CHARACTERISTICS AND DISTRIBUTION OF WATER MASSES OFF THE OREGON COAST

by

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CHARACTERISTICS AND DISTRIBUTION OF
WATER MASSES OFF THE OREGON COAST

The first extensive evaluation of water masses off the Oregon coast was done in 1941 when Richard Tibby studied eighty hydrographic stations off the western coast of North America which had been occupied by the "E. W. Scripps" during 1939. Tibby found that "a series of temperature-salinity curves from stations located at various points from the Gulf of Alaska to Central America show a regular transition in the character of the water masses from north to south and clearly indicate that the water along the entire coast is a mixture of two extreme water masses." (12, p. 112) These specific water masses were identified as Pacific Equatorial Water and Pacific Subarctic Water. (12, p. 112)

Tibby analyzed each hydrographic station for the percentage of Equatorial Water present. This method of separating the water structure at a given station into component parts was introduced by H. U. Sverdrup and R. Fleming who used and described the method in their report on the results of the 1937 "Bluefin" cruises off Southern California. (10, p. 290)

Tibby constructed a total of six vertical sections, two of which lie off the Oregon coast. The two sections off Oregon are shown as Figures 1 and 2. Tibby's figures originally represented the mixture in terms of percentage of Equatorial Water. The reproduced figures

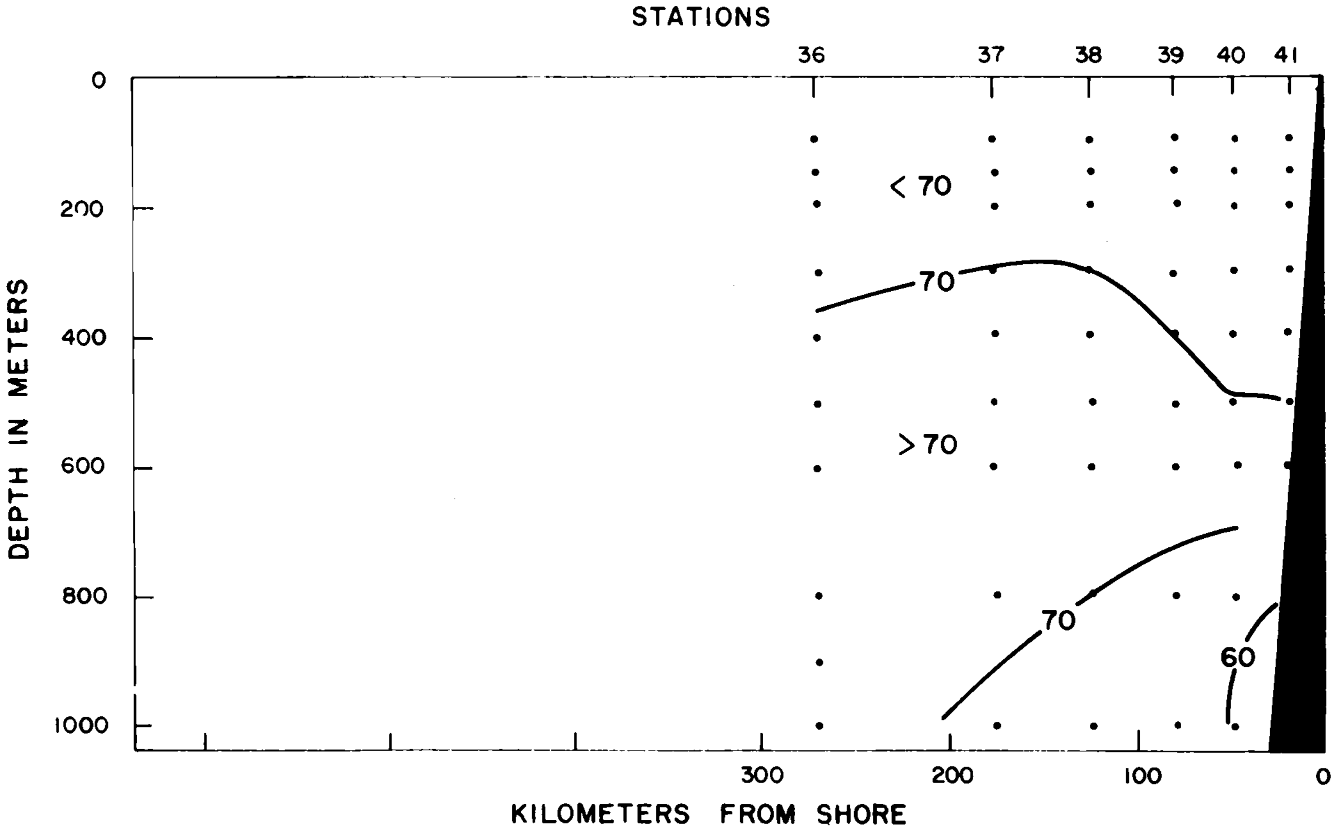

FIGURE 1. Section off Cape Blanco, Oregon, showing percentage of Subarctic Water. (12, p. 119)

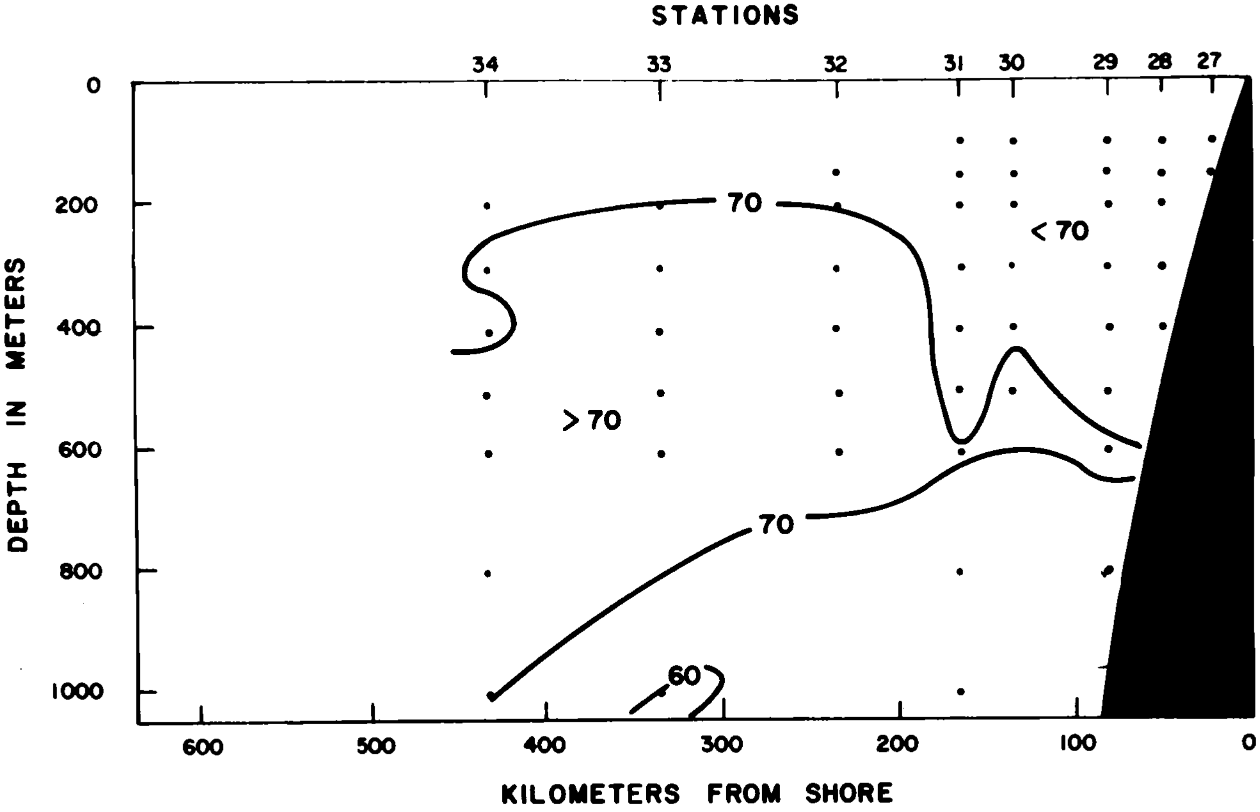

FIGURE 2. Section off Cascade Head, Oregon, showing percentage of Subarctic Water. (12, p. 119)

show the mixture as the percentage of Subarctic Water. Percentage of Equatorial Water equals 100 minus percentage of Subarctic Water.

Substantially more data have become available since 1939, but no comparable or more comprehensive recent work has been done on the water masses in this region. This paper is an expansion and extension of the work done by Tibby, concentrating the analysis on the water off the Oregon coast and including many more deep stations than were available to Tibby. A seasonal analysis showing the changes of the water masses by season is also included.

In 1949 and 1950 the Marine Life Research Program of Scripps Institution of Oceanography included several series of stations off the Oregon coast. The NORPAC data include stations off the coast taken in 1955 by Scripps Institution of Oceanography. Additional individual cruises have been made in Oregon waters. However, even with this increased interest in oceanography, by 1958 there were only about 375 hydrographic stations out to a distance of 500 kilometers off the whole Oregon coast.

Mr. Joseph Reid, in charge of the Marine Life Research Program (hereafter called MLR), has analyzed the MLR data for temperature, salinity, and oxygen distribution but has not carried out any water mass analysis. (7, p. 34-47)

In June, 1958, the Department of Oceanography at Oregon State University initiated a series of regular hydrographic stations off Oregon. However, it was not until June, 1961, with the use of the "R/V Acona," that the hydrographic stations were extended sufficiently, both in depth and in distance from shore, that they could be used in this study.

GENERAL DESCRIPTION OF WATER MASSES, CURRENTS, AND UPWELLING IN THE NORTH PACIFIC OCEAN

The Oregon waters exist as part of the North Pacific circulation system, and the local water masses can only be understood in the context of the water structure in the entire Eastern North Pacific. To understand and describe the water masses and the processes effecting change and variability in the waters off the Oregon coast, it is necessary to first describe the general pattern of water masses, circulation, and structure in the North Pacific.

Water Masses

Sverdrup *et al* have identified five different water masses in the North Pacific. These are the Pacific Equatorial, Eastern North Pacific Central, Western North Pacific Central, Pacific Subarctic, and North Pacific Intermediate. (9, p. 741) The locations of the first four, which are found at the surface, are shown in Figure 3. This classification was made by grouping and analysis of the available temperature-salinity curves for the North Pacific. The following brief summary of distribution and properties is limited to the water masses which effect the area of study.

Subarctic Water. Subarctic Water extends over the entire North Pacific at latitudes north of 45°N. Sverdrup extended this classification to water south of 45°N along the North American coast but for

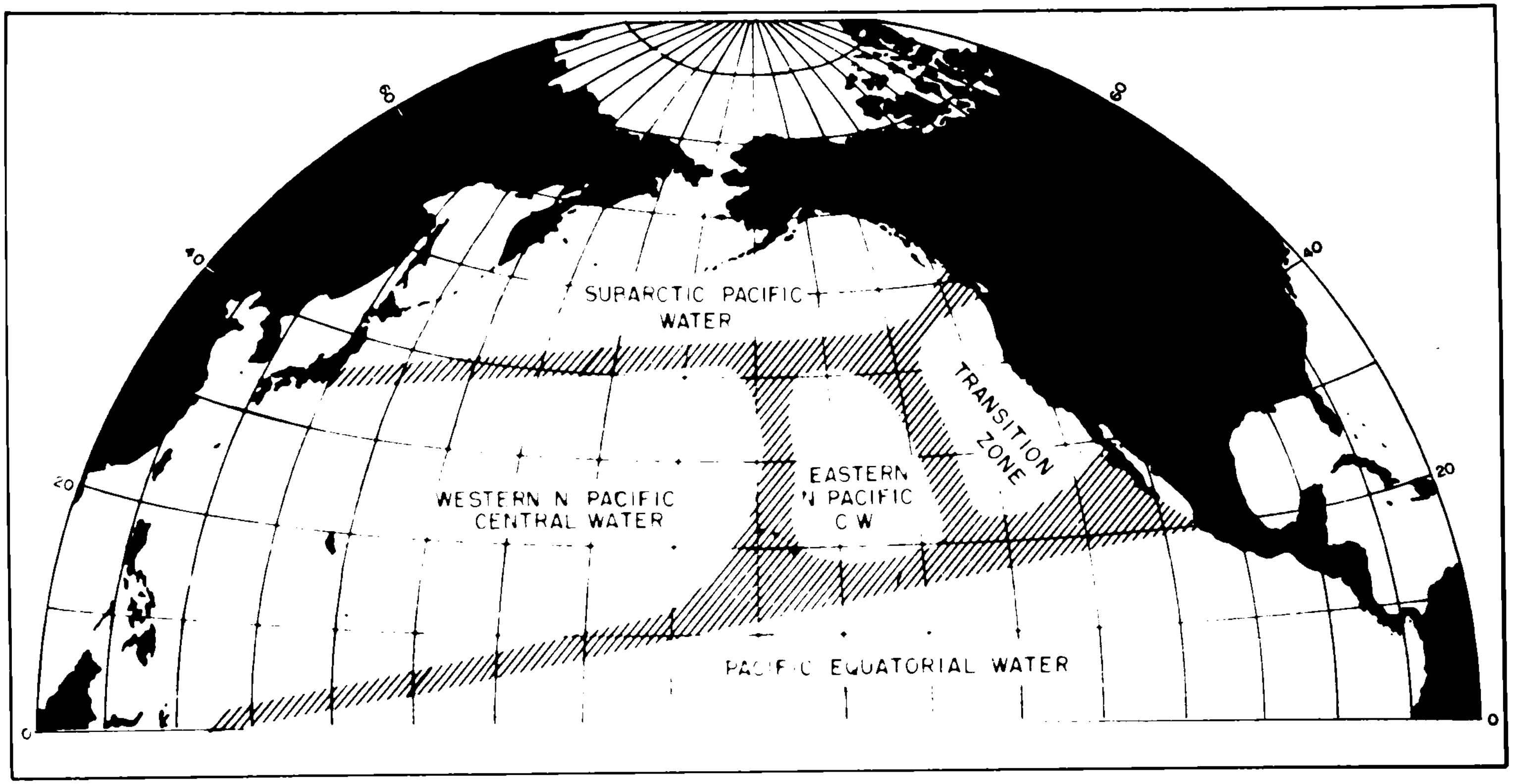

FIGURE 3. Water masses of the North Pacific Ocean.
(adapted from 9, p. 740)

