Appendix I

Oceanography of Bristol Bay

Description of area

Bristol Bay is that part of the Bering Sea eastward of a line drawn from Cape Sarichef to the Kuskokwim River (Fig. 1). It is the southeastern terminus of the shallow continental shelf in the Bering Sea, and is separated from the North Pacific Ocean by the Alaska Peninsula.

According to the U.S. Coast Pilot (1954) the annual mean air temperature is approximately 35° F and the annual rainfall 30 to 40 inches; fog occurs during every month of the year. Depending on the severity of the winter temperatures, ice begins to form along the shore in October or November, grows until March and melts by April. Solid fields of drift ice have been reported offshore in the Bay as late as May.

Although the shores of the Bay are low, the encircling mountains form a large watershed area. In spring, after the ice breaks up in the rivers, snowmelt and runoff enter the Bay through numerous river systems such as the Kuskokwim, Nushagak, Kvichak, Naknek, Egegik, Ugashik and others. The extensive runoff during spring and summer and the presence of ice during winter result in a considerable range of oceanographic conditions in the shallow Bay.

The movement of water in the Bay is affected by runoff, ice, prevailing winds, tidal currents, and the movement of oceanic water off the continental shelf. Winds are usually from a northerly direction in late autumn and during winter, and shift to a southerly direction in late spring. The range of tide at the Naknek River entrance is about 24 feet and results in tidal currents in excess of 3 knots. This is contrasted with a tidal range of about 3 feet at the Pribilof Islands.
The Bay is of particular interest oceanographically because, as shown by recent drift bottle experiments, drifting objects enter the Bay from the extreme western Aleutians, the Gulf of Alaska, and as far south as lat. 45° N in the central Subarctic (Fig. 2). However, none have been recovered in the headwaters of the Bay.

Previous oceanographic investigations

The work of Saur et al (1952) discussed earlier (page 13) included a summary of cruises conducted in the Bering Sea. Omitted from this summary were cruises by the Japanese Fisheries Training School vessel Hakuho-Maru during 1930 and 1933 to 1936, and the USCGT Redwing during 1938 to 1941.

Since 1949 oceanographic data have been obtained in Bristol Bay from aboard Japanese Fisheries Agency vessels; and, since 1956 from vessels chartered by the U.S. Bureau of Commercial Fisheries in conjunction with crab investigations. Most of these data are not published.

Hebard (1959) obtained direct-current measurements at four locations in the Bay during June 1957 and ascertained the presence of rotary (although elongated in northeast and southwest direction) tidal currents. Velocities of 0.1 to 1.7 knots were observed with little difference between the direction of flow at the surface and the bottom. A net or average flow of less than 0.1 knot in a counterclockwise direction was deduced.

An oceanographic survey in the Bering Sea during winter 1955 (U.S. Navy Hydrographic Office, 1958) greatly contributed to an understanding of oceanographic conditions on the continental shelf. It was known that during the winter most of the shelf area is covered with sea ice, and one was tempted to speculate that the freezing-out process would result in the formation of cold, very saline water. This would result in very dense, bottom water that would flow off the continental shelf seeking a lower level of
equivalent density. The 1955 data showed that in the Bristol Bay area the water column was isothermal with temperatures of -0.5 to -1.5° C (Fig. 3) and isohaline with salinities of 31.5% to 31.8% (Fig. 4). Similar temperatures and salinities have been found on the shelf at depths from 50 to 100 metres during spring and early summer. Hence, this water is not dense enough to form intermediate or bottom water in the Bering Sea.

Oceanographic investigations, USCGT Redwing

These surveys during 1938 to 1941 are by far the most extensive and complete ever obtained in Bristol Bay. The work was terminated by World War II and since there is no record of prior analysis of these data, they are used to a great extent in this report to define conditions in the Bay. This is justified by the fact that conditions (temperature and salinity) have not appreciably changed from that period to the present day. Recent oceanographic coverage is not adequate to show a comparison of specific properties at specific depths; however, comparison of average monthly air temperatures for 1939 and 1959 at Dillingham (located near the head of the Bay, shown in Fig. 5) provides convincing evidence that the climate has been relatively stable.

The Redwing investigations were based upon a network of oceanographic stations at 20-mile intervals that extended from the headwaters of the Bay out over the continental shelf. Stations were repeated during the same and subsequent years.

During 1938, stations were occupied during August and September. The vertical distributions of salinity and density (sigma-t) presented by Favorite and Pedersen (1959a) show two of the most characteristic features of the Bay: the counterclockwise flow as shown by the density profile between Cape Seniavin and Cape Newenham (Fig. 6); and the vertical homo-
geneity of the water column at the head of the Bay as shown by the salinity profile seaward of Cape Chichigef (Fig. 7).

Another interesting feature revealed by the 1938 data was the thermal stratification of the water column. Values of temperature, salinity and current speed at station 30-6 are shown in Table 1. Between 15 and 16 metres depth the temperature decreased 4.76°C. In this particular case, the water column was essentially isohaline. Current speeds show no appreciable change in the area of the temperature discontinuity indicating that solar heating is the dominant cause of the temperature structure.

Extensive hydrographic and current data were collected during May to August, 1939 (Favorite et al., 1961). Surface current measurements, obtained by observing the set and drift of a drift-stick released from the anchored vessel at various locations provided a fairly comprehensive picture of tidal currents (Fig. 8). The water in the Bay oscillated in a northeast-southwest direction. Velocities in excess of 2 knots occurred along the shore and considerably reduced velocities were found in the central part of the entrance of the Bay. Thus, even though the survey was as synoptic as possible utilizing one vessel (approximately 2-hour time interval between stations), the structure probably varied rapidly and considerably. Nevertheless, stations occupied as many as three times during the period May to August permit a gross picture of conditions in the Bay during the spring and summer.

