Seasonal variation in temperature, salinity, and density over the continental shelf off Oregon[1]

Adriana Huyer

School of Oceanography, Oregon State University, Corvallis 97331

Abstract

Seasonal variations in the hydrography of the waters over the continental shelf off Oregon were observed in a set of hydrographic data collected along 44°39'N at intervals of a few weeks to a few months from 1961 through 1970. The temperature is determined only partly by the local heating and cooling cycle: at the surface it is low (9°C) in winter, increasing in spring, lowest in summer, highest in early fall, and decreasing in winter; near the bottom, it is highest in winter and lowest in summer. The summer minimum is associated with coastal upwelling and a strong southward geostrophic current. Variations in salinity are governed by runoff, both locally and through the Columbia River effluent, as well as by coastal upwelling and advection. Neither temperature nor salinity is negligible in determining sigma-*t*. In summer, sigma-*t* decreases with distance offshore, and isopycnals slope downward from shore; in winter, sigma-*t* increases with distance offshore, and isopycnals slope upward from shore. Steric sea level also slopes downward from the coast in winter, and upward in summer. Alongshore geostrophic flow is southward in summer and northward in winter. The variations in temperature, salinity, and sigma-*t* are caused by seasonal cycles in the surface heat balance, precipitation and runoff, the local wind, and the alongshore flow.

The physical oceanography of the Oregon continental shelf has been studied extensively, but so far there have been only a few studies of seasonal variations there. Since the seasonal variations are large, neglecting them may result in serious errors in interpreting observations of other phenomena. The purpose of this paper is to describe the seasonal variations in the temperature, salinity, and sigma-*t* of the water over the Oregon continental shelf, their implications, and their causes. The data that provide the basis for this study were collected along the Newport Hydro Line, a line of hydrographic stations along 44°39'N, which were occupied at intervals of a few weeks to several months over a 10-year period from 1961 to 1970. Near the coast, stations were separated by 18 km beginning 9 km from shore (Fig. 1). At each station, observations were made by Nansen or NIO water sampling bottles and reversing thermometers, and salinities were determined by titration or with an inductive salinometer (Oregon State Univ. School Oceanogr. Data Rep. 7, 12, 24, 27, 33, 35, 36, 42, 49). During some years (e.g. 1966 and 1968) the stations were occupied almost every month; during others (e.g. 1965) as many as 3 months passed between consecutive occupations.

This study was made possible through the efforts of W. V. Burt, J. G. Pattullo, and other scientists at Oregon State University who believed in the value of repeated observations along the Newport Hydro Line. Many of the observations were made on cruises supported by the Office of Naval Research.

Description of observations

Because of the difficulty of communicating directly in three dimensions (depth, distance offshore, and time), the data are displayed in several different two-dimensional ways. Figure 2 shows a typical distribution of each parameter in the time-depth plane for a single year. Both temperature and salinity distributions show

[1] This study was begun while the author was employed by the Marine Environmental Data Service, Environment Canada. It was partly supported by the Coastal Upwelling Ecosystems Analysis program of the Office for the International Decade of Ocean Exploration under National Science Foundation grants IDO 71-04211 and OCE 76-00594.

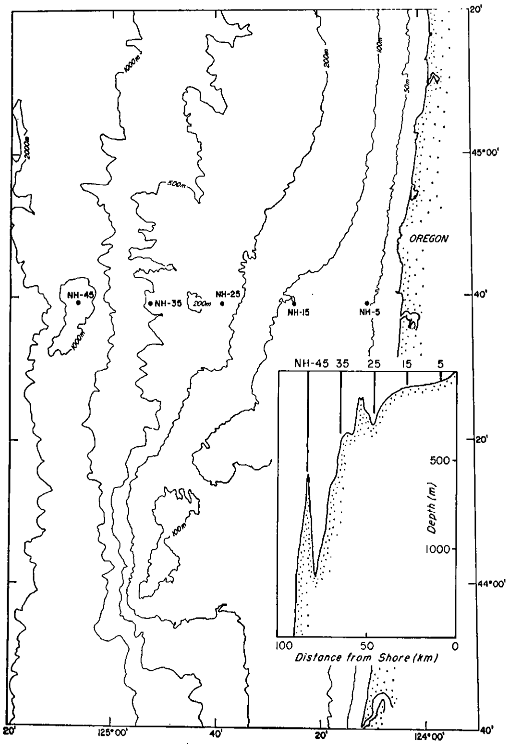

Fig. 1. Location of hydrographic stations along Newport Hydro Line over continental shelf and upper part of continental slope.

a domelike structure, with isograms rising from the bottom in spring (April, May, and/or June) and descending in fall (September, October, and November). Since temperature decreases and salinity increases with depth, the isopycnals show a similar structure. In the near-surface water, isohalines descend in late winter or early spring and rise again in early summer; isotherms descend in early fall and rise again early in winter. As a result, there are two minima in the near-surface density: one in spring due to low salinities, one in fall due to high temperatures.

Figure 3 shows the seasonal variation of each parameter at the sea surface and near the bottom (about 50 m at NH-5, 75 m at NH-15, and 200 m at NH-25). Data points are shown for all years except 1962 and 1969, which appeared somewhat exceptional. The dashed and solid lines represent the inferred seasonal cycles: their shapes were determined by first plotting the curves separately for each year, mentally combining these curves, and smoothing the result. Although this method is highly subjective, it results in curves more representative of any given year than would be obtained by averaging the data by month or week, because the timing of extrema varies from year to year.