purposes of differentiation in this paper the coastal water will be referred to as the Transition Zone. Subarctic Water is characterized by temperatures between 2° and 4° C and salinities as low as 32 o/oo at the surface increasing to 34 o/oo at 300 meters and then slowly increasing to 34.65 o/oo at the bottom. (9, p. 712) There is no subsurface salinity minimum in the Subarctic Water.

Eastern North Pacific Central Water. Between the Hawaiian Islands and the Transition Zone lies the Eastern North Pacific Central Water. It is characterized by temperatures from 10° to 16° C and salinity values from 34 o/oo to 34.6 o/oo. This water mass is confined to the upper 500 meters of the region, and is above the salinity minimum. (9, p. 714)

Pacific Equatorial Water. Along the American coast between latitudes 18°S and 20°N and extending westward across the Pacific Ocean is the Pacific Equatorial Water with temperatures from 6° to 15° C and salinity values of 34.5 o/oo to 35.2 o/oo. In general this water mass is over 1000 meters thick. (9, p. 706)

North Pacific Intermediate Water. Underlying both the Central and Equatorial Water Masses is the North Pacific Intermediate Water which appears as a salinity minimum layer. Temperatures range from 6° to 10° C and salinity values are around 34.0 o/oo to 34.1 o/oo. The origin of the North Pacific Intermediate Water and the salinity minimum is not clearly understood. Sverdrup considered it formed by the convergence and mixing of the Kuroshio and Oyashio currents. (9, p. 740)

J. Reid has ascribed the formation of the water to vertical mixing in the subarctic gyre. (6, p. 53) In any case the water is formed to the north and flows at depth south under the Central and Equatorial Water Masses. (9, p. 717) No salinity minimum is present in the Transition Zone and therefore North Pacific Intermediate Water cannot be separated from Subarctic Water.

Currents

There are three primary surface current systems which effect the Oregon coastal area: the Gulf of Alaska current system, the California current system, and the Davidson Current. The deep circulation will also modify the coastal water mass. The deep circulation is the only mechanism which can reasonably transport Equatorial Water into this region. The general pattern of surface currents observed in the North Pacific is shown in Figure 4.

Gulf of Alaska Current System. Here, the Gulf of Alaska Current System will be considered as comprising that part of the North Pacific Drift, in the Central North Pacific roughly north of 40°N; that branch of the North Pacific Drift which flows northward into the Gulf of Alaska; and the narrow westward flowing Aleutian Current, just south of the Aleutian Archipelago.

The other branch of the North Pacific Drift turns south forming the California Current. The position of the branching or divergence is thought to vary with season, being at approximately 50°N in the summer and moving southward in winter. (2, p. 9)

California Current System. The California Current, which is the

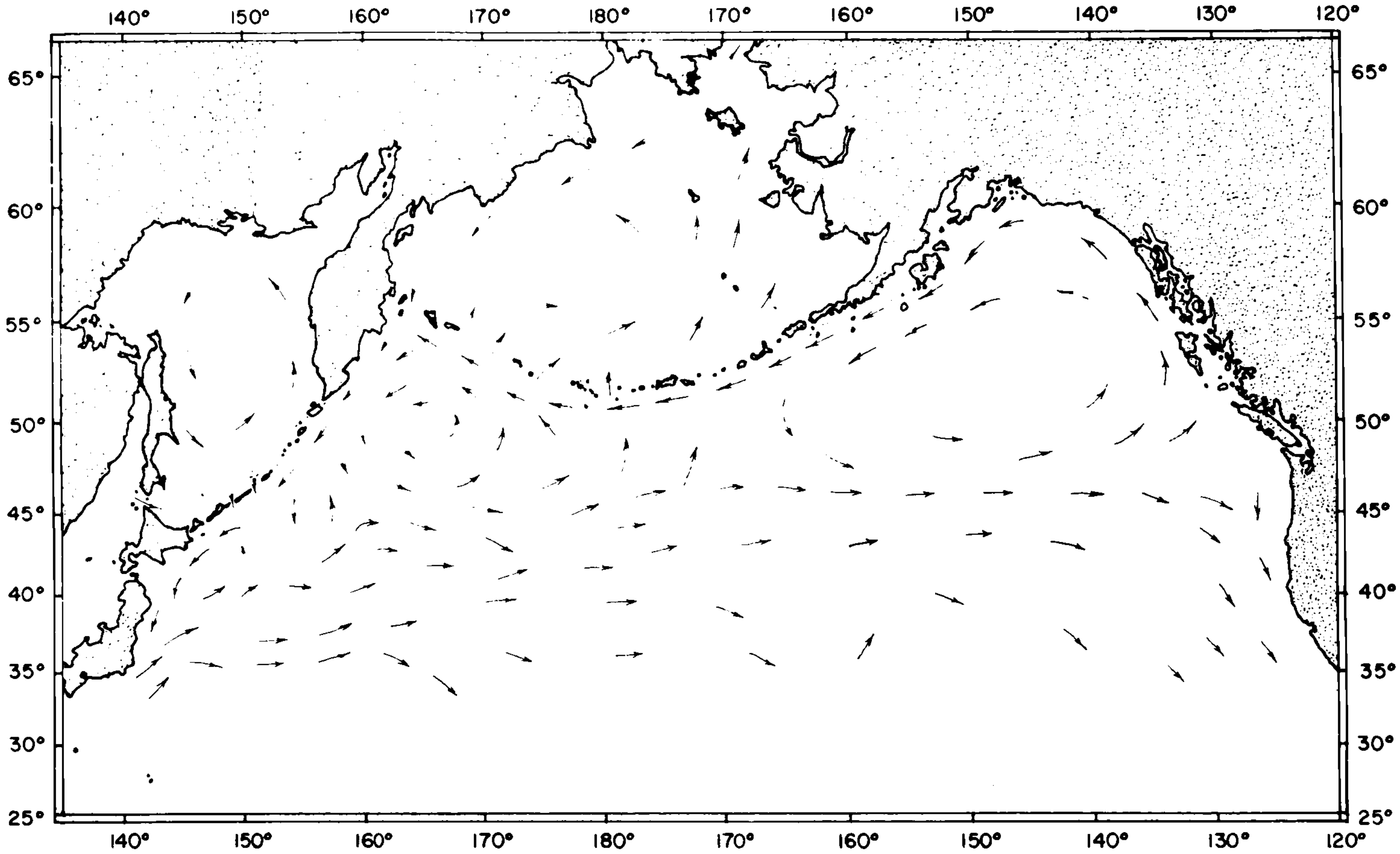

FIGURE 4. Surface currents of the North Pacific Ocean.
(3, p. 7)

continuation of the North Pacific Drift, flows southward off North America between latitude 48°N and 23°N. No well defined outer boundary of this current exists, but the significant transport is contained in the region between the coast and longitude 125°W at latitude 32°N. (9, p. 724) No strong currents have yet been recorded in the California Current System. It has been described as "a wide body of water which moves sluggishly toward the southeast." (9, p. 724)

Davidson Current. During the months October through February a countercurrent develops near the shore known as the Davidson Current. (9, p. 725) This is a northward flowing current at the surface which transports water from the south to the north. The Davidson Current has been ascribed by Munk to the result of local wind stress. "It should be noted that this current-countercurrent system is a consequence of the local wind stress curl and dynamically altogether different from the current-countercurrent system along the western side of the oceans, which has been interpreted as a boundary phenomenon." (4, p. 87)

In this study, the term Davidson Current has been arbitrarily limited to the seasonal northward flowing surface current off California and Oregon. This accords with the definition adopted by Sverdrup et al. (9, p. 725) They also suggest the surface currents may be a manifestation of a deeper northward-flowing current along the continental margin normally at about 200 meters but which may occasionally reach to the surface in near shore regions in the absence of northerly winds. (9, p. 727)

Deep Currents. McAlister, and Murty and Rattray have examined the wind driven, deep circulation in the Eastern North Pacific Ocean. They have found a general northward flow in the deep water below 1500 meters throughout the Eastern North Pacific. (3, p. 47) (5) This is also consistent with Stommel's theoretical representation of the abyssal circulation. (8, p. 87)

Upwelling

Upwelling has been defined as "ascending motion occurring in regions of diverging currents (divergences), which may be present anywhere in the sea but which are particularly conspicuous along the western coasts of the continents, where prevailing winds carry the surface waters away from the coasts." (9, p. 140)

Off the Oregon coast the winds are from the proper direction and of the right magnitude to produce upwelling during summer and fall. (13, p. 51) Significant upwelling is regularly observed in Oregon coastal waters during the summer. It has been believed that the upwelled water (which appears at the surface) rises from moderate depths only, "probably less than 200 meters," and therefore upwelling may significantly influence only the upper few hundred meters. (9, p. 725) Recent Oregon State University data suggest that at times the upwelled water may come from as deep as 400 meters in regions of intense upwelling.

THE WATER MASSES OFF THE OREGON COAST

In this paper, particular attention is paid to characteristics of the water mass immediately adjacent to the coast of Oregon to a distance approximately 1400 kilometers offshore. A temperature-salinity curve typical of this area is shown in Figure 5. (curve b) Temperature-salinity curves for adjacent areas to the north (curve c) and to the south (curve a) are also shown in Figure 5. The form of the temperature-salinity curve for the region off Oregon between 200 and 700 meters suggests that an intrusion of less saline and lower temperature water takes place in this depth range. This would be consistent with southerly flow. Below 700 meters no clear indication of flow direction is readily apparent from the temperature-salinity curve.