Temperature distribution, 1939

Three locations that exhibit representative temperature structures have been selected from the 1939 data (Fig. 9). The observations were obtained in June, July, and August.
Table I

<table>
<thead>
<tr>
<th>Z</th>
<th>Temperature</th>
<th>Salinity</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(10.76)</td>
<td>(31.85)</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>(10.66)</td>
<td>(31.85)</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>(10.44)</td>
<td>(31.85)</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>-</td>
<td>.59</td>
</tr>
<tr>
<td>15</td>
<td>10.39</td>
<td>31.85</td>
<td>.49</td>
</tr>
<tr>
<td>16</td>
<td>5.63</td>
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<td>17</td>
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</tr>
<tr>
<td>20</td>
<td>4.97</td>
<td>31.87</td>
<td>.47</td>
</tr>
</tbody>
</table>

( ) Observation recorded 2 hours earlier - vessel anchored.

- No observation made.
At the entrance to the Bay (Station A) the June temperature structure was isothermal at approximately 1\(^\circ\) C. We can assume from Fig. 3 that during winter the temperature was about -1.5\(^\circ\) C. Thus, by June, heat from solar incident radiation had been distributed uniformly throughout the water column and increased the temperature of the water column by about 2.5 \(^\circ\)C. We can also assume that some of the radiation had been utilized to melt the supposed ice cover. During June and July, most of the heat gain was confined to the upper 10 metres, resulting in a sharp 6 \(^\circ\)C thermocline. As implied in Fig. 4, and as will be shown in the next Section, the water column was essentially isohaline; thus, the water column may be considered thermally stratified and the 1.5 \(^\circ\)C temperature increase in the lower layer was the result of diffusion, and advection. By August, surface cooling and mixing had already begun as evidenced by the deepening of the thermocline. However, as shown subsequently in the discussion of surface temperatures, another process was involved in cooling the surface waters in the central part of the Bay, and maximum surface temperatures of about 10 \(^\circ\)C can be expected in late summer.

At Station B in June the waters near the surface were warmer than at A and were in the 5\(^\circ\) C range. This increase in heat content is believed to be due to the shallow depth, which presented a smaller water column to be heated, as well as the fact that part of this water column was fed by the river runoff which gained additional heat while passing over the warm and very shallow flats at the head of the Bay. During July and August there was a progressive increase in the water temperatures to 10\(^\circ\) C, and tidal and wind mixing usually resulted in isothermal conditions.

Conditions at Station C were similar to those at Station B; but, because the depths were considerably shallower, the waters were correspondingly warmer. By August, temperatures in the 12\(^\circ\) C range were evident.
Thus, in winter, the offshore conditions are isothermal at about -1.5° C and during spring and summer a pronounced shallow thermocline develops. It begins to decay in late summer or early autumn. Whereas, inshore, where similar winter conditions can be assumed to prevail, a minor thermocline develops in spring, but quickly disappears in summer.

Horizontal temperature distribution indicate that there was a sharp separation between the inshore and offshore areas. Surface temperatures during May and June (Fig. 10) showed a marked temperature front lying along a line from Port Hiden to Cape Peirce; seaward of the front, temperatures in the 1° and 2° C range were found, and a counterclockwise flow was indicated. However, shoreward of the front the isotherms showed the presence of another more pronounced counterclockwise eddy or gyre. It appears that the warm dilute runoff has been contained eastward of the Cape and been forced to recirculate shoreward of the front. The absence of an indication of this inshore gyre in the bottom temperature distribution (Fig. 11) implies that this feature is confined to the surface. The time interval and area involved indicate that this is not a tidal phenomenon.

By August, the generally accepted peripheral counterclockwise flow in the Bay is evident from the surface isotherms (Fig. 12). However, just inshore of the temperature front which extended across the Bay in spring, an anomalous region of cold temperatures occurred which is interpreted as an area of upwelling. Again, as in spring, the bottom temperature distribution (Fig. 13) shows an almost uniform gradient of temperatures from the head of the Bay seaward. The area of cold temperatures at the surface, indicative of upwelling, and a similar gradient of bottom temperatures were also present in August 1938.

Figure 14 which shows the difference between surface and bottom temperatures during August 1939 clearly indicates the absence of any thermocline in
the water column inshore of a line between Port Heiden and Cape Peirce. One
would also expect to see a considerable difference in the turbidity and
water colour on either side of this boundary, but no data are available.

Salinity distribution, 1939

The salinity distribution in the Bay corresponded to the temperature
distribution. As shown in Fig. 4, the 1955 winter conditions show the
water structure to be isohaline with the central shelf area having a salinity
of about 31.8%. Figure 15 shows the vertical distribution of salinity during
June, July, and August 1939 at the same stations (A, B, and C) discussed in
the temperature section.

At location A the water column was isohaline at about 31.8% during
all three months. At B, which was further inshore, isohaline conditions
also prevailed. Dilution occurred in July, but in August more saline con-
ditions were encountered. This is due to an intrusion from the southwest
which is evident in the horizontal distributions that follow. An adjacent
Station reflected the progressive dilution characteristic of the inshore
area, which was clearly reflected in the values at C during August. By
late August, the temperatures reached a maximum and began to decrease,
however, there is evidence that further dilution occurred after this period.
The absence of an appreciable halocline offshore at Position A implies that
the river runoff moved counterclockwise along the coastline and did not extend
to the central part of the Bay.

