THE GEOSTROPHIC CIRCULATION AND DISTRIBUTION OF WATER PROPERTIES OFF THE COASTS OF VANCOUVER ISLAND AND WASHINGTON, SPRING AND FALL 1963

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ABSTRACT

Analysis of oceanographic data collected during the spring and fall cruises of the RV *George B. Kelez* in 1963 within 220 kilometers of the coasts of Vancouver Island and Washington indicated a net volume transport toward the north; the flow was about 3 x 10^6m.^{3} sec. off northern Vancouver Island, but only 1 x 10^6m.^{3}/sec. off Washington.

The major structural features were consistent in each of the nine vertical sections of salinity, temperature, or dissolved oxygen normal to shore between the Columbia River and Cape Cook.

A water mass that had higher salinity, higher temperature, and lower dissolved-oxygen concentration than offshore water existed over the continental slope below the halocline. The implied northward flow at depth along the coast was very weak. These data add to the increasing body of information concerning the California Undercurrent.

At a conference on fishery-oceanography at San Francisco, Calif., on June 2, 1947, the need became obvious for repeated oceanographic surveys along the Pacific coast up to about 500 km. offshore (Sette, 1947). A gap existed at the time of this conference between proposed sampling off the California coast by Scripps Institution of Oceanography and off the Canadian coast by the Pacific Oceanographic Group. This gap narrowed when the Department of Oceanography, at Oregon State University, began a survey of Oregon coastal waters in June 1958, and the Department of Oceanography at the University of Washington in January 1961 began a study of the area influenced by the Columbia River effluent. Extensive oceanographic observations from the Columbia River to northern Vancouver Island in the spring and fall of 1963, by the Oceanographic Section of the Bureau of Commercial Fisheries Biological Laboratory, Seattle, Wash., also filled in a portion of the gap. The purpose of the spring cruise was to determine oceanographic conditions in the coastal environment within 185 km. of shore (Ingraham, 1964); the fall cruise was planned to determine whether significant changes had occurred since spring. The locations of oceanographic stations for both cruises are shown in figure 1.

This report presents the significant features of the distributions of salinity, temperature, dissolved oxygen, and water mass and the circulation as shown by geostrophic currents at the surface and at 200 meters.

CIRCULATION

Interesting aspects of the circulation close to the coast are the extent, continuity, and source of the surface Davidson Current and of the subsurface California Undercurrent, and the relationship of the two. The flow in the Davidson Current has been clearly shown by drift bottles released during fall, winter, and early spring from as far south as central California and recovered along the coast of British Columbia. This surface current extends at least 93 km. from shore; it usually has an average speed of about 15 cm./sec. but speeds of about 40 cm./sec. have been found (Schwartzlose, 1963). Burt and Wyatt (1964) reported similar minimal velocities for drift bottles released off Oregon during January 1961 and recovered off Vancouver Island.

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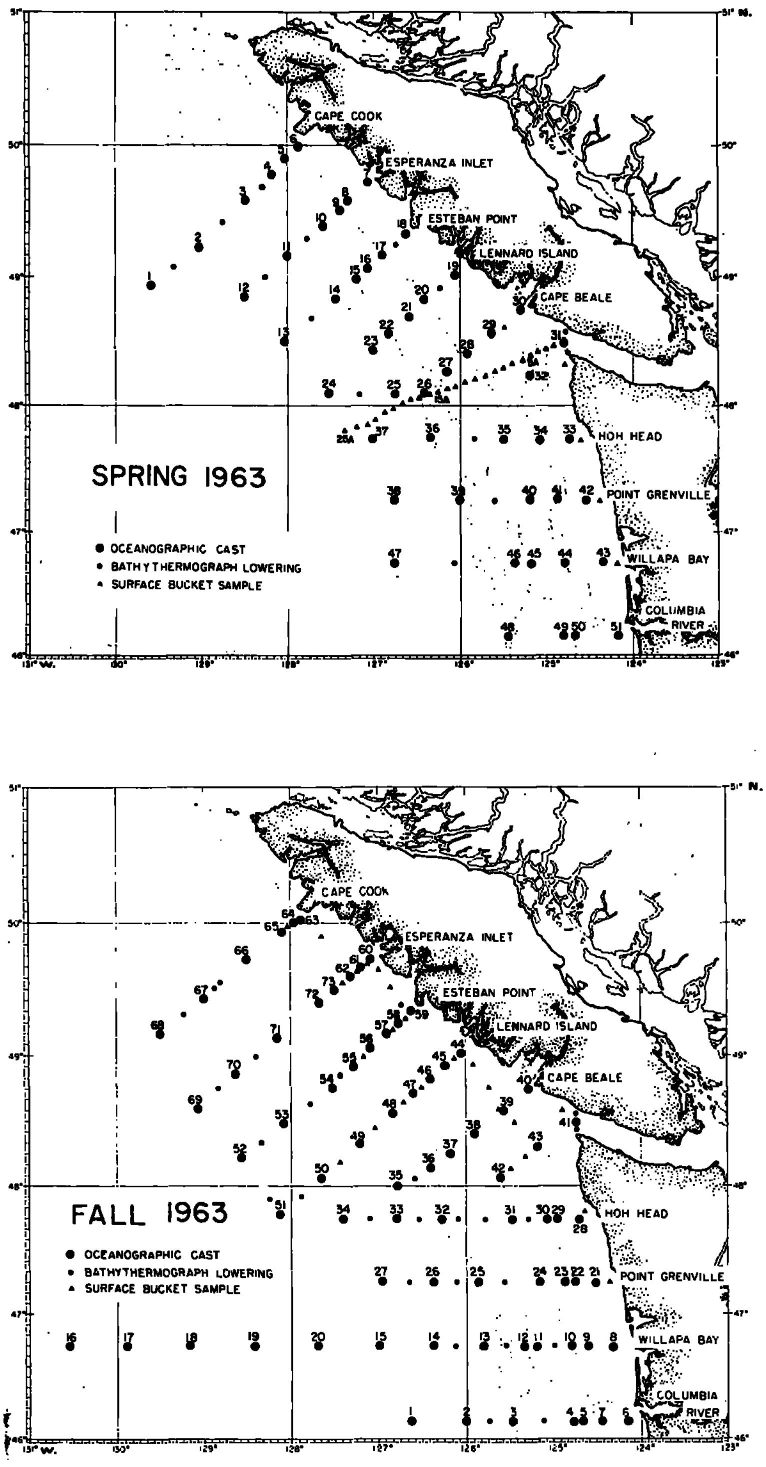

FIGURE 1.—Locations of oceanographic stations, RV *George B. Kelez*, April 30, to May 17 and October 23 to November 24, 1963. (The 183- and 1,829-m. depth contours are shown.)

The cause of the Davidson Current is not clearly understood. Off the coast of Oregon it appears to result from local wind stress, but direct measurements during October 1958 and January 1959 (Reid and Schwartzlose, 1963) indicate that the driving force of this current is not local winds; it may be a surface manifestation of a deeper northward-flowing countercurrent that develops when winds weaken seasonally (Sverdrup, Johnson, and Fleming, 1942). This northward countercurrent which opposes the offshore California Current has been reported off central California below 200 m. throughout the year (Reid, Roden, and Wyllie, 1958). Northward flow also was reported off Washington and Oregon below 200 m. during the summers of 1955–57 and 1959; this report was based upon limited observations (Dodimead, Favorite, and Hirano, 1963). Our closely spaced observations during 1963 permit a more detailed evaluation of the size and continuity of the surface Davidson Current, the subsurface California Undercurrent, and other major features of the circulation off the coasts of British Columbia and Washington.

GEOSTROPHIC CURRENTS

Geostrophic currents reflect the general circulation associated with the distribution of mass. They are calculated from an arbitrarily selected reference depth and are, therefore, relative currents. The 1,000-db. (decibar) surface has been used as a reference surface in the North Pacific Ocean by Reid (1961), Dodimead et al. (1963), Budinger, Coachman, and Barnes (1964), and Favorite (1966) because they had

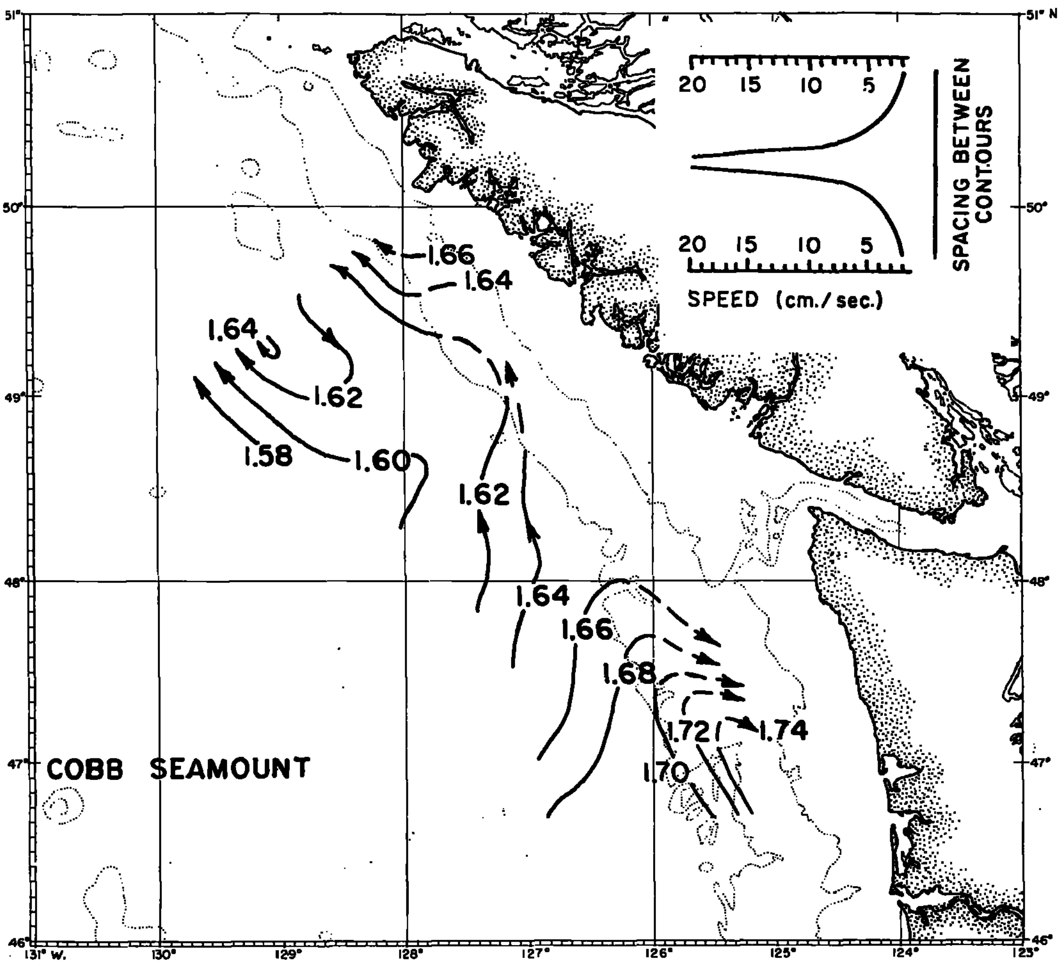

FIGURE 2.—Geopotential topography, 0/1,500 m., spring 1963. (The 183- and 1,829-m. depth contours are shown.)

sufficient data only to 1,000 m. Bennett (1959), using a deeper reference level, obtained greater surface velocities for the Gulf of Alaska. In the absence of a known depth of no motion, the deepest level compatible with all the data (1,500 db.) was selected for the reference surface in this study. Other assumptions that limit the accuracy of geostrophic currents are: (1) synoptic data, (2) unaccelerated flow, (3) lack of internal wave or tidal influence, and (4) absence of friction.

Caution must be used in the estimation of the surface velocity from geostrophic currents alone. The Ekman Current (Sverdrup et al., 1942) caused by local, variable wind stress must be added to the geostrophic current, for it is reasonable to assume in the absence of direct measurements of current that the Ekman velocities at the surface may exceed the surface geostrophic velocities. Examination of transport values computed from mean monthly pressure charts (Fofonoff and Ross, 1961) suggests that Ekman velocities of 3 to 10 cm./sec. generally toward the southeast may be expected in this coastal area during spring and fall. Although the short-term Ekman Currents, averaged on a daily basis, may be even greater, they are negligible below 200 m. They were neglected in this discussion which is concerned primarily with the main portion of the water column below 200 m.

The data from the cruises of the *Kelez* permit construction of the first geostrophic current charts off the Washington coast from a reference level of 1,500 db. Relative currents flow along contour lines of equal geopotential

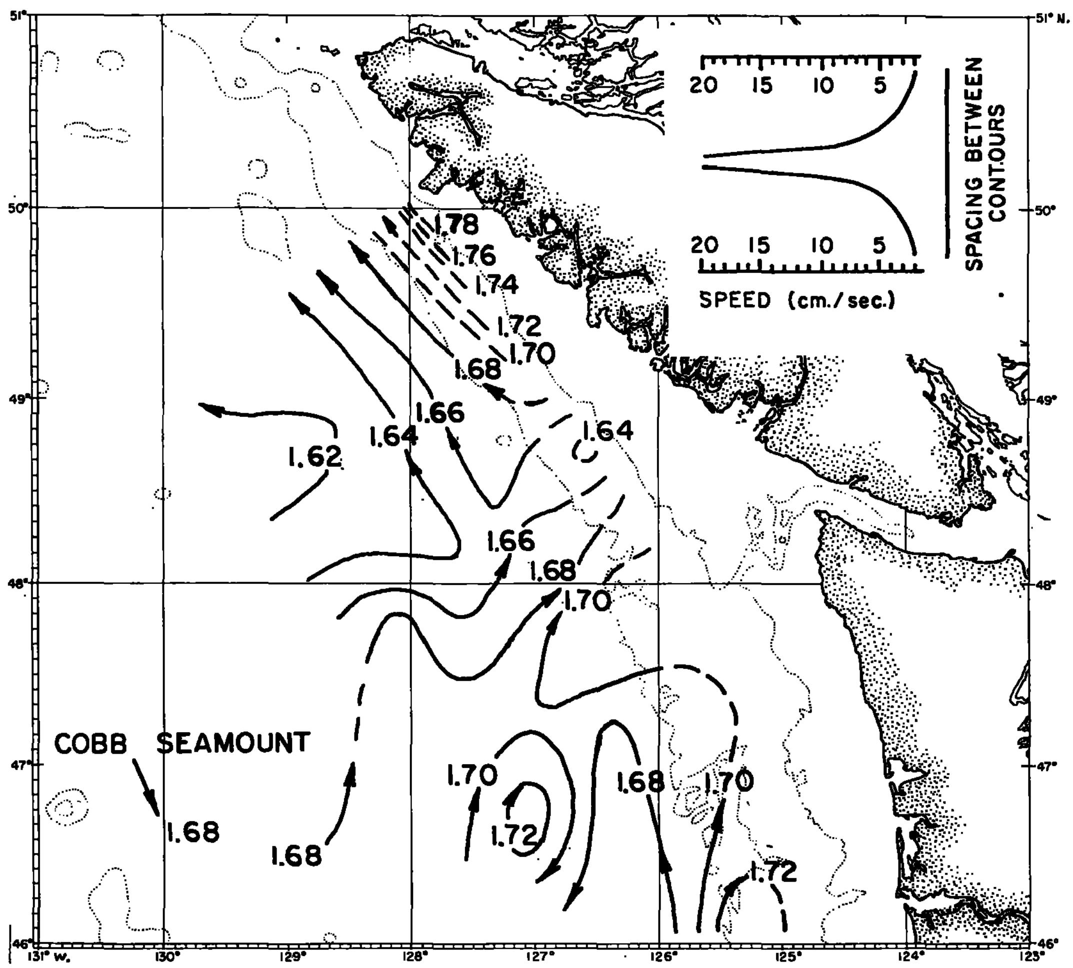

FIGURE 3.—Geopotential topography, 0/1,500 db., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

depth with speed proportional to the gradient across them. Broken lines (figs. 2–5) represent currents in water shallower than the reference depths, which are calculated by the method used by Bennett (1959).

