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Curtis Allan Collins for the Master of Science in Oceanography
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Title STRUCTURE AND KINEMATICS OF THE PERMANENT OCEANIC FRONT OFF THE OREGON COAST

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Using the hydrographic data collected by the ACONA from June 1961 to May 1963, the Oregon coastal front has been examined. Representative sigma-t surfaces were chosen to delineate the front, and changes in position of these surfaces with time were used to obtain zonal flow rates for the frontal and surface layers.

From May to early October upwelling resulted in offshore flow. Onshore flow was indicated from late October to January, and indeterminate zonal flow occurred during the remainder of the year. Flow within the front agreed with these surface flows in ten of the fourteen observational periods.

STRUCTURE AND KINEMATICS OF THE PERMANENT OCEANIC FRONT OFF THE OREGON COAST

by

Curtis Allan Collins

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Professor of Oceanography, Department of Oceanography

In Charge of Major

Redacted for Privacy

Chairman, Department of Oceanography

Redacted for Privacy

Dean of the Graduate School

Typed by: Rose Bethel

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THE PROBLEM AND DEFINITIONS OF TERMS USED

The oceanic troposphere is usually thought of as a nearly homogeneous surface layer lying above a water mass. These two layers are separated by a region of rapid density change, the pycnocline, which is often considered as a discontinuity or "front," particularly when it intersects the geopotential surfaces at some angle. This condition is approximated by nature in many areas, and the front is very useful for establishing boundary conditions for hydrodynamic considerations.

In this paper the author has examined the characteristics and behavior of a front off the Oregon coast. Here, the structure of the oceanic troposphere is such that the thickness of the front is normally greater than the thickness of the upper layer as the latter is either thin or nonexistent. Below the front, which may extend to a depth of 300 meters at offshore stations, modified Pacific Subarctic water is found.

The Problem

It was the purpose of this study (1) to examine the density structure of the front, (2) to infer from changes in this structure water flow that occurred within the front, as well as that flow which occurred above the front, and (3) to relate structure and flow so determined to oceanographic and climatological processes known to occur off the coast of Oregon.

From an oceanographic viewpoint, the importance of this study is that it is a step in completing the structural organization of Oregon coastal waters. Also, inferences that can be drawn from local data may be applicable to other areas of the world oceans.

There are also some immediate applications possible. Virtually all frontal features, i.e., intensity, MLD, net density difference, etc., are of prime importance to submariners if their vessels are to be trimmed properly. Refraction of sound by the pycnocline, primarily due to the associated thermocline, effects sonar and scientific sound measurements. Finally, surface fronts have been shown to be areas of whale and fish abundance (25).

Definitions of Terms Used

Density. The density, $\rho_{s,\theta,p}$, of a parcel of sea water is a function of three parameters: temperature (θ), salinity (s), and pressure (p). When working with density, oceanographers have introduced the notation $\sigma_{s,\theta,p}$ to avoid repetition. The definition of $\sigma_{s,\theta,p}$ is: $\sigma_{s,\theta,p} = (\rho_{s,\theta,p} - 1)1000$. For example, a density of 1.02455 corresponds to $\sigma = 24.55$.

When evaluated at atmospheric pressure, the quantity corresponding to $\sigma_{s,\theta,p}$ is simply written σ_t, i.e., sigma-t. The significance of sigma-t surfaces is best described by Sverdrup, et.al. (22, p. 416):

> ....in the ocean no surfaces exist along which interchange or mixing of water masses can take place without altering the distribution of mass and thus altering the potential energy and entropy of the system (except in the trivial case that isohaline and isothermal surfaces coincide with level surfaces). There must exist, however, a set of surfaces of such a character that the change of potential energy and entropy is at a minimum if interchange and mixing takes place along these surfaces. It is impossible to determine the shape of these surfaces, but the sigma-t surfaces approximately satisfy the conditions.

For this reason, the density parameter σ_t finds widespread use in oceanography. As the pressure term is negligible at the shallower depths to be considered, this density parameter was especially appropriate for this study. Thus, within the text of this thesis the term "density" refers specifically to the density approximated by sigma-t values.

Front. The term "front" originated within the science of meteorology where it has been defined (13, p. 273) as the interface or transition zone between two air masses of different density. Oceanographic usage of the term "front," requires only the substitution of "water" for "air" in this definition. Thus, an oceanic front is defined as the interface between two water masses of different density. It is to be noted that the terms "front" and "pycnocline" are equivalent.

Since ambiguous application of the term "front" has occurred in oceanography (3), Huschke's further comments are appropriate (13, p. 278):

> The term front is used ambiguously for: (a) frontal zone, the three-dimensional zone or layer of large horizontal density gradient, bound by (b) frontal surfaces across which the density gradient is discontinuous...; and (c) surface front, the line of intersection of a frontal zone ...with the earth's surface...

Within this thesis, the terms "oceanic front," "front," pycnocline," and "frontal zone" will be used interchangeably. The term "frontal surface" will not be used. "Surface front" will be defined according to Huschke's category (c) above.

Halocline, thermocline, pycnocline. The halocline is a layer of the ocean in which the change of salinity with depth is noticeably larger than in the layers above and below the halocline. The thermocline and pycnocline are defined in a similar manner by reference to changes of temperature with depth and changes of density with depth, respectively.

Mixed layer depth (MLD). The mixed layer depth is the depth below the sea surface to which mixing has established isothermal conditions (6, p. 1).

Station and Date Symbols. To identify a hydrographic station, Oregon State University adopted a two-group symbol. The first group consists of two or three letters which represent the hydrographic station "line," or series of stations. Each line is on a parallel of latitude. The second group consists of one to three numerals which indicate the distance of the hydrographic station from the coast. Example: NH105 is a station 105 nautical miles due west of Newport, Oregon. Other hydrographic station line symbols are BH (Brookings), CH (Coos Bay), and AH (Astoria).

Occasionally in this paper a date group will be used with the station symbol, and more often, with only the station line designator. The date group consists of a four-numeral group, the first two numerals of which indicate the year and the last two numerals indicate the month. Example: 6206 represents June 1962.

Upper Zone. The upper zone has been defined (7, p. 159) as the layer of water included between the base of the halocline and the surface. Thus, it would include, besides the halocline, the thermocline and the surface layer, since off the Oregon coast the halocline is always the deepest of the three.

Organization of the Thesis

The thesis is organized into four parts. The first part is a review of pertinent literature. The second describes the method used to obtain a graphical representation of the structure of the upper layer and presents the results obtained by the use of this method. The next section includes the application of a technique to evaluate the graphical representations kinematically. The final part treats those dynamical considerations obviously necessary for the completeness of the thesis; however, no complete dynamic solution is given.

REVIEW OF LITERATURE

Literature on the Northeastern Pacific Ocean

A striking feature of the northeastern Pacific Ocean is the quasi-isothermal halocline between depths of about 100 and 200 meters (7, p. 158), and all papers on the general oceanography of this region have devoted some space to a description of this phenomena. (This constitutes part of what is called the front.)

Tully and Barber (24) have demonstrated that the features of an estuarine system occur in the northeastern Pacific Ocean and that "the limit of downward mixing from the surface is the limit of the halocline." Also, they estimated the rate of vertical transfer of water across the halocline as ten to twenty meters per year. However, it is to be noted that this exchange across the halocline is so slow that the halocline structure in any locality may be considered constant (15, p. 8). Indeed, for the purposes of this study the water in the halocline may be considered in "permanent" residence.