Surface salinities during May-June, 1939 (Fig. 16) also indicate an
inshore counterclockwise gyre which moved coastal dilution southward, in-
shore of the temperature front previously discussed. The differences in
salinity values between the surface and bottom (Fig. 17) show the feature to
be confined to the surface waters at the head of the Bay. By August (Fig. 18)
the tongue of dilute water had been transported northwestward out of the Bay. The low salinity values at the head of the Bay indicate that there still was an extensive extrusion of runoff into the Bay in late summer. Salinity distribution at the bottom is shown in Fig. 19.

Approaches to Bristol Bay

In 1940 part of the emphasis of the Redwing investigations was shifted seaward of the Bay and this permits showing a possible source of the upwelled water.

The surface temperatures in August (Fig. 20) varied from 5° to 11° C. The low temperatures which are shown near the Pribilof Islands are attributed to turbulence and a downward transfer of heat rather than any unusual source of cold water from the oceanic areas. The warmest water is found, as would be anticipated, along the shores of Bristol Bay. The cold area in the central part of the mouth of the Bay between Port Heiden and Cape Peirce is also evident.

Bottom temperature contours (Fig. 21) coincide with the bottom topography. The cold area eastward of the Pribilof Islands is believed to reflect the delay in melting of offshore ice, and thus a delay of seasonal warming of the water column.

The bottom salinities (Fig. 22) show a shoreward intrusion of oceanic water, between the Pribilof Islands and Unimak Island, which was confined seaward of a line between Port Heiden and Cape Peirce. The salinity distribution dominates the distribution of density as shown by the contours of sigma-t (Fig. 23). However, it is impossible to ascertain from the data if the movement of water at these depths is along the isolines. If so, the oceanic water moves counterclockwise around the Bay. If it flows across the isolines the water intrudes into the Bay as a tongue or wedge resulting
in an upward movement or upwelling.

Edge of Continental Shelf

A discussion of Bristol Bay would not be complete without showing the distribution of properties in the zone between the continental shelf and the oceanic area seaward of the shelf. In this case, the most complete data are from the cruise of the M/V Attu (Favorite and Pedersen, 1959b).

Vertical profiles of temperature, salinity, dissolved oxygen and density are shown in Fig. 24.

The line of stations did not extend far enough onto the shelf to show the cold temperatures, characteristic of this area, as shown in Fig. 21. Surface warming had already begun, hence there was very little indication of the changes in oceanographic environment as one approaches the shelf from seaward that are evident in the salinity profile structure. Values of dissolved oxygen greater than 0.7 mg at/l near, and over the shelf, indicate high phytoplankton population.

Although solar heating in spring and summer tends to make the surface temperatures relatively uniform over and seaward of the shelf, the presence of ice, or the temperatures that exist immediately after the ice has melted, reveal a marked change in environment at the edge of the continental shelf. Data collected aboard the M/V Tordenskjold (Love, 1959) during 1956 illustrated this condition (Fig. 25).

Summary

Bristol Bay is characterized by an extensive shallow continental shelf which isolates the Bay from the oceanic circulation systems, and by an extensive water-shed surrounding the Bay which releases large amounts of snow melt and fresh water runoff into the Bay from early spring to late autumn. The combination of these features and the wind and tidal systems
result in a relatively constant annual cycle of environmental conditions, which are in sharp contrast to those of the adjacent Bering Sea. The boundary between the shelf area and the deep Bering Sea basin, delineated by the sharp continental slope, is also evidenced by changes in physical and chemical properties of the water column.

In early autumn, the heat content of the shallow Bay is quickly dissipated. Cold air temperatures and dilute surface water permit the early formation of ice along the shores, and by winter, ice is present over a large part if not all of the Bay. During winter, temperatures and salinities of approximately \(-1^\circ C\) and \(31.6\%\) occur in the ice fields; whereas, in contrast, the central Bering Sea is usually void of ice and temperatures from 2 to \(3^\circ C\) and salinities of 33.0 to 33.4\% occur at the surface.

The ice cover in the Bay retards the spring warming of the surface layer, but melting of the ice dilutes the surface layer causing sufficient vertical stratification to confine the rapidly increasing net heat gain to the upper 10 to 20 metres of the water column. In the inshore area the temperatures reach 12\(^\circ\) to 13\(^\circ\) C and the water column is isothermal. In the offshore area, summer heating results in the formation of a shallow, sharp thermocline with a magnitude of 5 to 8 \(C^\circ\) in mid-summer. Surface temperatures reach 10 to 11\(^\circ\) C. In late summer, wind mixing, advection and vertical diffusion can raise the bottom temperatures in the offshore waters to temperatures of 3 to 4\(^\circ\) C or higher.

The movement of water in the Bay, as implied by the distribution of properties, is counterclockwise. Drift stick and direct current measurements indicate the water in the Bay oscillates with a tidal period from the surface to the bottom in a northeast-southwest movement; however slope currents induced by the wind, and pressure distributions in the Bering Sea must also produce short and long term effects on the general flow which
were not obvious in these current measurements.

One of the striking oceanographic features of the Bay is the evidence of a sharp boundary between the headwaters and the offshore waters. This occurs in the central part of the Bay along a line between Cape Pierce and Port Heiden and appears to be associated with a vertical movement of water intruding over the continental shelf between the Pribilof Islands and Unimak Island.