Method of Analysis

The method used in the analysis of the water mass off the Oregon coast is similar to that used by Tibby in 1941. (12, p. 115) It is assumed that the observed distribution of temperature and salinity is maintained by horizontal flow and by lateral mixing of two extreme water masses (in the case of the water off Oregon, these are the Pacific Equatorial and the Subarctic Water Masses). Mixing is a assumed to take place primarily along σ_t surfaces, without change of density. It is recognized that "a body of water cannot be displaced even along a σ_t surface without somewhat altering the distribution of mass, nor will the mixing of two bodies of equal σ_t but of different temperature and salinities result in a mass of the same σ_t ." (12,p. 115)

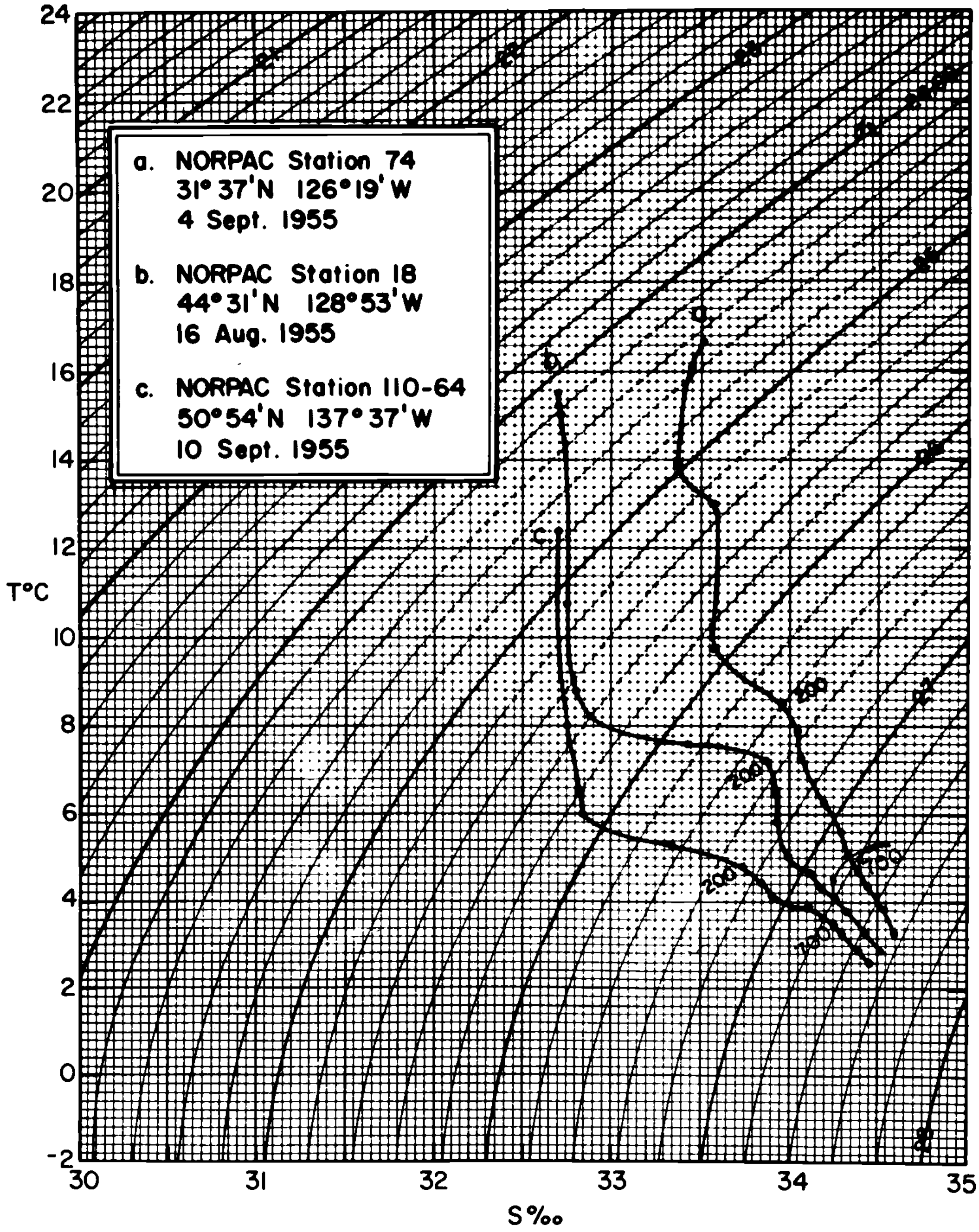

FIGURE 5. Temperature-salinity curves for California, Oregon, and Washington waters.

However, departures from the original $\sqrt{t}$ are small and may be disregarded as a first approximation.

With the above assumptions, and by selecting two stations - one to represent Subarctic Water ("Carnegie" station 124, 52° 19'N 162° 02'W) and one to represent Equatorial Water ("Bushnell" station 299, 9° 02'N 86° 50'W) - it is possible to construct a water mass analysis diagram (Figure 6) from which the percentage of Subarctic Water can be found for water of a particular temperature and salinity. Such a water mass analysis diagram has been described by Tibby. (12, p. 115) (11, p. 78)

In applying this diagram (Figure 6) to the analysis of a water mass, it must be kept in mind that this diagram is valid only under conditions where mixing may reasonably be limited to only lateral mixing and therefore can not be used in the upper few hundred meters of water where vertical mixing is important in determining the water characteristics. In the description of the halocline in the Northeastern Pacific Ocean, Fleming has shown that the depth of the halocline and the salinity at the bottom of the halocline do not vary seasonally. Seasonal effects and wind mixing do not appear to affect depths greater than the bottom of the halocline. (1, p. 160) This depth is generally less than 200 meters in the Northeastern Pacific, and observations at 200 meters and below may be assumed to lie beneath the zone of seasonal influence.

Successful use of this method requires that the water types possess significant difference in either temperature or salinity.

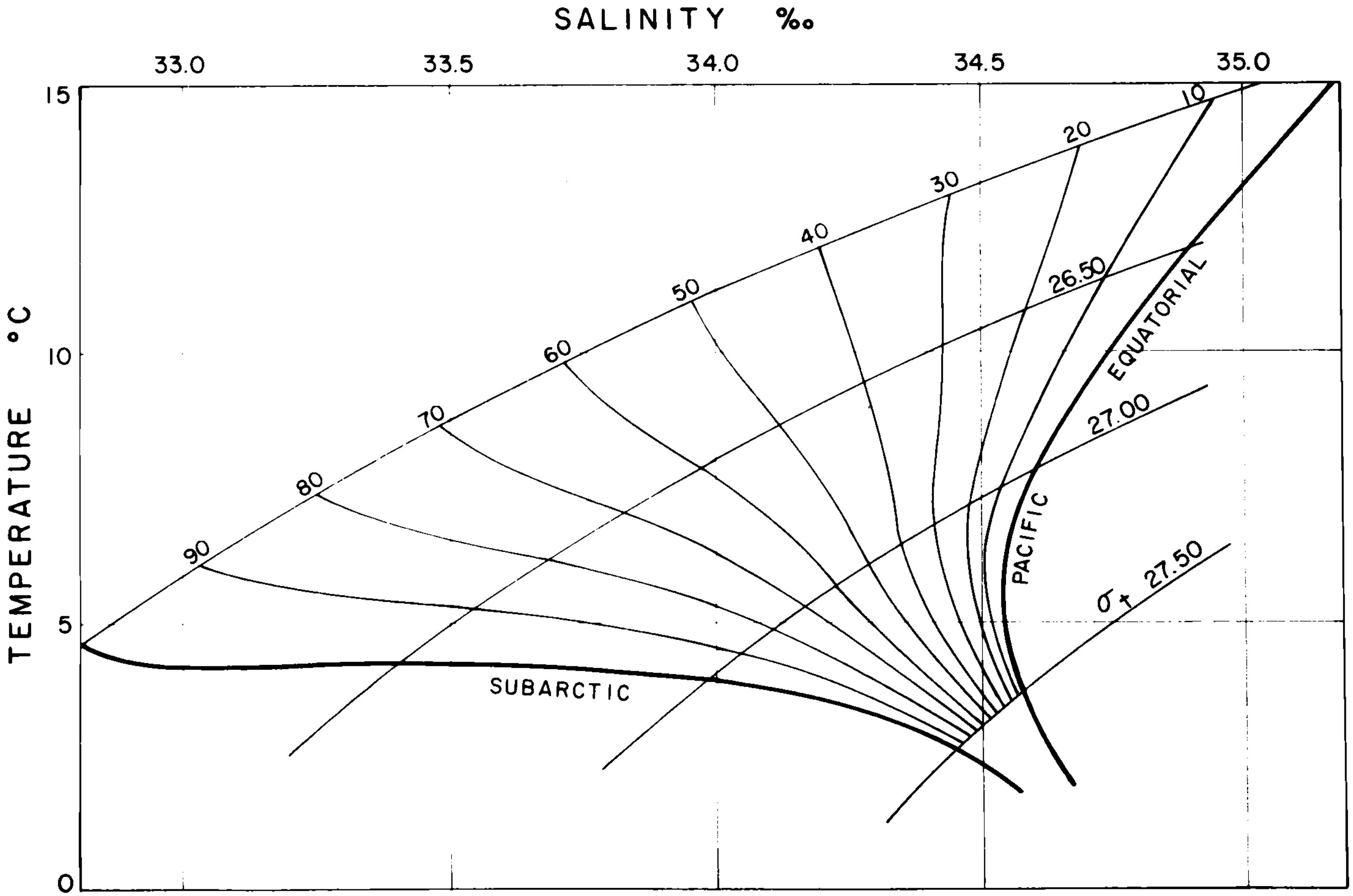

FIGURE 6. Water mass analysis diagram.

Differences at depth of temperature and salinity are small throughout the North Pacific. Tibby has commented: "below a depth of about 1000 meters the differences in the T-S relationships of the two extreme water masses are so small that application of the method is doubtful." (12, p. 115)

It was decided, however, to try the method to a depth of 2000 meters. Four stations were analyzed to the 2000 meter depth. Results for three of these stations were consistent with each other and with the distribution above 1000 meters. Results from the fourth station were inconsistent with all other stations. Even though the sample was small, the agreement between the three stations was such as to appear reasonable to include them. The fourth station was dropped and no further use made of the station in the water mass analysis. (The three stations used are NORPAC 17, 21, and 23. The station dropped was NORPAC station 19.)

Hydrographic Stations

For the purposes of this study, it was necessary to employ hydrographic stations occupying lines approximately normal to the coast. Three sources of data were utilized: physical and chemical data of the Marine Life Research Program, Scripps Institution of Oceanography; NORPAC hydrographic data, Scripps Institution of Oceanography; and Oregon State University hydrographic data.

A total of 71 hydrographic stations were used for the analysis. A list of all stations used, position, date, and collection group is given in Table 1. The position of all stations with respect to the coast is shown in Figure 7.

All stations extended to 600 meters, and more than 50 stations extended to or below 1000 meters, the depth limit for the main

TABLE 1. Stations used in water mass analysis

Station Number	Position Lat.	Position Long.	Date	Source*
201	44°22'N	125°03'W	May 4, 1949	MLR
204	44°14'N	127°41'W	May 3, 1949	MLR
201	44°23'N	124°55'W	July 10, 1949	MLR
204	44°14'N	127°44'W	July 10, 1949	MLR
201	44°23'N	125°15'W	August 10, 1949	MLR
202	44°20'N	125°50'W	August 10, 1949	MLR
203	44°18'N	126°46'W	August 11, 1949	MLR
204	44°14'N	127°42'W	August 11, 1949	MLR
205	44°13'N	128°37'W	August 11, 1949	MLR
206	44°09'N	129°33'W	August 11, 1949	MLR
207	44°06'N	130°29'W	August 12, 1949	MLR
208	44°04'N	131°20'W	August 12, 1949	MLR
201	44°24'N	125°10'W	September 12, 1949	MLR
204	44°14'N	127°42'W	September 12, 1949	MLR
201	44°22'N	125°10'W	October 12, 1949	MLR
204	44°14'N	127°42'W	October 13, 1949	MLR
201	44°24'N	124°55'W	November 20, 1949	MLR
204	44°14'N	127°42'W	November 19, 1949	MLR
15	46°03'N	125°09'W	August 16, 1955	NORPAC
16	45°42'N	125°59'W	August 16, 1955	NORPAC
17	45°08'N	127°22'W	August 16, 1955	NORPAC
18	44°31'N	128°53'W	August 16, 1955	NORPAC
20	42°58'N	132°34'W	August 18, 1955	NORPAC
21	42°18'N	135°19'W	August 18, 1955	NORPAC
22	42°15'N	139°01'W	August 20, 1955	NORPAC
23	42°20'N	142°39'W	August 20, 1955	NORPAC
AH135	46°14'N	124°56'W	June 29, 1961	OSU
AH145	46°14'N	125°11'W	June 29, 1961	OSU
AH165	46°14'N	125°40'W	June 29, 1961	OSU
AH185	46°14'N	126°08'W	June 29, 1961	OSU
AH105	46°15'N	126°37'W	June 29, 1961	OSU
AH125	46°14'N	127°07'W	June 28, 1961	OSU
AH145	46°15'N	127°33'W	June 28, 1961	OSU
AH165	46°14'N	128°04'W	June 28, 1961	OSU
NH 45	44°39'N	125°07'W	June 26, 1961	OSU
NH 65	44°39'N	125°35'W	June 27, 1961	OSU
NH 85	44°40'N	126°03'W	June 27, 1961	OSU
NH105	44°39'N	126°31'W	June 27, 1961	OSU
NH125	44°39'N	126°59'W	June 27, 1961	OSU
NH145	44°39'N	127°28'W	June 27, 1961	OSU
NH165	44°39'N	127°55'W	June 27, 1961	OSU
CH 35	43°21'N	125°10'W	June 19, 1961	OSU
CH 65	43°20'N	125°52'W	June 20, 1961	OSU
CH105	43°21'N	126°47'W	June 20, 1961	OSU