Fleming (7, p. 163) explained the quasi-isothermal halocline by proposing that

> ...water in the upper zone follows trajectories corresponding to isotherms that represent the geographic features of halocline temperatures. As the waters move along such trajectories, surface dilution and winter mixing...progressively increase the range of salinity in the halocline as the surface layer becomes more dilute.

While Fleming did not apply this concept to nearshore waters, he gave four factors which must be taken into account in such areas. These are: (1) intrusion of coastal water, (2) divergence along the coast, (3) river runoff, and (4) inshore mixing processes.

The Naval Postgraduate School has published a series of theses concerning the thermal structure in the center of the northeastern Pacific Ocean. Luskin (15) developed a thermohaline convection model which offers a satisfactory mechanism for formation of the mixed layer and suggested its use as a forecasting tool for MLD. Edgren and MacPherson (6) investigated the influences on mixed layer depth during the cooling season with two results: (1) convection caused seasonal decay of the thermocline: (2) a major portion of short term fluctuations in thermal structure appeared to be associated with an internal wave of 27-foot height which had an energy peak centered near 12 hours. Geary (12) showed that wind mixing was the dominant factor in determining the MLD during the heating season.

Literature on Oregon Coastal Waters

The results of early cruises into Oregon coastal waters may be obtained from three sources. Tibby (23) examined data from cruises prior to 1941 and used isentropic analysis to determine the percent of Equatorial water present. Reid (20) summarized results of the California cooperative oceanic fisheries investigations, discussing temperature, salinity, oxygen, and phosphate distribution. Wyatt and Kujala (28) presented analyses of hydrographic data obtained from Oregon coastal waters from June 1960 through May 1961.

Since May 1961, data collected by personnel aboard the R/V ACONA have provided a basis for several investigations into the structure of the Oregon coastal waters. Rosenburg (21) dealt with the structure and movements of the Pacific Subarctic water mass. The movements of the Columbia River plume are under study by the staff of the University of Washington (1). Maughan (16) used a series of drogue cruises, drift bottle results, and Pilot Chart data to define movements of the surface layer adjacent to the Oregon coast. As drogues were also placed at various depths below the surface, Maughan was able to conclude that currents to a depth of 100 meters were geostrophic.

It is apparent that most of the literature pertaining to the front is concerned with the thermocline or the halocline or both. This is natural and desirable when attempting to describe the causes of the features, because different processes affect the distributions of temperature and salinity. However, in discussing water flow, density is often the important parameter. Discussion of the pycnocline, *per se*, has been notably lacking in earlier work.

SEA WATER CHARACTERISTICS AND THE FRONT

Temperature, Salinity, and Density Structure off the Oregon Coast

The distribution of temperature with depth 105 miles offshore of Newport during 1962 is illustrated in Figure 1. The thermocline was principally a seasonal feature. It was always found above a depth of 100 meters. In winter months the thermocline was not well defined; from 50 meters upward the total increase in temperature was only about one degree Centigrade. The thermocline was shallowest during summer with a minimum depth of ten meters in July. The largest temperature difference across the thermocline, greater than eight degrees, occurred in September.

The distribution of salinity with depth (Fig. 2) was such that the halocline terminated at a depth of approximately 150 meters at NH 105 with a salinity of about 33.8 $^{o}/oo$. This was true for all months except July 1962, when the halocline continued to 200 meters with a base salinity of 33.9 $^{o}/oo$. The halocline had a fairly constant gradient below a depth of 50 meters where the salinity varied between 32.6 and 32.8 $^{o}/oo$.

The salinity/depth curves at NH 105 above 50 meters showed variation with season but no regular cycle as with temperature.

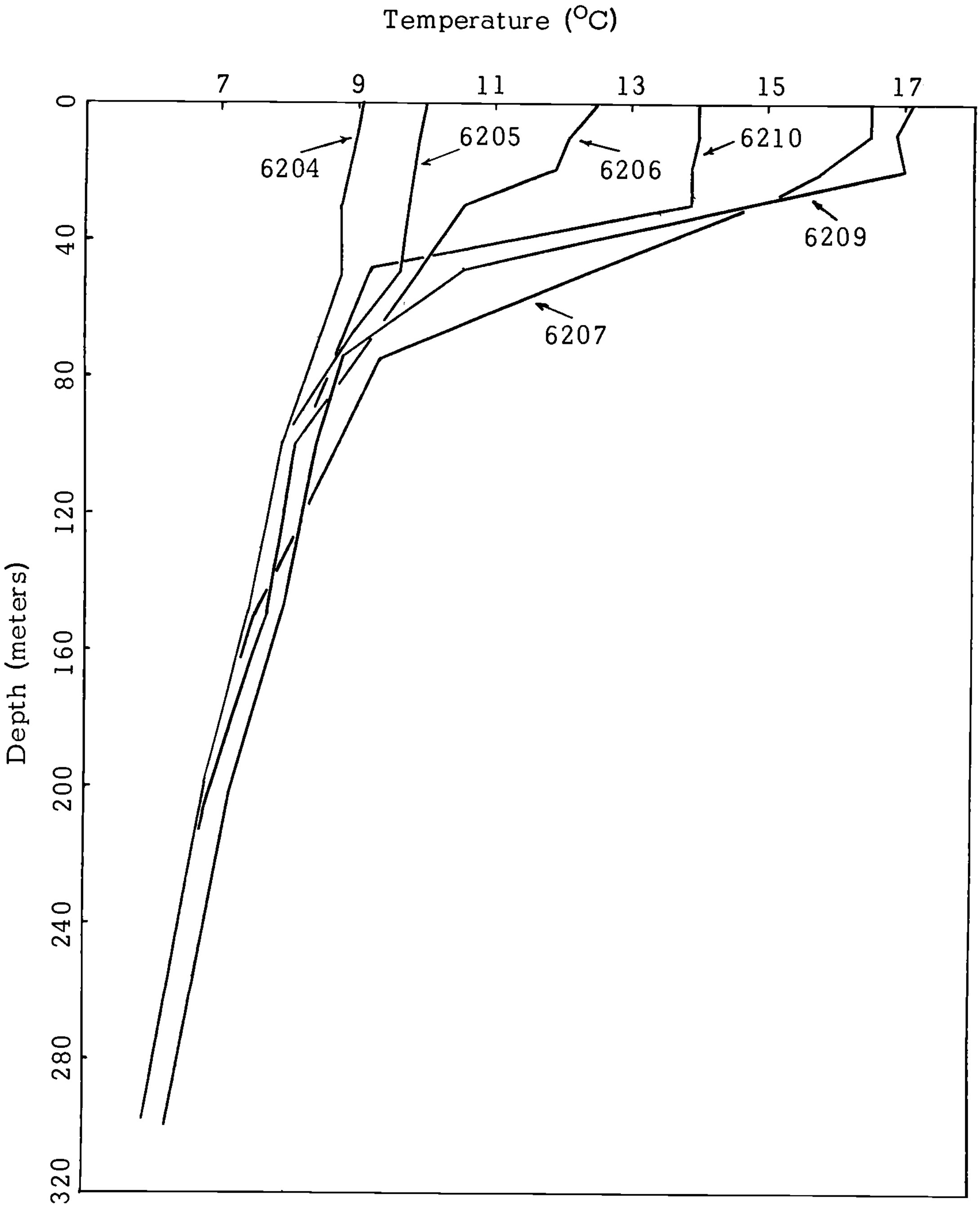


Figure 1. Temperature versus depth at NH 105 during cruises taken throughout 1962.

