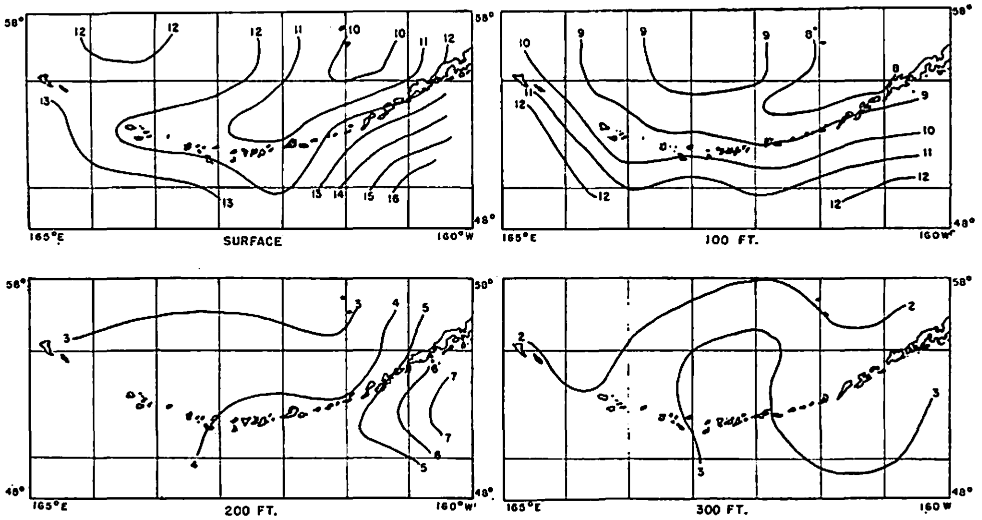
SALINITY



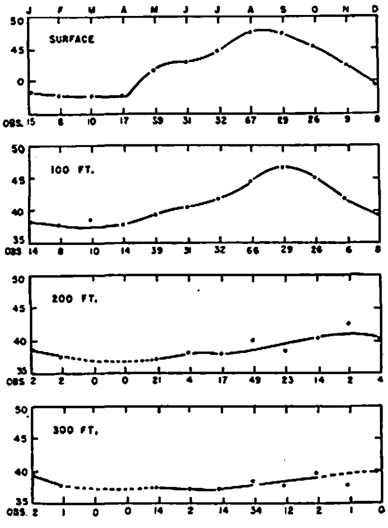
PO4 — P (ug-at /L)

LOCATION OF VERTICAL SECTIONS

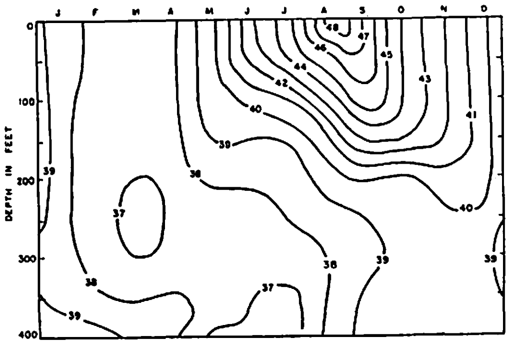
FIGURE 12. Vertical Distribution of Properties in the Northern Pacific Ocean.



ANNUAL TEMPERATURE RANGE



SEASONAL TEMPERATURE VARIATION
52°-53°N 178°-179°E



ANNUAL CYCLE OF TEMPERATURE DISTRIBUTION
52°-53°N 179°-180°E

FIGURE 13. Temperature Conditions in the Aleutian Island Area.
(All values in °F.)