At the surface, the temperature shows maxima in June and early autumn, and minima in winter and summer; the summer minimum decreases in intensity with distance offshore. Nearshore, the summer temperature minimum coincides with a

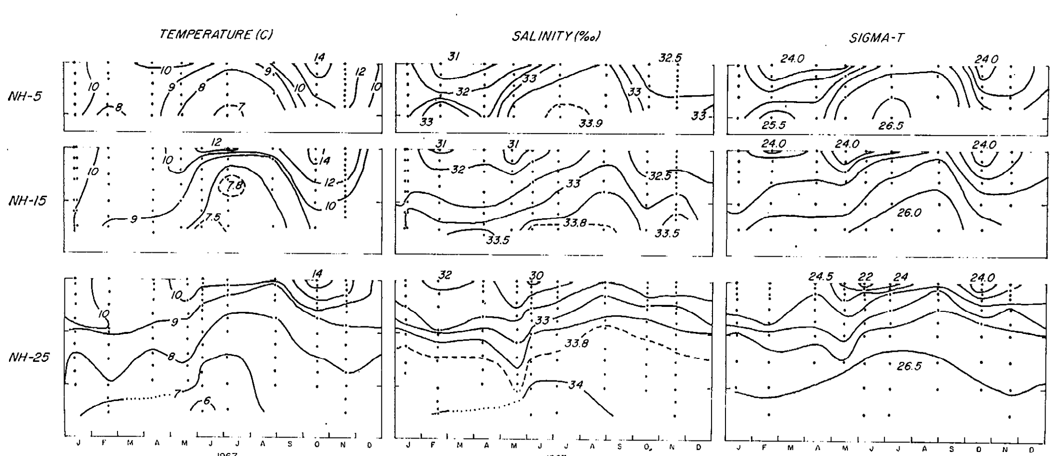

Fig. 2. Time-depth distribution of temperature, salinity, and sigma-*t* at NH-5, NH-15, and NH-25 during 1967.

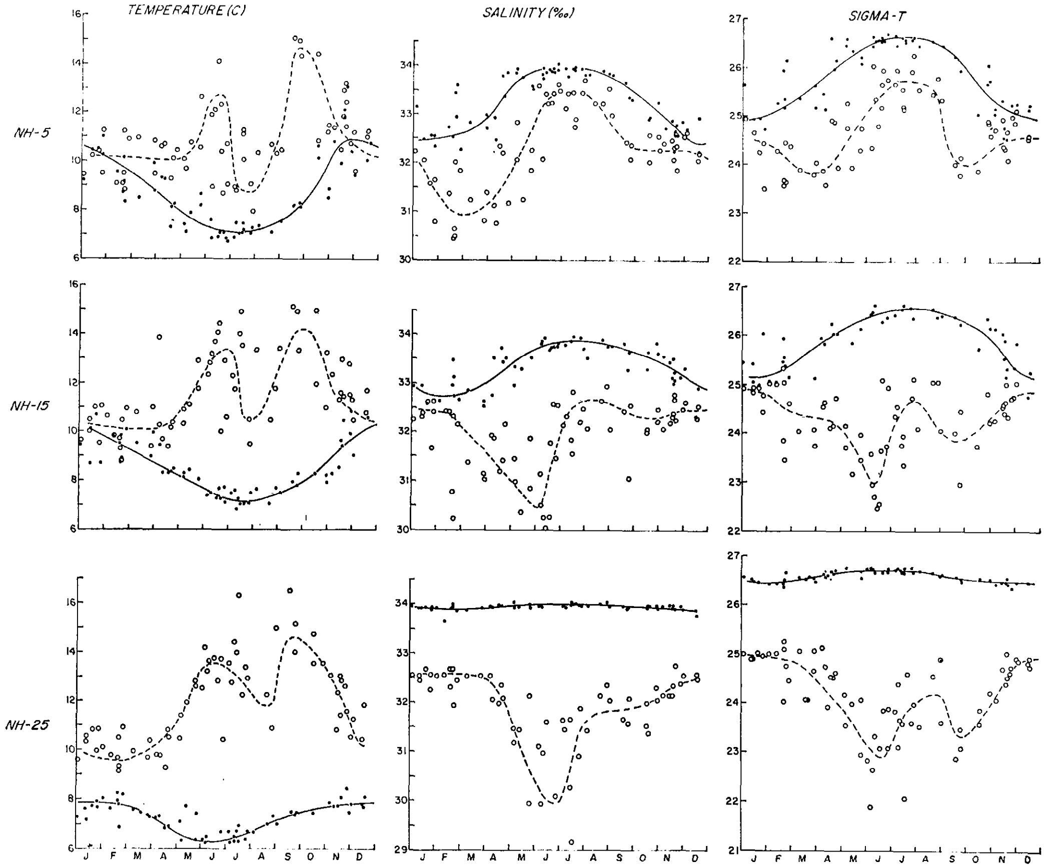

Fig. 3. Seasonal variation in temperature, salinity, and sigma-t at sea surface (○) and near deep bottom (●). Data points from 1961, 1970, and 1963–1968. Dashed and solid lines are inferred seasonal cycles (*see text*).

maximum in salinity so that the surface density is greatest in summer. At the outer shelf (NH-25) the summer salinity minimum coincides with a temperature maximum, producing a density minimum in June. Near the bottom, each parameter has a single maximum and minimum during the year. The temperature minimum occurs about the same time as the salinity maximum, and the temperature maximum as the salinity minimum, with a resulting density maximum in summer and a density minimum in winter. Nearshore, the difference between surface and near-bottom properties is greatest in spring and fall and least in winter; farther offshore the difference is greatest in early summer.