References


Fig. 1. General area chart showing selected contours of bottom topography in meters. (25, 50, and 75 meter contours not shown southward of Alaska Peninsula.)
Fig. 2. Release and recovery points of selected drift bottles (F.C.F., Seattle, Wash.)
Fig. 3. Vertical profile of temperature (°C) at entrance to Bristol Bay, winter 1955
Fig. 4. Vertical profile of salinity (‰) at entrance to Bristol Bay, winter 1955
Fig. 5. Comparison of average monthly air temperatures during 1939 and 1959 at Dillingham, Alaska.
Fig. 6. Vertical profiles of salinity and sigma-t between Cape Seniavin and Cape Newenham, August 1938.
Fig. 7. Vertical profile of salinity and sigma-\( T \) seaward of Cape Chichagof.
Fig. 8. Surface drift-stick observations, 1939
Fig. 9. Vertical temperature structure at three selected stations, 1939
Fig. 10. Surface temperatures (°C.), May, June, 1939
Fig. 11. Bottom temperatures (°C.), May and June, 1939
Fig. 12. Surface temperatures (°C.), August, 1939
Fig. 13. Bottom temperatures (°C.), August, 1939
Fig. 14. Difference in temperature (°C.) between surface and bottom, August, 1939
Fig. 15. Vertical salinity structure at three selected stations, 1939
Fig. 16. Surface salinity (‰), May, June 1939
Fig. 17. Difference in salinity (%) between surface and bottom, May-June 1939
Fig. 18. Surface salinity (‰), August, 1939
Fig. 19. Bottom salinity (%), August 1939
Fig. 20. Surface temperatures July-August, 1940
Fig. 21. Bottom temperatures July-August, 1940
Fig. 22. Bottom salinity July-August, 1940
Fig. 23. Bottom sigma-t July-August, 1940
Fig. 24. Vertical profiles of properties near the edge of continental shelf, June, 1958. (Shelf indicated by stippling.)
Fig. 25. Vertical profile of temperature near the edge of the continental shelf at 170°W, June 1956. (Shelf indicated by stippling)
Appendix II

Review of oceanography of the waters near the West Coast of Vancouver Island, British Columbia

Lane (1962a, b) has recently reported on the oceanography of the waters off the west coast of British Columbia. The following is a brief review of these studies.

Beginning with a study of Nootka Sound in 1933 (Tully, 1937) Canadian oceanographers have carried out investigations in the coastal areas. Many of these were localized studies, while others attempted to define and describe the more general distributions in the coastal waters.

The local studies include those in Nootka Sound (1933); Barkley Sound (1937, 1950, 1953); the approaches to Juan de Fuca Strait (1937, 1938); Dixon Entrance (1938); the Swiftsure area (1938); and in the area about La Perouse Bank (1960). These areas are identified in Fig. 1.

Those cruises operating in a more extensive area were the coastal surveys, which covered the shelf area off Vancouver Island (1935, 1936); and off the Queen Charlotte Island (1935); the offshore survey (1936), which operated seaward from the north, central and southern portions of Vancouver Island, Project Offshore (1950-52), reported by Doe (1955). The more recent cruises are the coastal surveys (1957) which included the area from 46° N to 56° N to about 200 miles offshore; the Coastal Seaway cruises (1958, 1959), which monitored several lines of stations seaward of both Vancouver Island and the Queen Charlotte Islands; and the Seaways Program (1960-61) which was a modification of the latter.

The data from all these expeditions have been processed and most of them have been reported (Pacific Oceanographic Group, MS, 1957-60). These reports also include daily seawater observations of temperature and salinity.
from 21 locations along the British Columbia coast, for varying periods; some since 1933. Recently Tabata (1959) and Hollister (1960) have presented a system of classifying the monthly means of these observations. This classification was undertaken to assist in the work of establishing correlations between fisheries statistics and coastal oceanographic conditions.

Meteorological data are available in the records and publications of the Meteorological Division, Department of Transport. River discharge data are available from records and publications of the Water Resources Division, Department of Northern Affairs and National Resources, Canada and Water Resources Division, United States, Department of the Interior.

Studies of these data have shown that the coastal area is not wholly dominated by oceanic influences, as are most coastal areas in other parts of the world. Instead, the oceanography of the Canadian coastal area is determined by the relative influence of the considerable estuarine discharge and the character of the oceanic waters. A study of the oceanic circulation has shown that off the North American coast the ocean waters separate to form the California Current and the Alaskan Gyre. The area of separation is continually shifting, hence the character of the oceanic water adjacent to the coast varies considerably. The estuarine discharge from the many inlets varies with precipitation and snow storage. In addition, the area is subject to variable winds and strong tides. However, none of these studies were adequate to observe the seasonal sequence of events and to define the mechanisms.

An examination of these data by Lane (1962a) showed that although such features as seaward and vertical gradients, and the coastwise continuity are real, there were considerable variations in short distances and short times which complicate and frequently negate the basic trend. Thus, it was not possible to assume simple continuity between widespread lines of
observations, such as seaward from the southern, central and northern ends of Vancouver Island, nor was it reasonable to assume more than a first order consistency of structure. In addition, short term variations were as great or greater than the seasonal or yearly variations.

In a second paper Lane (1962b) concentrated attention on the considerable data from a local area and assessed the variability and its relation to causitive factors (insolation, wind, precipitation, and tides). The area in which sufficient data were available was that seaward of Amphitrite Point (Fig. 2). It is also the widest expanse of the coastal area. He subdivided this area into three belts - each belt having some distinct oceanographic features of structure. The position of these belts (Inshore, Shelf and Slope) are shown in Fig. 2. In these belts he was able to deduce a model of temperature and salinity structure and related the major oceanographic features of the model to tides and meteorological elements. It is considered that these ideas, when amplified and extended will lead to a reasonable understanding of the coastal phenomena. At the moment this description entails much simplification. It is briefly discussed.