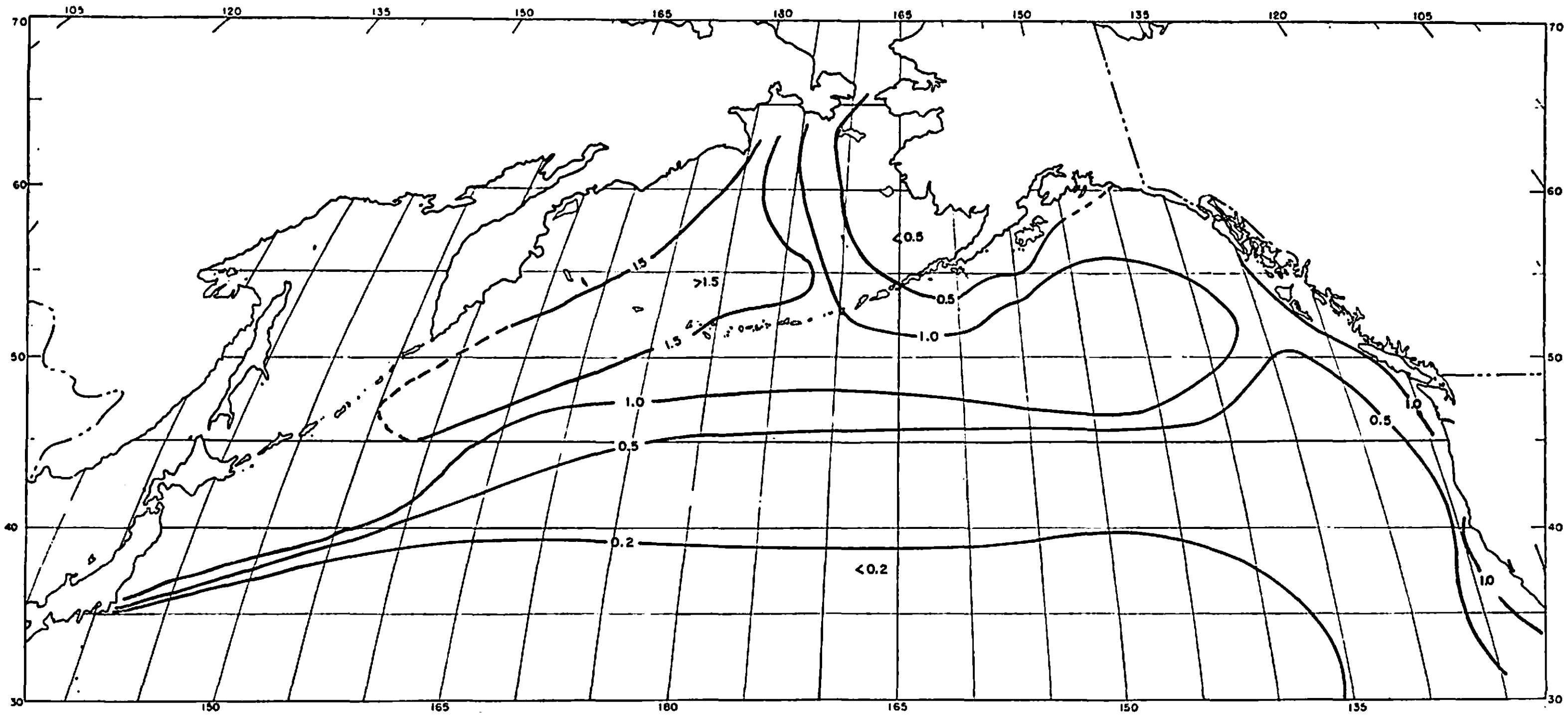


FIGURE 14. Distribution of Phosphate at the Surface (μg-at/L.)