Station Number	Position Lat.	Long.	Date	Source*
CH125	42°20'N	127°13'W	June 20, 1961	OSU
CH145	43°21'N	127°40'W	June 20, 1961	OSU
NH 25	44°39'N	124°39'W	August 21, 1961	OSU
NH 35	44°39'N	124°53'W	August 21, 1961	OSU
NH 45	44°39'N	125°07'W	August 21, 1961	OSU
NH 65	44°40'N	125°35'W	August 21, 1961	OSU
NH 85	44°40'N	126°03'W	August 22, 1961	OSU
NH105	44°40'N	126°30'W	August 22, 1961	OSU
NH125	44°40'N	126°50'W	August 22, 1961	OSU
NH145	44°39'N	127°27'W	August 22, 1961	OSU
NH165	44°40'N	127°55'W	August 22, 1961	OSU
NH 25**	44°39'N	124°39'W	October 30, 1961	OSU
NH 35**	44°39'N	124°53'W	October 30, 1961	OSU
NH 45**	44°39'N	125°07'W	October 30, 1961	OSU
NH 65**	44°39'N	125°35'W	October 30, 1961	OSU
NH 85**	44°39'N	126°03'W	October 31, 1961	OSU
NH125**	44°39'N	126°59'W	October 31, 1961	OSU
NH145**	44°39'N	127°27'W	October 31, 1961	OSU
NH 25**	44°39'N	124°39'W	December 2, 1961	OSU
NH 35**	44°39'N	124°53'W	December 2, 1961	OSU
NH 45**	44°39'N	125°07'W	December 2, 1961	OSU
NH 65**	44°39'N	125°35'W	December 2, 1961	OSU
NH 85**	44°39'N	126°03'W	December 2, 1961	OSU
NH105**	44°39'N	126°31'W	December 2, 1961	OSU
NH125**	44°39'N	126°59'W	December 3, 1961	OSU
NH145**	44°39'N	127°27'W	December 3, 1961	OSU
NH165**	44°39'N	127°55'W	December 3, 1961	OSU

*Abbreviations for sources are as follows: MLR - Marine Life Research Program cruises of Scripps Institution of Oceanography, NORPAC - NORPAC cruises of Scripps Institution of Oceanography, OSU - Oceanographic cruises of Oregon State University. A list of all data sources are given in appendix.

**Beginning with October 1961 and through December 1961, all OSU stations' final positions were not available and the values given are from the cruise plans of Oregon State University for cruises 6110B and 6112A.

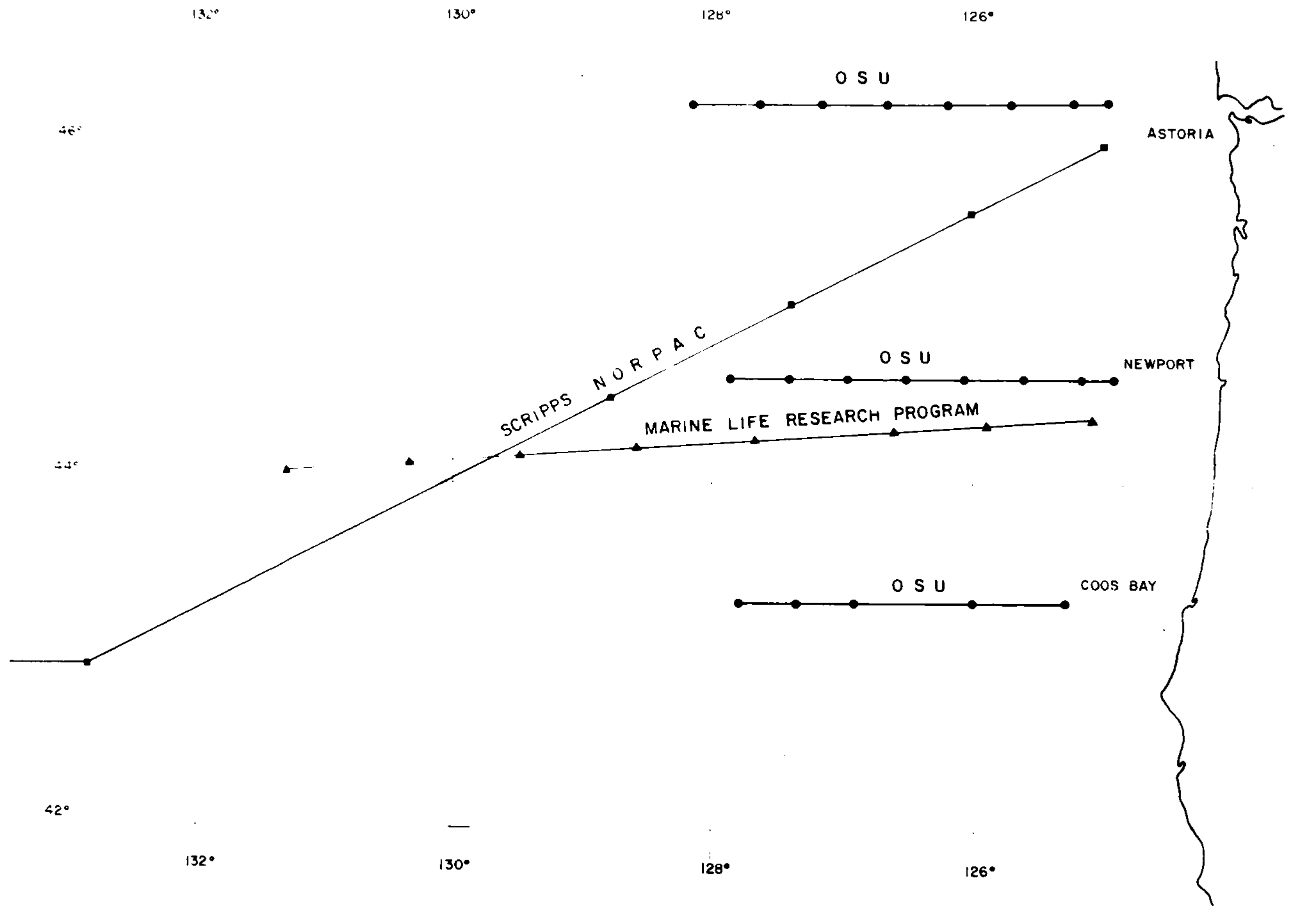

FIGURE 7. Position of stations off the Oregon Coast.

analysis. Three NORPAC stations extending to or below 2000 meters were used for the analysis below 1000 meters. Certain Oregon State University data for October and December were not interpolated to standard depths when the observed depth lay within 10 meters of a standard depth. In these cases, the values for the observed depths were taken as those for the standard depth.

Physical Characteristics and Distribution of Offshore Water Masses

Temperature and salinity values for each hydrographic station were plotted on water mass analyzer diagrams (similar to that shown in Figure 6). The percentage Subarctic Water was obtained for each standard depth, and the vertical sections were constructed and contoured. The percentages were read and plotted with an estimated accuracy of 5 per cent.

The most extensive coverage of the water masses off the coast is illustrated by the NORPAC section for August. (Figure 8) Here, Modified Subarctic Water (more than 80% Subarctic) appears about 1100 kilometers offshore with a tongue extending shoreward. This water is identified with the main stream of the California Current System.

Beneath the shoreward extension of Modified Subarctic Water, Modified Equatorial Water (less than 40% Subarctic) is found. The presence of this Modified Equatorial Water is an indication of a northward-flowing current at this depth.

The percentage of Subarctic Water present near the surface (200 meters) decreases seaward; this is particularly noticeable beyond 800

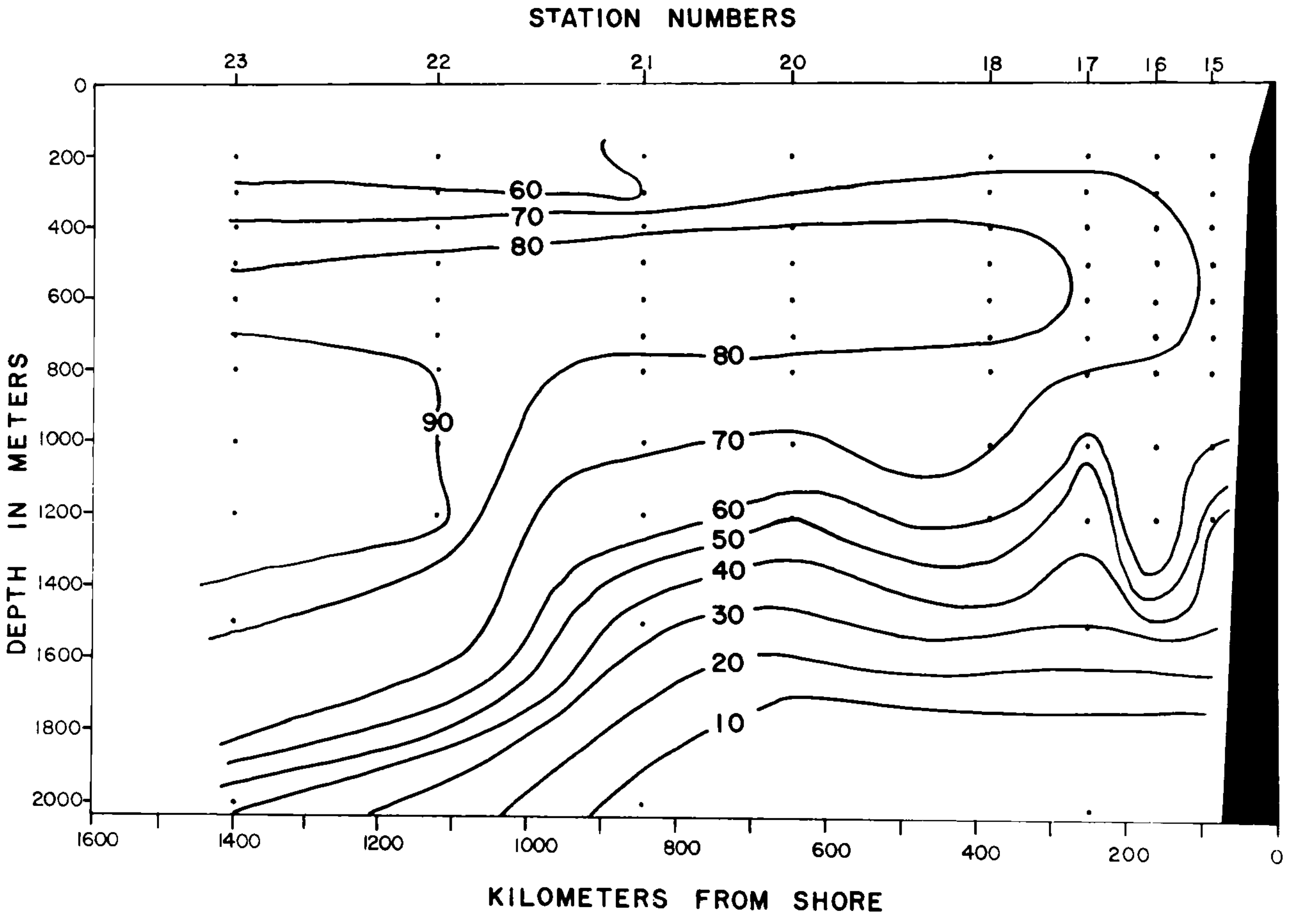

FIGURE 8. NORPAC section off Oregon showing percentage of Subarctic Water. August 1955.

kilometers. Several factors may account for this decrease. The wind system at this time may favor relatively stronger flow to the south near shore at this depth. The decreases would then represent relatively greater mixing of Modified Subarctic and Eastern North Pacific Central Water further from shore. Or, it may possibly represent a downward extension of seasonal changes in the surface 200 meters.

A better understanding of the processes contributing to the observed distribution in the NORPAC section (Figure 8) can be obtained by examining the temperature and salinity structure carefully, and also by comparing adjacent sections. Temperatures and salinities for each depth were averaged and the deviation from the average plotted in Figures 9 and 10. From these figures it is seen that the Modified Equatorial Water as determined by this analysis is related to a positive salinity deviation. The Modified Subarctic Water is related to negative salinity and temperature deviations. The water from 200 to 300 meters, 800 kilometers from shore, is largely of positive temperature and salinity deviations.