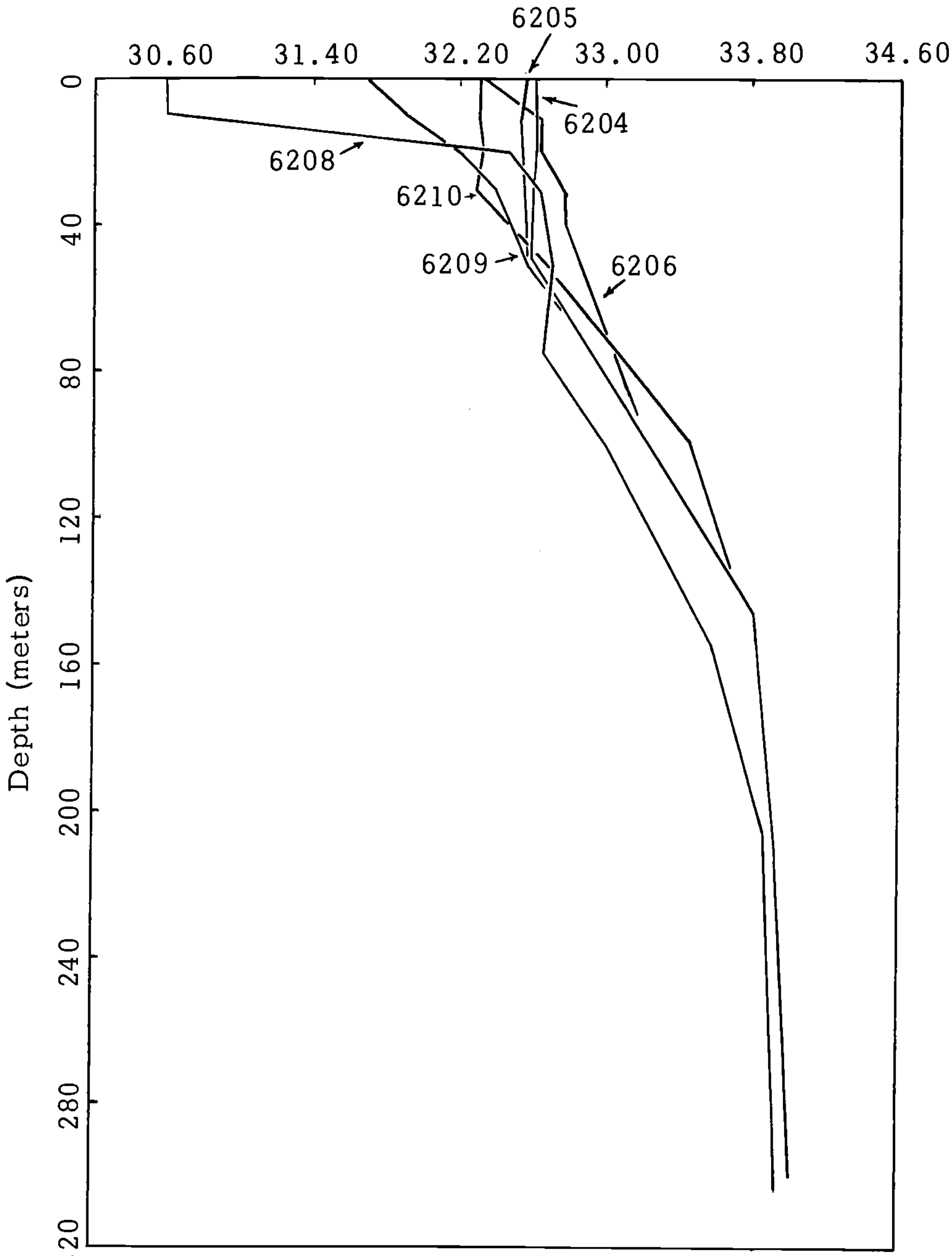


Figure 2. Salinities versus depth at NH 105 during cruises taken throughout 1962.

In the winter months conditions were nearly isohaline to 50 meters; in late summer months a second shallow halocline was superimposed on the existing structures, probably due to the effect of the fresh Columbia River effluent.

Since density is a function of temperature and salinity, a front may be produced by (1) a thermocline, (2) a halocline, or (3) both these phenomena coinciding. Figures 1 and 2 illustrate that the third case applies to the Oregon coastal front. Further, since the thermocline is shallow and principally seasonal, and the halocline is deeper and permanent, the front is a permanent feature with seasonal variation in extent. Its lower part is a result of the halocline alone; its upper portion a result of the halocline and the thermocline acting together. Thus, although it is possible to use two salinity values to describe the front as Fleming (7) has done, density values offer the distinct advantage of including effects of the seasonal thermocline, and are in addition, directly related to dynamics (p. 2).

To select density values that can be considered representative of the front, it was necessary to examine the vertical distribution of density.

The density structure at NH 105 for each of the 1962 cruises is shown in Figure 3. The 200 meter Nansen bottle was below the front at NH 105 for all cruises. The sigma-t value at 200 meters was 26.6.