From the time-depth plots of the parameters for each year and from the seasonal variation at the surface and in the deep water, we picked 2 months of each year to represent winter and summer conditions. Criteria for choosing the winter month included weak stratification at NH-15, warmest deep temperature, and more-or-less level isotherms; the month chosen to represent winter was January in 1961, 1966, and 1970 and February in 1962–1965 and 1967–1969. Criteria for summer included shallowest depth of low-temperature isotherms and high-salinity isohalines and coldest deep temperature; the month chosen to represent summer was July for each year from 1962–1968, June 1970, Au-

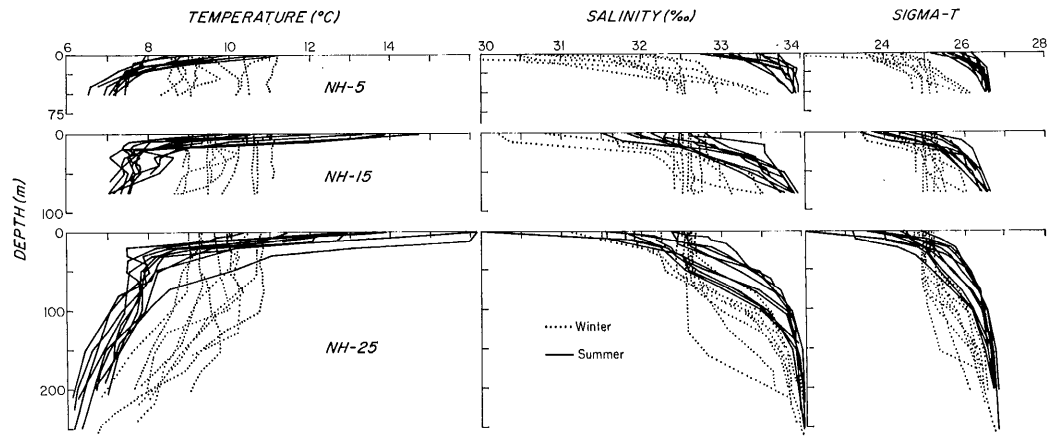

Fig. 4. Summer and winter profiles of temperature, salinity, and sigma-*t*. Summer values in August 1961, July 1962–1968, September 1969, and 28 June 1970. Winter values in January 1961, 1966, and 1970, February 1962–1965, and 1967–1969.

gust 1961, and September 1969. Vertical profiles of the temperature and salinity observations during these months are shown in Fig. 4. Nearshore, at NH-5, the vertical salinity gradient is strong in winter but weak in summer; in contrast, the vertical temperature gradient is weak in winter but strong in summer. Sigma-*t* profiles resemble the salinity profiles, and the density stratification at NH-5 is stronger and more variable in winter than in summer. At NH-5, the water is more saline, cooler, and denser in summer than in winter over almost the entire water column.

Over the midshelf, at NH-15, the vertical gradient of all three parameters is usually greater in winter than in summer. As at NH-5, year-to-year differences are greater in winter than in summer and smaller than the difference between the two seasons. The surface water is less saline, warmer, and hence less dense in summer than winter, but at middepth and below the water is more saline, cooler, and denser in summer than in winter. Temperature inversions similar to those described by Huyer and Smith (1974) are seen at NH-15 in almost every summer profile but in only a few of the winter profiles.

Farther from shore, at NH-25, there is a surface mixed layer in winter, 25–50 m deep, with about the same temperature and salinity as at NH-15. At the surface, the water is warmer and less saline in summer than in winter, but at 50 m the water is cooler and more saline in summer. At greater depths, the water is much cooler and slightly more saline in summer than in winter. Winter and summer salinity profiles begin to converge near the bottom, but the differences between winter and summer near-bottom temperatures usually exceed 1°C. Year-to-year variations in the winter temperature are as large at 200 m as they are at the surface, and about the same as at NH-5 and NH-15.

Comparison of the vertical profiles of temperature and salinity with those of sigma-*t* (Fig. 4) shows how important salinity is in determining the density distribution over the Oregon shelf. At NH-5, winter and summer temperature profiles overlap but sigma-*t* profiles do not. At NH-15 and NH-25 temperature inversions are common but stability is maintained by the vertical salinity gradient.

A careful study of the vertical profiles of sigma-*t* (Fig. 4) gives information about the slope of the isopycnals with distance offshore and depth. For example, in summer, the 26.5 isopycnal slopes upward toward shore from about 150 m at NH-25, through about 75 m at NH-15, to about 50 m at NH-5. These slopes are shown much

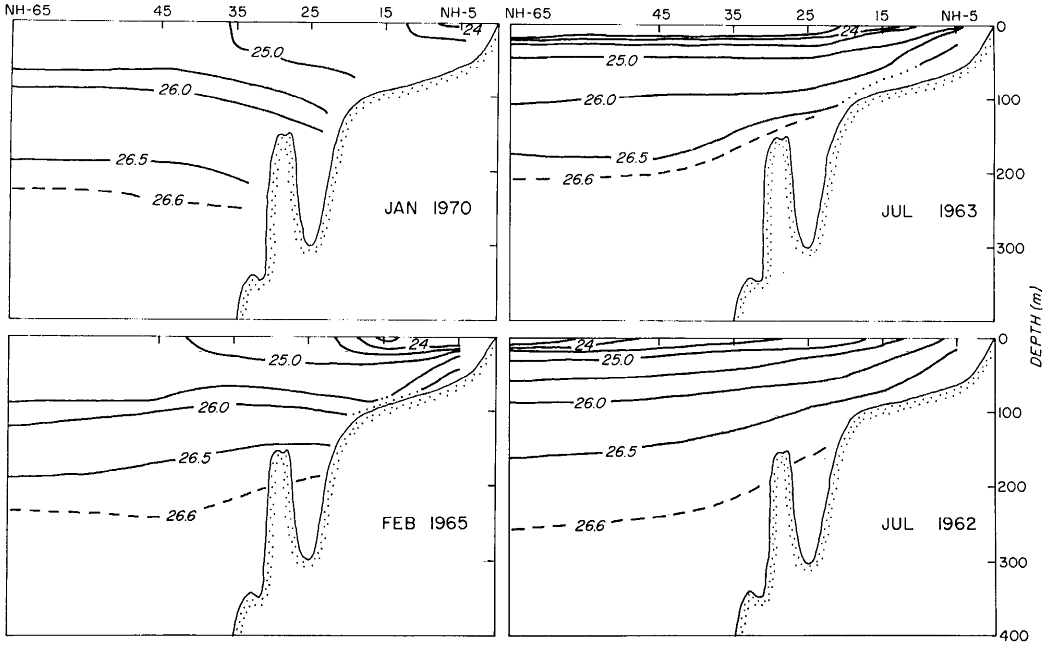

Fig. 5. Vertical sections of sigma-t, showing normal and extreme isopycnal slopes for summer and winter.