August sections from the MLR and OSU data are shown in Figures 11 and 12. These two sections and the NORPAC section (Figure 8) represent three different years; yet the same general features are present in each year. In both the NORPAC and MLR sections the 80% Subarctic Water isoline is located 400 kilometers from shore. The OSU

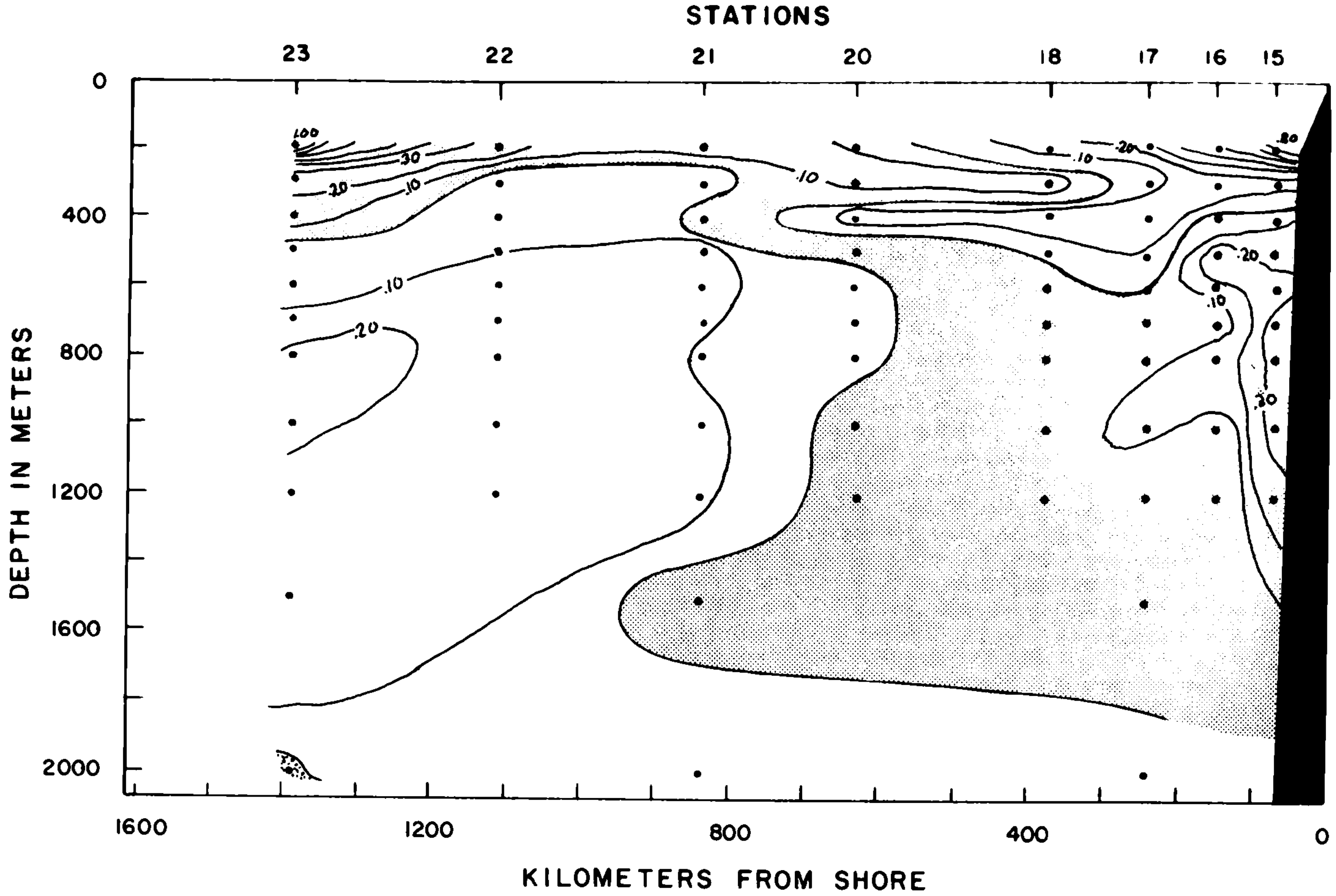

FIGURE 9. Deviation of temperature from average. Stippled area represents positive deviation. August 1955.
(contour interval 0.1°C)

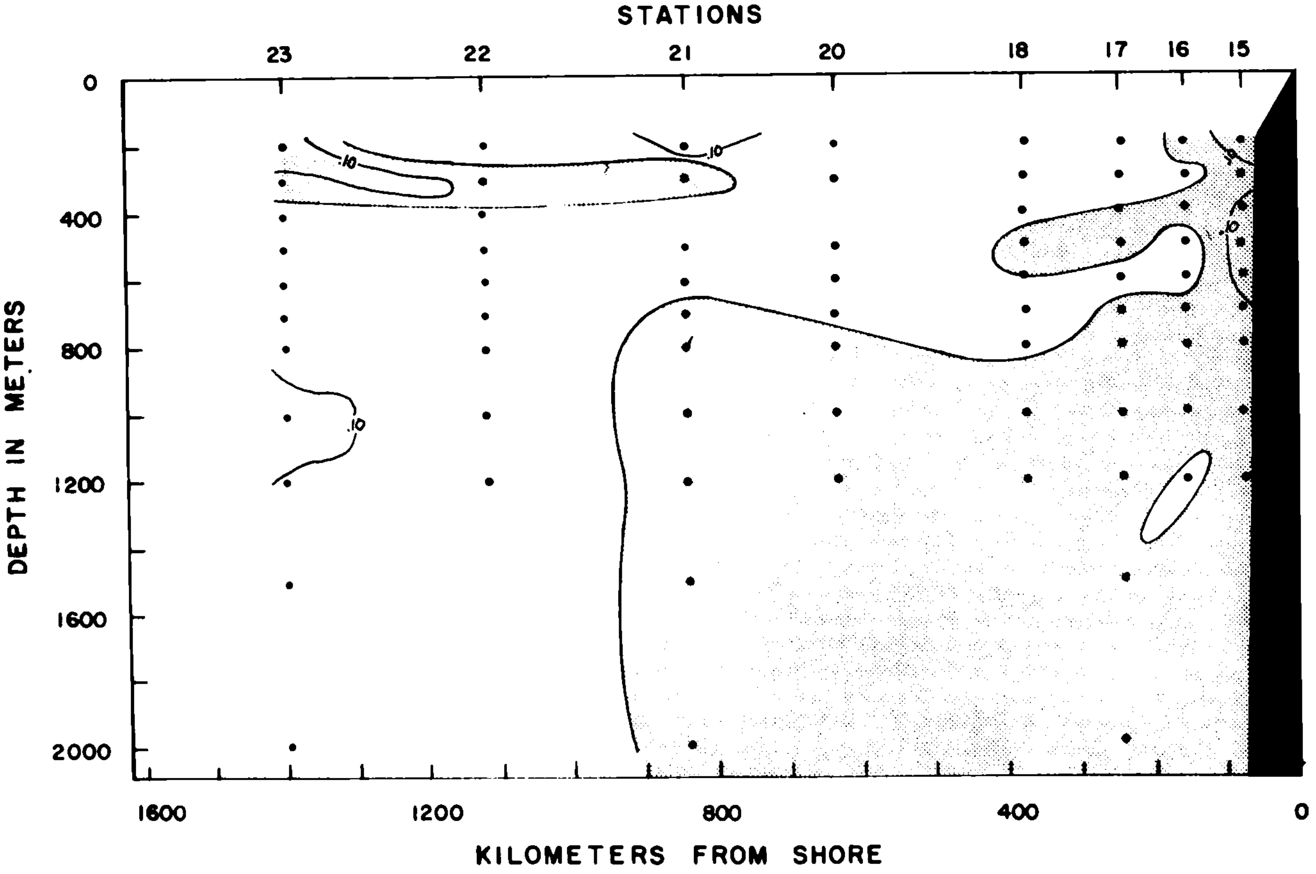

FIGURE 10. Deviation of salinity from average. Stippled area represents positive deviation. August 1955. (contour interval 0.1‰)

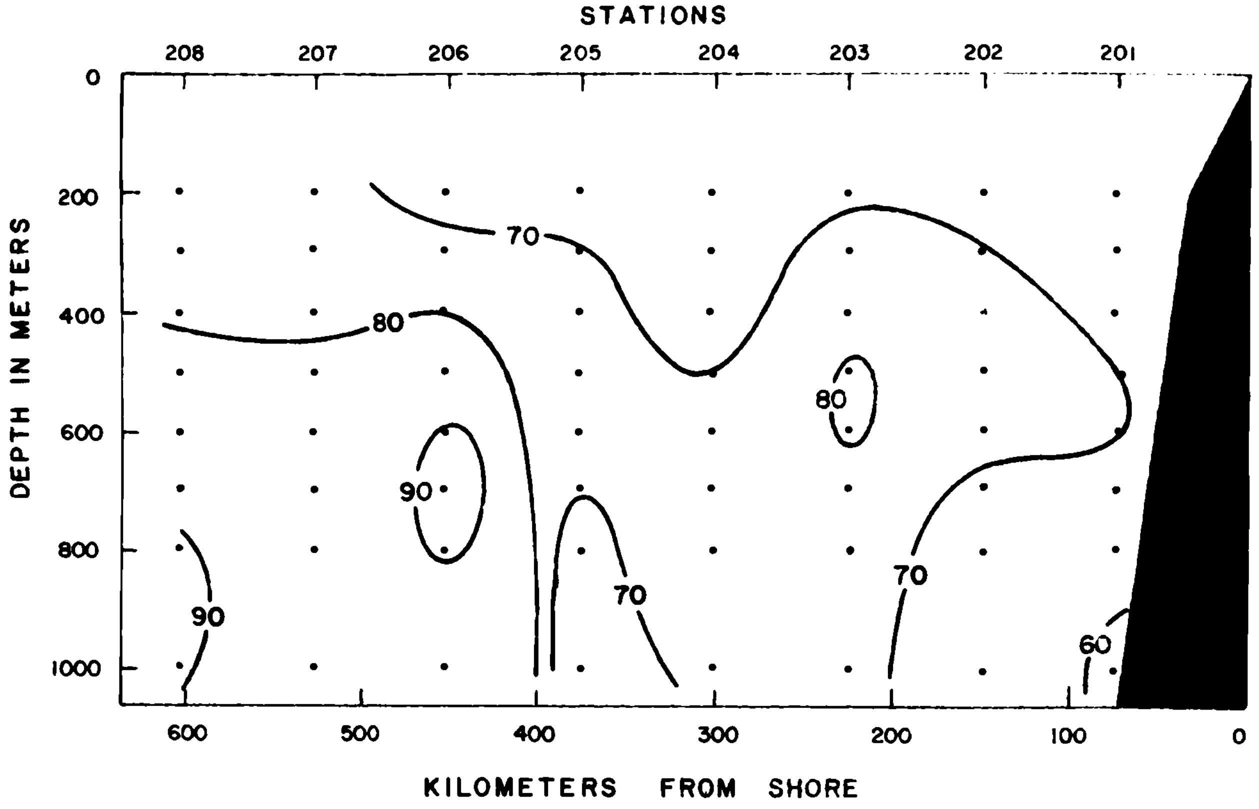

FIGURE 11. August 1949 section off Newport, Oregon, showing percentage of Subarctic Water.