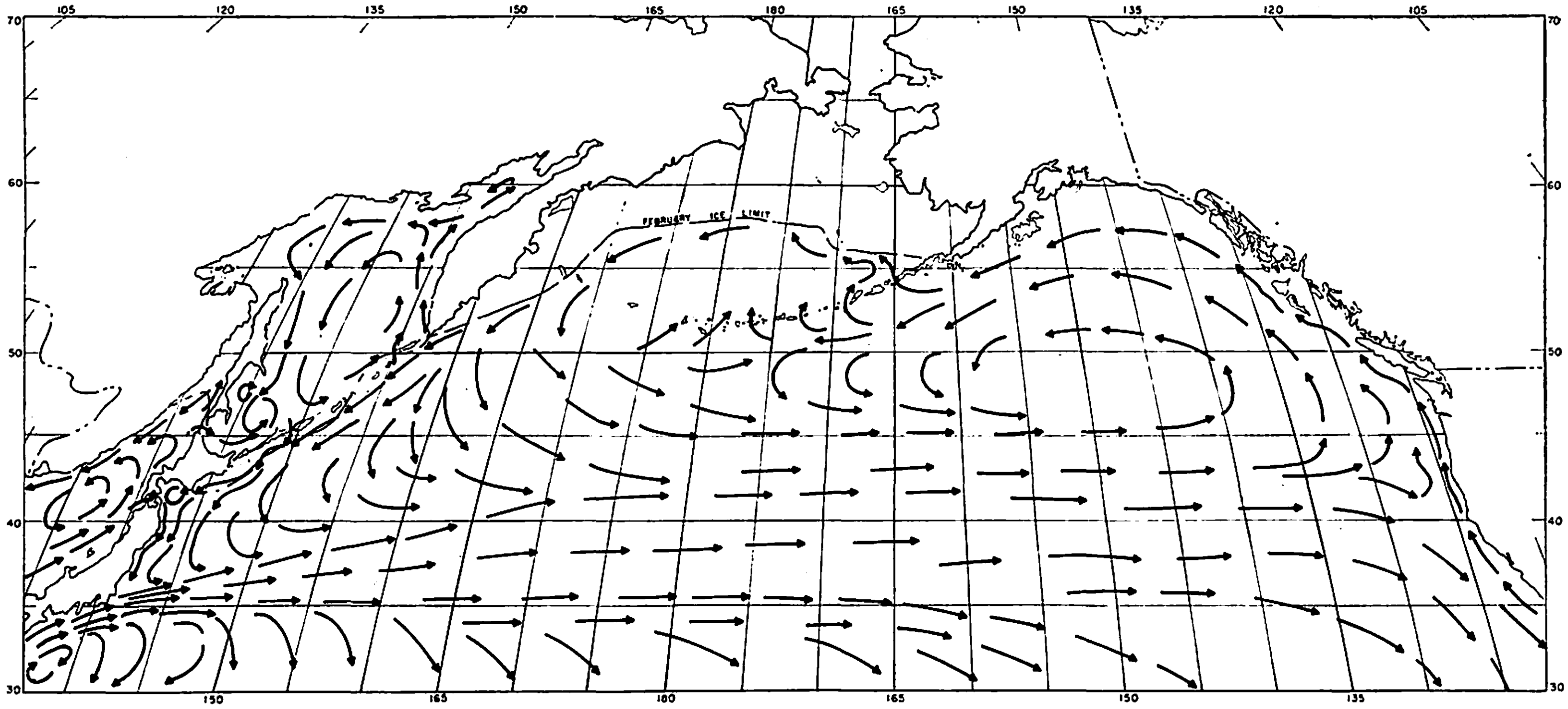


FIGURE 15. Surface Currents—February.