more clearly in vertical sections (Fig. 5). Isopycnals are generally level or slope downward toward the coast in winter. An extreme example of this occurred in January 1970; in February 1965, the near-bottom isopycnals slope upward near the coast, but near-surface isopycnals are about level. Winter observations from other years fall between these extremes. In summer, isopycnals slope upward toward the coast; in July 1963 isopycnal slopes are less steep, and in July 1962 isopycnal slopes are steeper than is usual for summer. Even so, the 1965 winter distribution, with some upward-sloping isopycnals, does not resemble the 1963 summer distribution as closely as it does the 1970 winter distribution. Hence, we observe that year-to-year variations in the same season are smaller than the seasonal variation.

Discussion

Temperature-salinity characteristics—Figures 2, 3, and 4 show that at some times temperature and salinity vary together, but at other times they do not. This behavior suggests variations in the temperature-salinity (T-S) characteristics of the water. We plotted temperature against salinity for the months chosen earlier to represent summer and winter (Fig. 6) to see if there was a systematic difference between the two seasons. Envelopes were drawn to include almost all data points from the two different seasons, and it is obvious from Fig. 6 that there is indeed a difference between the T-S characteristics from the two seasons. At NH-5, the water is both colder and more saline in summer than in winter. In winter, all the water there has salinities less than those in the permanent halocline, which occurs from about 32.8–33.8‰ (Fleming 1958). In summer, the water at NH-5 has salinities corresponding to water in the lower part of or below the permanent halocline. At NH-15, only water from the upper part of the halocline and above is observed in winter, when the halocline is deep; in summer, when the halocline is shallower, water from the lower part of the halocline is also observed. In the salinity range corresponding to the permanent

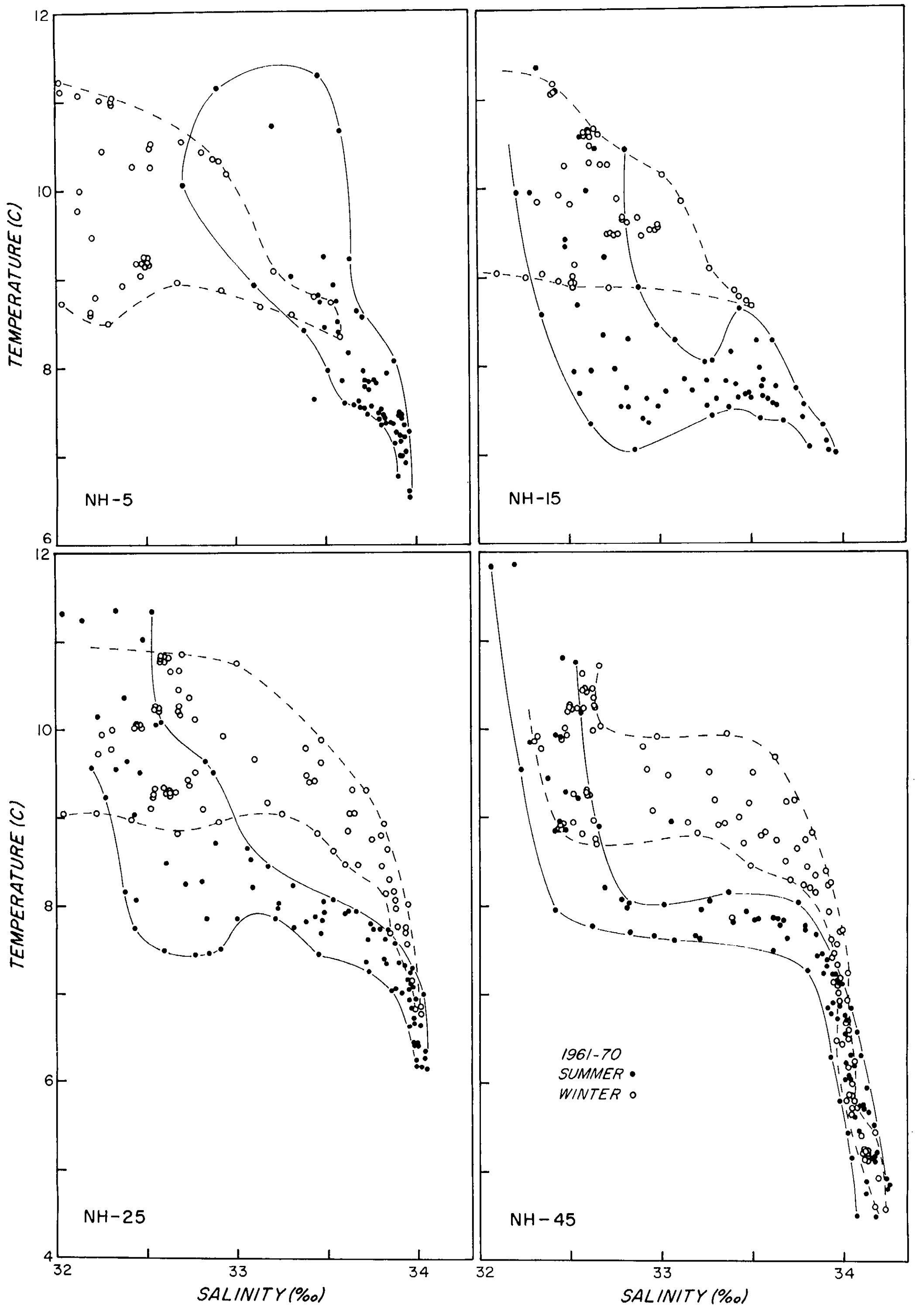

Fig. 6. Temperature-salinity characteristics in summer and winter, at NH-5, NH-15, NH-25, and NH-45. Legend to Fig. 4 lists dates of observations.

halocline, water is more than a full degree colder in summer than in winter. At NH-25, and farther seaward, water from above, below, and within the halocline is present in both seasons. Again, we see that the water in the halocline is colder in summer than in winter, although the difference is not as great at NH-25 as it is at NH-15. This difference is also observed at NH-35 and NH-45 but continues to decrease with distance offshore and is not observed at NH-85, about 150 km from shore. In summer, the halocline temperature is lowest at about NH-15, and increases farther seaward with distance from shore. In winter, temperature in and above the halocline appears to decrease with distance from shore.