The model defines the annual sequence of temperature and salinity structure in five seasonal stages (Fig. 3 to 7) where the letters define the water masses:

<table>
<thead>
<tr>
<th></th>
<th>Oceanic</th>
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</tr>
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<tbody>
<tr>
<td>Upper Zone</td>
<td>OU</td>
<td>CU</td>
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<tr>
<td>Halocline</td>
<td>OH</td>
<td>CH</td>
</tr>
<tr>
<td>Lower Zone</td>
<td>OL</td>
<td>CL</td>
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</tbody>
</table>

Stage 1 (Fig. 3), from December through March, is in general a period of strong southeast winds, minimum insolation, maximum cooling and runoff. The latter, in this case, is a result of local precipitation as distinct from that in the spring which is associated with mainland rivers and the
spring thaw of high regions of ice and snow. The strong southeast winds lead to a condition of convergence and vertical mixing. These associated with cooling lead to a relatively narrow northward flow of cool, well-mixed and brackish water along the coast.

Stage 2 (Fig 4), through March and April, is largely a period of variable winds, increasing insolation and decreasing runoff. The convergence mechanism relaxes and the brackish water tends to spread seaward. This condition attains fulfillment in Stage 3 (Fig. 5), the period May through July. Also at this time, the mainland rivers are in freshet and tidal action conduces to the formation of large pools of brackish water. Because of these pools, there are marked short term variations in the near-surface waters.

Stage 4 (Fig. 6), from July through October, occurs during the prevalence of weak northwest winds and minimal fresh water discharge from the land. A weak divergence condition may enhance the spread of brackish water seaward. On the other hand, persistent northwest winds will produce a strong divergence condition, in which case there is not only a spread of brackish water seaward by a replenishment of these waters from depth, resulting in a breakdown of the new coastal structure and the appearance of relatively cold saline waters. Such conditions have been observed but are not necessarily the persistent characteristics of the area.

Stage 5 (Fig. 7), from October through December is a time of increasing southeast winds and precipitation. During this stage the oceanic upper zone (OU) deepens. This results in an intensification of the top of the oceanic halocline (OH). Its base descends due to the advent of convergence.
References


FIG. 3
FIG. 4
FIG. 5

STAGE 3
MAY through JULY

POSITIONS

SALINITY (%)

TEMPERATURE (°C)

(LANE, 1962b)
FIG. 6

(a)

STAGE 4
JULY through OCTOBER

(b)

TEMPERATURE(°C)

SALINITY(‰)

STAGE 4
JULY through OCTOBER

(LANE, 1962b)
STAGE 5
OCTOBER through DECEMBER

SALINITY (%o)

TEMPERATURE (°C)

LANE, 1962b

FIG. 7
REVIEW OF OCEANOGRAPHY OF THE SUBARCTIC PACIFIC REGION

by

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Figures 1-233
Fig. 1. Representative T-S curves of Subarctic and Eastern Pacific Waters
Fig. 2. Regions and zones in the northern Pacific (adapted from Fleming, 1955)
Fig. 3. Position of Subarctic boundary during summer 1958
Fig. 4. Geography of Subarctic Pacific Region
Fig. 5. Bathymetry (metres)
Fig. 6. Evaporation minus precipitation - winter, summer and annual conditions (adapted from Jacobs, 1951)
Fig. 7. Mean sea level pressure (millibars) and prevailing surface winds during winter (contours indicate the percentage of time the winds are Force 3 and less)
Fig. 8. Mean sea level pressure (millibars) and prevailing surface winds during summer (contours indicate the percentage of time the winds are Force 3 and less)
Fig. 10. Annual cycle of incident energy (gram cal/cm²/day) from lat. 35° to 60° N
Fig. 11. Average cloud cover and insolation during winter and summer.
Fig. 12a. Monthly mean sea surface temperature charts, January, February, March, 1956 (adapted from Saur and Eber, 1962)
Fig. 12b. Monthly mean sea surface temperature charts, April, May, June, 1956 (adapted from Saur and Eber, 1962)
Fig. 12c. Monthly mean sea surface temperature charts, July, August, September, 1956 (adapted from Saur and Eber, 1962)
Fig. 12d. Monthly mean sea surface temperature charts, October, November, December, 1956 (adapted from Saur and Eber, 1962)
Fig. 13. Recognized major current systems prior to 1955
Fig. 14. Surface circulation in the Bering Sea (Goodman et al., 1942)
Fig. 15. Dynamic height anomaly, surface over 500 decibars, July - August 1949 (Saur et al., 1952)
Vertical temperature curves of typical water systems based on data from the R.V. Tenyo-Maru, 1954 (Hirano, 1957).

K: Kuroshio water, O: Okhotsk water, B: Bering water, C: Central water of the Western Subarctic Region, Mb: Mixing water between the Kuroshio and the Okhotsk water. The right edge of Mb shows the curve at sts. 44, 46 and 48 approximately. Curves in broken line show the water in the mixing region Ma at sts. 25 and 98.

Regional distributions of water systems in the western Subarctic Region based on data from the R.V. Tenyo-Maru, 1954 (Hirano, 1957).

A: water originating from the Gulf of Alaska, Ma: water in the mixing region off the Sanriku, Mc: mixing water between the Central water of W.S.R. and the mixing water Mb, Md: mixing water between the Okhotsk water and the Central water of W.S.R.