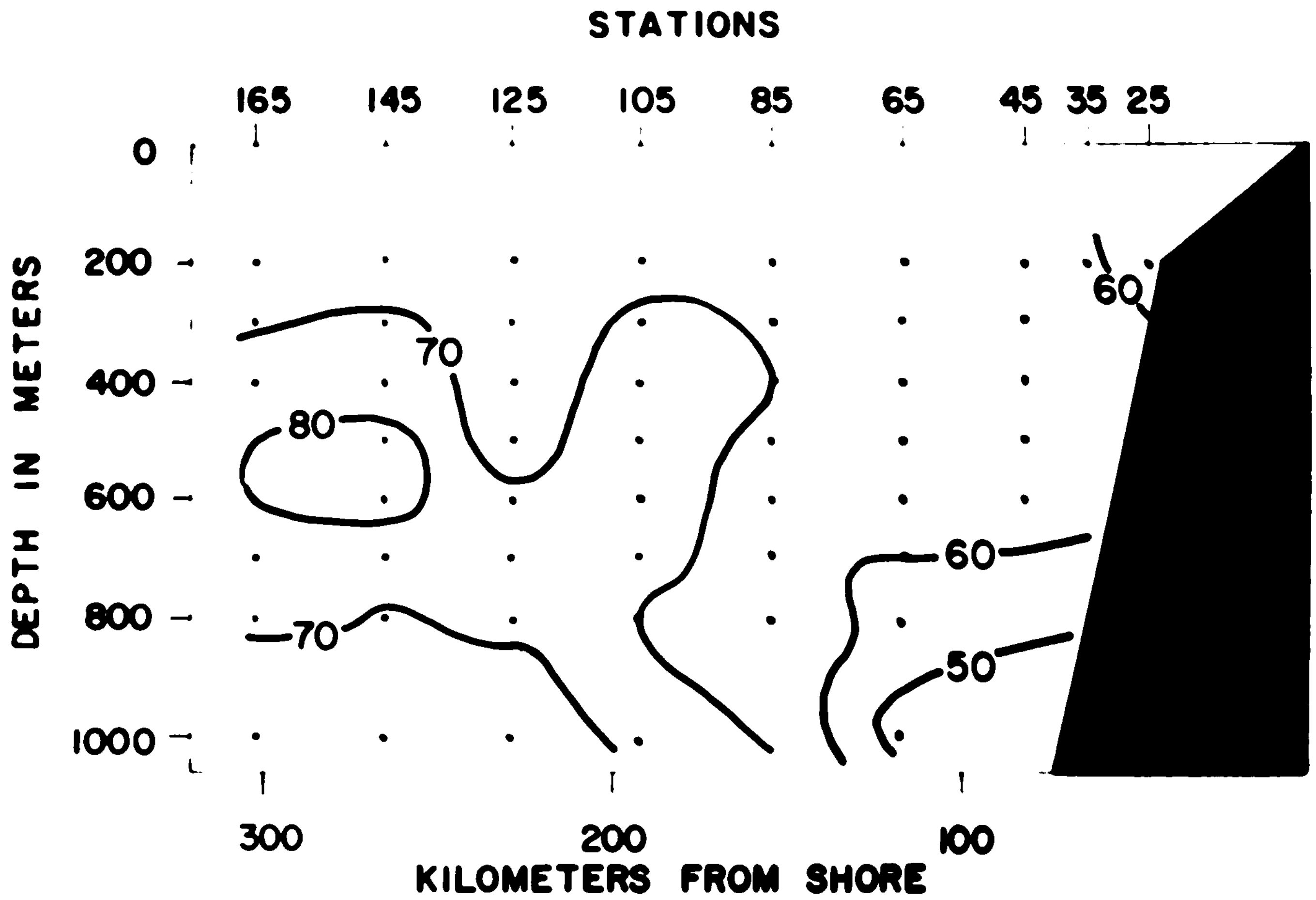

FIGURE 12. August 1961 section off Newport, Oregon, showing percentage of Subarctic Water.

section did not extend 400 kilometers. All three sections show higher values in per cent Equatorial Water near shore at depths greater than 800 meters.

Because of closer spacing of stations, the MLR and OSU sections show details and irregularities that are masked or lost in the widely spaced stations of the NORPAC section.

Figures 13, 14, and 15 show three sections from OSU data for June, 1961 along the Oregon coast. The location of these sections was shown in Figure 7. The sections are: off Astoria (Figure 13), off Newport (Figure 14), and off Coos Bay (Figure 15). These three sections show the distribution of properties only out to 300 kilometers and therefore represent only conditions near shore.

Stations in the Astoria and the Coos Bay sections did not extend below 600 meters in most cases. The inshore stations for the Newport section are also shallow casts, and thus it is impossible to check on the near shore deep water. The three sections do show a similar distribution of the Modified Subarctic Water Mass along the coast. In each section the inshore limit of the intrusion of the Modified Subarctic Water, as indicated by the 80% Subarctic Water isoline, is located about 200 kilometers offshore.

Seasonal Variation

Seasonal variation in the water masses off the coast is shown in Figures 12, 14, 16, and 17. These four sections to 300 kilometers off Newport, show water characteristics for the months of June, August, October, and December.

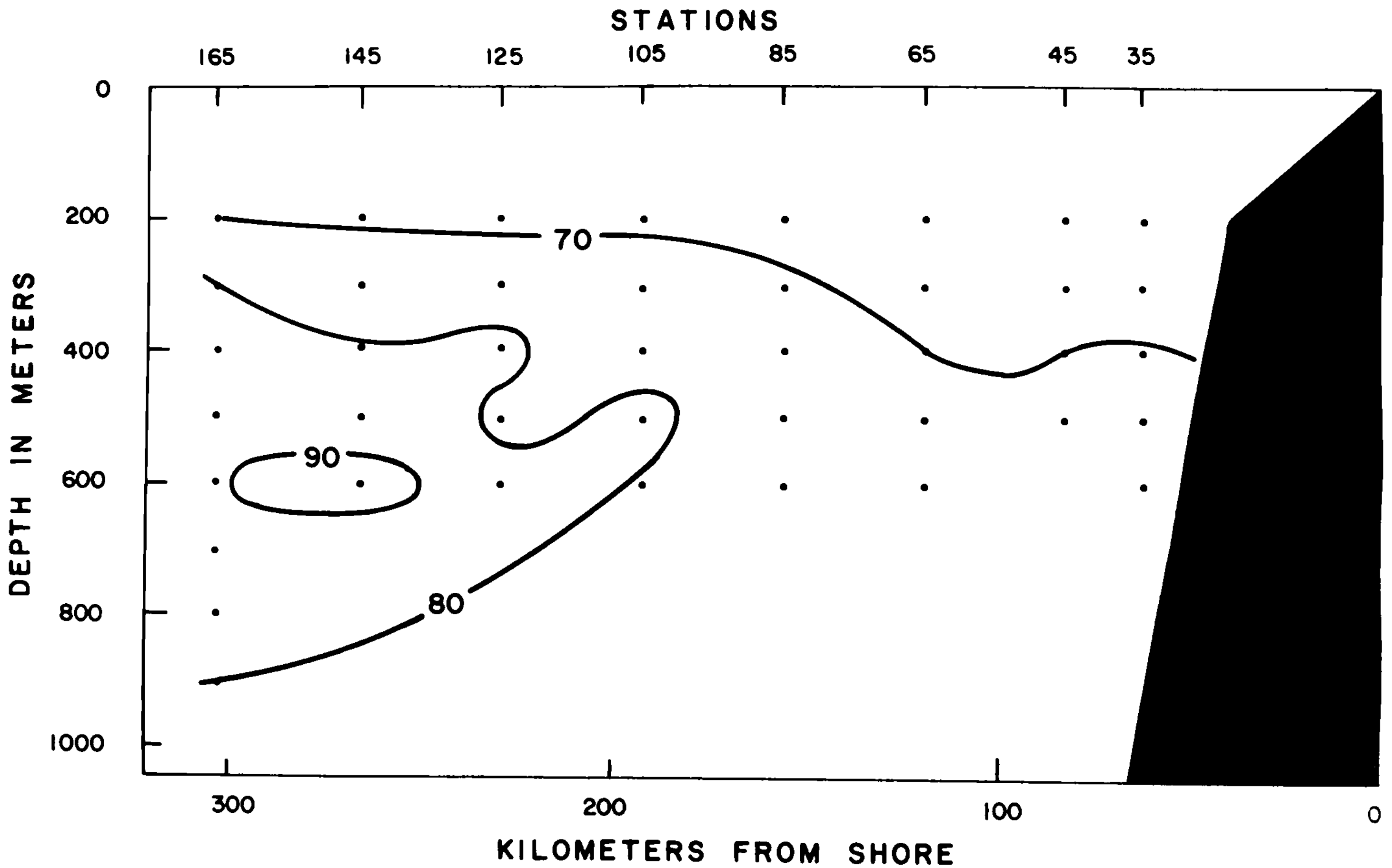

FIGURE 13. June 1961 section off Astoria, Oregon, showing percentage of Subarctic Water.

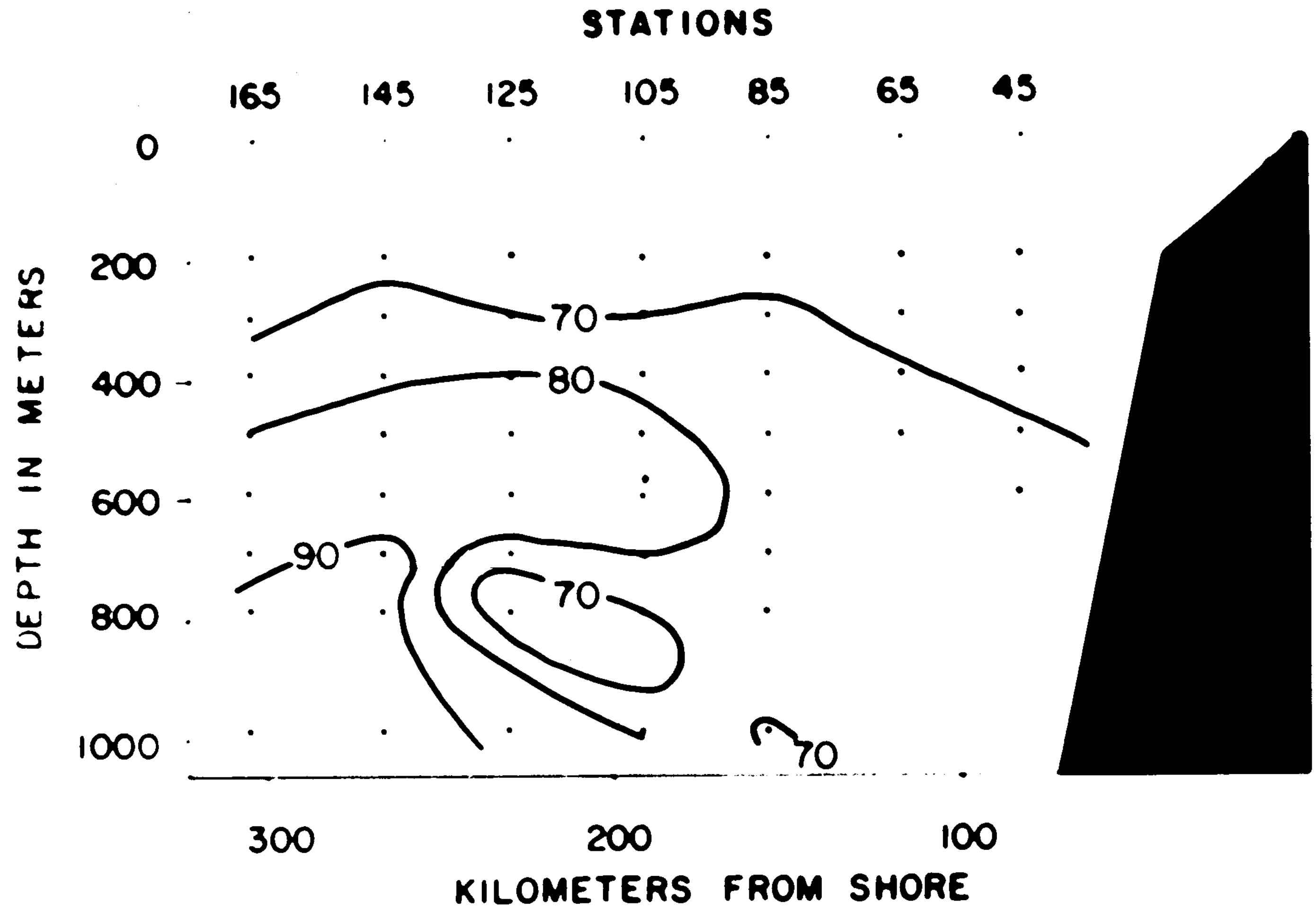

FIGURE 14. June 1961 section off Newport, Oregon, showing percentage of Subarctic Water.