Fleming (1958) has shown that the temperature in the halocline decreases with increasing latitude in the central North Pacific. He observed that north of 45°N (where flow is predominantly northward) the halocline temperature increases on approaching land and that south of 45°N (where flow is predominantly southward) the halocline temperature decreases on approaching land. The data presented here come from 44°39′N, very near Fleming's division line. We observe halocline temperatures to increase toward shore (implying northward flow along the continent) in winter and to decrease toward shore (implying southward flow) in summer. This seasonal variation of the flow has been observed in direct current measurements over the continental shelf (Huyer et al. 1975) and by drift bottles (Wyatt et al. 1972). It is also apparent in the estimates of the geostrophic flow relative to 600 db described below. The *T-S* characteristics suggest that the seasonal variation in the flow extends seaward to at least NH-45, 80 km from the coast.

The seasonal change in the temperature of the halocline was not detected in earlier studies of the *T-S* characteristics of water along the Oregon coast (Pattullo and Denner 1965; Bourke and Pattullo 1974). These studies used primarily data from shore stations; because of the heating and mixing in the nearshore zone such data are not truly representative of the water over the shelf.

Steric height and sea level—Associated with changes in the density of a column of seawater are changes in its volume, and hence its height, called the "steric height." Changes in steric height are computed relative to a reference surface, usually chosen to be one below which the density changes are negligible compared with those above. In regions of shallow water, estimates of steric height depend strongly on the method of extrapolating isopycnals inshore from the intersection between the reference surface and the ocean bottom (Reid and Mantyla 1976). Brunson and Elliott (1974) had concluded that changes in steric height accounted for only 30% of the observed seasonal change in sea level at Newport, Oregon; they implicitly assumed that surfaces of steric height were level under the sea floor. Reid and Mantyla (1976), on the other hand, extrapolating the slopes of steric height surfaces into the continental slope and shelf, showed that steric height changes can account for the entire seasonal variation in sea level measured by the tide gauge at Newport.

We used data from the Newport Hydro Line and the method described by Reid and Mantyla (1976) to examine the seasonal variation of steric height over and near the continental shelf. Starting with the nearest offshore station pair reaching 600 db, the gradient of steric height along the deepest common pressure surface was extrapolated to the next inshore station; this extrapolation was continued inshore to NH-5. The steric height of the sea surface relative to 600 db was calculated in this way for every possible occupation of the line during the 10-year period (Fig. 7). Mean monthly sea level at Newport is shown for the 9-year period beginning in 1967; agreement between the measured sea level and steric height at NH-5 is good in both amplitude and phase, especially considering the difference in averaging.

The amplitude of the seasonal cycle decreases rapidly with distance from shore. Nearshore, steric height is least in summer and greatest in winter; the summer minimum occurs progressively later across the shelf and slope. At NH-45, there is very

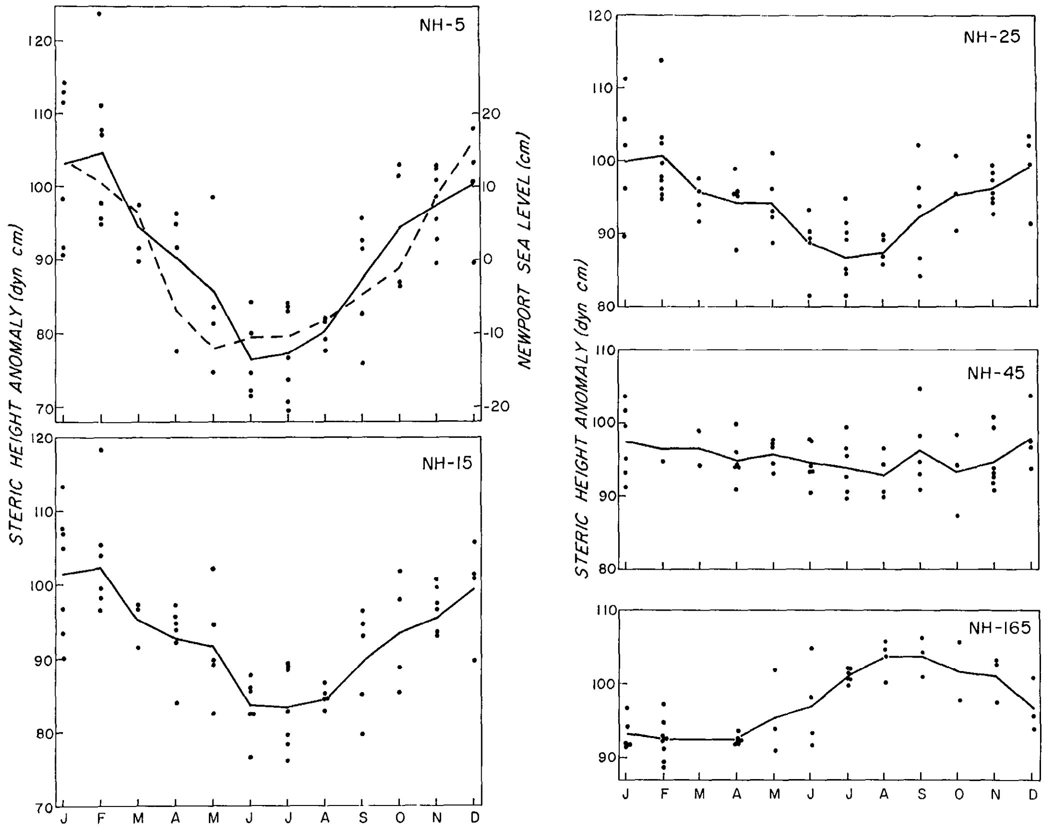

Fig. 7. Steric height anomaly at surface relative to 600 db, at NH-5, NH-15, NH-25, NH-45, and NH-165, about 300 km from coast. Points plotted without regard to date within each month. Solid line connects monthly mean values. Dashed line is mean monthly sea level at Newport, Oregon, 1967–1975, above 9-year mean.