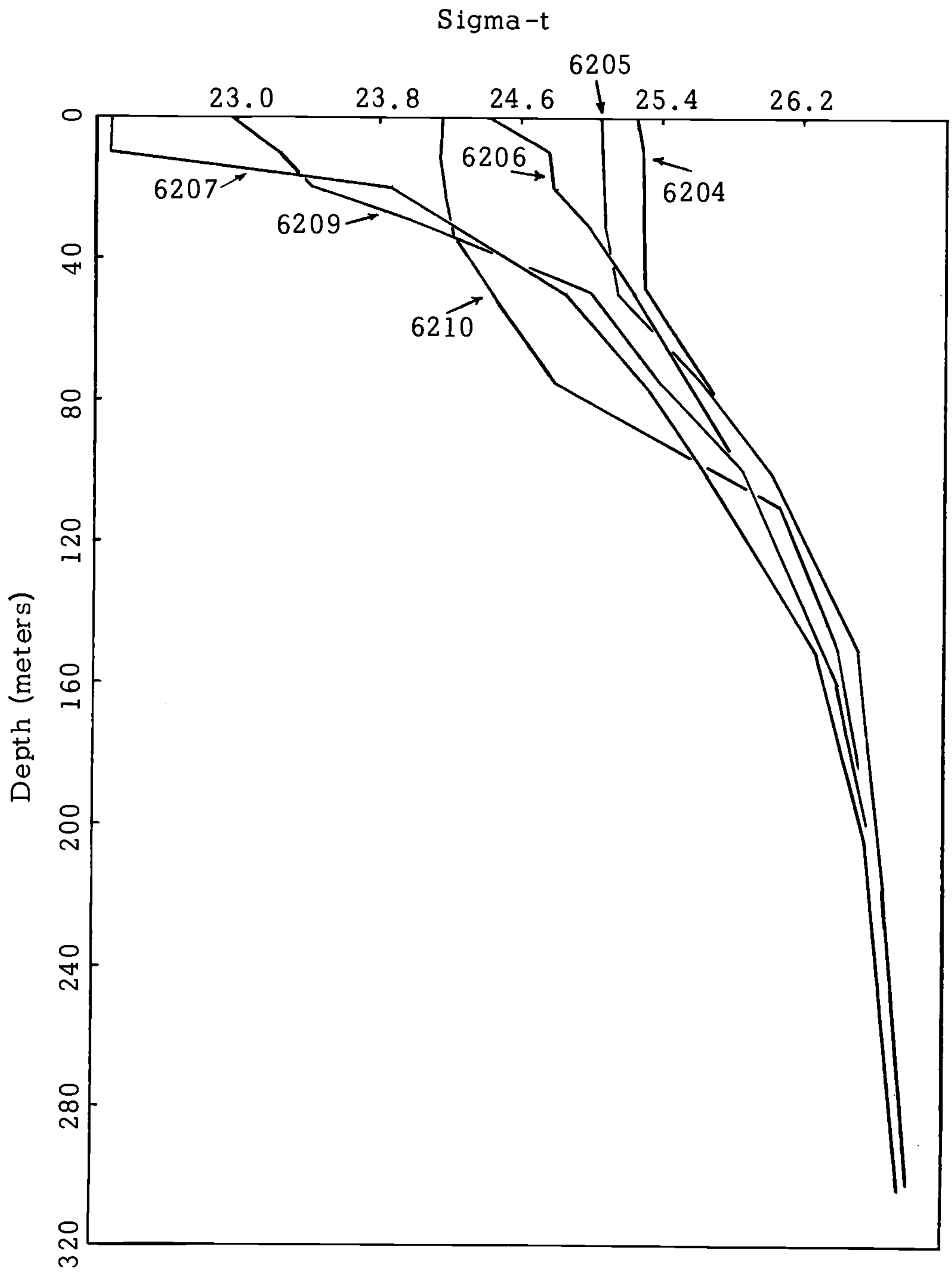


Figure 3. Sigma-t versus depth at NH 105 during cruises taken throughout 1962.

Further, the density gradient between the 150 and 200-meter Nansen bottle was always smaller than that between 100 and 150 meters. The density at 150 meters ranged from σ_t = 26.5 in May to σ_t = 26.3 in July.

Above the 50-meter bottle, the water was of constant density in the late winter months. In other months the front extended above 50 meters, reaching a minimum depth of ten meters in July when the surface density was also a minimum, σ_t = 22.3.

The water between the 50 and 150-meter bottle always lay within the front. The density at 50 meters reached a minimum sigma-t value of 24.3 in November and a maximum value of σ_t = 25.3 in March. Thus, during all seasons at NH 105, sigma-t values between 25.3 and 26.3 lay within the front. The minimum vertical thickness of the front was 100 meters and the minimum change of sigma-t in this depth interval was one unit.

Figure 4 illustrates the density structure at each station along the Newport hydrographic line during July 1962. The 200-meter Nansen bottle was definitely below the front at all stations; in fact, the front probably did not extend below a depth of 150 meters. The sigma-t values at 150 meters for this month ranged from 26.3 (NH 105) to 26.7 (NH 25). The upper part of the front intersected the sea surface

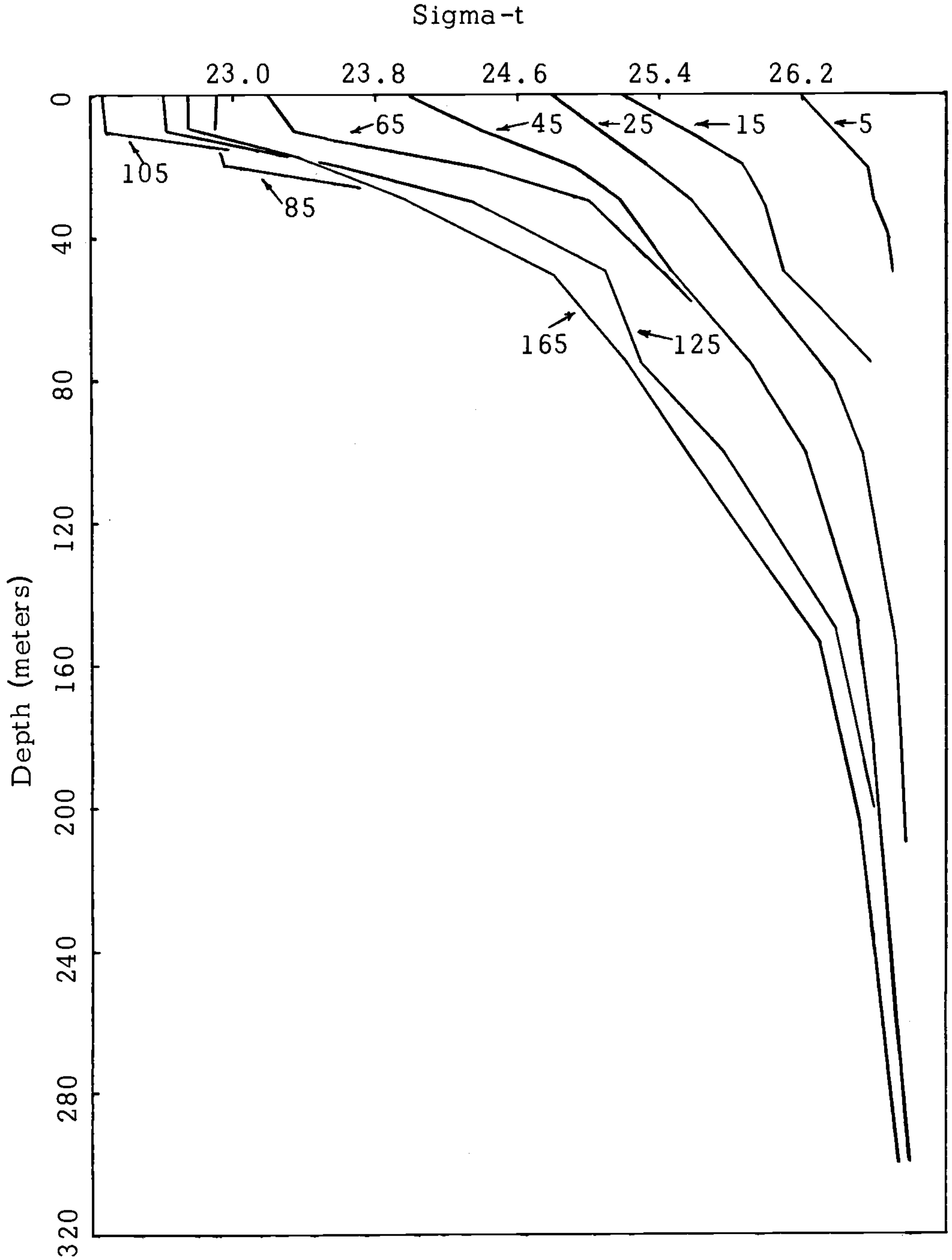


Figure 4. Sigma-t versus depth at stations along the Newport hydrographic line, July 1962.

at the inshore stations, lay at a depth of ten meters at NH 85 and NH 105, and was below 20 meters at stations farther offshore. Close to shore at NH 5, a very shallow station (57 meters), all water was denser than $\sigma_t = 26.2$. From this the author inferred that the front intersected the front between NH 5 and NH 15, or approximately ten miles offshore. The upper extremety of the front had values ranging from $\sigma_t = 25.2$ (NH 15) to $\sigma_t = 22.3$ (NH 105). This analysis was continued for other months with similar results.

Since they always occurred within the frontal layer, sigma-t values of 25.5 and 26.0 were selected to delineate the frontal structure. The depth of these isopycnals indicate the depth of the front; the depth difference between them is inversely proportional to the intensity or stability of the front (22, p. 418).