Fig. 16. Vertical temperature curves of typical water systems and their regional distributions in the western Subarctic Region (Hirano, 1957)
Fig. 17. Geopotential topography, 100/750 decibars (Mishima and Nishizawa, 1955)
Fig. 18. Calculated surface currents relative to bottom in Gulf of Alaska (Thompson et al., 1936)

Fig. 19. Returns from drift bottles released between January 3 and March 7, 1933, and January 9 and February 25, 1934 (Thompson and Van Cleve, 1936)
Fig. 20. Water masses in the Gulf of Alaska (Doe, 1935)
Fig. 21. Station Positions, summer 1955
Fig. 22. Station Positions, summer 1956
Fig. 23. Station Positions, winter 1957
Fig. 24. Station Positions, summer 1957
Fig. 25. Station Positions, winter 1958
Fig. 26. Station Positions, summer 1958
Fig. 27. Station Positions, winter 1959
Fig. 28. Station Positions, summer 1959
Fig. 29. Typical salinity structures at Ocean Station "P"
Fig. 30. Salinity and temperature structures at Ocean Station "P", March 1958 to April 1959
Fig. 31. Heat budget at Ocean Station "P", 1957 (after Tabata, 1961)
Fig. 3. Salinity and temperature structures at Ocean Station "N", September 1958 to February 1959
Fig. 33. Values of salinity at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m)
Fig. 34. Typical salinity, temperature and dissolved oxygen structures in the Subarctic Region, summer 1958
Fig. 35. Sequence of salinity, temperature, and dissolved oxygen structures from lat. 50° to 40° N., summer 1956
Fig. 36. Typical temperature structures at Ocean Station "P" (dotted line at top winter structure indicates possible deviation with extreme cooling)
Fig. 37. Growth and decay of the thermocline at Ocean Station "P"
Fig. 38a. Features of the thermocline at Ocean Station "P", March, April, May, 1956
Fig. 38b. Features of the thermocline at Ocean Station "P", June, July, August, 1956
Fig. 38c. Features of the thermocline at Ocean Station "P", September, October, November, 1956
Fig. 39. Schematic diagram of significant features of structure
Fig. 40. Temperatures at the surface and 100 metres depth, Ocean Station "P", 1956 through 1959
Monthly Mean Sea Surface Temperature (°C) at OCEAN STATION "P" (Lat. 50°N; Long. 145°W.)

Fig. 41. Monthly mean sea surface temperature at Ocean Station "P", 1955 through 1959.
MONTHLY MEAN AIR AND SEA TEMPERATURES (°C)
AT STATION "P"
August 1956-July 1958

Fig. 42. Monthly mean air and sea temperatures at Ocean Station "P", August 1956 to July 1958
Fig. 43. Values of temperature at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m)
Fig. 44. Typical dissolved oxygen structures at Ocean Station "P"
Fig. 45. Values of dissolved oxygen at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m)
Fig. 46. Locations of vertical sections, summer 1955
Fig. 47. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°E, summer 1955
Fig. 48. Vertical sections of salinity, temperature and dissolved oxygen along Kuril Islands, summer 1955
Fig. 49. Vertical sections of salinity, temperature and dissolved oxygen along long. 180°, summer 1955
Fig. 50. Vertical sections of salinity, temperature and dissolved oxygen approx. long. 160°W, summer 1955
Fig. 51. Vertical sections of salinity, temperature and dissolved oxygen approx. long. 148°W, summer 1955
Fig. 52. Vertical sections of salinity, temperature and dissolved oxygen approx. lat. 47°N, summer 1955
Fig. 53. Vertical sections of salinity, temperature and dissolved oxygen approx. lat. 39°N, summer 1955
Fig. 54. Locations of vertical sections, summer 1956
Fig. 55. Vertical sections of salinity and temperature along Kuril Islands, summer 1956
Fig. 56. Vertical sections of salinity and temperature along long. 175°E, summer 1956
Fig. 57. Vertical sections of salinity and temperature along long. 180°, summer 1956.
Fig. 58. Vertical sections of salinity and temperature along long. 175°W, summer 1956
Fig. 59. Vertical sections of salinity and temperature along long. 160°W, summer 1956
Fig. 60. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W, summer 1956
Fig. 61. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 48° N, Summer 1956.
Fig. 62. Vertical sections of salinity and temperature along approx. lat. 40°N, summer 1956
Fig. 63. Locations of vertical sections, winter 1957
Fig. 64. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 157°W, winter 1957
Fig. 65. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 147°W, winter 1957
Fig. 66. Vertical sections of salinity, temperature and dissolved oxygen from long. 140°W to Vancouver Island
Fig. 67. Locations of vertical sections, summer 1957
Fig. 68. Vertical sections of salinity, temperature and dissolved oxygen along long. 145°E, summer 1957
Fig. 69. Vertical sections of salinity and temperature along approx. long. 165°E, summer 1957
Fig. 70. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°E, summer 1957
Fig. 71. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 180°, summer 1957
Fig. 72. Vertical sections of salinity and temperature along long. 175°W, summer 1957.
Fig. 73. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 160°W, summer 1957
Fig. 74. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W, summer 1957
Fig. 75. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 47°N, summer 1957
Fig. 76. Locations of vertical sections, winter 1958
Fig. 77. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 150°W, winter 1958
Fig. 78. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 49°N, winter 1958
Fig. 79. Locations of vertical sections, summer 1958
Fig. 80. Vertical sections of salinity, temperature and dissolved oxygen along long. 145°E, summer 1958
Fig. 81. Vertical sections of salinity, temperature and dissolved oxygen along long. 155°E, summer 1958
Fig. 82. Vertical sections of salinity, temperature and dissolved oxygen along long. 165°E, summer 1958
Fig. 83. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°E, summer 1958
Fig. 84. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°W, summer 1958
Fig. 85. Vertical sections of salinity, temperature and dissolved oxygen along long. 160°W, summer 1958
Fig. 86. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 45°N, summer 1958
Fig. 87. Locations of vertical sections, winter 1959
Fig. 88. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 130° W, winter, 1959
Fig. 89. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 47° N, winter, 1959
Fig. 90. Locations of vertical sections, summer 1959
Fig. 91. Vertical sections of salinity, temperature and dissolved oxygen along long. 150°E, summer 1959
Fig. 92. Vertical sections of salinity and temperature along long. 165°E, summer 1959.
Fig. 93. Vertical sections of salinity; temperature and dissolved oxygen along long. 175°E, summer 1959
Fig. 94. Vertical sections of salinity, temperature and dissolved oxygen along long. 180°, summer 1959.
Fig. 95. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°W, summer 1959
Fig. 96. Vertical sections of salinity, temperature and dissolved oxygen along long. 160°W, summer 1959
Fig. 97. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W, summer 1959
Fig. 98. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 48°N, summer 1959
Fig. 99. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 38°N, summer 1959
Fig. 100. Geopotential topography, 0/1000, 0/2000 and 1000/2000 decibars, summer 1959
Fig. 101. Geopotential topography, 0/1000 decibars, summer 1955
Fig. 102. Geopotential topography, 0/1000 decibars, summer 1956
Fig. 103. Geopotential topography, 0/1000 decibars, winter 1957
Fig. 104. Geopotential topography, 0/1000 decibars, summer 1957
Fig. 105. Geopotential topography, 0/1000 decibars, winter 1958
Fig. 106. Geopotential topography, 0/1000 decibars, summer 1958
Fig. 107. Geopotential topography, 0/1000 decibars, winter 1959
Fig. 108. Geopotential topography, 0/1000 decibars, summer 1959
Fig. 109. Schematic diagram of surface circulation
Fig. 110. Geopotential topography 200/1000 decibars, summer 1955
Fig. 111. Geopotential topography 200/1000 decibars, summer 1956
Fig. 112. Geopotential topography 200/1000 decibars, winter 1957
Fig. 113. Geopotential topography 200/1000 decibars, summer 1957
Fig. 114. Geopotential topography 200/1000 decibars, winter 1958
Fig. 115. Geopotential topography 200/1000 decibars, summer 1958
Fig. 116. Geopotential topography 200/1000 decibars, winter 1959