little seasonal variation: changes from year-to-year in any given month are larger than the seasonal variation of the monthly mean. At NH-165, about 300 km from shore, the steric height is greatest in late summer and least in late winter as expected from the annual heating and cooling cycle; the seasonal variation of steric height is similar to that reported for station 40150 (at 40°30′N, 150°30′W) by Pattullo et al. (1955).

Since the amplitude of the seasonal change in steric height is a function of distance offshore, the slope of the sea surface also varies seasonally (Fig. 8). In March and October, there is no significant sea level slope between NH-5 and NH-45; in summer, the sea surface slopes downward from NH-45 to the coast, and in winter the sea surface slopes upward toward the coast. Between NH-45 and NH-165, the slope is downward toward the coast from May to September and upward between December and May.

Geostrophic flow—The computations of steric height relative to 600 db can also be used to estimate the geostrophic flow. The flow at 600 db is probably quite weak compared to flow near the surface. Hence the geostrophic flow relative to 600 db is a reasonable estimate of the absolute geostrophic flow. From Fig. 8, we saw that the sea level over the continental shelf slopes downward toward shore in summer and upward toward shore in winter: the geostrophic flow at the surface must therefore

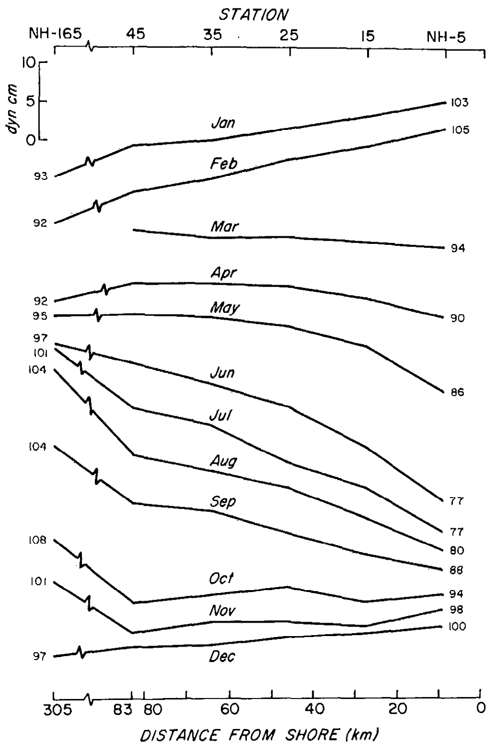

Fig. 8. Mean monthly steric height anomalies at surface relative to 600 db, as function of distance from shore.

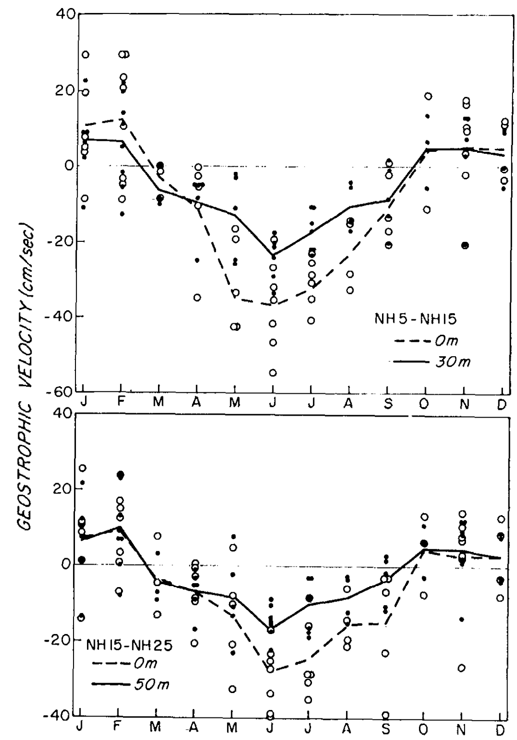

Fig. 9. Estimates of alongshore geostrophic flow between NH-5 and NH-15, at surface (○) and at 30 m (●); and between NH-15 and NH-25, at surface and at 50 m.

be southward in summer and northward in winter.

Estimates of the geostrophic flow over the shelf are shown in Fig. 9 for each occupation of the Newport Line. Between October and February, the geostrophic flow is usually northward, but southward flow is also observed; on the average, the flow is northward and there is little or no mean vertical shear. In summer, southward flow with a mean vertical shear is predominant. At the surface, almost no estimates of the geostrophic flow between March and September are northward; in fact, none are northward for the inner part of the shelf between March and August.

Although a mean vertical shear is apparent in the summer southward flow, the estimates of the geostophic flow do not indicate the presence of a poleward undercurrent over the shelf. That such an undercurrent is present in late summer is well known from direct current observations (e.g. Huyer et al. 1975). Its absence in the estimates of geostrophic flow can be attributed to two independent causes: the lack of near-bottom temperature and salinity data, and the need to extrapolate slopes of equal steric height surfaces into the continental slope and shelf. The latter probably leads to significant errors, since poleward flow seems to be enhanced along the continental slopes of both Washington (Cannon et al. 1975; Reed and Halpern 1976) and California (Wooster and Jones 1970), with a width comparable to the spacing (≃35 km) of the hydrographic stations seaward of the slope. Extrapolating across such a narrow poleward current would result in overestimates of the downward slope of surfaces of equal steric height, and hence overestimates of the southward current. Except for the absence of the poleward undercurrent, the estimates of geostrophic flow agree well with the seasonal variation of the flow inferred from direct current observations (Huyer et al. 1975).