Surface Currents, 0 to 1,500 db.

Eddies complicated the pattern of surface geostrophic currents during the spring, but the predominant surface current within 185 km. of shore was generally toward the north (fig. 2). A major feature was the apparent divergence of onshore flow near southern Vancouver Island. North of the divergence, water from offshore veered toward the northwest and flowed generally parallel to the coast. Northwestward velocities were 10 and 12 cm./sec. at two locations on the northernmost line of stations, and a speed of 18 cm./sec. occurred off the Washington coast near lat. 47° N. The latter flow turned eastward toward shore and was not evident north of lat. 47°30′ N.

Although large eddies were also present off the coast of Washington during fall, they were absent off Vancouver Island (fig. 3). Maximum speed off the coast of Washington was 11 cm./sec. in the anticyclonic eddy near lat. 47° N., long. 127° W. The northward flow of 10 cm./sec. off the Columbia River in the vicinity of the 1,829-m. depth contour appeared to be dissipated by eddies as it proceeded north. Offshore water near lat. 48° N. flowed northeasterly toward southern Vancouver Island as it had during spring, but the distinct divergence over the continental slope was absent in the fall, and most of the water appeared to flow

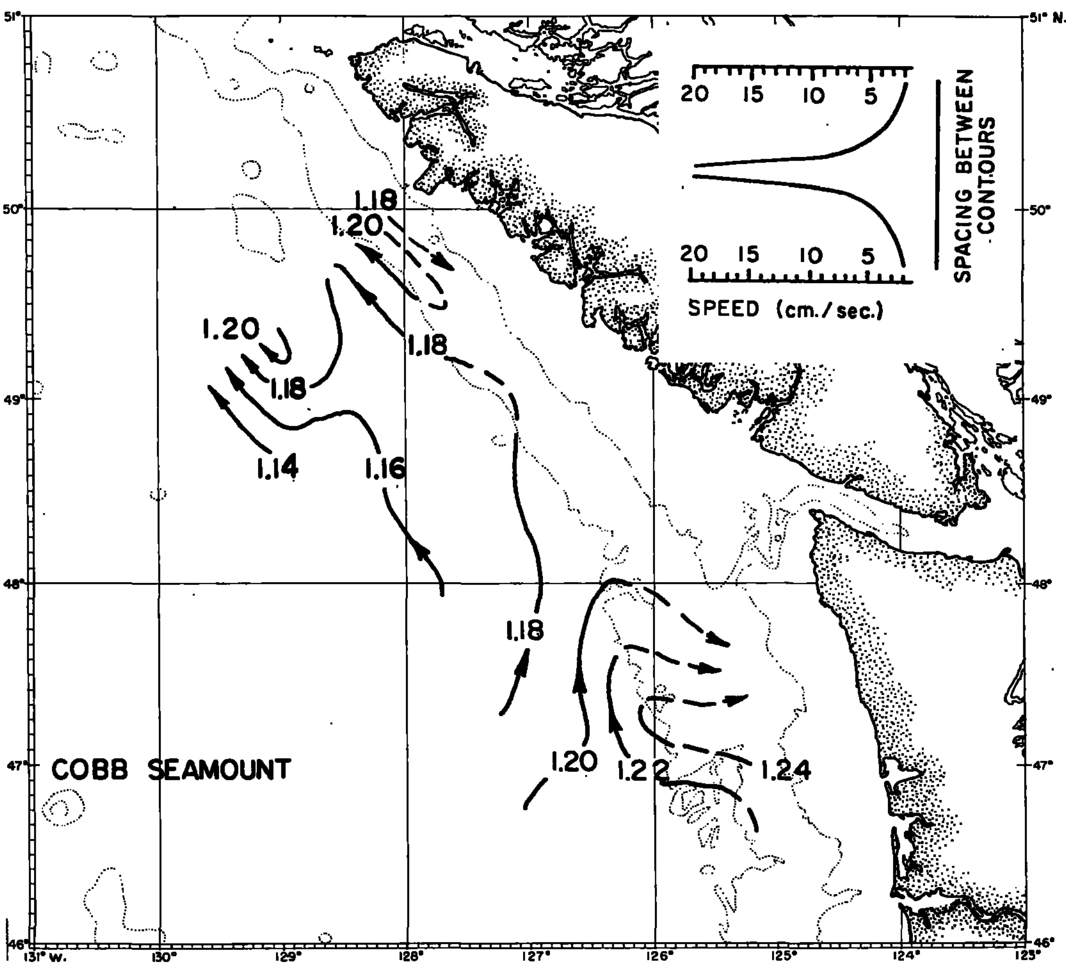

FIGURE 4.—Geopotential topography, 200/1,500 m., spring 1963. (The 183- and 1,829-m. depth contours are shown.)

northwesterly along the coast. A maximum speed of 20 cm./sec. occurred close to shore near Cape Cook.

Results from additional stations along the Willapa Bay line at 30-mile intervals to Cobb Seamount indicated that just east of Cobb Seamount was a weak southerly flow which suggests a meander in the general onshore movement.

In summary, the gross aspects of the surface geostrophic currents during spring and fall were similar. A major, recurring feature was the broad northeasterly movement of offshore water toward southern Vancouver Island; this flow veered northwesterly generally parallel to the coastline. Most characteristic features of the circulation off Washington were the many eddies and the apparent lack of strong northward flow of near-shore water, the Davidson Current, across lat. 48° N. Drift bottle experiments during the winter of 1965, however, indicated a significant northward flow of water over the Continental Shelf off Washington and Vancouver Island. The onshore flow which restricts the northward movement of water along the coast of Washington suggests a cause for the formation of eddies.

Lower Zone Currents, 200 to 1,500 db.

Data collected during the spring and fall of 1963 indicate the bottom of the halocline did not extend to a depth of 200 m. in the coastal area. Geostrophic currents at 200 m., therefore, represent the movement of water which possesses nearly constant properties below the halocline and is isolated from the direct in-

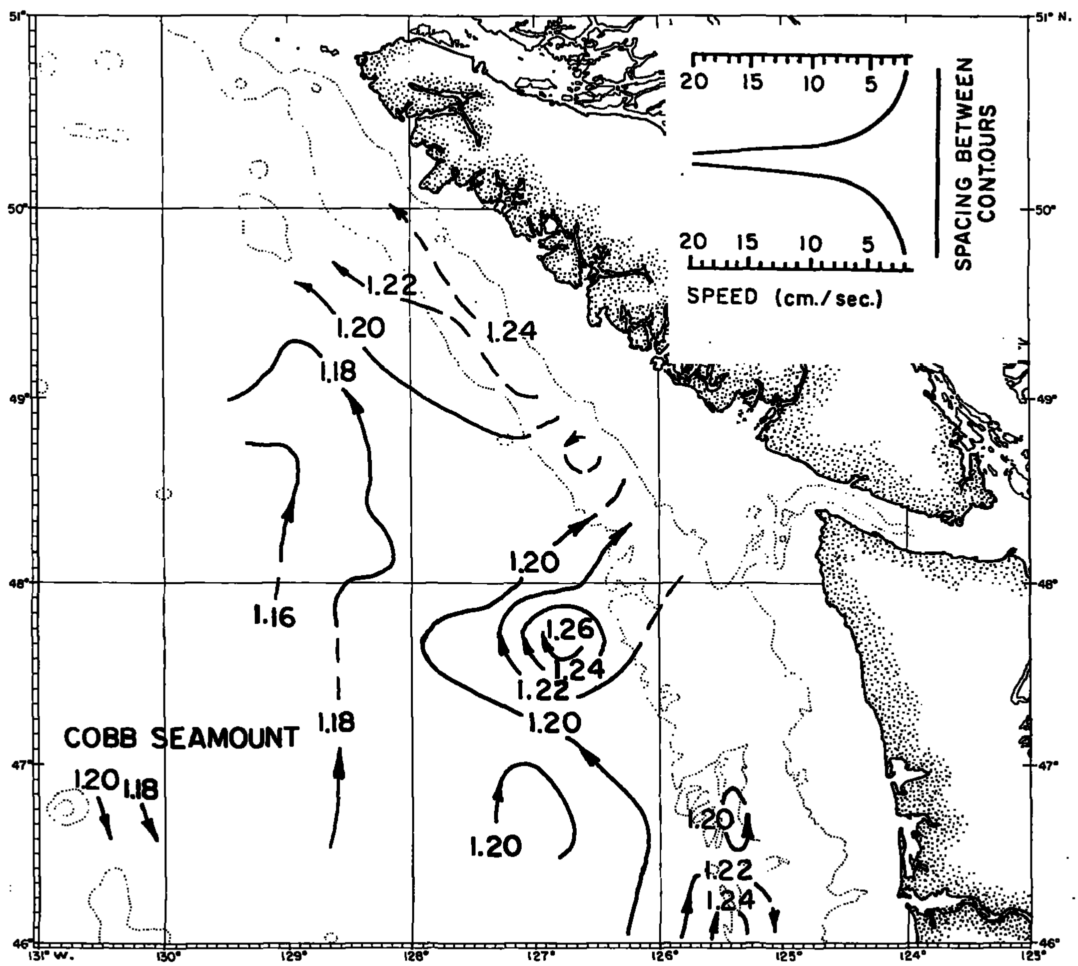

FIGURE 5.—Geopotential topography, 200/1,500 db., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

fluence of seasonal processes (Tully and Barber, 1960). During spring the directions of geostrophic flow at 200 m. and at the surface were nearly identical (fig. 4). An exception occurred near lat. 47° N., where water on the Continental Slope veered more sharply offshore than did the surface water. The deeper flow followed the 1,829-m. (1,000-fathom) depth contour and appeared to be influenced by the local bottom topography. The maximum current of 10 cm./sec. was at 200 m., whereas the surface flow was 6 cm./sec. This condition is contrary to the characteristic decrease in speed with depth throughout most of the Subarctic Region and occurred only in this one area off the coast of Washington.

Geostrophic currents at 200 m. during fall also followed closely the direction of the surface currents (fig. 5). The speed at 200 m. was generally one-half that of the surface current north of lat. 48° N., but speeds significantly greater than the surface flow were again present off Washington. The speed of the pronounced anticyclonic eddy just south of lat. 48° N. near the 1,829-m. depth contour was 15 cm./sec., at least three times the speed at the surface.

When Dodimead et al. (1963) showed the California Undercurrent flowing northward below 200 m., the surface water flowed south, opposing the Undercurrent. Because there was no southerly surface flow during the spring and fall of 1963, this apparent reversal did not exist; but if the surface current was the slower, the Undercurrent would be evident as a relative maximum at 200 m. in the velocity profile. The vertical distribution of velocity in the upper 1,500 m. during the fall, seaward from Willapa Bay, Hoh Head, and Esperanza Inlet, showed an area within 165 to 220 km. of the Washington coast in which pronounced maxima in the velocity did occur between depths of 200 m. and 300 m. (fig. 6). The direction of flow in adjacent maxima opposed each other, apparently forming eddies. The resultant current across any line normal to the coast of Washington, although northward, was very small. Volume transport calculations indicate the magnitude of the net flow.

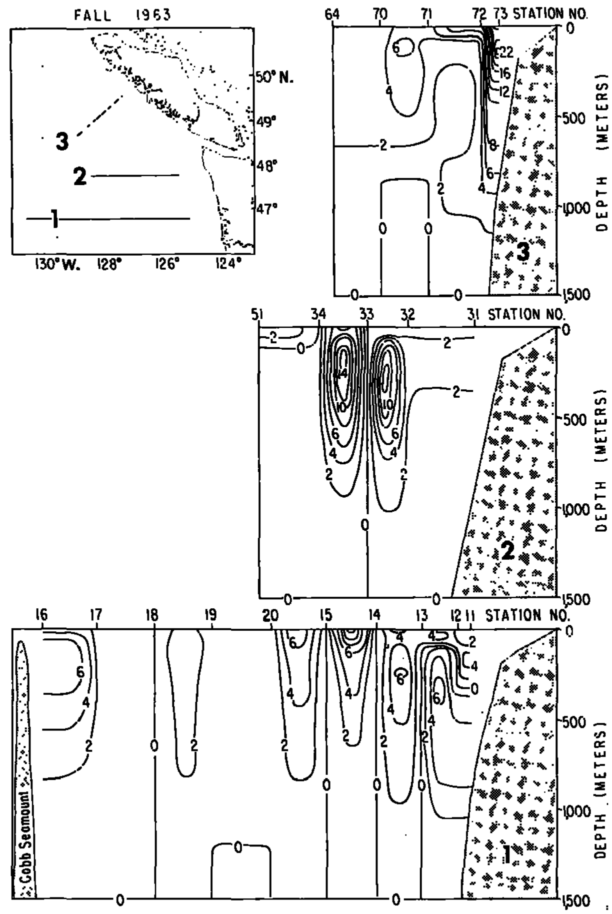

FIGURE 6.—Vertical sections of geostrophic velocity (cm./sec.) relative to 1,500 db. seaward from Willapa Bay, Hoh Head, and Esperanza Inlet, fall 1963. (Light shading indicates regions of northward flow.)