The depths of the selected values of sigma-t (25.5 and 26.0) were determined for all ACONA data from June 1961 to May 1963. The hydrographic data as regularly processed contained sigma-t values for standard depth intervals. However, these sigma-t values were indirectly computed via a modified Lagrange technique which tends to reduce density difference with depth, $d\sigma_t/dH$, in regions where the density difference with depth is large. As the front is a region where the density difference with depth is large, using the sigma-t values as usually prepared for standard depths would have introduced error into the calculations. Thus it was decided to interpolate the depths of the sigma-t surfaces linearly from sigma-t values obtained at observed depths, not from sigma-t values previously obtained for standard depths.

Although no study or comparison of the errors resulting from linear interpolation to those errors resulting from other computer interpolation techniques within the front were made, due to the lack of a true reference for the front, it was felt that the linearly interpolated values offer simplicity with about the same amount of error as other techniques. This simplicity is especially important when computer-obtained values are in error and it becomes necessary to return to the original data and compute the correct result by hand.

The computer program, written by Mrs. Sue Borden, required inputs of salinity, temperature, and observed depth. In addition to computing the depth of sigma-t surfaces 25.5 and 26.0, it indicated when a station contained no water within this sigma-t range and whether the water at such a station is more dense or less dense than the given sigma-t.

The Frontal Profile

By plotting the depths of these sigma-t surfaces along a station line, i.e. versus distance from shore, a graphical representation of the frontal zone can be obtained. These latitudinal profiles indicate clearly the depth of the sigma-t surfaces as well as the depth difference between them (see e.g. Figure 5). These profiles will henceforth be referred to as frontal profiles.

The frontal profiles obtained for Newport for the 12 month period ending in May 1963, are shown in Figure 5. The Newport profiles were chosen for presentation for two reasons: (1) there were more observations of this station line than of the other three; (2) these profiles seem representative of conditions along the other station lines.

NH 6205. The sigma-t surfaces of this frontal profile slope downward gradually with distance from shore. As both sigma-t surfaces deepen offshore, they diverge slightly.

The sudden rise of $\sigma_t = 26.0$ between NH 85 and NH 105 and its equally sudden deepening beyond NH 105 suggest the possible presence of internal waves (see page 26). Since Oregon State had made no internal wave studies, it was not possible to adjust observations to allow for these variations, or to even obtain a local estimate of the amplitude of these phenomena. However, even with such studies it may not be possible to adjust for periodic variations (19).

NH 6206. Northerly winds predominate for approximately 80% of the time during June (6, Fig. 21), and upwelling of deeper water toward the surface usually begins along the coast during this month.

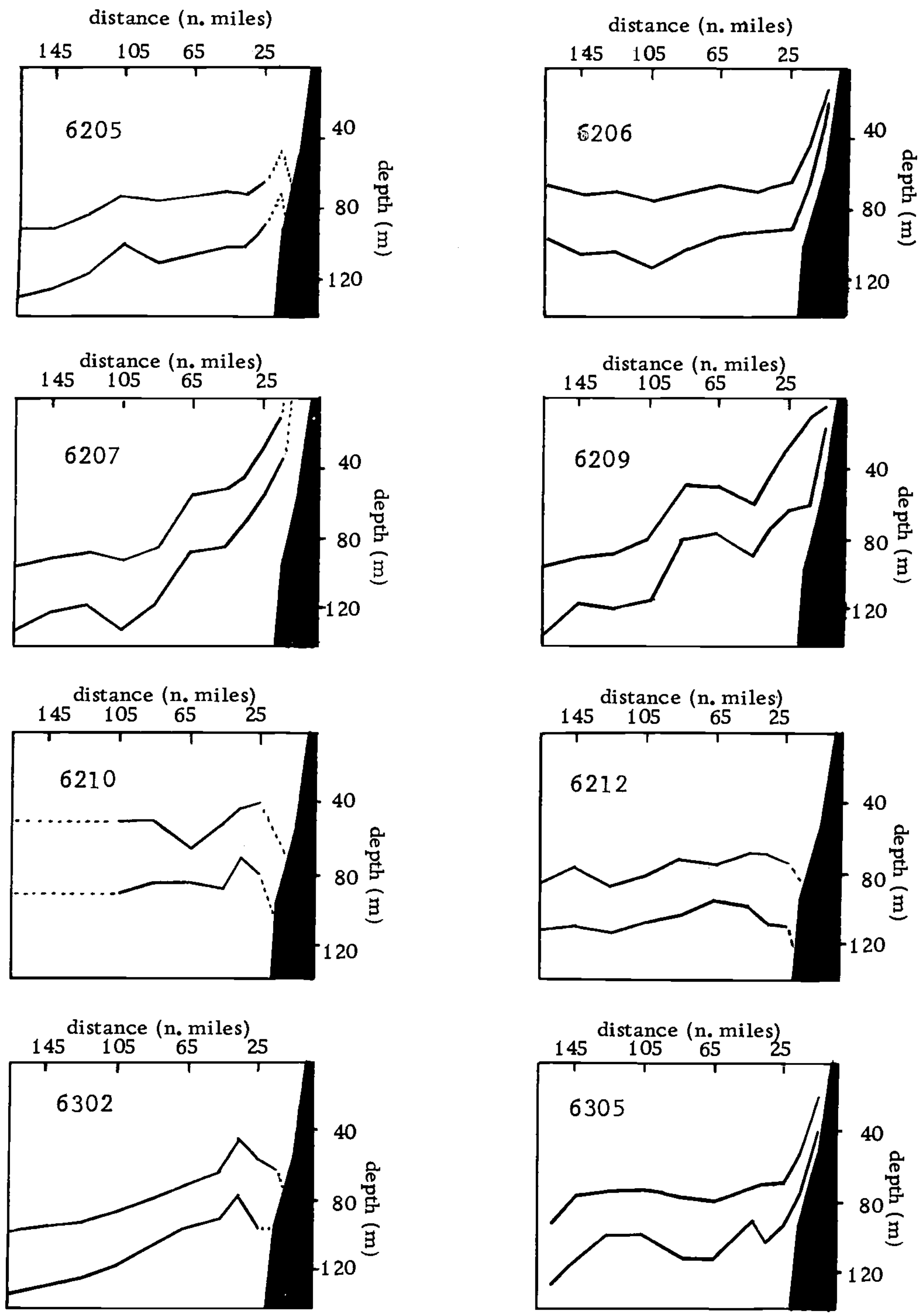


Figure 5. Newport frontal profiles, May 1962 to May 1963 (upper surface $\sigma_t = 25.5$, lower surface $\sigma_t = 26.0$).

The June 1962 frontal profile indicates upwelling by the sharp rise of the isopycnals toward the surface inshore from station NH 25.

Offshore from NH 25, the isopycnals deepen slightly with distance from shore, diverge with increasing depth, and reach their deepest point at NH 105.

NH 6207. This was what must be called the "classic" upwelling profile. The entire pycnocline layer appears to have been tilted, and the data indicated a well developed surface front between NH 5 and NH 15.

Divergence of the isopycnals with depth is marked.

NH 6209. The upwelling had begun to decay. The isopycnals were deeper at NH 45 than at NH 65 and NH 85. Offshore of NH 85 the front sloped downward, rapidly at first and then more gradually. Divergence with depth was noticeable but not well marked.

NH 6210. The downward slope of the isopycnals inshore of NH 25 indicated that upwelling had definitely ended. Although a great deal of variability existed in the sigma-t surfaces, they would appear to be nearly level. However, the absence of three offshore stations made complete interpretation difficult.