Causes of seasonal changes—The primary processes causing the seasonal changes in water over the Oregon shelf are surface heating and cooling, precipitation and evaporation, wind stress, and the large-scale circulation of the Northeast Pacific. These processes combine to produce secondary phenomena, such as coastal upwelling and concentrations of surface runoff, which in turn affect the distributions of temperature, salinity, and sigma-*t*.

A computation of the net surface heat exchange for this region (Lane 1965) shows that there is maximum cooling in January, maximum heating in July, and no net heat flux in March and in September or October. Comparison of Lane's seasonal heat flux estimates with the observed rate of heat storage (Pattullo et al. 1969) shows that the two are similar offshore, but that over the continental shelf the surface heat flux has about four times the amplitude of observed local heating; the differences imply warm advection (northward flow) from September through January and cold advection (southward flow) from February through August. This is consistent with the seasonal change in the temperature-salinity characteristics and also with the estimates of geostrophic flow over the continental shelf. Clearly, the local heat flux at the surface cannot be the main cause of the seasonal temperature variation over the shelf (Fig. 3), since a temperature minimum occurs when local heat flux is greatest.

Early studies of the evaporation-precipitation balance showed that annual precipitation exceeds evaporation in the subarctic Pacific (Jacobs 1951) so that dilution occurs in the surface layer (Tully and Barber 1960). More recently, it has been shown that oceanic rainfall is much less than coastal rainfall, and that the former cannot account for the freshwater input to the coastal waters of Oregon (Elliott and Reed 1973; Reed and Elliott 1973). Rainfall over the coast and adjacent land is highly seasonal (more in winter than in summer). It enters the continental shelf region as runoff from coastal rivers and streams and through the Columbia River. The coastal rivers have only small basins, and maximum runoff occurs soon after maximum precipitation; its effect is apparent in the low salinities observed at NH-5 in late winter (Fig. 3). The Columbia River has a much larger drainage basin; much of its precipitation occurs as snow, and maximum runoff is in June (Barnes et al. 1972). At sea, the effluent forms a thin (<20 m) plume of low salinity water whose position is determined by the wind stress and surface currents.

The wind along the Oregon coast is predominantly southward and northeastward in winter; it is largely governed by the North Pacific high pressure cell and a low pressure cell over the land whose strengths and positions vary seasonally (Reid et al. 1958). Away from the immediate influence of the land, at 45°N, 125°W, the alongshore wind fluctuates a great deal in winter, with occasional periods of southward wind; in summer, fluctuations are smaller and there are few periods when the wind is northward (Bakun 1975). Bakun (pers. comm.) has supplied 6-hourly estimates of wind stress at 45°N, 125°W; Table 1 summarizes these for the summer and winter seasons for the 5-year period from 1967–1972. In both winter and summer, the wind stress is about three times as strong when it is in the predominant direction; the wind is southward about 30% of the time in winter, and northward about 20% of the time in summer. The strength of the winter southward winds is about the same as the mean wind stress in summer; they may well be strong enough to cause the southward geostrophic currents that occur occasionally in winter (Fig. 9). The northward winds in summer are rather weak, and it is not surprising that the estimates of geostrophic current show no northward flow in summer. It is remarkable, however, that the mean annual

Table 1. Summary of Bakun's 6-hourly estimates of northward component of wind stress at 45°N, 125°W during summer and winter seasons, 1967–1972. Columns show date of first day of each season [chosen by inspection of Bakun's (1975) tables]; number of 6-hourly estimates; percentage of time alongshore wind stress was northward; mean of northward wind-stress estimates; mean of southward wind-stress estimates; and mean wind stress for season. Units of wind stress are dynes cm^{-2}.

	N	% Northward	$\bar{\tau}_N$	$\bar{\tau}_S$	$\bar{\tau}$
		WINTER			
28 Sep 67	732	74	1.46	-0.44	.97
2 Oct 68	828	72	1.20	-0.33	.77
15 Sep 69	828	72	1.11	-0.38	.69
15 Oct 70	748	69	1.13	-0.35	.67
18 Oct 71	708	67	0.92	-0.42	.48
		SUMMER			
29 Mar 68	748	20	0.22	-0.61	-0.44
27 Apr 69	564	10	0.31	-0.51	-0.43
10 Apr 70	750	17	0.16	-0.55	-0.43
14 Apr 71	748	22	0.24	-0.47	-0.31
12 Apr 72	804	14	0.22	-0.45	-0.36

surface current is southward (Fig. 9 and Huyer et al. 1975), while the mean annual wind stress is northward (Table 1).

Because of the Coriolis effect, currents associated with the wind stress have a component to the right of the wind. In winter, surface currents are northward and toward the coast: the Columbia River effluent lies along the Washington coast and does not affect the Oregon shelf region; the runoff from Oregon coastal rivers is concentrated nearshore and reduces the surface salinity at NH-5. In summer, the surface current is southwestward and the Columbia River effluent lies southward and offshore of the Oregon coast (Barnes et al. 1972); its effects are apparent in early summer at NH-15 and NH-25. The southward wind stress in summer, with the associated offshore transport, results in upwelling along the coast. The upwelling itself is highly variable; it is governed by the several day fluctuations (events) in wind stress (Huyer et al. 1974; Halpern 1976). However, its effects (presence of cold, dense water at shallow depths nearshore, sloped isopycnals, enhanced southward surface flow) persist through summer (Huyer 1974).