VOLUME TRANSPORT

Volume transports are calculated by integrating the geostrophic currents throughout the water column (Sverdrup et al., 1942). The volume transports indicate the resultant relative flow through the selected cross-sectional area, and are, therefore, a more reliable representation of the net flow in an area than a chart of the geostrophic currents at a particular depth. In the previous section on geostrophic currents, I pointed out that surface Ekman currents which were neglected may be in the same order of magnitude as the surface geostrophic velocities. In terms of the net transport in this coastal area during spring

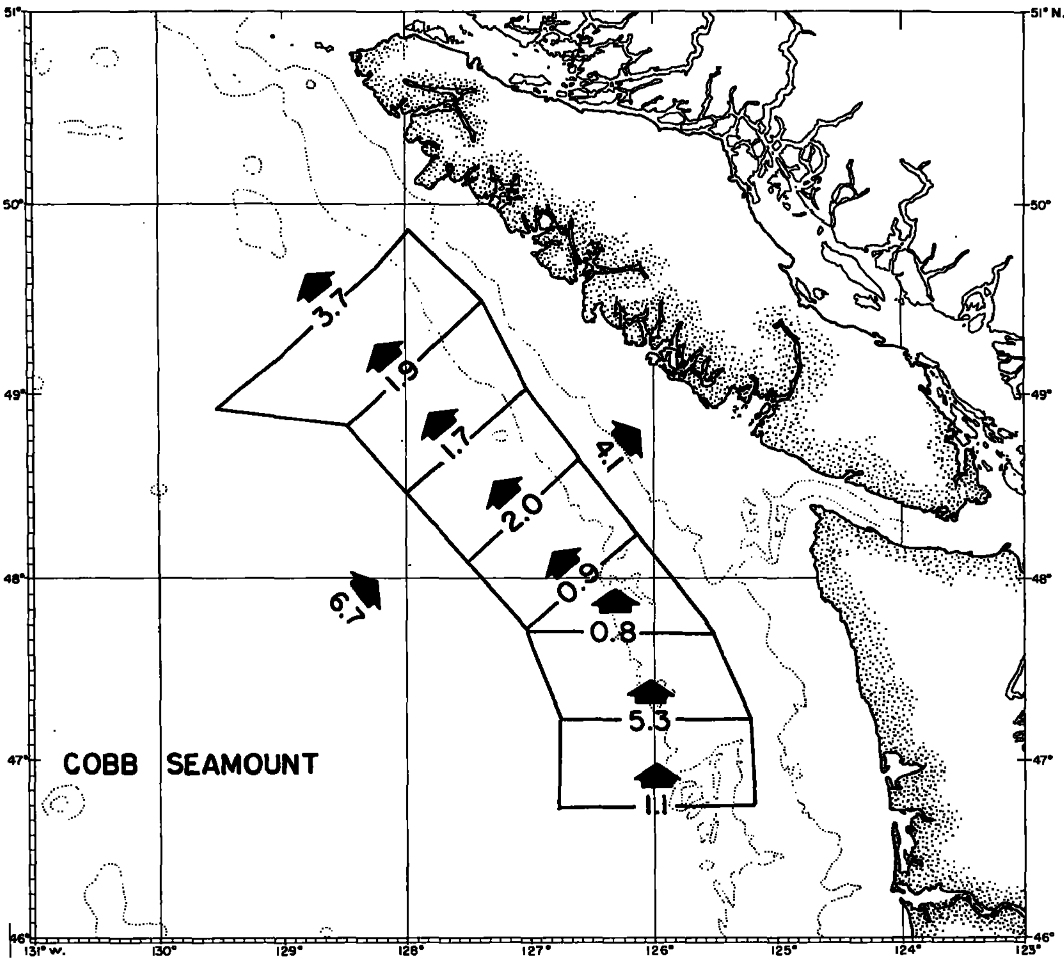

FIGURE 7.—Volume transport in 10^6m.^{3}/sec., 0 to 1,500 m., spring 1963. (The 183- and 1,829-m. depth contours are shown.)

and fall the zonal and meridional components of Ekman Transport computed by Fofonoff and Ross (1961) appear to contribute only 0.01 x 10^6m.^{3}/sec. and thus may be neglected.

During spring the net transport of water across each of the eight lines normal to the coast was directed toward the north and averaged approximately 2 x 10^6m.^{3}/sec. (fig. 7). This estimate appeared to give considerable credence to the existence of both the Davidson Current and California Undercurrent. On the other hand, the large northward flow of 5.3 x 10^6m.^{3}/sec. off the coast of Washington was part of an anticyclonic eddy; only a very weak net transport of less than 1 x 10^6m^3/sec continued northward across lat. 48° N. A relatively large volume 6.7 x 10^6m.^{3}/sec. entered the area from offshore, of which 4.1 x 10^6m.^{3}/sec. apparently flowed onshore across the Continental Slope where calculation of volume transport to 1,500 m. is less meaningful. The net northward transport increased to 3.7 x 10^6 m.^{3}/sec. across the northernmost line and had the same direction and magnitude as that reported by Bennett (1959) during August 1955 for the near-shore area between lat. 50° and 55° N., just north of this study area.

During fall the greatest northward transport again occurred off the northern coast of Vancouver Island; no significant change appeared in the volume of water flowing northward past Cape Cook (fig. 8). Off the Washington coast the net transport was again about 1 x 10^6m.^{3}/sec., but the direction reversed across succes-

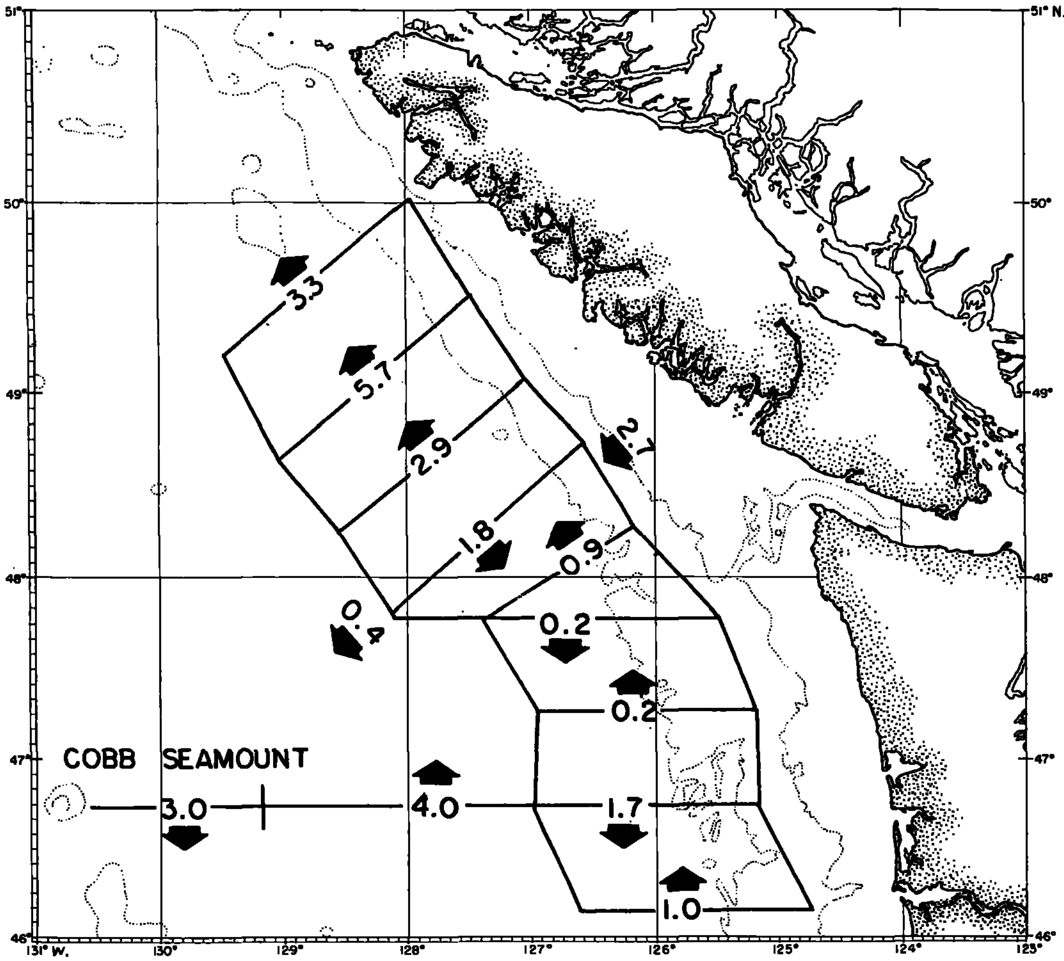

FIGURE 8.—Volume transport in 10^6m.^{3}/sec., 0 to 1,500 db., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

sive lines normal to shore. The onshore movement evident during spring had reversed to 0.4 x 10^6m.^{3}/sec. in the offshore part of the area and 2.7 x 10^6m.^{3}/sec. Seaward across the Continental Slope. The net transport across the line from Willapa Bay to Cobb Seamount was less than 1 x 10^6m.^{3}/sec. Compared with a transport of 14 x 10^6m.^{3}/sec. for the Gulf of Alaska (Bennett, 1959), these results indicate a lack of significant net transport along the coast of Washington within 500 km. of shore.

The surface Davidson Current and the subsurface California Undercurrent reported by previous authors, therefore, did not contribute more than 1 x 10^6m.^{3}/sec. to the net northward transport of water along the coast of Washington. Although the total volume of transport was the same in spring and fall, an increase in the California Undercurrent was implied by the distribution of properties at and below 200 m. south of lat. 48° N.

DISTRIBUTION OF PROPERTIES

Although the most common method of determining oceanic circulation is the calculation of geostrophic currents and transports from observed values of temperature and salinity at standard depths, deductions concerning flow can also be made directly from the observed distributions of these water properties. Reasonable confidence may be placed in the interpretation of the circulation, particularly when the direction of flow suggested from the distribution of properties supports the calculated geostrophic currents. The following items are discussed: features of the distributions of salinity, temperature, and dissolved oxygen; changes in these properties near the bottom along the continental terrace; and water mass movements implied by temperature-salinity relationships.

SALINITY

Throughout most of the Subarctic Region, the salinity structure consists of three distinct permanent zones: (1) an isohaline upper zone, which extends from the surface to about 100 m.; (2) a halocline, in which the salinity increases about 1‰ between 100 and 200 m.; and (3) a lower zone, in which the salinity gradually increases with depth. The mechanism for the maintenance of this structure was discussed by Dodimead et al. (1963).

Perhaps the most striking changes in the distribution of properties within the coastal areas occur in the salinity distribution in the upper zone and are due to the intrusions of fresh-water runoff from coastal rivers. Various authors have attempted to distinguish oceanic and coastal water on the basis of the salinity distribution near the surface. In the North Pacific Ocean, Doe (1955) used the 32.5‰ isohaline as the boundary between offshore and coastal water masses in the upper zone; Dodimead et al. (1963) defined the extent of a coastal domain by the 32.4‰ isohaline; and Budinger et al. (1964) suggested the Columbia River effluent could be traced by salinities less than 32.5‰. Good agreement has thus been reached concerning a definable boundary be-

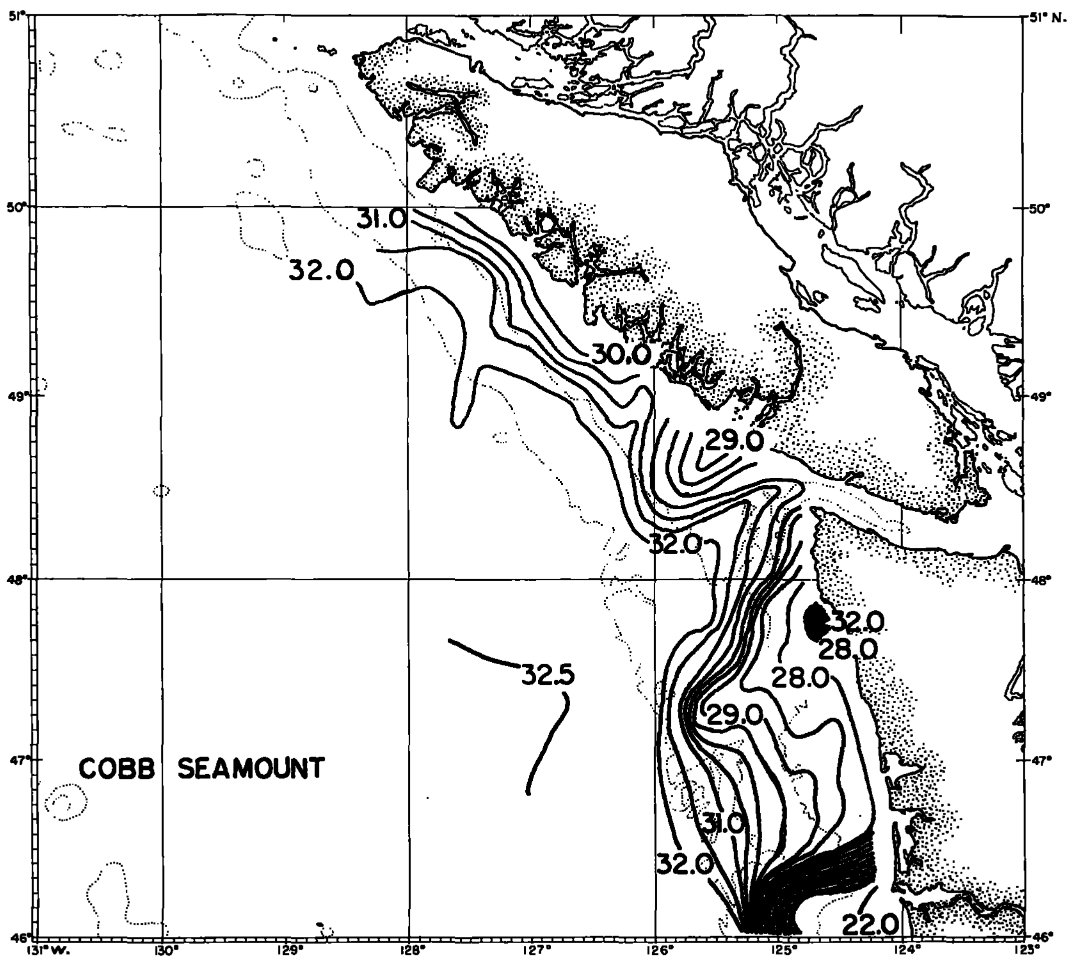

FIGURE 9.—Surface salinity (‰), spring 1963. (The 183- and 1,829-m. depth contours are shown.)

tween oceanic and coastal water, and the effects of dilution have been shown to extend over several hundred kilometers from shore (Favorite, 1961). Sharp gradients, or fronts, found closer to shore, however, are more interesting and much more complex.

The distribution of surface salinity during spring showed that the 32.5‰ isohaline approached within 160 km. of shore off the coast of Washington, but the most significant feature was the front associated with the 32.0‰ isohaline (fig. 9). The controversy regarding the precise definition of the term front in oceanographic usage has been discussed by Griffiths (1965). Front is used here in the sense that Cromwell and Reid (1956) defined the term, ". . . a band along the sea surface across which the density changes abruptly." The change of surface temperature near the front was not appreciable compared with the salinity change; thus the density change at the front was dominated by the relatively sharp decrease in surface salinity. Although no particular isohaline appeared to define the exact extent of the front throughout the area, gross changes in the position of the front may be seen by tracing the extent of the 32.0‰ isohaline. The largest gradient of surface salinity was about 80 km. from shore near lat. 46° N. where the front was apparently being maintained by effluent less was 22‰ from the Columbia River. The maximum seaward extent of the 32.0‰ isohaline was 112 km. near lat. 47° N.; at lat. 48° N. it had decreased to 64 km., and all along the coast of Vancouver Island it was confined to within 48 km. of shore. It is not clear whether the large tongue of dilute water off the central coast of Washington was a remnant of water from the Columbia River which had proceeded north along the coast during the winter or if it came directly from the Strait of Juan de Fuca. A patch of relatively high salinity water (> 32.2‰) about 11 km. seaward of Hoh Head indicated an area of local upwelling.