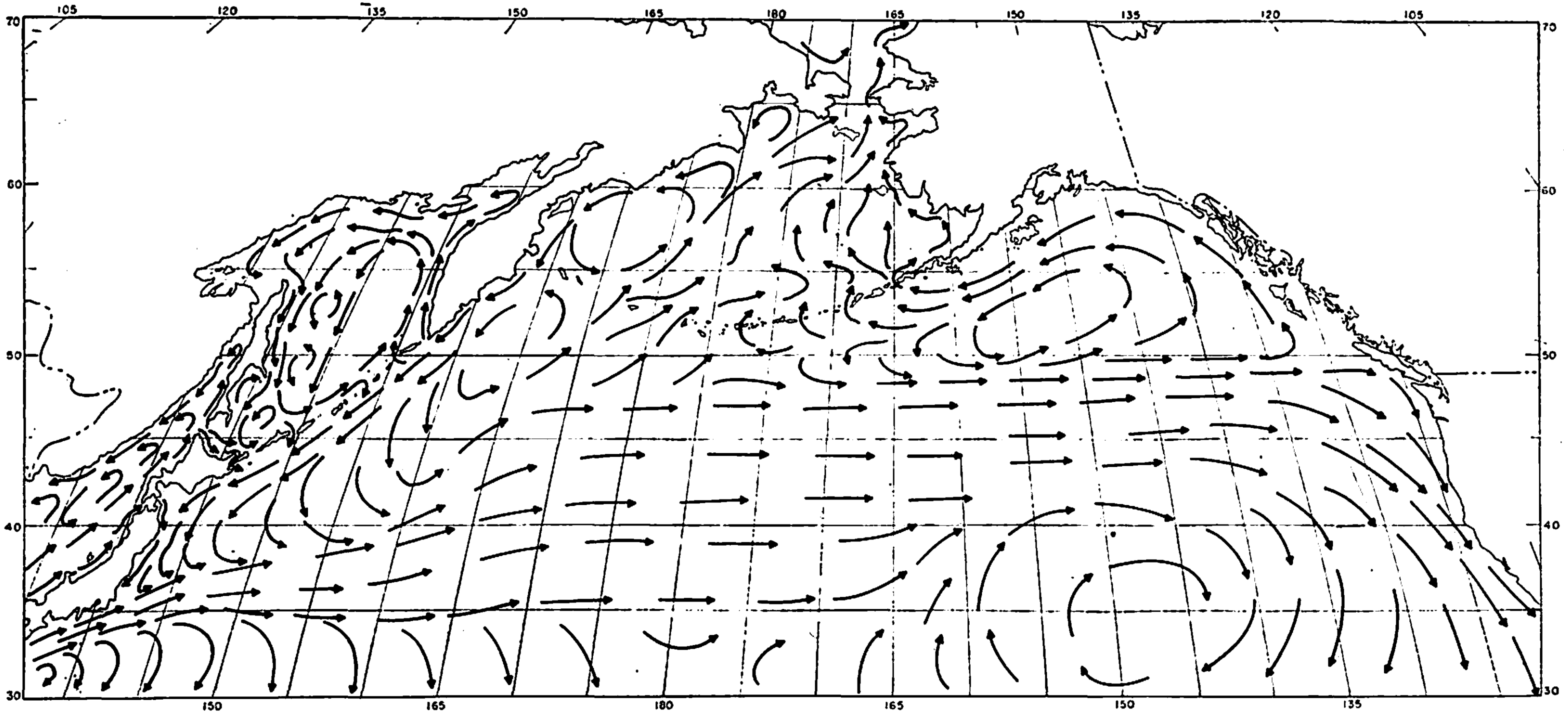


Figure 16. Surface Currents—August.