Advection of water properties by alongshore currents is seasonal because of the seasonal cycle in the currents. Over the shelf, the seasonal cycle in the alongshore flow is fairly well known (Huyer et al. 1975), but farther seaward it is not. Drift bottle data and some moored current meter data show that the same surface flow pattern (northward in winter and southward in summer) occurs well seaward of the shelf. This offshore seasonal cycle causes the seasonal differences in the halocline temperatures at NH-45 (Fig. 6). The offshore southward flow may be part of the California Current, and the northward flow has been linked to the Davidson Current (Burt and Wyatt 1964), which is usually considered to lie inshore of the California Current. However, the steric height relative to 600 m (Fig. 8) shows no evidence of mean southward flow offshore from December through May; Dodimead and Pickard (1967) also presented indirect evidence that southward flow does not occur in this part of the Pacific in winter. It seems likely that the boundary between the northward Alaska Current and the southward California Current shifts seasonally, as suggested by Fleming (1955).

The dominant cause of the seasonal variation in oceanographic parameters is the wind. It determines whether coastal upwelling occurs, the position of local runoff and the Columbia River plume, and to a limited extent the strength and direction of the alongshore geostrophic flow. However, the other processes (heating, runoff, and large-scale circulation) are also important, and we cannot readily predict the oceanographic parameters from a knowledge of the factors that influence them. Since there is a great deal of regularity in the seasonal cycles and since they are generally larger than year-to-year variations, they are themselves useful for predicting values of these parameters.

References

Bakun, A. 1975. Daily and weekly upwelling indices, west coast of North America, 1967–1973. NOAA Tech. Rep. NMFS SSRF-693.

Barnes, C. A., A. C. Duxbury, and B. A. Morse.

1972. Circulation and selected properties of the Columbia River effluent at sea, p. 41–80. *In* A. T. Pruter and D. L. Alverson [eds.], The Columbia River Estuary and adjacent ocean waters. Univ. Wash.

BOURKE, R. H., AND J. G. PATTULLO. 1974. Seasonal variation of the water mass along the Oregon–northern California coast. Limnol. Oceanogr. **19**: 190–198.

BRUNSON, B. A., AND W. P. ELLIOTT. 1974. Steric contribution to the seasonal oscillation of sea level off Oregon. J. Phys. Oceanogr. **4**: 304–309.

BURT, W., AND B. WYATT. 1964. Drift bottle observations in the Davidson Current off Oregon, p. 156–165. *In* Studies on oceanography. Univ. Tokyo.

CANNON, G. A., N. P. LAIRD, AND T. V. RYAN. 1975. Flow along the continental slope off Washington, autumn, 1971. J. Mar. Res. **33** (suppl.): 97–107.

DODIMEAD, A. J., AND G. L. PICKARD. 1967. Annual changes in the oceanic-coastal waters of the eastern subarctic Pacific. J. Fish. Res. Bd. Can. **24**: 2207–2227.

ELLIOTT, W. P., AND R. K. REED. 1973. Oceanic rainfall off the Pacific northwest coast. J. Geophys. Res. **78**: 941–948.

FLEMING, R. H. 1955. Review of the oceanography of the northern Pacific. Int. N. Pac. Fish. Comm. Bull. **2**: 1–43.

———. 1958. Notes concerning the halocline in the northeastern Pacific Ocean. J. Mar. Res. **17**: 158–173.

HALPERN, D. 1976. Structure of a coastal upwelling event observed off Oregon during July 1973. Deep-Sea Res. **23**: 495–508.

HUYER, A. 1974. Observations of the coastal upwelling region off Oregon during 1972. Ph.D. thesis, Oregon State Univ. 149 p.

———, R. D. PILLSBURY, AND R. L. SMITH. 1975. Seasonal variation of the alongshore velocity field over the continental shelf off Oregon. Limnol. Oceanogr. **20**: 90–95.

———, AND R. L. SMITH. 1974. A subsurface ribbon of cool water over the continental shelf off Oregon. J. Phys. Oceanogr. **4**: 381–391.

———, ———, AND R. D. PILLSBURY. 1974. Observations in a coastal upwelling region during a period of variable winds (Oregon coast, July 1972). Tethys **6**: 391–404.

JACOBS, W. C. 1951. The energy exchange between the sea and the atmosphere and some of its consequences. Bull. Scripps Inst. Oceanogr. **6**: 27–122.

LANE, R. K. 1965. Climate and heat exchange in the oceanic region adjacent to Oregon. Ph.D. thesis, Oregon State Univ. 115 p.

PATTULLO, J., W. V. BURT, AND S. A. KULM. 1969. Oceanic heat content off Oregon: Its variations and their causes. Limnol. Oceanogr. **14**: 279–287.

———, AND W. DENNER. 1965. Processes affecting seawater characteristics along the Oregon coast. Limnol. Oceanogr. **10**: 443–450.

———, W. MUNK, R. REVELLE, AND E. STRONG. 1955. The seasonal oscillation in sea level. J. Mar. Res. **14**: 88–155.

REED, R. K., AND W. P. ELLIOTT. 1973. Freshwater input to coastal waters off the Pacific Northwest. Limnol. Oceanogr. **18**: 683–686.

———, AND D. HALPERN. 1976. Observations of the California undercurrent off Washington and Vancouver Island. Limnol. Oceanogr. **21**: 389–398.

REID, J. L., AND A. W. MANTYLA. 1976. The effect of the geostrophic flow upon coastal sea elevations in the northern North Pacific Ocean. J. Geophys. Res. **81**: 3100–3110.

———, G. I. RODEN, AND J. G. WYLLIE. 1958. Studies of the California Current system. Cal. COFI Prog. Rep. **6**: 27–57.

TULLY, J. P., AND F. G. BARBER. 1960. An estuarine analogy in the subarctic Pacific Ocean. J. Fish. Res. Bd. Can. **17**: 91–112.

WOOSTER, W. S., AND J. H. JONES. 1970. California Undercurrent off northern Baja California. J. Mar. Res. **28**: 235–250.

WYATT, B., W. V. BURT, AND J. G. PATTULLO. 1972. Surface currents off Oregon as determined from drift bottle returns. J. Phys. Oceanogr. **2**: 286–293.

Submitted: 20 January 1976
Accepted: 15 November 1976