A vertical section of salinity extending seaward from Willapa Bay illustrates the major changes in salinity with depth and distance from shore during spring (fig. 10). Dilute water of less than 32.0‰ in which the iso-

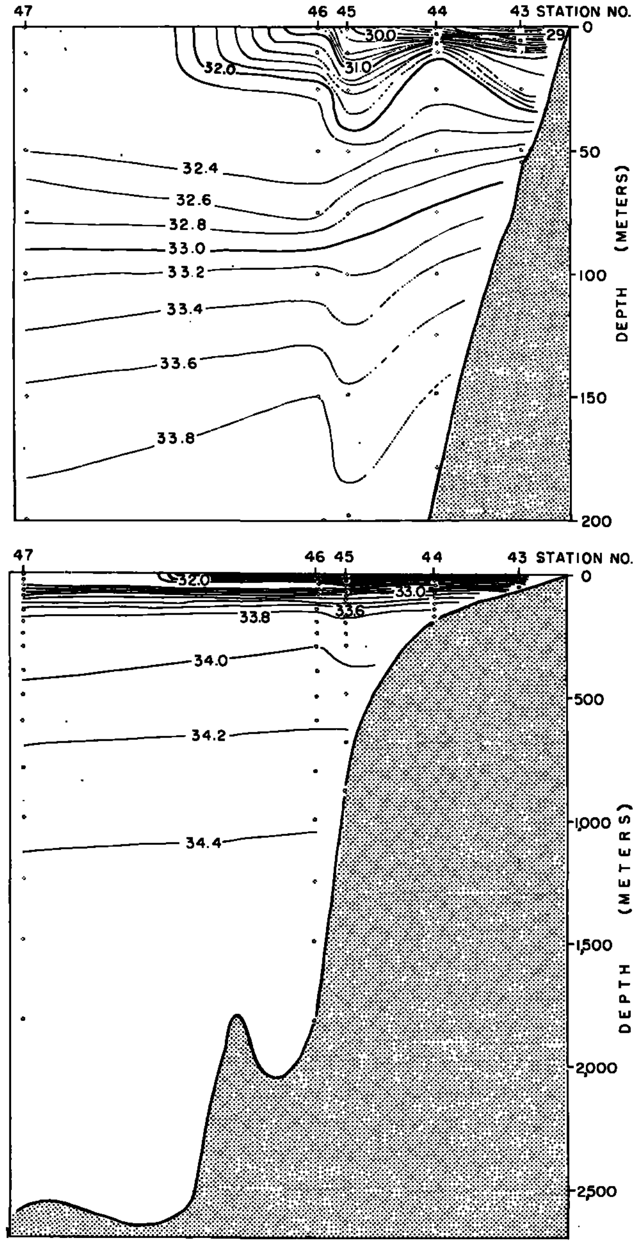

FIGURE 10.—Vertical sections of salinity (‰), 0 to 200 m. and 0 to 2,500 m., along Willapa Bay line, spring 1963.

lines were closely spaced, appeared to protrude seaward in the form of a tongue. Although the 32.0‰ isohaline that occurred at the leading edge of this tongue underwent large fluctuations in its seaward extent along the coast, the nearly constant depth of the 32.0‰ isohaline near shore shows that the major effect of the dilution off the coast of Washington was limited to the upper 30 to 40 m. Offshore, the three vertical zones characteristic of the Subarctic Region were present; although the boundaries between zones generally rose toward shore, the halocline and lower zone could be traced continuously inshore until they ended at the continental terrace.

Tully and Barber (1960) suggested that across the boundary of the halocline-lower zone 33.8 ± 0.1‰, only upward transfer of water existed; thus the depth of this surface forms the ultimate limit of downward transfer of water from the surface. Changes in properties below this surface are, therefore, primarily due to advection, not directly influenced by seasonal changes near the surface. The 33.8‰ surface was about 170 m. deep offshore but rose to about 130 m. near the 183-m. depth contour.

A horizontal section of salinity at 200 m. during spring showed uniform values of salinity just below the halocline; the range was from about 33.86‰ to 33.93‰ (fig. 11) —a marked contrast to the range of surface salinity, 22.0‰ to 32.5‰. A second important feature was the tongue of relatively high salinity (> 33.92‰) which appeared to point northward near the 1,829-m. depth contour off Willapa Bay. Although many of the features in the coastal area during the fall were similar to those during the preceding spring, important changes occurred near the surface between spring and fall. The salinity front was consistently nearer shore, 48 km. to 64 km. (fig. 12). The tongue of dilute water

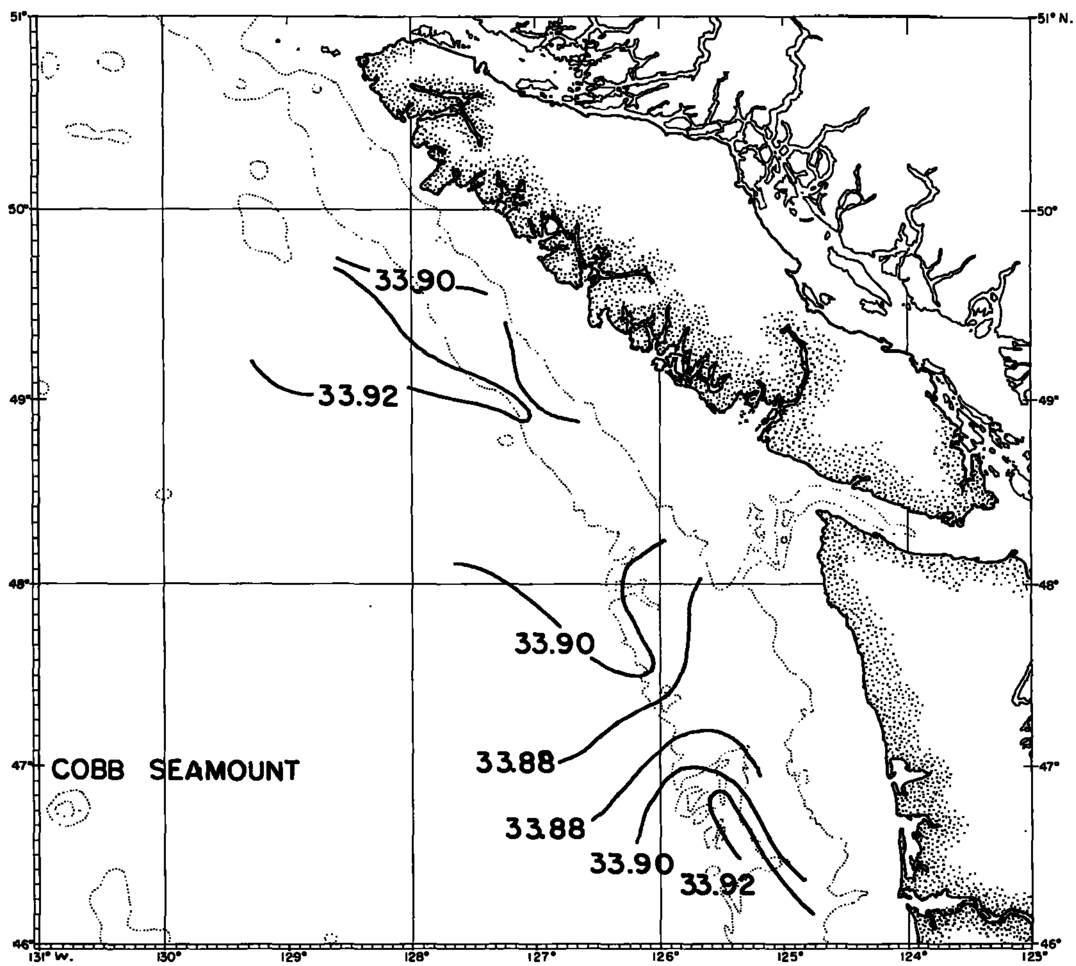

FIGURE 11.—Salinity (‰) at 200 m., spring 1963. (The 183- and 1,829-m. depth contours are shown.)

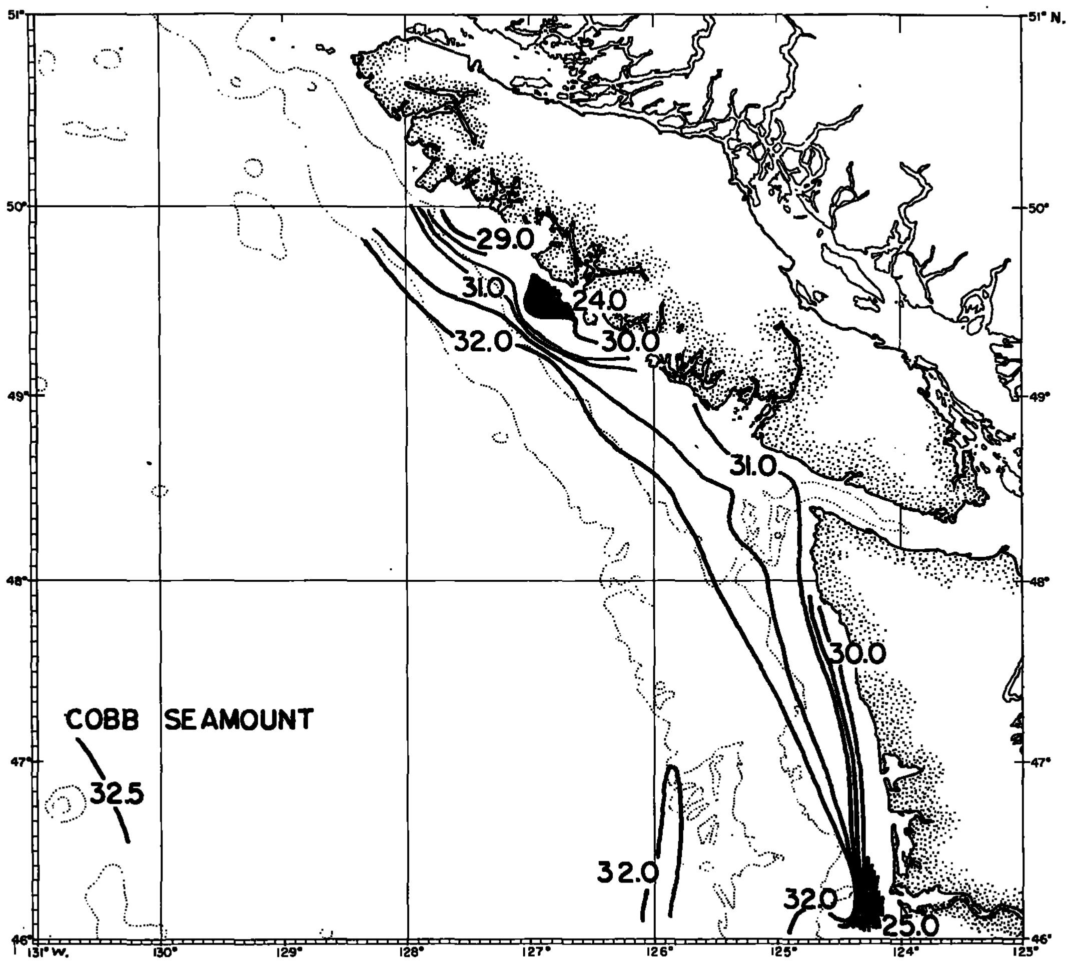

FIGURE 12.–Surface salinity (‰), fall 1963. (The 183- and 1,829-m. depth contours are shown.)

which had protruded twice as far seaward from the coast of Washington during the spring was absent in the fall. The 32.5‰ isohaline had shifted seaward from 160 km. to 400 km. by fall. Although the boundary between the halocline and lower zone fluctuated over a greater depth range during the fall, the major structural zones were again present and continuously defined along each section normal to shore. At 200 m. the maximum salinity increased to 33.96‰ between Willapa Bay and lat. 48° N. (fig. 13). The small tongue of greater salinity present during spring had enlarged to form a continuous ridge of high salinity along the coast with an axis about 140 km. from shore. This feature was more complex north of lat. 48° N. where the salinity decreased.

TEMPERATURE

In the Subarctic Pacific Region the water above the halocline begins to receive a net gain in heat in April and continues to warm into September (Dodimead et al., 1963). During the spring the surface-temperature gradient along the coast was uniform; temperatures from Vancouver Island to the Columbia River increased from 9.0° C. to 13.5° C. (fig. 14). Off the coast of Vancouver Island the surface isotherms were generally oriented northeast-southwest, normal to the shore, and showed no apparent relation to the surface-salinity front. Off the coast of Washington, however, the isotherms generally ran from north to south, parallel to shore. Their configuration agreed closely with the surface isohalines.

Vertical sections of temperature during

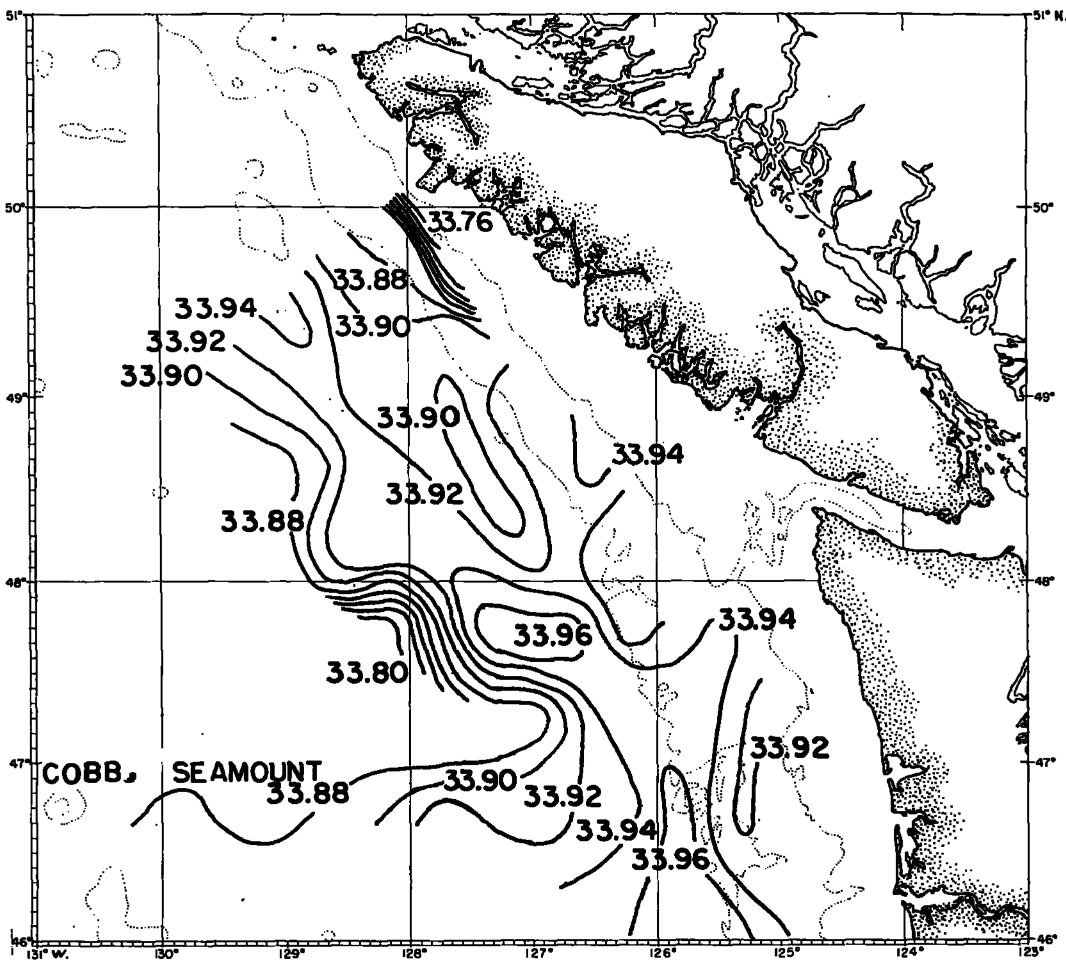

FIGURE 13.—Salinity (‰) at 200 m., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

spring, one seaward from Cape Cook and the other seaward from Willapa Bay, illustrate the changes in temperature with depth and distance from shore as well as difference in temperature along the coast between the northern and southern parts of the area (fig. 15).

Characteristically the decrease of temperature with depth throughout the water column was inconsistent only within the halocline which contained sporadic inversions not in excess of 0.5° C. Below the halocline the temperature decreased logarithmically toward the bottom.