North Pacific Ocean
Geopotential Topography
Dynamic Height Anomaly (DAD)

Winter 1959

Geopotential topography 200/1000 decibars, winter 1959
Fig. 117. Geopotential topography 200/1000 decibars, summer 1959
Fig. 118. Schematic diagram of circulation at 200 decibars
Fig. 119. Geopotential topography, 500/1000 decibars, summer 1955
Fig. 120. Geopotential topography, 500/1000 decibars, summer 1956
Fig. 121. Geopotential topography, 500/1000 decibars, winter 1957
Fig. 122. Geopotential topography, 500/1000 decibars, summer 1957
Fig. 123. Geopotential topography, 500/1000 decibars, winter 1958
Fig. 124. Geopotential topography, 500/1000 decibars, summer 1958
Fig. 125. Geopotential topography, 500/1000 decibars, winter 1959
Fig. 126. Geopotential topography, 500/1000 decibars, summer 1959
Fig. 127. Schematic diagram of circulation at 500 decibars
Fig. 128. Geopotential topography 0/200 decibars, summer 1955
Fig. 129. Geopotential topography 0/200 decibars, summer 1956
Fig. 130. Geopotential topography 0/200 decibars, winter 1957
Fig. 131. Geopotential topography 0/200 decibars, summer 1957
Fig. 132. Geopotential topography 0/200 decibars, winter 1958
Fig. 133. Geopotential topography 0/200 decibars, summer 1958
Fig. 134. Geopotential topography 0/200 decibars, winter 1959
Fig. 135. Geopotential topography 0/200 decibars, summer 1959
Fig. 136. Schematic diagram of circulation, 0/200 decibars
Fig. 137a. Temperature sections across Aleutian Chain at long. 175° E, 175° W, and 165° W, July 1957. (Aleutian Chain shown in black).

Fig. 137b. Temperature sections across Aleutian Chain at long. 175° E, July 1957 and 1958. (Aleutian Chain shown in black).
Fig. 138. Drift bottle releases in western Subarctic
Fig. 139. Drift bottle releases in central Subarctic
Fig. 140. Drift bottle releases in eastern Subarctic
Fig. 141. Annual mean geostrophic transports, 1955 through 1959
Comparison of zonal components of geostrophic mass transport computed from wind stress (upper arrow in each set) and volume transport computed from hydrographic data from 0 to 1200 metres (lower arrow in each set) during summer 1958. (Dashed line shows approximate extent of Alaskan Stream).

Comparison of meridional components of geostrophic mass transport computed from wind stress (left arrow in each set) and volume transport computed from hydrographic data from 0 to 1200 metres (right arrow in each set) during summer 1958. (Dashed line shows approximate extent of Alaskan Stream).

Fig. 142. Comparison of wind stress and volume transports, summer 1958.
Fig. 143. Salinity at 10 metres depth, summer 1955
Fig. 144. Salinity at 10 metres depth, summer 1956
NORTH PACIFIC OCEAN
SALINITY (‰)
AT 10 METRES DEPTH
WINTER 1957

Fig. 145. Salinity at 10 metres depth, winter 1957
Fig. 146. Salinity at 10 metres depth, summer 1957
Fig. 147. Salinity at 10 metres depth, winter 1958
Fig. 148. Salinity at 10 metres depth, summer 1958
Fig. 149. Salinity at 10 metres depth, winter 1959
Fig. 150. Salinity at 10 metres depth, summer 1959
Fig. 151. Temperature at 10 metres depth, summer 1955
Fig. 152. Temperature at 10 metres depth, summer 1956
Fig. 153. Temperature at 10 metres depth, winter 1957
Fig. 154. Temperature at 10 metres depth, summer 1957
Fig. 155. Temperature at 10 metres depth winter 1958
Fig. 156. Temperature at 10 metres depth summer 1958
Fig. 157. Temperature at 10 metres depth winter 1959
Fig. 158. Temperature at 10 metres depth, summer 1959
Fig. 159. Depth (metres) of upper zone, summer 1955
Fig. 160. Depth (metres) of upper zone, summer 1956
NORTH PACIFIC OCEAN
DEPTH (metres)
OF UPPER ZONE
WINTER 1957