Roughly, this profile appears to resemble the May profile in shape. It is to be noted, however, that both isopycnals were appreciably shallower in October than in May. The net effect of the upwelling season seems to have been to shift the pycnocline upwards.

NH 6212. The isopycnals during this period were essentially level. Inshore of NH 65 divergence of the isopycnals was indicated. The position of the front was somewhat lower than it was in October.

NH 6302. The absence of two offshore stations made analysis of this profile difficult. There was divergence of the sigma-t surfaces inshore of NH 35. Offshore of NH 45 the isopycnals sloped downward gradually, diverging with depth. The position of the front was very close to its position in May 1962.

NH 6305. This profile is very similar to that of 6206. The upward slope of the isopycnals inshore of NH 35 is an indication that upwelling was occurring. The front was nearly level from NH 45 to NH 125 although the lower sigma-t surface was very irregular. Offshore of NH 125 the front sloped downward.

The structure and seasonal cycles of the pycnocline profiles off Coos Bay and Astoria were similar to those off Newport. However, the Brookings profiles were notable for the distance offshore at which the surface front was found. In June 1961, for example, the front was 35 nautical miles off the coast.

As noted on examination of the profiles, frequently as the depth of the front increased the isopycnals diverged, i.e., the front itself became thicker. Figure 6 and Table 1 illustrate this relationship. The

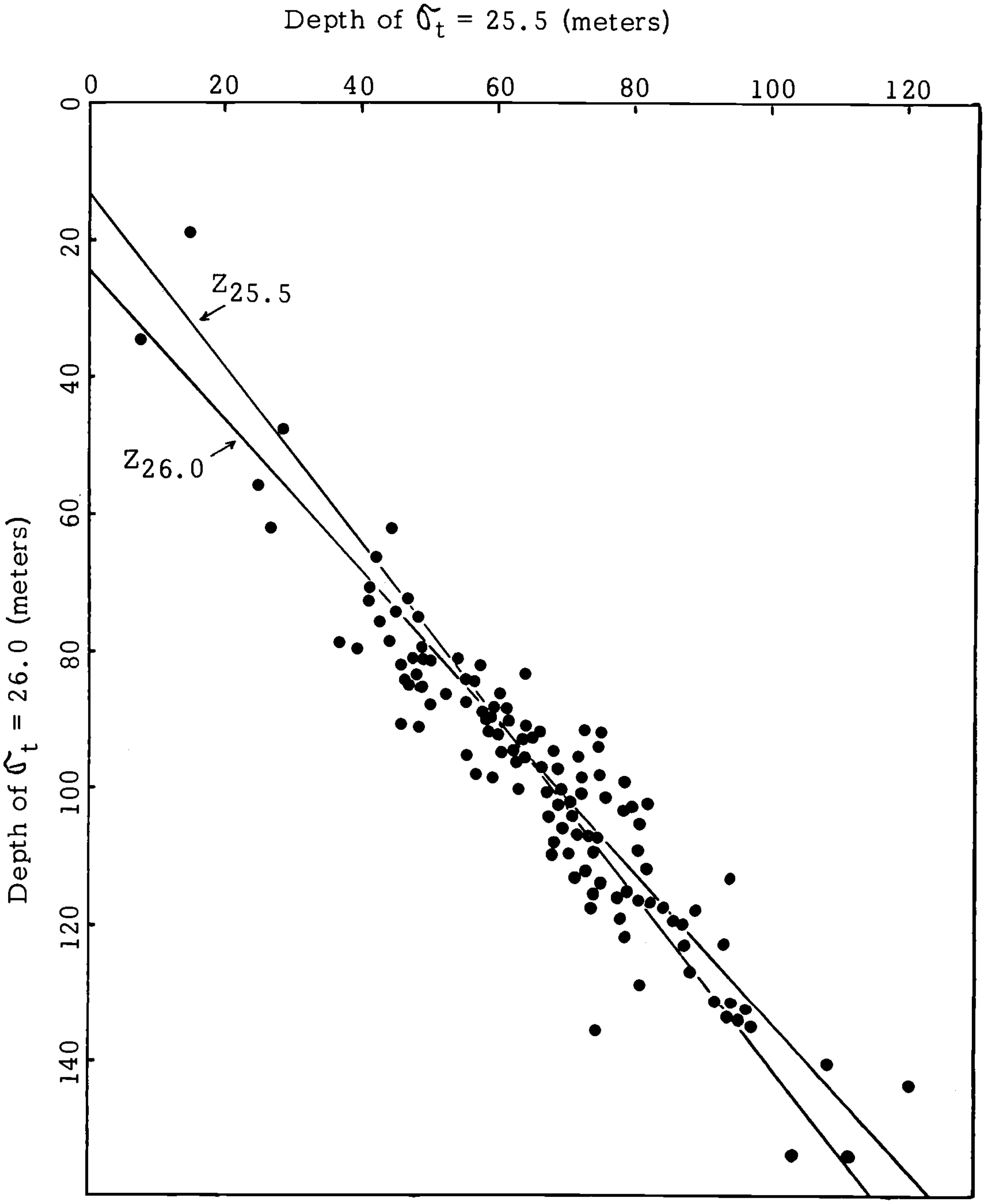


Figure 6. Depth of σ_t = 25.5 versus depth of σ_t = 26.0 along the Newport hydrographic line, June 1961 to May 1963 (regression lines illustrated).

depth of σ_t = 25.5 was plotted against the depth of σ_t = 26.0 in Figure 6 for Newport stations. The slope, intercept, correlation coefficient, and standard error of each of these variables as related to the other was obtained and is included in Table 1. The correlation coefficients were exceptionally high, above 0.90 in each case. Also in each case the regression coefficient is not one; that is, the change in depth of the 25.5 surface is always less than the corresponding change in depth at the 26.0 surface.

Table 1. Relationship between the depth of σ_t = 25.5 ($Z_{25.5}$) and the depth of σ_t = 26.0 ($Z_{26.0}$) June 1961 to May 1963.

Station line	Dependent variable	Slope m/m	Intercept m	Correlation coefficient	Standard error
Astoria	$Z_{25.5}$	0.672	1.200	0.928	7.142
	$Z_{26.0}$	1.282	12.007		9.868
Newport	$Z_{25.5}$	0.785	-10.166	0.939	8.125
	$Z_{26.0}$	1.224	23.216		6.787
Coos Bay	$Z_{25.5}$	0.748	-10.281	0.904	8.879
	$Z_{26.0}$	1.092	28.822		10.724
Brookings	$Z_{25.5}$	0.796	-13.599	0.971	10.136
	$Z_{26.0}$	1.185	22.495		8.310

Since such definitive results were obtained using depth of one sigma-t surface as a function of the depth of the other, it was decided to test the difference in depth of the sigma-t surfaces as a function of the depth of the lower sigma-t surface, 26.0. As the major difference between this relationship and the earlier one was to reduce one parameter from a 60 to 100-meter value to a 10 to 60-meter value, the relative error was increased; one would expect less correlation. The results indicate this was so (Table 2).

Table 2. Relationship between the depth of σ_t = 26.0 ($Z_{26.0}$) and the difference in depth between σ_t = 26.0 and σ_t = 25.5 ($Z_{26.0-25.5}$), June 1961 to May 1963.