As was true with salinity, the most pronounced changes within the area took place in the upper layers. The dilute water near shore had a weak vertical gradient. Offshore from Cape Cook the upper 50 m. was isothermal, but toward the south, the magnitude of the seasonal thermocline increased between the surface and 30 m. Within the halocline off the Washington coast the isotherms rose toward shore over the Continental Shelf, but beyond the shelf they sloped slightly downward toward shore. The temperature increase from Cape Cook to Willapa Bay extended to a depth of at least 200 m. In the lower zone, the isotherms were relatively level. Although the variations of temperature at a particular depth below the halocline were small, the temperature distribution at 200 m. did show an unusual feature. A tongue of cold water (<6.8° C.) extended shoreward near the middle of Vancouver Island, interrupting a band of warmer water

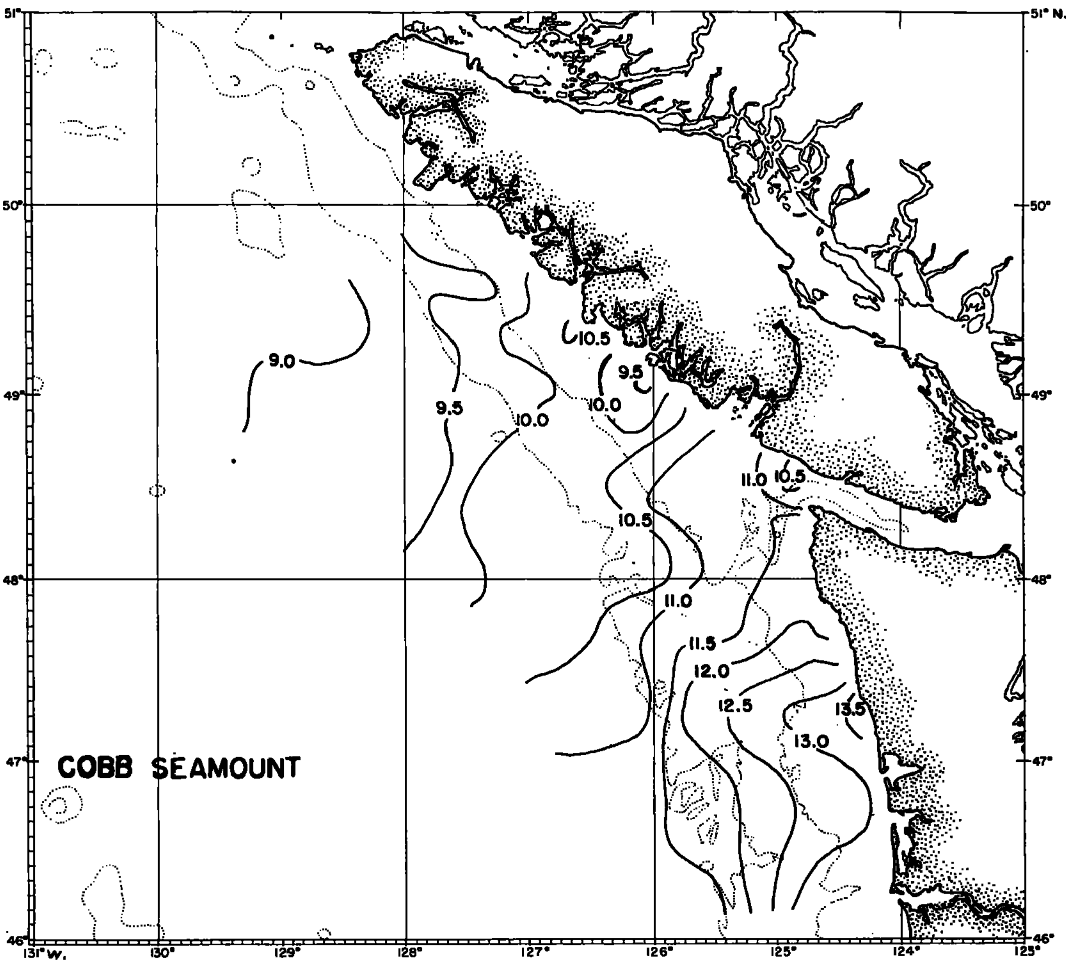

FIGURE 14.—Surface temperature (°C.), spring 1963. (The 183- and 1,829-m. depth contours are shown.)

(>7.2° C.) near the 1,829-m. depth contour (fig. 16).

Differences between temperatures during spring and fall were most pronounced above the halocline, in the zone affected by seasonal heating. Significant changes also occurred, however, within the lower zone which is not influenced directly by the seasonal heating; changes in circulation are implied.

Although the gradient of the surface temperature between northern Vancouver Island and the Columbia River was the same during each season, temperatures were generally 1.0° C. higher at each location during the fall (fig. 17). The most pronounced changes were near shore. During spring, warming was appreciable only near the surface in the dilute water off the coast of Washington, but in the fall the water was distinctly warmer over the entire Continental Shelf than offshore. The resulting temperature distribution shows a tongue of warm water extending northward along the coast and the maximum temperature along any line normal to shore near the edge of the Continental Shelf.

Comparison of fall and spring conditions along the same two vertical sections indicated many differences and similarities with depth and distance from shore. The most pronounced differences were in the upper 70 m. In contrast to the gradual decrease of temperature seaward during spring was the presence of two maxima during the fall—one at the surface near the edge of the Continental Shelf and the

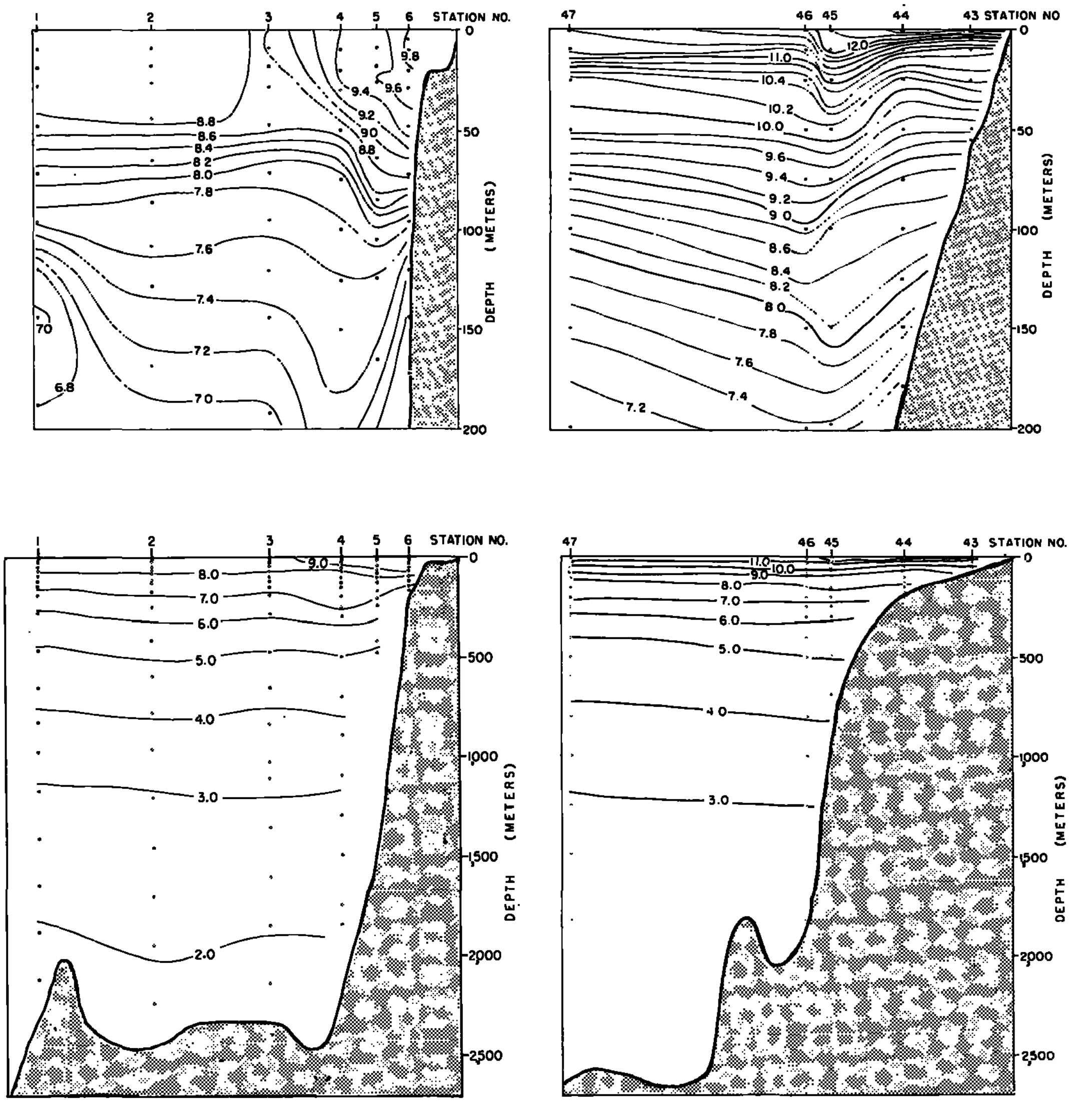

FIGURE 15.—Vertical sections of temperature (°C.), 0 to 200 m. and 0 to 2,500 m., along Cape Cook and Willapa Bay lines, spring 1963.

other at depth between 20 and 50 m. near shore. Apparently both maxima resulted from surface cooling and vertical mixing which had affected only the dilute water in the upper 20 m. Seaward of the salinity front, the upper 50 m. of the water column was isothermal off Cape Cook during both seasons. Southward of Cape Cook the magnitude of the thermocline again increased but by fall had deepened from the range 0 to 30 m. to between 50 and 70 m. in the top of the halocline. Temperature inversions were more frequent in the fall within the halocline, and the near-shore isotherms showed a slight depression or convergence. Vertical sections normal to shore during fall as in the spring showed the logarithmic decrease of temperature with depth and the level isotherms in the lower zone extending seaward from the Continental Slope.

Despite this general uniformity in temperature structure, minor changes did occur in the temperature distribution at 200 m. (fig. 18). The tongue of warmer water (> 7.2° C.) noted during spring changed: it became continuous along the coast, occupied a much larger area, and had a greater maximum temperature dur-

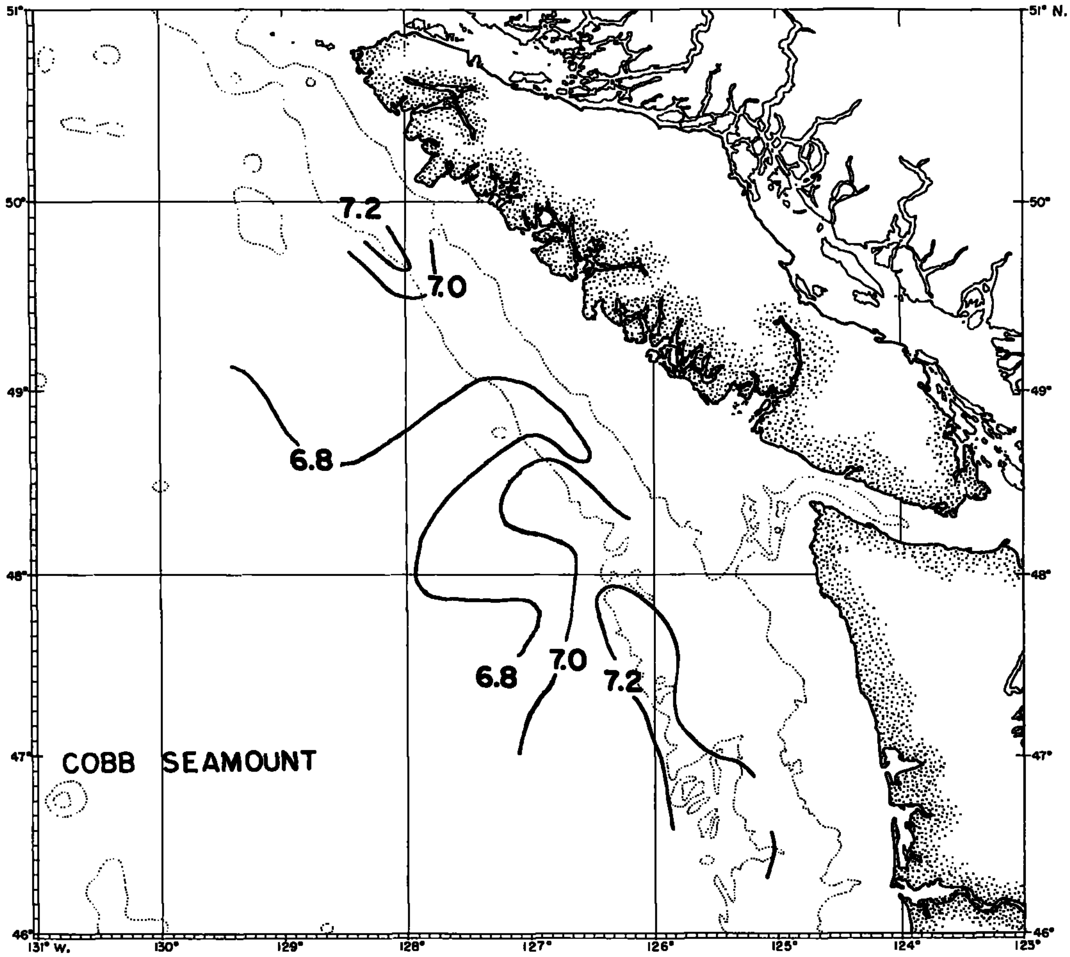

FIGURE 16.—Temperature (°C.) at 200 m., spring 1963. (The 183- and 1,829-m. depth contours are shown.)

ing fall—7.6° C. Although this increase in temperature between spring and fall was slight, it may be significant compared with the small range of values at 200 m. The association of the warm water near the coast of northern Vancouver Island with the lowest salinity values implied a local convergence. Offshore the cold water was also of low salinity. The warm water off the coast of Washington near the 1,829-m. depth contour, however, was associated with the high-salinity ridge; a significant change in water mass is indicated.

DISSOLVED OXYGEN

The distribution of dissolved oxygen during the spring was obtained only over the continental terrace between the depths of 55 m. and 1,829 m. As with the distributions of temperature and salinity, the sharpest vertical gradient occurred within the halocline. Below the saturated or mixed layer, about 50 m. deep, values decreased sharply to about 300 m. Below 300 m., concentrations decreased gradually to a minimum near 900 m., below which values gradually increased toward the bottom.