Fig. 161. Depth (metres) of upper zone, winter 1957
Fig. 162. Depth (metres) of upper zone, summer 1957
Fig. 163. Depth (metres) of upper zone, winter 1958
Fig. 164. Depth (metres) of upper zone, summer 1958
Fig. 165. Depth (metres) of upper zone, winter 1959
Fig. 166. Depth (metres) of upper zone, summer 1959
Fig. 167. Salinity at bottom of upper zone, summer 1955
Fig. 169. Salinity at bottom of upper zone, winter 1957
Fig. 170. Salinity at bottom of upper zone, summer 1957
Fig. 171. Salinity at bottom of upper zone, winter 1958
Fig. 172. Salinity at bottom of upper zone, summer 1958
Fig. 173. Salinity at bottom of upper zone, winter 1959
Fig. 174. Salinity at bottom of upper zone, summer 1959
Fig. 175. Temperature at bottom of upper zone, summer 1955
Fig. 176. Temperature at bottom of upper zone, summer 1956
NORTH PACIFIC OCEAN
TEMPERATURE (°C)
AT BOTTOM OF UPPER ZONE

WINTER 1957

Fig. 177. Temperature at bottom of upper zone, winter 1957
Fig. 178. Temperature at bottom of upper zone, summer 1957
Fig. 179. Temperature at bottom of upper zone, winter 1958
Fig. 180. Temperature at bottom of upper zone, summer 1958
Fig. 181. Temperature at bottom of upper zone, winter 1959
NORTH PACIFIC OCEAN
TEMPERATURE (°C)
AT BOTTOM OF UPPER ZONE

SUMMER 1959

Fig. 182. Temperature at bottom of upper zone, summer 1959
Fig. 183. Depth (metres) of surface of salinity = 33.8%, summer 1955
Fig. 184. Depth (metres) of surface of salinity = 33.8%, summer 1956
Fig. 185. Depth (metres) of surface of salinity = 33.8%, winter 1957
Fig. 186. Depth (metres) of surface of salinity = 33.8%, summer 1957
Fig. 187. Depth (metres) of surface of salinity = 33.8%, winter 1958
NORTH PACIFIC OCEAN
DEPTH (Metres)
OF SURFACE OF SALINITY = 33.8% 
SUMMER 1958

Fig. 188. Depth (metres) of surface of salinity = 33.8 %, summer 1958
Fig. 189. Depth (metres) of surface of salinity = 33.8%, winter 1959
Fig. 190. Depth (metres) of surface of salinity = 33.8‰, summer 1959
Fig. 191. Temperature on the surface of salinity = 33.8 ‰, summer 1955
Fig. 192. Temperature on the surface of salinity = 33.8%, summer 1956
Fig. 193. Temperature on the surface of salinity = 33.8%, winter 1957
Fig. 194. Temperature on the surface of salinity = 33.8 %, summer 1957
Fig. 195. Temperature on the surface of salinity = 33.8 %, winter 1958
Fig. 196. Temperature on the surface of salinity - 33.8 %, summer 1958
Fig. 197. Temperature on the surface of salinity - 33.8%, winter 1959
Fig. 198. Temperature on the surface of salinity = 33.8%, summer 1959
Fig. 199. Depth (metres) of surface of salinity - 34.0‰, summer 1955
Fig. 200. Depth (metres) of surface of salinity = 34.0%, summer 1956
Fig. 201. Depth (metres) of surface of salinity - 34.0%, winter 1957
Fig. 202. Depth (metres) of surface of salinity = 34.0 %, summer 1957
Fig. 203. Depth (metres) of surface of salinity = 34.0 %, winter 1958
Fig. 204. Depth (metres) of surface of salinity = 34.0%, summer 1958
Fig. 205. Depth (metres) of surface of salinity = 34.0%, winter 1959
Fig. 206. Depth (metres) of surface of salinity = 34.0%, summer 1959
Fig. 207. Temperature on the surface of salinity = 34.0%, summer 1955
Fig. 208. Temperature on the surface of salinity = 34.0%, summer 1956
Fig. 209. Temperature on the surface of salinity = 34.0%, winter 1957
Fig. 210. Temperature on the surface of salinity = 34.0%, summer 1957
Fig. 211. Temperature on the surface of salinity = 34.0%, winter 1958
Fig. 212. Temperature on the surface of salinity = 34.0 %, summer 1958
Fig. 213. Temperature on the surface of salinity = 34.0%, winter 1959
Fig. 214. Temperature on the surface of salinity = 34.0%, summer 1959
Fig. 215. Temperature-salinity curves (Dodimead, 1958)
Fig. 216. Schematic diagram of upper zone domains
Fig. 217. Upper zone domains, summer 1955
Fig. 218. Upper zone domains, summer 1956
Fig. 219. Upper zone domains, winter 1957
NORTH PACIFIC OCEAN
UPPER ZONE DOMAINS
SUMMER 1957

Fig. 220. Upper zone domains, summer 1957
Fig. 221. Upper zone domains, winter 1958
Fig. 222. Upper zone domains, summer 1958
Fig. 223. Upper zone domains, winter 1959
Fig. 224. Upper zone domains, summer 1959
Fig. 225. Schematic diagram of lower zone domains
Fig. 226. Lower zone domains, summer 1955
Fig. 227. Lower zone domains, summer 1956
Fig. 228. Lower zone domains, winter 1957
Fig. 229. Lower zone domains, summer 1957
Fig. 230. Lower zone domains, winter 1958
Fig. 231. Lower zone domains, summer 1958
Fig. 232. Lower zone domains, winter 1959
Fig. 233. Lower zone domains, summer 1959