Station line	Dependent variable	Slope m/m	Intercept m	Correlation coefficient	Standard error
Astoria	$Z_{26.0-25.5}$	0.328	-1.199	0.773	7.142
	$Z_{26.0}$	1.822	41.590		16.830
Newport	$Z_{26.0-25.5}$	0.215	10.166	0.602	18.957
	$Z_{26.0}$	1.679	47.063		6.786
Coos Bay	$Z_{26.0-25.5}$	0.251	10.282	0.579	8.879
	$Z_{26.0}$	1.338	50.503		20.498
Brookings	$Z_{26.0-25.5}$	0.204	13.600	0.725	29.519
	$Z_{26.0}$	2.576	18.975		8.305

Nevertheless, the relation established is a valuable one. It means that one only has to determine the location of one sigma-t surface and the location of the second can be predicted. Physically it means that when the upper layer (the layer above the front) thickens, so does the front, and proportionately.

Note also that the difference in depth between unit sigma-t surfaces, multiplied by 10^{-3}, is inversely proportional to the stability (22, p. 418). Therefore, this observational result is that the stability decreases when the depth of the front increases.

Superimposed on the trends of the frontal layer was "noise," i.e., shoaling and deepening of the sigma-t surfaces from station to station. This phenomenon was probably due to internal waves. Two characteristics of internal waves are (4, p. 517): (1) their largest vertical displacements are found at the boundary surface between different strata; (2) their amplitude is usually considerably larger than that of the ordinary wave at the free surface.

To eliminate effects of such variations, the mean for all cruises was taken (Table 3). The smooth slope of the mean Newport profile was interrupted by a ten-meter rise at NH 125. This was especially noticeable in the lower mean sigma-t surface, 26.0. Since the depth of the sigma-t surfaces is shallower at NH 125 than the mean depth of NH 105 and NH 145 in all but four of the Newport frontal profiles, this rise may be a permanent or recurring feature.

nautical miles from coast	Astoria			Newport			Coos Bay			Brookings		
	depth		no. of obs.	depth		no. of obs.	depth		no. of obs.	depth		no. of obs.
	σ_t=25.5	σ_t=26.0		σ_t=25.5	σ_t=26.0		σ_t=25.5	σ_t=26.0		σ_t=25.5	σ_t=26.0	
15	57.2	76.5	7	----	-----	--	46.7	78.0	10	----	-----	-
25	59.6	93.3	8	51.6	81.8	15	56.2	88.3	10	----	62.4	5
35	64.6	96.3	8	54.7	84.0	15	57.7	91.4	11	46.8	74.4	5
45	76.8	109.3	8	62.1	92.3	15	57.7	99.3	9	54.1	87.0	6
65	71.9	108.6	8	64.6	95.7	12	69.6	111.3	10	93.0	129.0	6
85	76.6	113.9	8	69.9	100.8	14	73.2	108.0	9	87.6	123.0	6
105	72.1	106.8	8	79.0	113.3	12	69.5	100.2	8	85.0	125.3	6
125	77.4	113.4	7	74.2	106.8	13	77.7	114.5	8	83.5	122.6	6
145	77.1	115.4	7	88.7	122.2	13	81.6	122.3	8	93.2	126.5	6
165	75.7	115.0	6	87.4	126.2	13	92.2	129.7	4	105.0	139.0	2

Table 3. Mean depth of σ_t=25.5 and σ_t= 26.0 and the number of observations for the period from June, 1961 to February, 1963.

The rise was especially well developed off Newport during July 1962. This profile, along with those profiles of Astoria and Coos Bay for the same month, is shown in Figure 7. The rise seemed to be closest to shore in the north. This fact suggests some relationship between the frontal rise and the Columbia River.

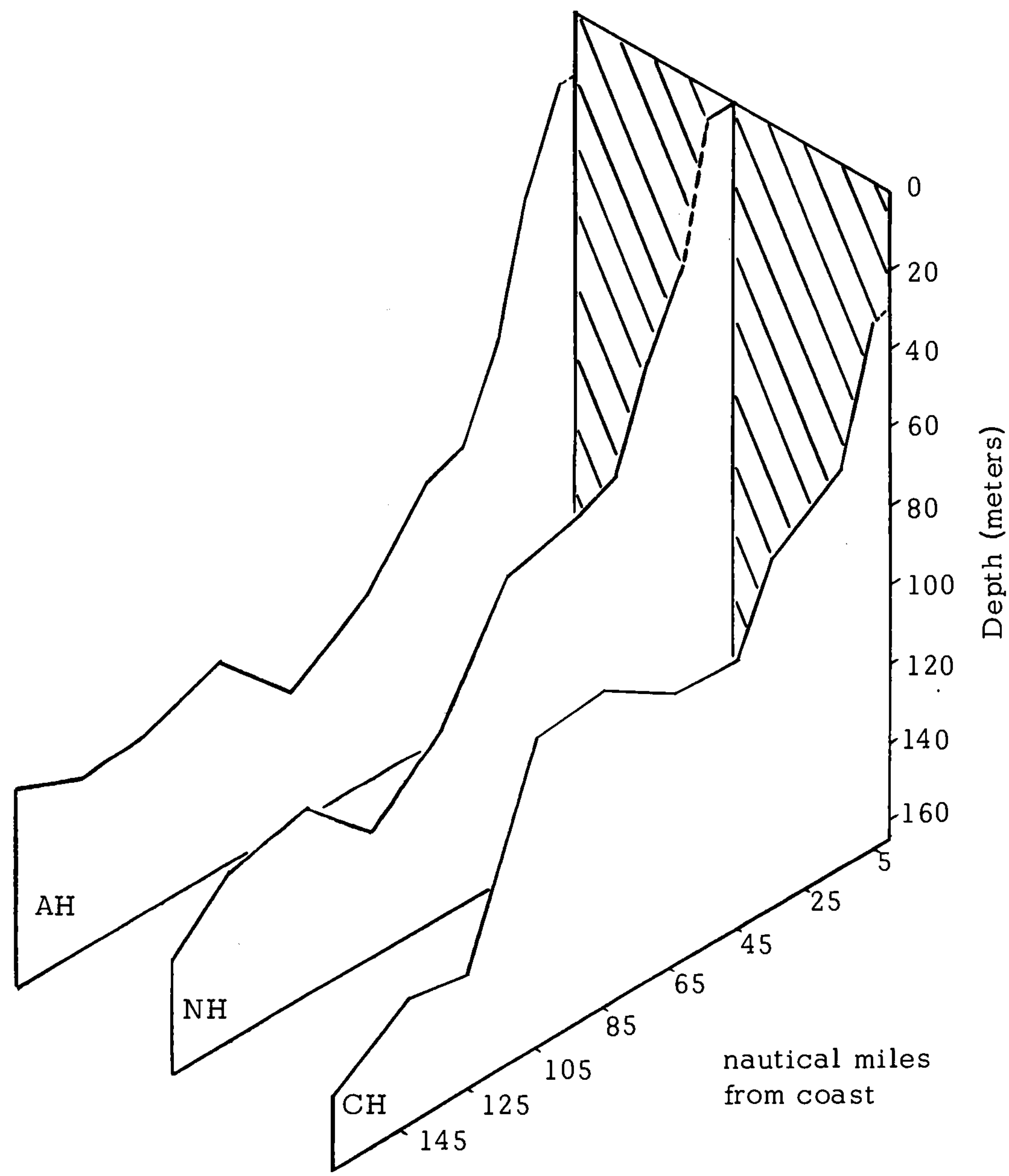
Both the position of the Columbia effluent and its volume change with time. The relation of the volume of discharge of the Columbia River (26) to the depth of $\sigma_t = 26.0$ at NH 125 is shown by Figure 8.