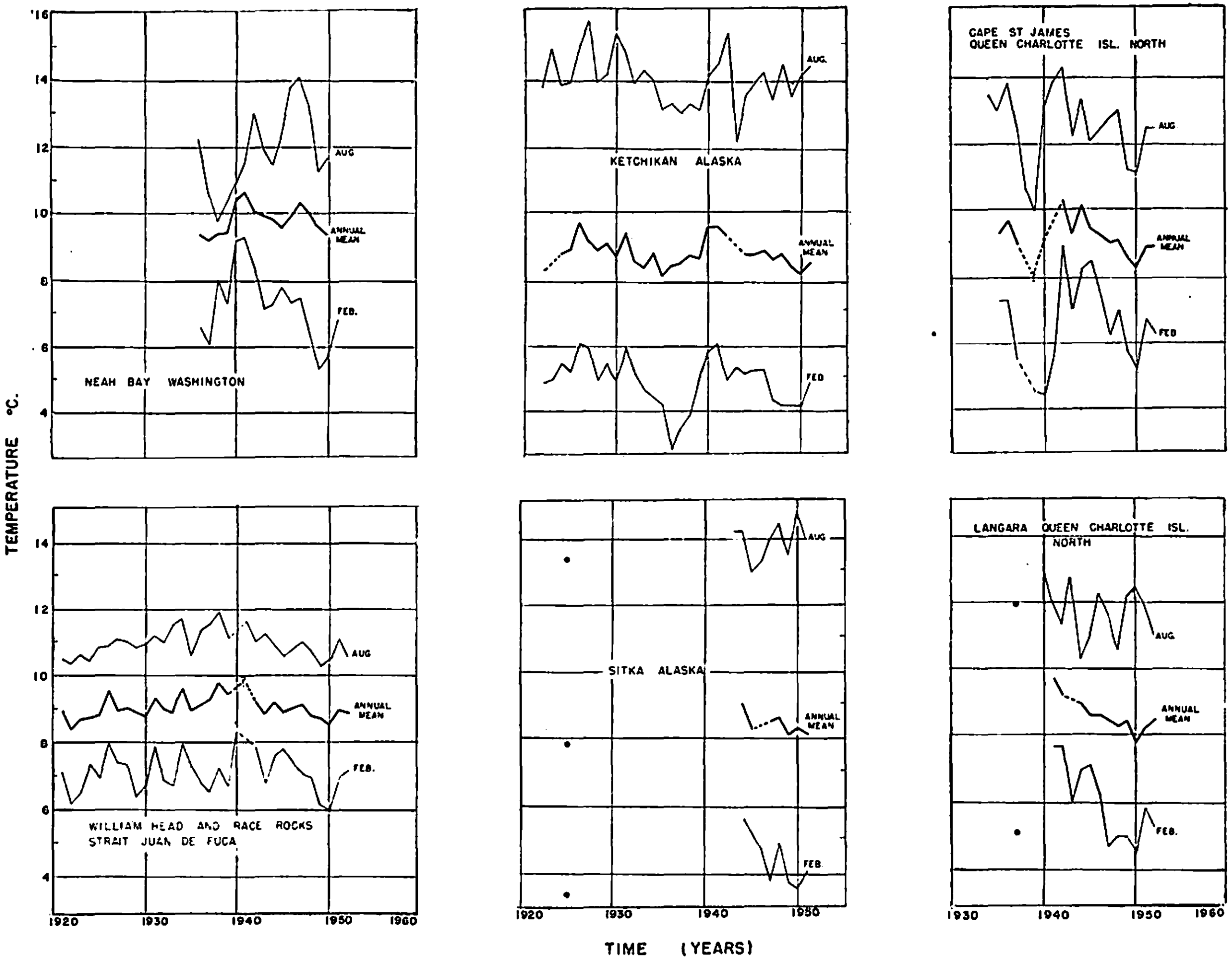
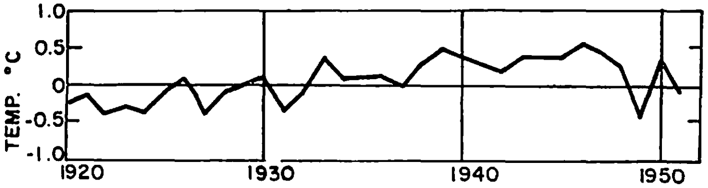
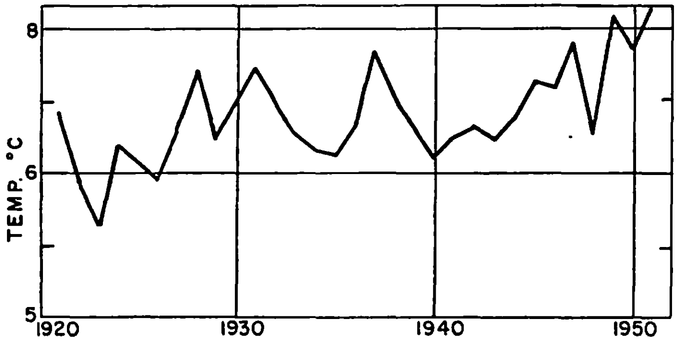