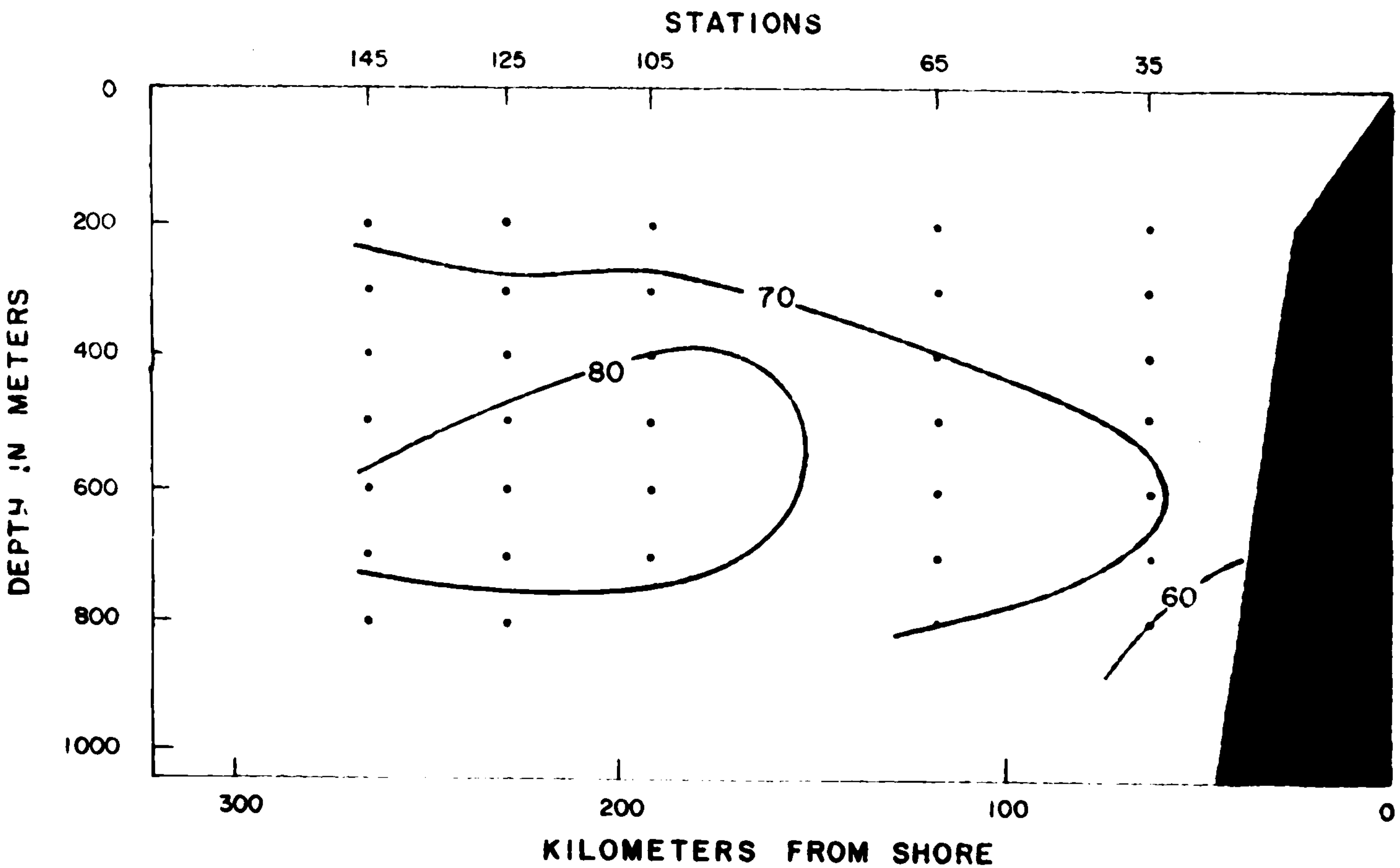

FIGURE 15. June 1961 section off Coos Bay, Oregon, showing percentage of Subarctic Water.

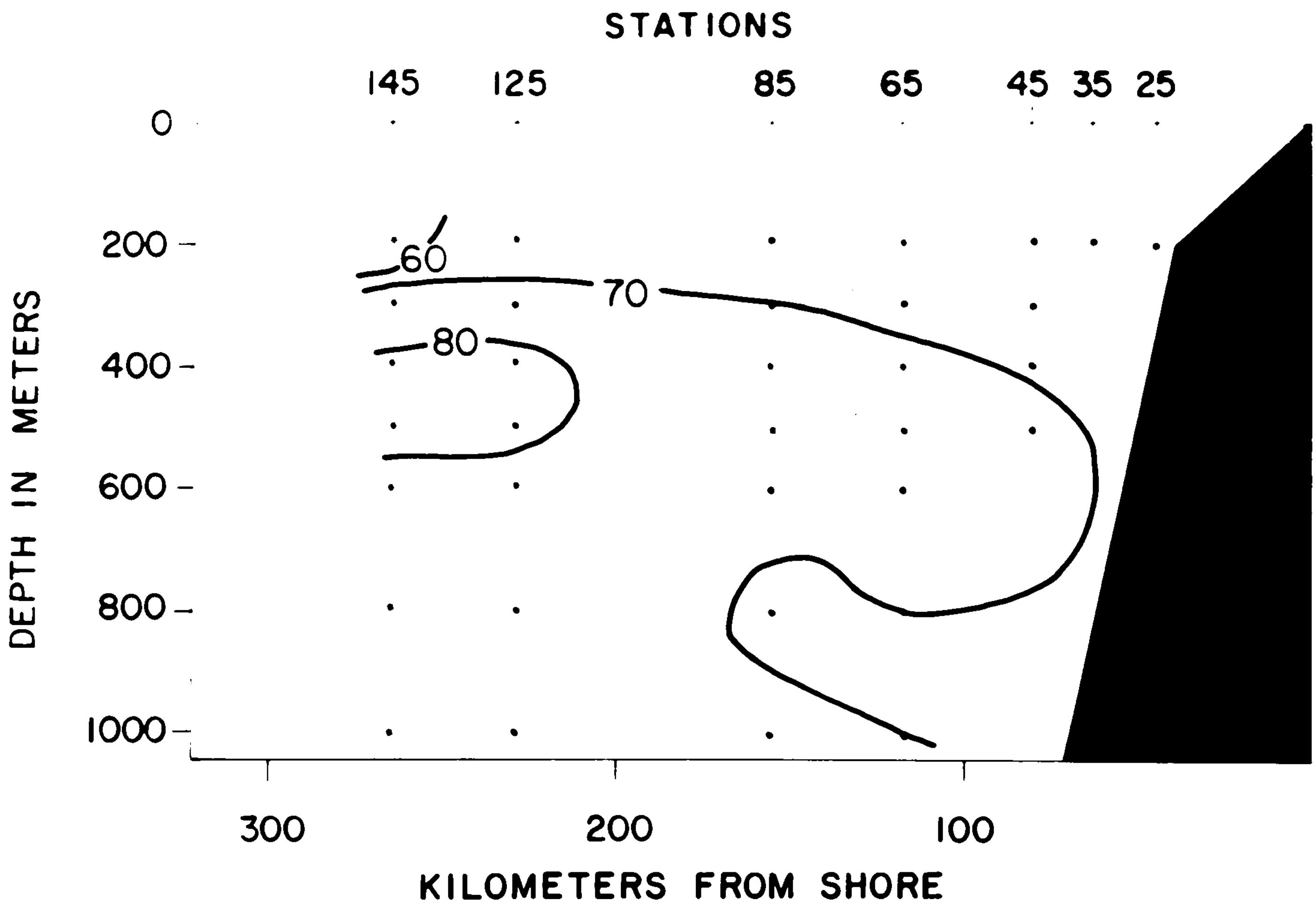

FIGURE 16. October 1961 section off Newport, Oregon, showing percentage of Subarctic Water.

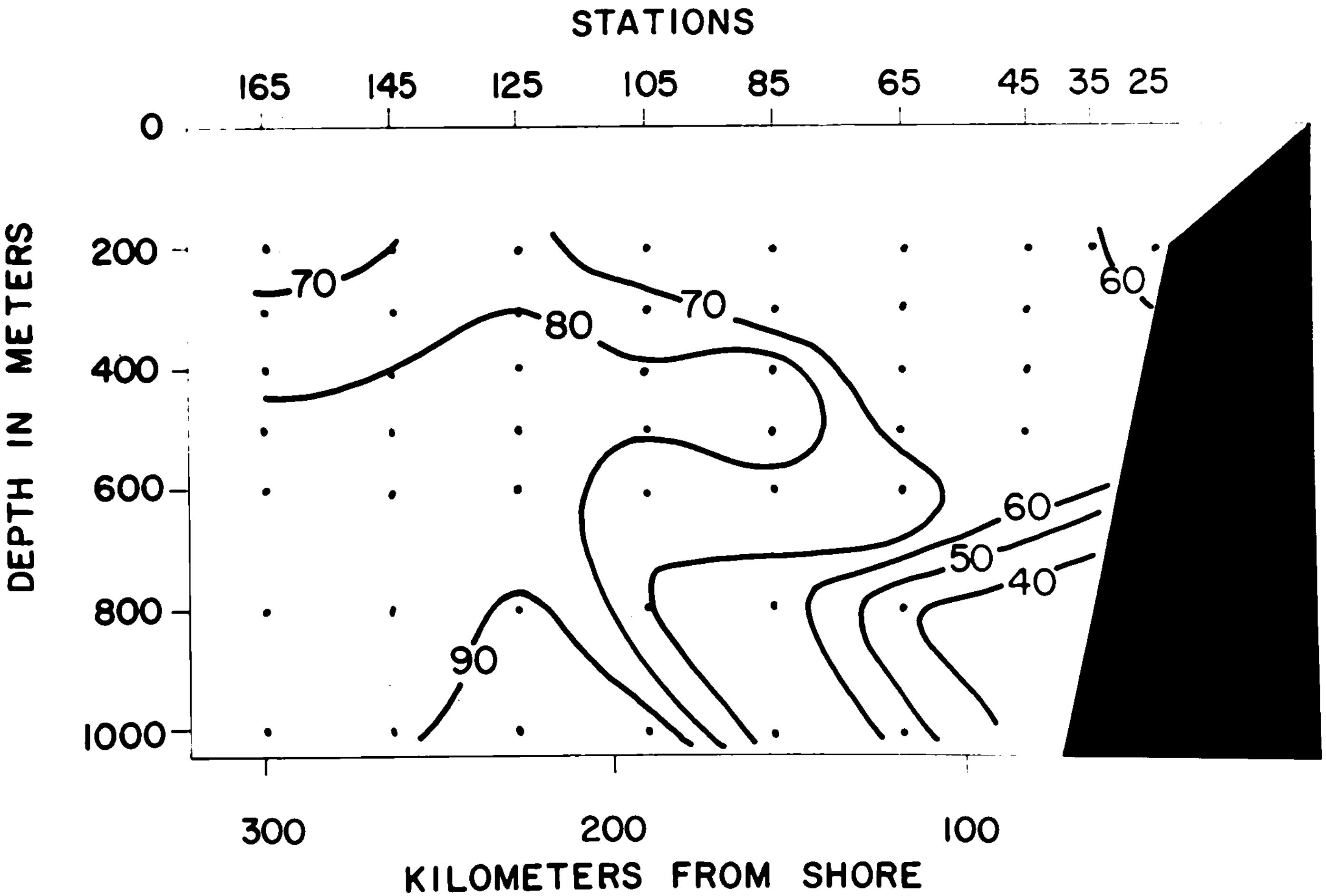

FIGURE 17. December 1961 section off Newport, Oregon, showing percentage of Subarctic Water.

In June the 80% Subarctic Water isoline lies within 200 kilometers of shore, while by August it has moved out to 250 kilometers. In October it is again approaching 200 kilometers offshore, and by December lies within 125 kilometers of shore. This near shore water above 600 meters contains a smaller proportion of Subarctic Water in August than during any of the other three months. A slight countercurrent to the north is indicated near the coast in August, and a strong countercurrent in December.

MLR data from 1949 were also analyzed for evidence of seasonal variation. Diagrams were drawn which show the variation in the percentage of Subarctic Water present at two different stations for months for which data were available. One of these stations was near shore (75 kilometers from the coast), and the other located offshore (300 kilometers from the coast). Both stations lie near the Newport section. The diagrams are shown in Figure 18 and 19. The graph for the 300 kilometer station (Figure 18) shows that during July and August of 1949 no Subarctic Water greater than 80% was present. The 75 kilometer diagram represents a more complex situation indicating that circulation and mixing in the inshore zone may be more complicated.