Samples obtained at each station during the fall permit comparison of conditions near shore and offshore. The vertical section off Willapa Bay shows the complex distribution of dissolved oxygen in the upper 300 m. (fig. 19). Deeper isolines were relatively level and the oxygen minimum near 900 m. extended offshore without significant change in depth. The isolines within the upper 300 m. usually fol-

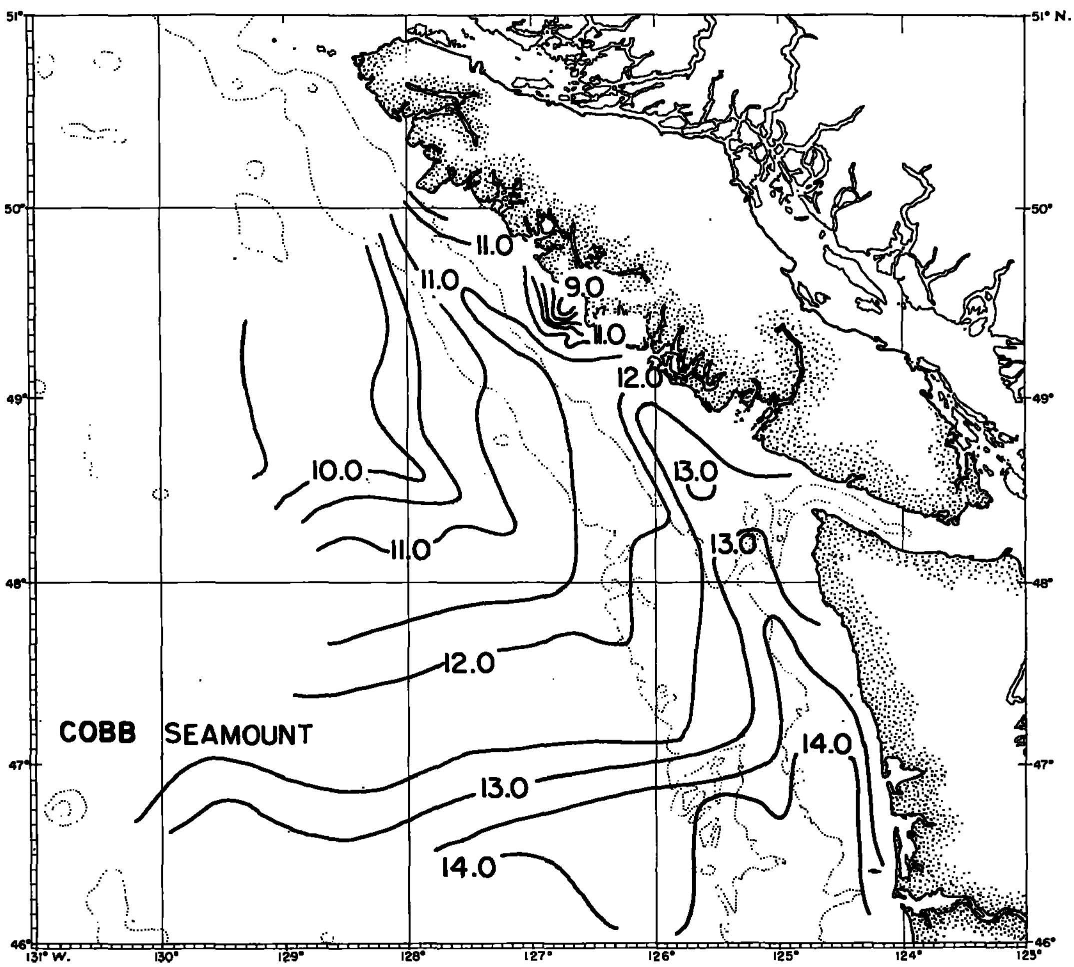

FIGURE 17.—Surface temperature (°C.), fall 1963. (The 183- and 1,829-m. depth contours are shown.)

lowed the configuration of the isohalines or isotherms, but were inclined generally upward toward shore. The rise reflected lower oxygen values near shore during spring and fall; minor inversions of dissolved oxygen were more frequent during fall, just below the bottom of the halocline near 200 m. A plot of dissolved oxygen at 200 m. during the fall (fig. 20) showed that this band of low oxygen concentration (< .20 mg. at./l.) was continuous along the entire coast over the Continental Slope and closely followed the high-salinity ridge (fig. 13).

Comparison of fall conditions with those over the Continental Slope during the preceding spring indicated that oxygen values at 200 m. had decreased on the average, by about 0.05 mg.at./l. If we assume that the seasonal change in biological utilization of dissolved oxygen was negligible, this decrease in dissolved oxygen concentration corroborates the change in water-mass characteristics between spring and fall previously indicated by the increase in temperature and salinity at 200 m. off the coast of Washington.

CONDITIONS NEAR THE BOTTOM

To determine changes in salinity, temperature, and dissolved-oxygen concentrations at a particular depth close to the sea floor along the continental terrace, samples were obtained as near the bottom as feasible—55 m., 183 m., 914 m., and 1,829 m. along each of the nine lines normal to shore. At the 55-m. and 183-m. sta-

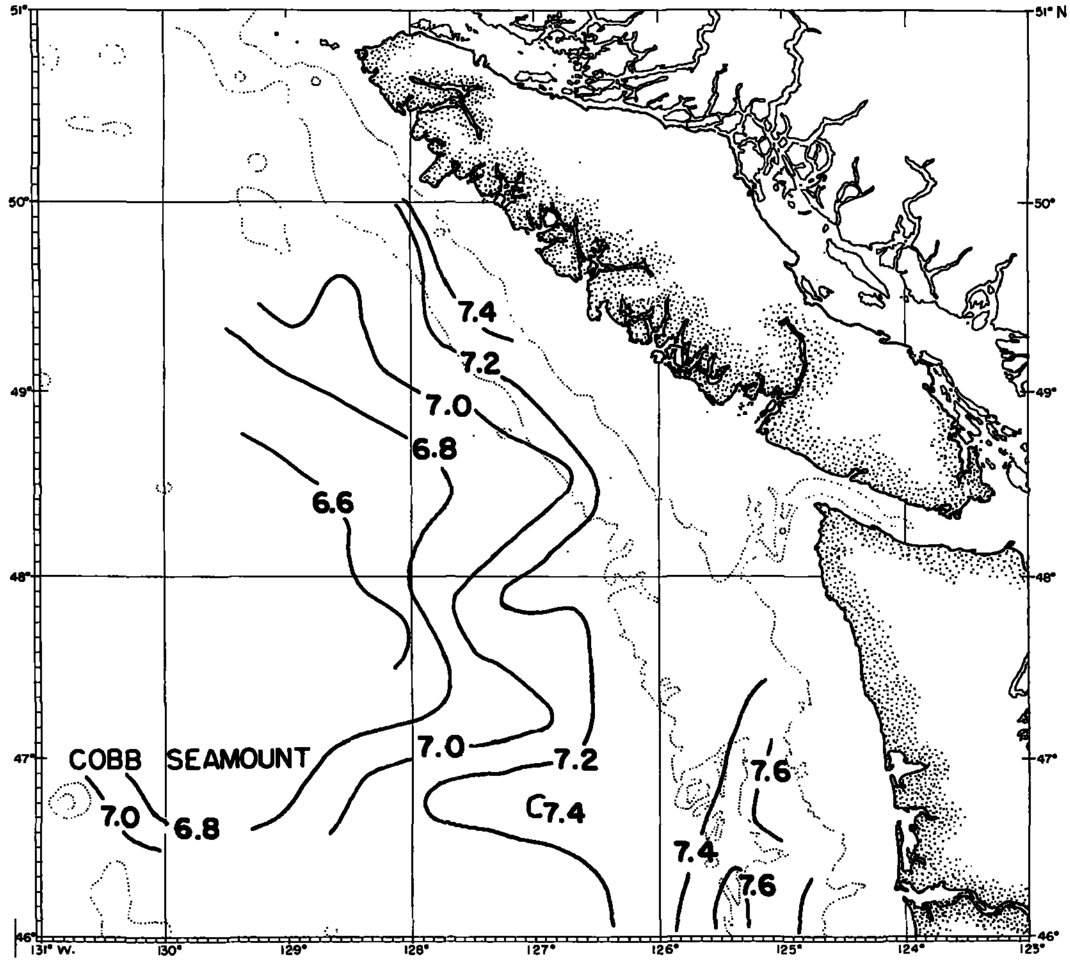

FIGURE 18.—Temperature (°C.), at 200 m., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

tions, Nansen bottles were tripped 5 m. from the bottom by two methods. In the first method, the Nansen bottle is placed 5 m. above a weight suspended on the end of the wire, and the bottle is tripped by a messenger when a change in wire tension indicates the weight is striking the bottom. In the second method, a Nansen bottle attached to a tripping mechanism is reversed when a weight suspended 5 m. below the device strikes the bottom. Although agreement of results from both methods was good, values obtained by the first method were used for most stations. Because of the limited depth range of the vessel's echo sounder (about 550 m.) and the inability to detect the bottom by wire tension at great depths, the locations of the 914-m. and 1,829-m. stations were determined from charted depths; thus, the interval between the deepest bottle and the bottom depended upon the accuracy of the charted soundings and the vessel's position.

The spring values of salinity and temperature near the bottom varied most at shallow depths along the Continental Shelf and were uniform along the Continental Slope (fig. 21). At 55 m. salinity values were uniform between 31.9‰ and 32.0‰ north of the Strait of Juan de Fuca, but increased off Washington. The maximum of 33.4‰ was near the mouth of the Columbia River. The range of temperature values at 55 m. was about 1.0° C. The minimum value occurred off the Columbia River. The maximum salinity and minimum temperature indicated that water which is

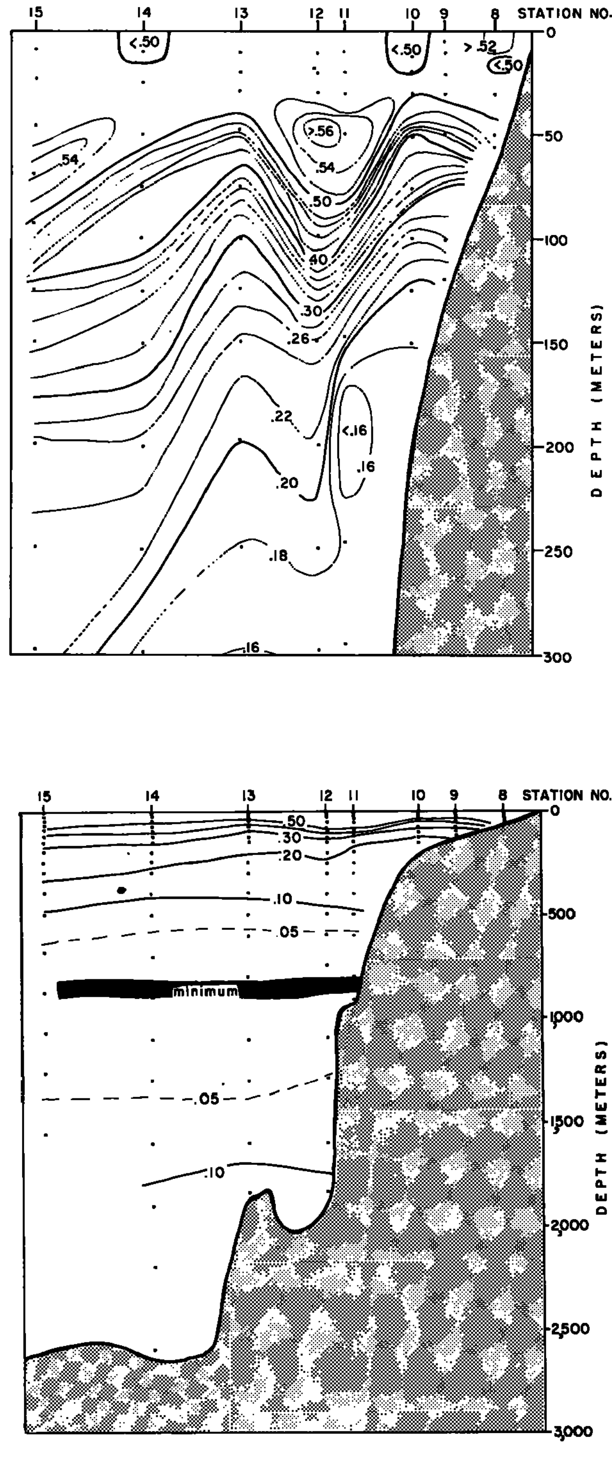

FIGURE 19.—Vertical sections of dissolved oxygen (mg.at./l.), 0 to 300 m. and 0 to 3,000 m., along Willapa Bay line, fall 1963.

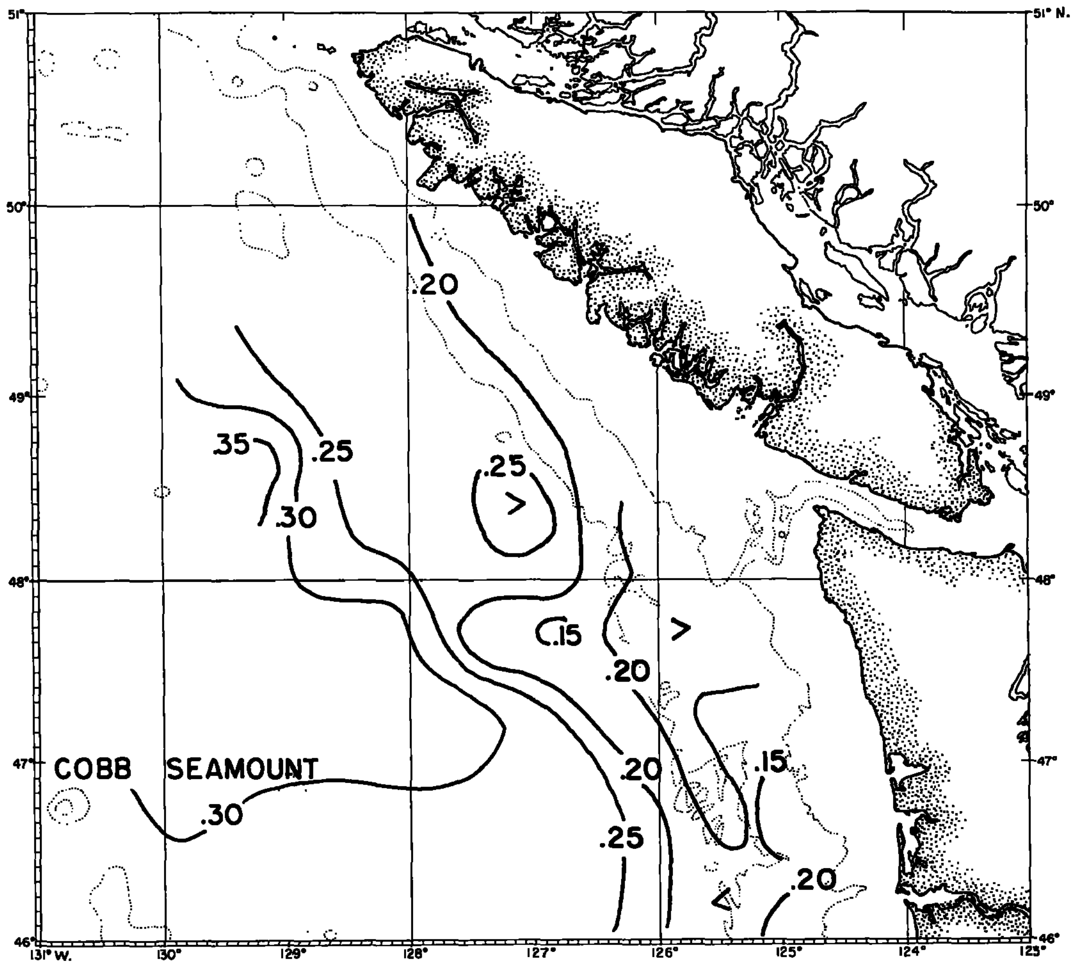

FIGURE 20—Dissolved oxygen (mg.at./l.) at 200 m., fall 1963. (The 183- and 1,829-m. depth contours are shown.)

normally found at a greater depth had moved shoreward in this area. Conditions near the bottom were reversed from those at the surface where the salinity was at a minimum and the temperature was at a maximum. At 183 m. the range of salinity was much smaller—between 33.67‰ and 33.95‰ — but the range of temperature at 183 and 55 m. was the same, 1.0° C. The salinity did not vary significantly along the coast and temperatures increased only slightly toward the south—about 0.1° C. Upwelling, therefore, was not taking place at 183 m. The range of values continued to decrease with depth. Changes in salinity ranged from 0.08‰ at 914 m. to 0.07‰ at 1,829 m., and differences in temperature ranged from 0.15° C. at 914 m. to 0.10° C. at 1,829 m. These minor variations indicated no significant change in salinity or temperature near the bottom along the Continental Slope during spring between the Columbia River and Cape Cook.