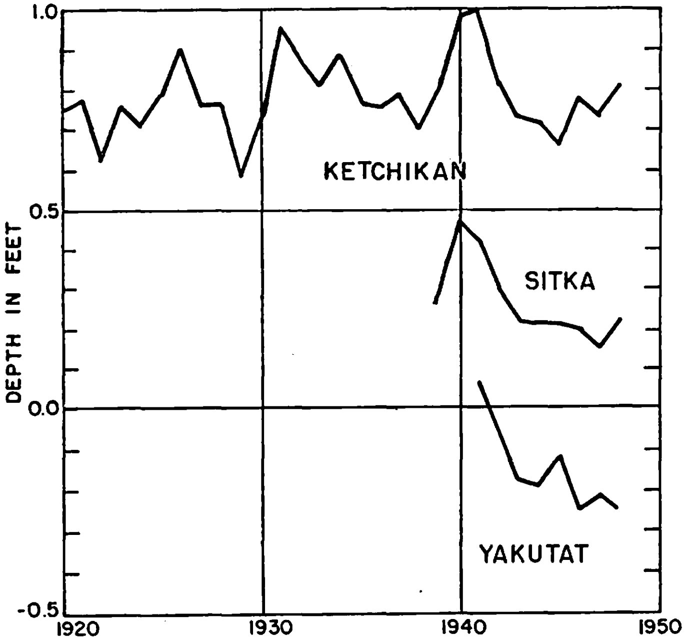
FIGURE 17. Long-term Sea Surface Temperature Changes in Northern Pacific.



YEARLY ANOMALIES OF THE SURFACE TEMPERATURE
FAROES ISLAND – ATLANTIC OCEAN
(AFTER J. SMED)



MEAN SURFACE TEMPERATURE
ST. ANDREWS N.B. ATLANTIC OCEAN
(AFTER W. TEMPLEMAN & A.M FLEMING)



YEARLY SEA LEVEL – ALASKA
(AFTER H.A. MARMER)

FIGURE 18. Long-term Sea Surface Temperature Changes in North Atlantic and Yearly Sea Level in Alaska.