Of interest in Figure 19 is the 60% isoline near the 300 meter level that appears from May to July, is absent during August, September, and October and then reappears in November. This late winter and spring increase in the proportion of southern water near shore may be attributed to the Davidson Current. In those months in which

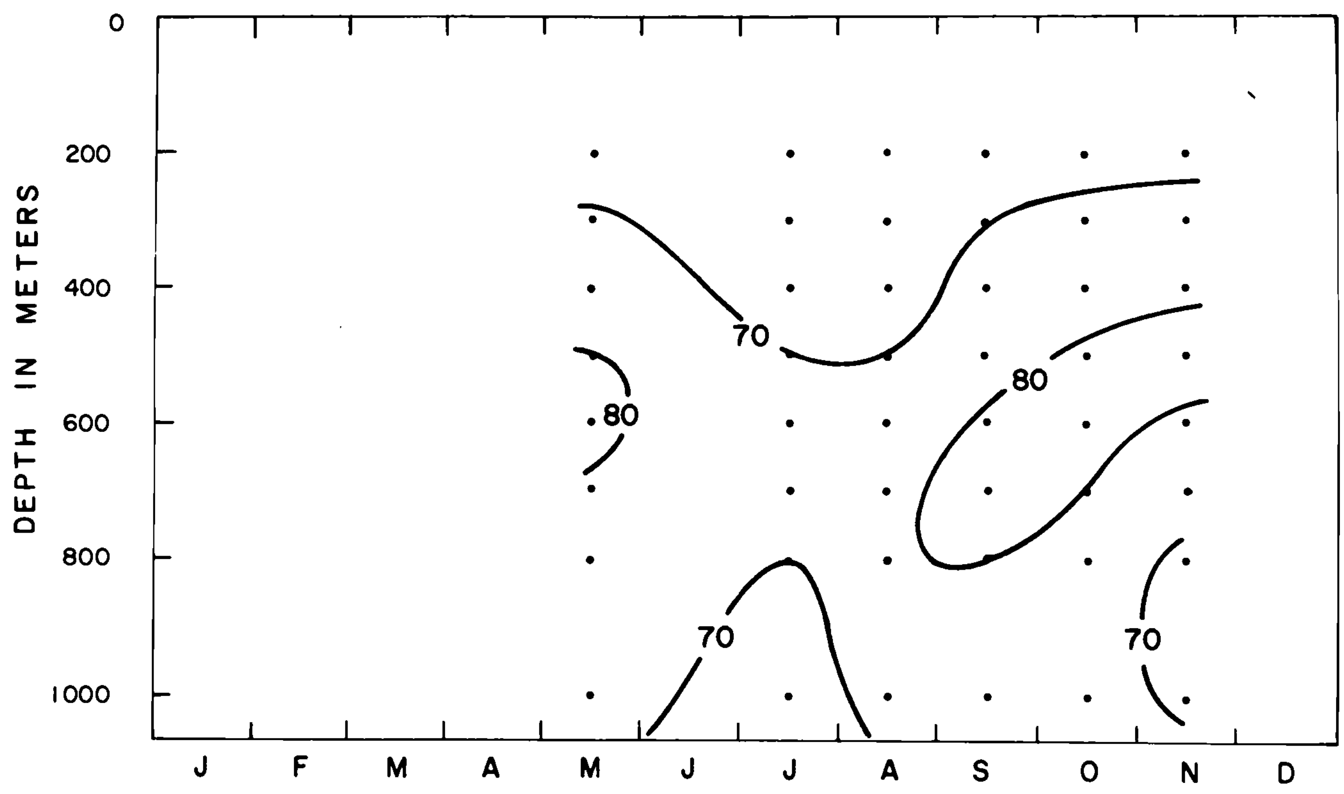

FIGURE 18. Variation in percentage of Subarctic Water for 1949 at Marine Life Research Program station 204.

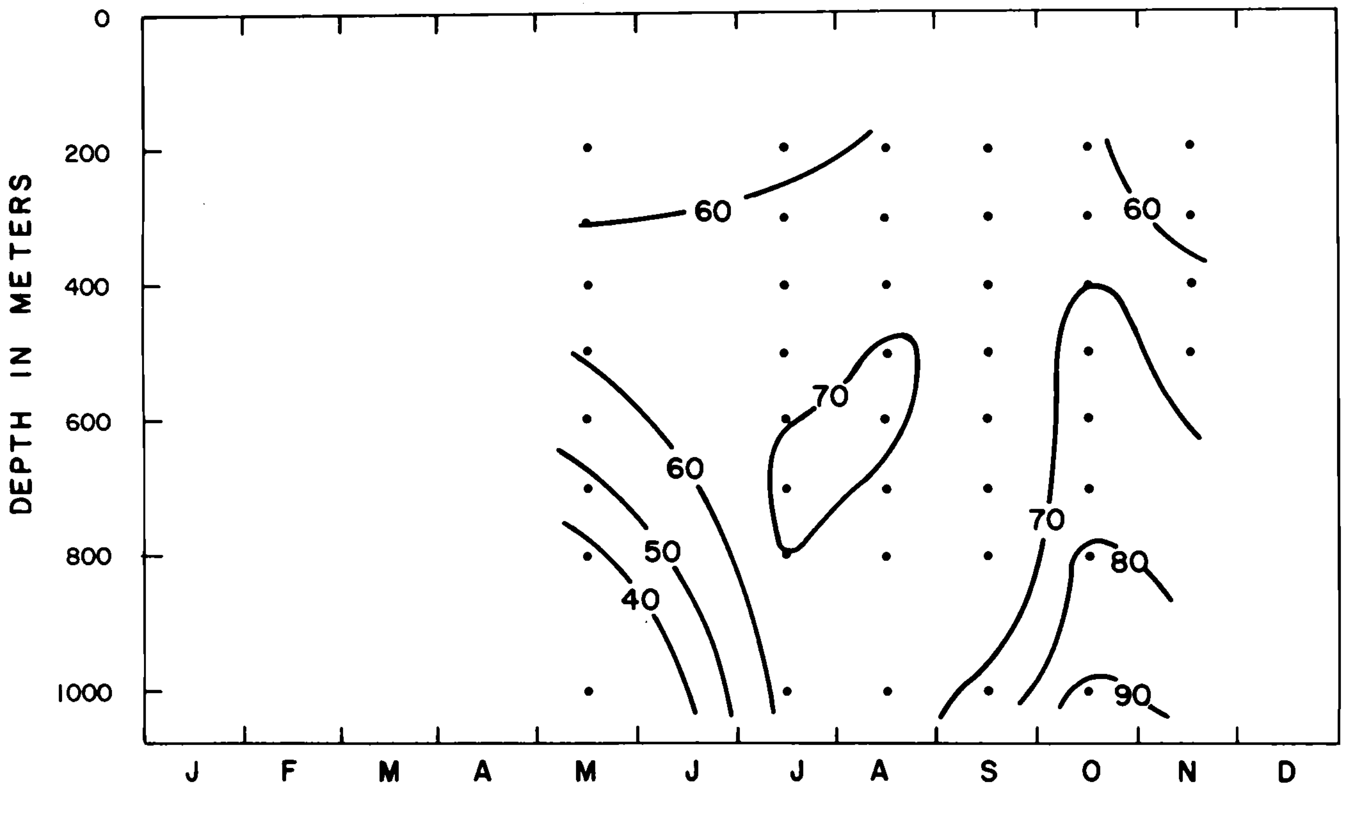

FIGURE 19. Variation in percentage of Subarctic Water for 1949 at Marine Life Research Program station 201.

it appears, the Davidson Current brings southern water northward at the surface. When the current is well developed it may be strong enough to effect water properties at the 300 meter level.

SOURCES OF OBSERVED DISTRIBUTION

The observed distribution of properties in the Eastern North Pacific must represent a balance of the advective and mixing processes and surface exchange acting in this region. If vertical processes can be neglected below 200 meters, then the distribution of properties will be related to mixing and advection occurring beneath the layer of seasonal influence.

In these conditions, isentropic analysis will describe the mixing and exchange occurring with respect to stationary source water masses. Combined with independent knowledge of the magnitude of the exchange coefficients in the sea, it can afford information of the current structure of the oceans. Isentropic analysis will rarely provide a complete description of the separate processes of mixing and advection, but should indicate the most likely set of conditions. Using isentropic analysis, conclusions about the location, variability, and extent of both currents and mixing may be drawn from the distribution of properties described for the Oregon coast.

The more prominent features of the coastal current system are the southward offshore drift of the California Current and a suggested general northward drift at depth intensifying to a stronger, shallower northward coastal boundary current at the edge of the continental shelf. The Davidson Current also influences the inshore region during winter months.

The California Current has already been defined as a sluggish southward flowing current transporting Subarctic Water along the North American coast. The large offshore body of Modified Subarctic Water represents the main body of the California Current.

The variations observed during the year suggest that there is substantial seasonal variation. The tongue of Subarctic Water that extends very near shore during the winter moves offshore during the summer months. Inshore, at depths of 300 to 800 meters during summer months, the percentage of southern water increases. These changes may be related to strong upwelling which occurs off this coast during summer and early fall. Upwelling may effect the water at depths greater than 200 meters, and extend the influence of vertical mixing below the surface zone. The primary effect of the upwelling would appear, however, to be modification of surface water from water at depth rather than modification at depth due to surface exchange. However, results of isentropic analysis are used with caution in this region.

An alternate explanation for the inshore increase in southern water during the summer is an increase in the northward current component. Yoshida and Tsuchiya noted that at the time of upwelling "the fall of isotherms toward the coast in the layers over several hundred meters above 1000 meter level indicates the presence of northward current at and somewhat above these depths." (14, p. 14)

The increase in southern water is more likely associated with this northerly current, than directly with upwelling.

Another potential cause of variability in the percentage of Subarctic Water in the inshore regions from winter to summer is large scale change in the current system. It is believed that the divergence of the North Pacific Drift moves up and down the coast seasonally. (2, p. 9) This divergence is located at about 50°N in the summer, somewhat south of this latitude during the winter. In the summer months the water off the Oregon coast would have greater contact with the deep Modified Equatorial Water, and should reflect this greater contact and opportunity for mixing.

The northward drift at depth, which Stommel and others have predicted by theoretical studies, is shown in this study by an increase in Equatorial Water below 800 meters. The current appears to be stronger near the continental slope. At times this current may extend upward within 600 meters of the surface very near the coast, but the main body lies below the 1000 meter level. The analysis indicates that the northward drift continues to 2000 meters and below. Theoretical studies have predicted such a current between 1500 meters and 4000 meters in the Eastern North Pacific. (5) (3, p. 48)

The NORPAC data for the Eastern North Pacific show that this current transports water at a depth of 1000 meters toward the Oregon coastal area that is of higher salinity and higher temperature than other water at 1000 meters at this latitude in the Eastern North Pacific. Since there is no reason to expect substantial changes in diffusion coefficients in the Eastern North Pacific, the water near shore must have a northward component relative to the offshore water. Some estimate of the values of the ratio of eddy diffusion to velocity, K/u, may be obtained by the method used by Sverdrup. (9, p. 481-486) Using this method and NORPAC data, values of K/u were obtained ranging from 400 to 1500 kilometers. These values are somewhat smaller than the values (600 to 3200 kilometers) found by Sverdrup in the West Atlantic. This would indicate that advection plays an important and significant role in the observed distribution of properties in the coastal region.

Substantial advection of southern water at depth, more intense and rising nearer the surface closer to the shelf, appears the only reasonable source which can supply the observed Equatorial Water at depth off the Oregon coast.

Before an unequivocal analysis can be made, additional methods will have to be derived to study the water below 2000 meters. Many more stations will be needed. There are few stations at depths greater than 2000 meters in the region off Oregon. Direct current measurement, biological tracers, and methods other than direct isentropic analysis will be required to study this water in detail.

The Davidson Current, or the northward drift of the surface waters, is present off the Oregon coast during the winter (as indicated by drift bottle returns); but the Davidson Current as a feature at 200 meters, as described by Sverdrup, does not appear to be a year-round feature. The Davidson Current appears mainly a surface current without much extension below 200 meters, and distinct from the general northerly flow sometimes observed as part of the California Current System.

The presence of the Davidson Current is indicated by a change in the water characteristics in the near shore region. An increase in percentage Equatorial Water as shown by the water mass analyzer diagram (Figure 6) may mean an increase in temperature or salinity or both and does not necessarily imply that the water has an origin in the Pacific Equatorial Water Mass when some other means of change may be postulated. The water in the Davidson Current is very likely formed off the coast of California by surface contact and mixing. The increase in percentage Pacific Equatorial Water in the region of the Davidson Current reflects a downward intrusion and extension of the surface zone and surface exchange effects rather than an intrusion of true Pacific Equatorial Water.

SUMMARY

In general analysis of waters of the Eastern North Pacific, Tibby found that the waters along the North American coast represent a mixture of Subarctic and Pacific Equatorial Water. Using isentropic analysis with much more extensive data, which have become available since Tibby's study, the waters off the Oregon coast have been studied in detail. In some stations, analysis and inference has been extended to 2000 meters.

Four water masses are found to be present. The most extensive one occupies most of the area above 1000 meters and consists largely of Subarctic Water mixed with a small amount of Pacific Equatorial Water. This water is flowing south and represents a part of the

California Current System. There is some seasonal variability, and during the summer some of this water may flow to the north. This water mass has been called Modified Subarctic Water.

A second water mass is the Modified Pacific Equatorial Water which flows north beneath the Modified Subarctic Water. This Modified Pacific Equatorial Water is found at a variable depth from below 800 meters at the continental slope to at and below 200 meters at 1400 kilometers from shore. No estimate is available as to the lower limit of this water mass. More and deeper stations plus other techniques will be needed to define its distribution and extent.

Flowing in the same northerly direction as the deep water mass, but only at the surface, very close inshore, and during the winter months, is a coastal water mass. This water is seasonally driven by the wind and is formed by surface exchange to the south. It is a surface feature and very seldom extends to depths greater than 400 meters.

A water mass was also found located in the upper 400 meters about 800 kilometers off shore. This water mass is apparently the result mixing of the Subarctic and Eastern North Pacific Central Water Mass.

Variations in the position of the water masses near shore have been described. The Modified Subarctic Water moves off shore during the summer months. This movement may be attributed to upwelling or to seasonal changes in the California Current System. It is also noted that the Modified Equatorial Water varies in depth but no seasonal fluctuation can be determined.

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APPENDIX

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