Values of dissolved oxygen near the bottom at 55 m. during spring were lowest off the mouth of the Columbia River (fig. 22). This situation appeared to corroborate the upwelling of deeper water, although biological utilization may have contributed to the low values. Oxygen, like salinity and temperature, followed no significant trend at a particular depth along the Continental Slope.

At 55 m., values of salinity, temperature, and dissolved oxygen in the fall were significantly different from those during spring.

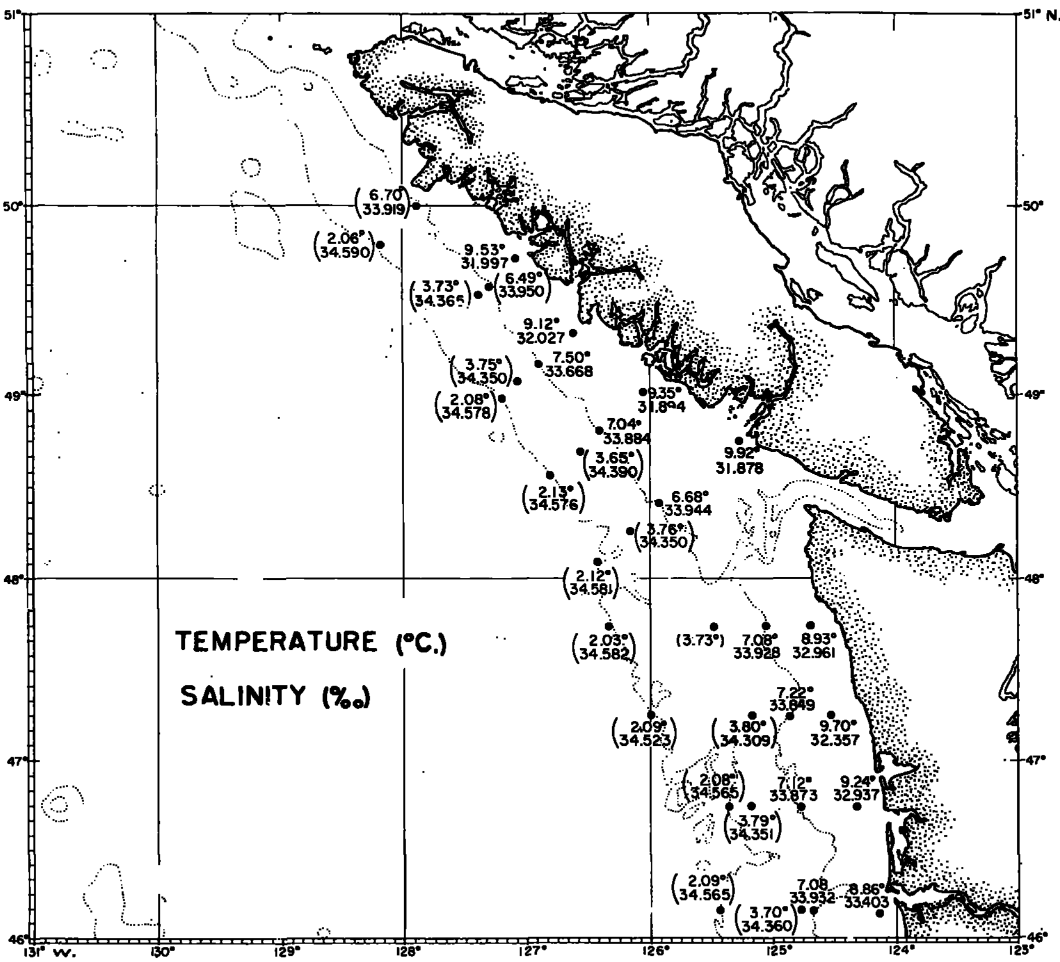

FIGURE 21.—Temperature (°C.) and salinity (‰) near the bottom at 55, 183, 914, and 1,829 m. along the continental terrace, spring 1963. (The 183- and 1,829-m. depth contours are shown, and the values in parentheses are interpolated.)

Thus, more uniformity of salinity values — range from 31.6‰ to 32.3‰ — indicated absence of upwelling. By fall, temperatures at 55 m. had increased 3° C. off Vancouver Island, and 4° to 6° C. off the Washington coast. The increase was about 0.6° C. even at 183 m.

DISTRIBUTION OF WATER MASS BELOW 200 METERS

Analysis of distribution of temperature, salinity, and dissolved oxygen indicated significant changes in characteristics of water mass in near-shore areas and also between seasons. Water masses of different character conventionally have been defined by the temperature vs. salinity (T-S) curve plotted from serial oceanographic data (Sverdrup et al., 1942). All T-S curves from spring data were grossly similar; each had a characteristic s-shape and occupied a narrow envelope. The T-S curves of stations farthest offshore were consistently displaced downward toward the left, however. Waters here were colder and less saline than near the coast. The T-S curves from 10 stations within 500 km. of shore along the Willapa Bay-Cobb Seamount line during fall illustrate this displacement (fig. 23). The heavy curves on the lower and right-hand sides are general curves that represent the extreme water masses in the North Pacific Ocean—the Subarctic and Equatorial Pacific Water Masses; they indicate that the coastal water is a mixture of two water masses. The separation

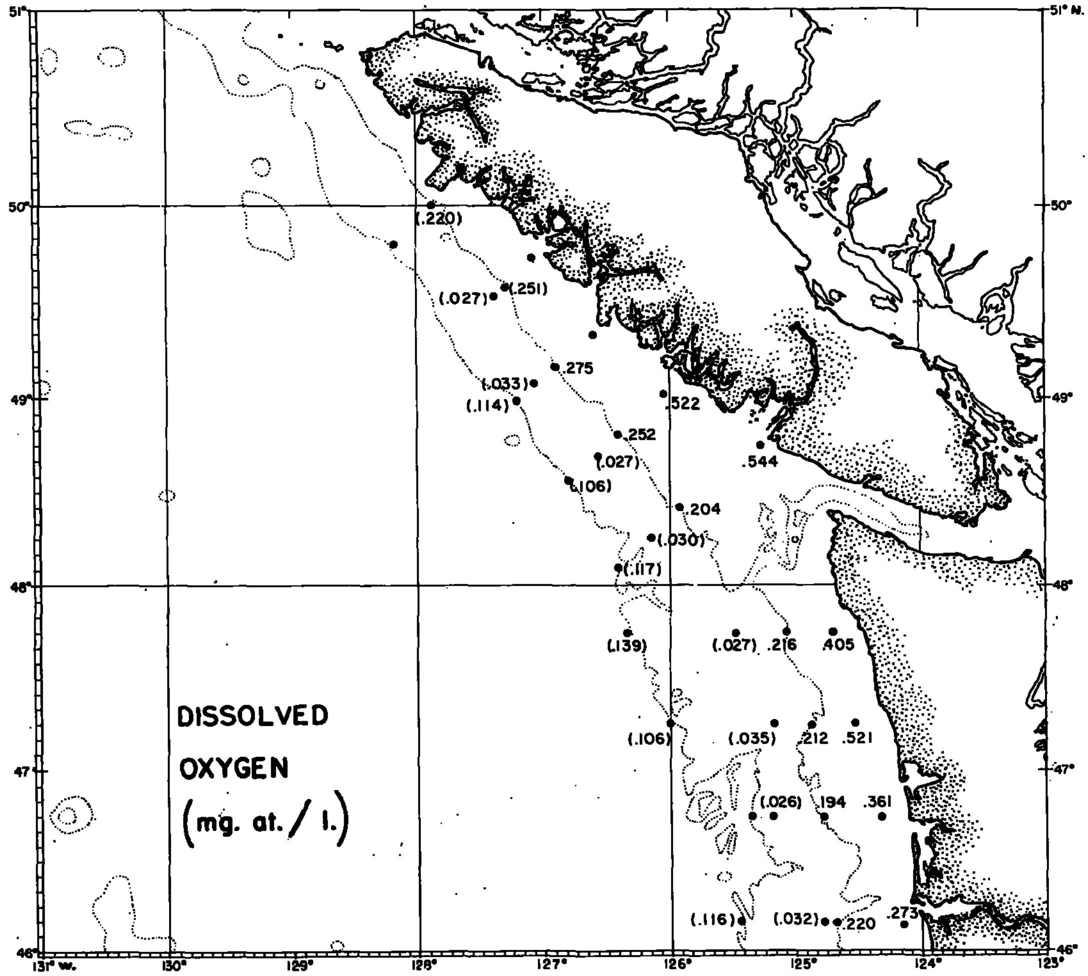

FIGURE 22.—Dissolved oxygen (mg.at./l.) near the bottom at 55, 183, 914, and 1,829 m. along the continental terrace, spring 1963. (The 183- and 1,829-m. depth contours are shown, and values in parentheses are interpolated.)

between the offshore water mass that intrudes from the west and the coastal water mass that intrudes from the south was not distinct at all depths. Near 200 m. three distinct groups of curves existed. Stations 11 to 13 near shore had the most southern characteristics; stations 16 to 19 offshore had the most northern characteristics; and stations 14, 15, and 20 in the center were intermediate between the coastal and offshore water masses. Below 400 m. the boundary between the coastal and offshore water masses was distinct and lay between stations 14 and 15, about 165 to 220 km. from shore.

The study of horizontal changes in the characteristics of water masses throughout the coastal area showed that the differences in temperature were greatest on the salinity surface 34.0‰. Dodimead et al. (1963) suggested that temperatures greater than 6.0° C. on this surface defined the extent of the California Undercurrent Domain which appeared to originate south of lat. 35° N. Their geostrophic calculations, however, indicated only a weak northward flow below 200 m. during 4 of the 5 summers in 1955-59. The temperature distribution on the 34.0‰ salinity surface during spring and fall of 1963 showed the isolines were predominantly parallel to shore although a tongue of warm water apparently entered the area over the Continental Slope from the south. The boundary between the coastal and offshore water masses was marked by a temperature gradient on the seaward side

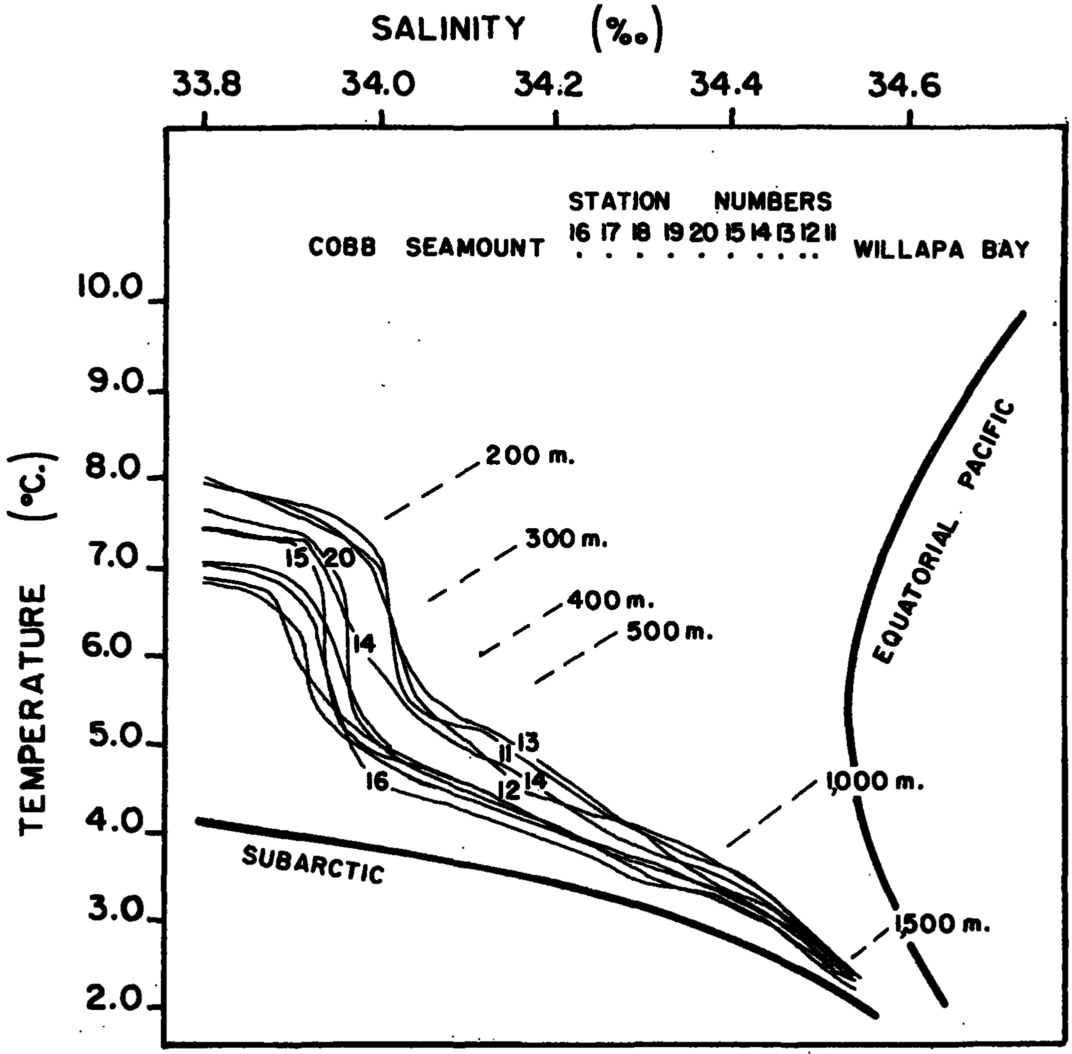

FIGURE 23.—Temperature vs. salinity curves for water of salinity greater than 33.8‰ between Willapa Bay and Cobb Seamount, fall 1963.

of the tongue. During spring the 6.0° C. isotherm was discontinuous off southern Vancouver Island (fig. 24) where the geostrophic currents indicated onshore movement (fig. 4). The distribution of temperature greater than 6.0° C. showed a band of more southern water about 40 km. wide seaward of the Continental Shelf.

The configuration of the isotherms on 34.0‰ surface was generally similar to the geostrophic currents at 200 m., and the southern water mass was located to the right (if one faces downstream), even when the current was southbound.

The greater area encompassed by the southern water (> 6.0° C.) off the coast of Washington during the fall suggests that the northward flow was greater during fall (fig. 25), but the increased flow was not reflected in the net volume transport.

A more quantitative approach to the description of the distribution of water masses along the Pacific Coast of the United States was made by Tibby (1941) who applied the method of Sverdrup and Fleming (1941) to data obtained by the *E. W. Scripps* in 1939.