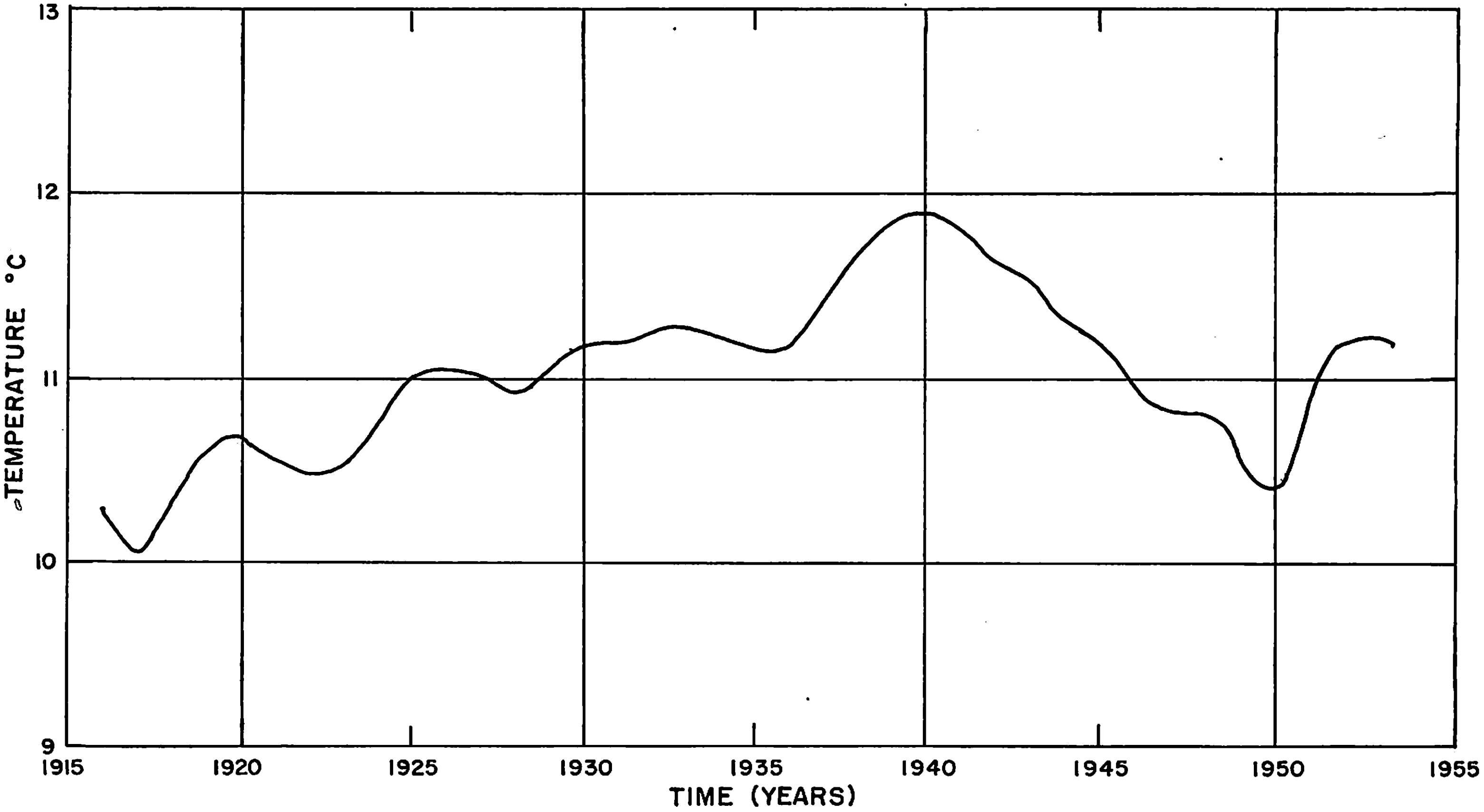
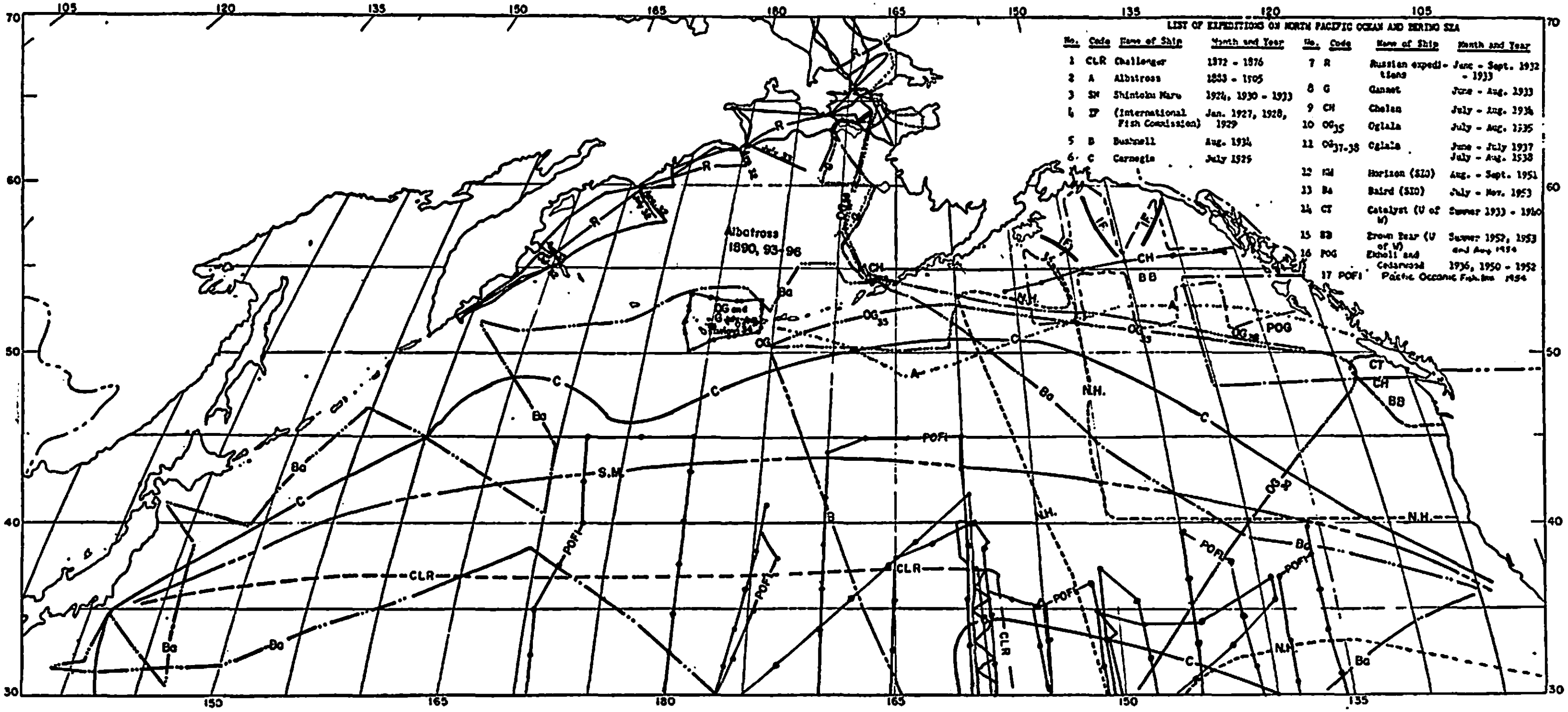


FIGURE 19. Mean Annual Sea Surface Temperature at Departure Bay, Georgia Strait, British Columbia.



LIST OF EXPEDITIONS ON NORTH PACIFIC OCEAN AND BERING SEA

No.	Code	Name of Ship	Month and Year
1	CLR	Challenger	1872 - 1876
2	A	Albatross	1888 - 1905
3	SM	Shintoku Maru	1924, 1930 - 1933
4	IF	(International Fish Commission)	Jan. 1927, 1928, 1929
5	B	Bushnell	Aug. 1934
6	C	Carnegie	July 1929
7	R	Russian expeditions	June - Sept. 1932 - 1933
8	G	Gannet	June - Aug. 1933
9	CH	Chelan	July - Aug. 1934
10	OG_{35}	Oglala	July - Aug. 1935
11	OG_{37-38}	Oglala	June - July 1937 July - Aug. 1938
12	HM	Horizon (SIO)	Aug. - Sept. 1951
13	Ba	Baird (SIO)	July - Nov. 1953
14	CT	Catalyst (U of W)	Summer 1933 - 1940
15	BB	Brown Bear (U of W)	Summer 1952, 1953 and Aug 1954
16	POG	Ekholl and Cedarwood	1936, 1950 - 1952
17	POFI	Pacific Oceanic Fish. Inv.	1954

FIGURE 20. Major Oceanographic Expeditions in the Northern Pacific Ocean.

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Research Institute
Akershus, Oslo, Norway

1 National Research Council
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Attention: Cimmittee on Undersea Warfare

1 Office of Technical Services
Department of Commerce
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1 Pacific Oceanographic Group
c/o Pacific Biological Station
Nanaimo, British Columbia, Canada

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Fort Crockett
Galveston, Texas

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