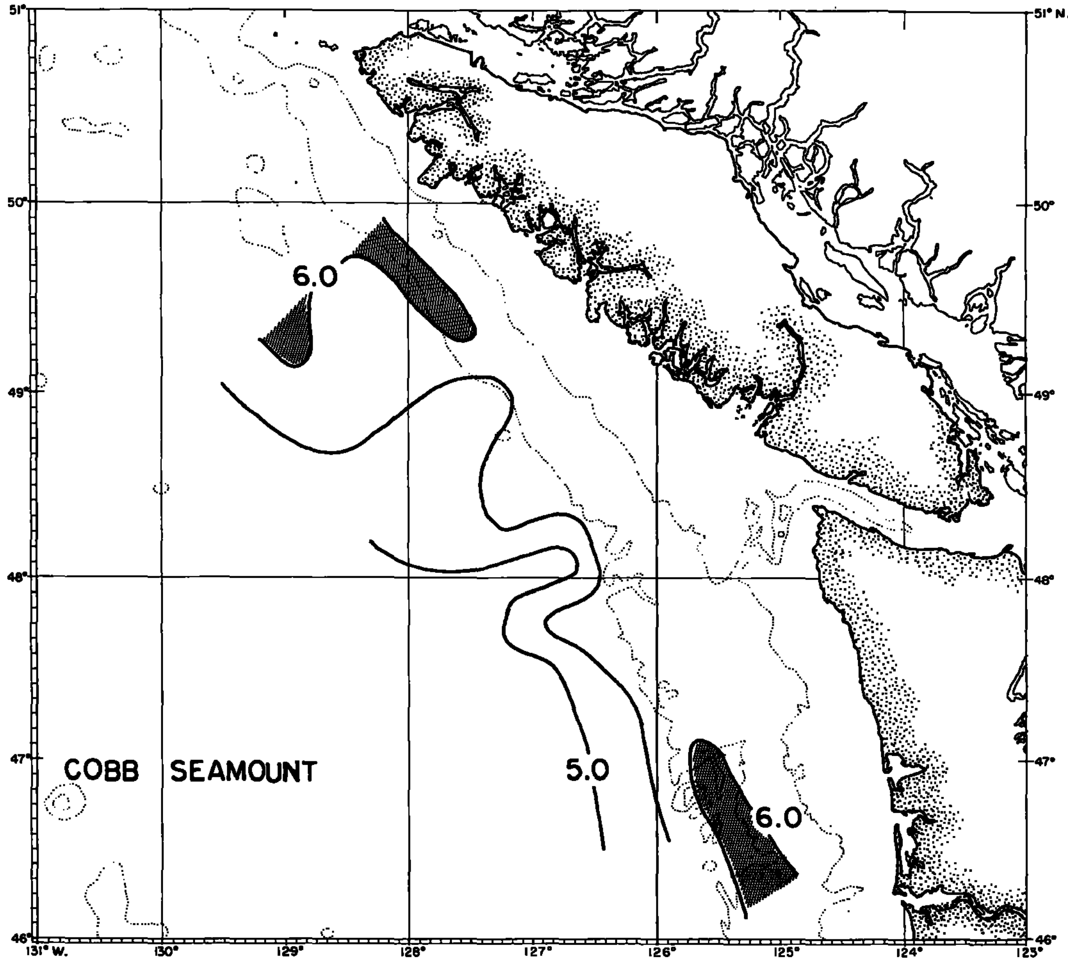

FIGURE 24.—Temperature (°C.) on salinity surface 34.0‰, spring 1963. Shaded portion is above 6.0° C. (The 183- and 1,829-m. depth contours are shown.)

He showed a relatively higher percentage of Equatorial Pacific Water to be present along the Pacific Coast near shore from lat. 25° N. to lat. 45° N. All vertical sections normal to shore showed a greater percentage of southern water toward the bottom and toward shore. The low percentages of southern water in the northernmost sections (between 20 and 40 percent) suggested increased mixing with Subarctic Water to the north.

The percentage of Equatorial Pacific Water off the Washington coast along lat. 46°45′ N. during the fall of 1963 agreed closely with Tibby's results (fig. 26). Because this location is 222 km. farther north than Tibby's most northern line, however, a slightly lower percentage was found. Percentages were not only relatively high near the bottom and near shore, but the high percentages between 200 m. and 400 m. immediately below the halocline extended offshore as far as 500 km. This situation resulted in a pronounced minimum, from 10 to 20 percent, between 600 and 900 m. Values increased sharply within 220 km. of shore. The depth of this minimum percentage of Equatorial Pacific Water coincided surprisingly well with the depth of the oxygen minimum. This determination of distribution of water masses suggests a change in circulation with depth; between 400 m. and 1,000 m., Subarctic Water may move onshore from the west; whereas, between 200 m. and 400 m. and between 1,000 m. and 1,300 m., southern water may move northward along the coast.

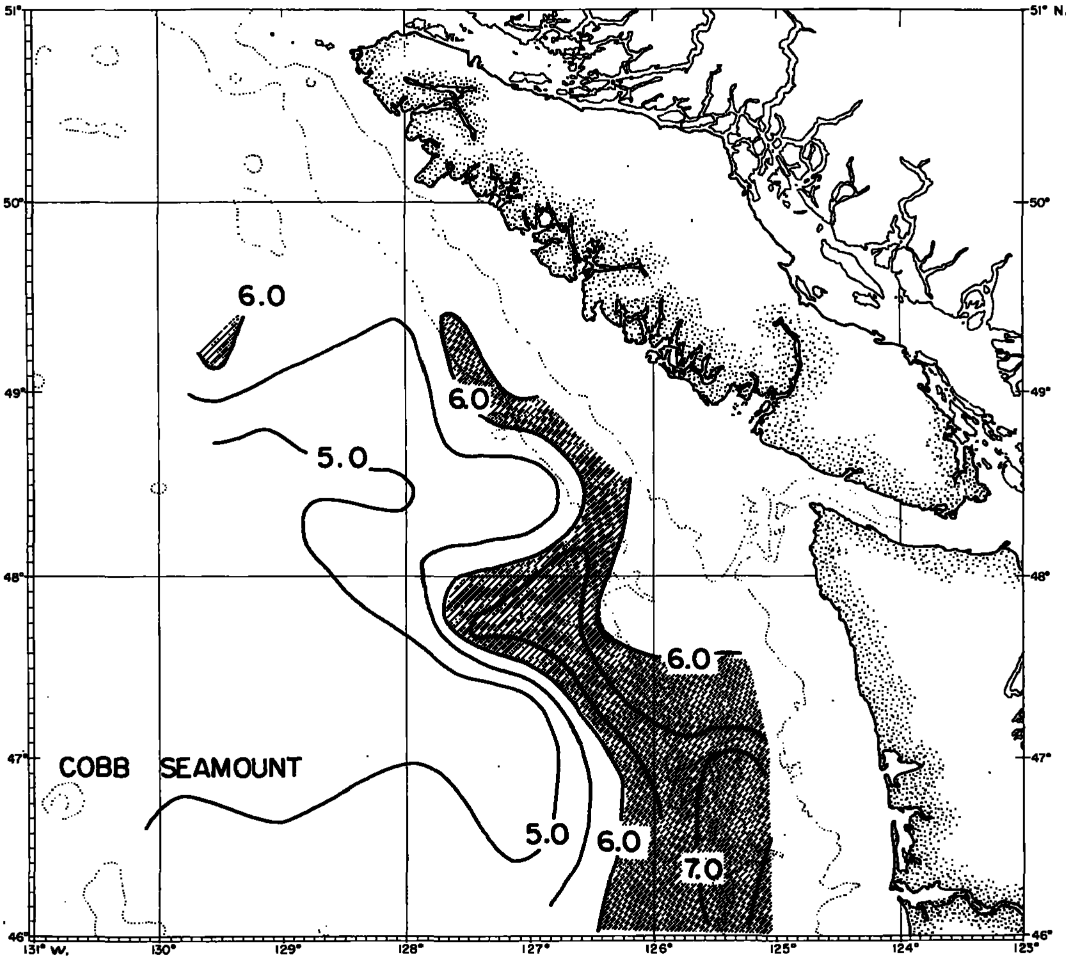

FIGURE 25.—Temperature (°C.) on salinity surface 34.0‰, fall 1963. Shaded portion is above 6.0° C. (The 183- and 1,829-m. depth contours are shown.)

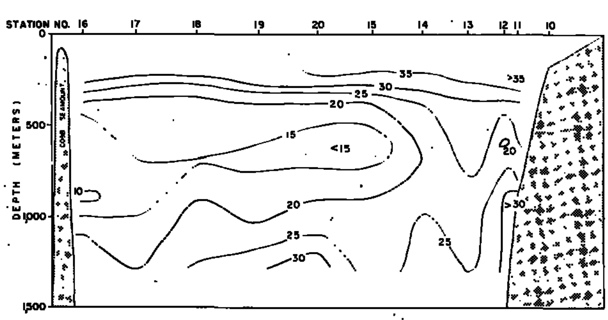

FIGURE 26.—Vertical section of the percentage of Equatorial Pacific Water for water greater than 33.8‰ between Willapa Bay and Cobb Seamount, fall 1963.

SIGNIFICANT OCEANOGRAPHIC FEATURES OF COASTAL WATER

Data obtained during the spring and fall 1963 at closely spaced stations along nine lines normal to shore between the Columbia River and Cape Cook, Vancouver Island, have permitted a description of the significant oceanographic features in the spring within 220 km. of the Vancouver Island and Washington coasts and changes that occurred by the succeeding fall.

Surface geostrophic currents, 0/1,500 db., were similar during both spring and fall. Offshore water flowed northeasterly toward the middle of Vancouver Island and then turned toward the northwest generally parallel to the coast. Eddies off the coast of Washington were such that the northward flow over the Continental Slope, perhaps the Davidson Current, did not appear to continue north of lat. 48° N.

Geostrophic currents, 200/1,500 db., followed the same direction as the surface currents, and showed maxima of subsurface velocity in the eddies off the Washington coast.

The net volume transport, based on a 1,500 db. reference level, was 3 x 10^6m.^{3}/sec. northward past Cape Cook during both spring and fall. A shoreward component of total transport 6.7 x 10^6m.^{3}/sec., was present in the spring, but by fall the transport had reversed to the seaward at 0.4 x 10^6m.^{3}/sec. Northward transport of 4 to 5 x 10^6m.^{3}/sec. occurred locally off the coast of Washington, but was associated with strong anticyclonic eddies which had nearly an equivalent southward transport. Although the existence of the California Undercurrent may be implied by the distribution of properties and supported by the direction of the geostrophic currents at 200 m., the Current did not appear to contribute more than 1 x 10^6m.^{3}/sec. to the net northward flow along the coast of Washington.

The most striking and permanent feature of the distribution of properties within the area was the surface salinity front which extended to a maximum distance of 112 km. seaward from the coast of Washington during the spring, but was confined within 64 km. of the coast in the fall. Vertical sections normal to the shore showed that the major structural features of salinity, temperature, and dissolved oxygen were consistent along each of the nine lines. The distribution of properties varied considerably above 200 m. within the main halocline, thermocline, and oxycline. Below 200 m. the range of values of salinity, temperature, and dissolved oxygen at a given depth was comparatively small. The major feature below the halocline was the nearly horizontal isolines of temperature, salinity, and dissolved oxygen along each vertical section. The concentration of dissolved oxygen had a pronounced minimum at about 900 m. throughout the study area. Minor variations at 200 m. in the fall indicated that a ridge of high-salinity water, also associated with high temperature and low dissolved oxygen, was especially well developed along the Continental Slope of Washington.

Samples obtained near the bottom confirmed the absence of any significant change in the salinity, temperature, or dissolved oxygen at a particular depth along the Continental Slope between the Columbia River and Cape Cook. Thus, the only significant variations in water properties occur in the upper 200 m.

The T-S curves indicated that a water mass of high salinity and high temperature was present over the Continental Slope. Off the coast of Washington the boundary between water masses of slightly different characteristics was distinct below 400 m. between 165 and 220 km. from shore. The more southern water mass near shore occupied a greater portion of the coastal area during the fall than in the spring. Although this implied an increase in northward flow at depth, the California Undercurrent, increased flow was not reflected in the net volume transport.

LITERATURE CITED

BENNETT, E. B.
1959. Some oceanographic features of the northeast Pacific Ocean during August 1955. J. Fish. Res. Bd. Can. 16(5): 565–633.

BUDINGER, THOMAS F., LAWRENCE K. COACHMAN, and CLIFFORD A. BARNES.
1964. Columbia River effluent in the northeast Pacific Ocean, 1961, 1962: selected aspects of physical oceanography. Dep. Oceanogr. Univ., Wash., Seattle, Tech. Rep. No. 99, 78 pp.

BURT, WAYNE V., and BRUCE WYATT.
1964. Drift bottle observations of the Davidson Current off Oregon. *In* Studies on Oceanography, Tokyo, Dedicated to Prof. Hidaka: 156–165. Univ. Wash. Press, Seattle, Wash.

CROMWELL, TOWNSEND, and JOSEPH L. REID, JR.
1956. A study of oceanic fronts. Tellus 8(1): 94–101.

DODIMEAD, A. J., F. FAVORITE, and T. HIRANO.
1963. Salmon of the North Pacific Ocean, Part II, Review of the oceanography of the Subarctic Pacific Region. Int. N. Pac. Fish. Comm., Bull. 13, 195 pp.

DOE, L. A. E.
1955. Offshore waters of the Canadian Pacific Coast. J. Fish. Res. Bd. Can. 12(1): 1–34.

FAVORITE, FELIX.
1961. Surface temperature and salinity off the Washington and British Columbia coasts, Au-

gust 1958 and 1959. J. Fish. Res. Bd. Can. 18(3): 311–319.

(in press). The Alaskan Stream. Int. N. Pac. Fish. Comm., Bull.

FOFONOFF, N. P., and C. K. ROSS.
1961. Transport computations for the North Pacific Ocean 1961. Fish. Res. Bd. Can., MS. Rep. Ser. (Oceanogr. and Limnol.), No. 128, 5 pp.

GRIFFITHS, RAYMOND C.
1965. A study of ocean fronts off Cape San Lucas, Lower California. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 499, 54 pp.

INGRAHAM, W. JAMES, JR.
1964. Distribution of physical-chemical properties and tabulations of station data, Washington and British Columbia coasts, May 1963. U.S. Fish Wildl. Serv., Data Rep. 5, 3 microfiches, 88 pp.

REID, J. L., JR.
1961. On the geostrophic flow at the surface of the Pacific Ocean with respect to the 1,000-decibar surface. Tellus 13(4): 489–502.

REID, JOSEPH L., JR., GUNNAR I. RODEN, and JOHN G. WYLLIE.
1958. Studies of the California Current System. Calif. Coop. Oceanic Fish. Invest. Rep., July 1, 1956-January 1, 1958: 28–56.

REID, JOSEPH L., JR., and RICHARD A. SCHWARTZLOSE.
1963. Direct measurements of the Davidson Current off Central California. J. Geophys. Res. 67(6): 2491–2497.

SCHWARTZLOSE, RICHARD A.
1963. Nearshore currents of the western United States and Baja California, as measured by drift bottles. Calif. Coop. Oceanic Fish. Invest. Rep., July 1, 1960 to June 1, 1962: 15–22.

SETTE, OSCAR E.
1947. South Pacific fishery investigations. *In* U.S. Fish. Wildl. Serv., Div. Fish. Biol., Annu. Rep. Fiscal Year 1947, pp. 60–62. Washington, D. C. [Processed.]

SVERDRUP, H. U., and R. H. FLEMING.
1941. The waters off the coast of southern California, March to July, 1937. Scripps Inst. Oceanogr., Bull. 4: 261–378.

SVERDRUP, H. U., MARTIN W. JOHNSON, and RICHARD H. FLEMING.
1942. The oceans, their physics, chemistry, and general biology. Prentice-Hall, Inc., N.Y., 1087 pp.

TIBBY, RICHARD B.
1941. The water masses off the west coast of North America. J. Mar. Res. 4(2): 112–121.

TULLY, J. P., and F. G. BARBER.
1960. An estuarine analogy in the Subarctic Pacific Ocean. J. Fish. Res. Bd. Can. 17(1): 91–112.