If the Columbia River discharge volume is compared with the depth of $\sigma_t = 26.0$ which occurred at NH 125 two months later, the depth of $\sigma_t = 26.0$ increased in all cases but one with an increase in the volume of discharge of the river. A two-month lag would correspond to a flow of six cm/sec in a southerly direction. This flow speed, as well as the direction of the flow, approximately agrees with currents inferred from other data, i.e. hydrographic data (1).

However, there is no correspondance between the dips in the mean profiles of Astoria and Coos Bay and the volume of discharge.

The depth of $\sigma_t = 26.0$ was next compared with a direction-magnitude wind parameter obtained at 40°N, 128°W (27). The wind parameter was obtained as a product of the percent of the month that the wind had a northerly component of magnitude with the beaufort force of the

Figure 7. Depth of sigma-t surface 26.0, July 1962.



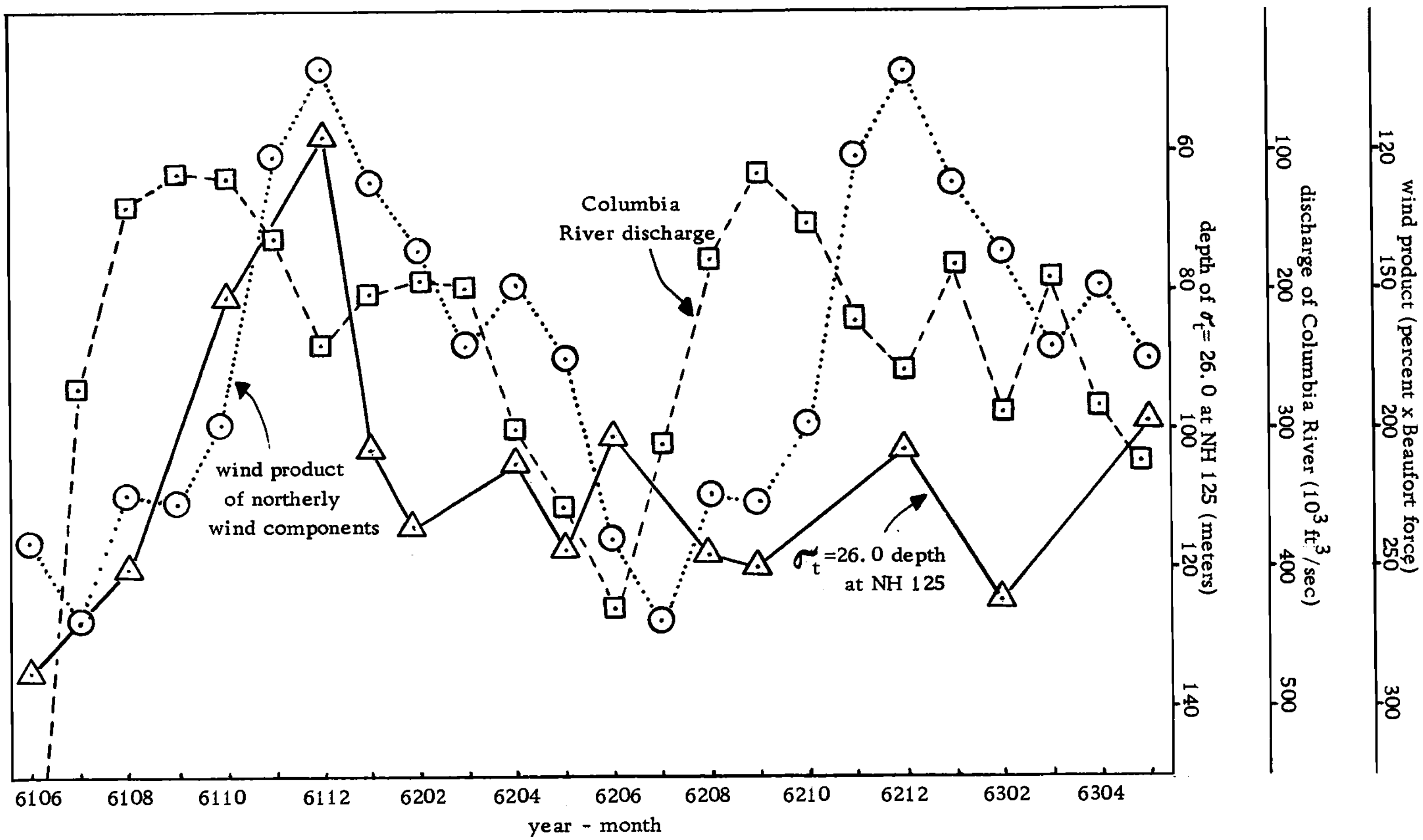


Figure 8. Columbia River discharge, depth of σ_t = 26.0 at NH 125, and the wind product of the northerly component of surface wind.

magnitude. The result is shown in Figure 8. This indicated that the smaller this wind product, the shallower the sigma-t surface. This relationship failed twice, once in June 1962, and again in May 1963. Also the percent-magnitude of winds with northerly components related much better to the depth of sigma-t 26.0 at hydrographic stations than the Columbia River discharge. This fact suggests that the upwelling effect of northerly winds, not their influence on the river effluent, has more effect on pycnocline depth.

The Surface Front

When the front intersects the surface, a surface front is formed across which the density changes abruptly. As surface fronts are often easily recognizable from vessels passing through the region, several surface fronts have been observed and studied (3, 14).

The following characteristics have been found common to surface fronts (3):

1. Surface convergence: Components of surface currents are directed into frontal zones. This maintains the front and also results in horizontal mixing within the frontal zone. The mixing produces water that has the temperature/salinity characteristics of the frontal layer.

2. Sinking: Since currents are converging along frontal areas,

continuity requires a flow to compensate for this. This could be accomplished by sinking beneath the surface. To support the sinking hypothesis, Cromwell and Reid (3, p. 98) not only cite Japanese literature as reporting fishing nets sinking along fronts, but they also placed a drag within a front with the following result:

> Upon reaching the front, the pole, which previously had lain tilted, became suddenly vertical and sank slowly as though pulled from below. Although we remained in the area for an hour and watched the flag, it was not sighted again.

3. Divergence at depth (3, p. 98): Given the two preceding features of flow, there must be horizontal divergence at depth.

Surface convergence along the Oregon coastal front when it forms a surface front would result in modification of water properties to those of the type that is contained in the front. From the frontal profiles, it is easily seen that as early as May (1963) the front begins to slope upwards shoreward and to steepen in gradient. Between June and July the front definitely intersected the surface. Newly modified water of frontal density formed at the front would sink and flow out through the front. This would require an increase in the volume of the frontal layer during these months unless as much flowed out of the section as was replenished by mixing.

With respect to the three frontal characteristics of surface convergence, sinking and divergence at depth, only the later can be absolutely identified off the Oregon coast with the data available.

Surface velocities reported by Maughan (16, p. 21) are not contrary to the possibility of surface convergence, and the observation of a 25 cm/sec onshore surface flow in September 1962, at NH 55 would require surface convergence. A simultaneous observation of currents on the inshore side of the front has not been made. Similarly, sinking along this front has not been directly observed. Thus it is impossible to assign, on the basis of previous data, numerical values to such processes as the rate of creation of pycnocline water; however it would seem highly probably that such processes do occur.

KINEMATICS

Due to the presence of the coastline and the principal circulation of the ocean, the largest portion of near surface water transport off the Oregon coast occurs in a north-south direction. Such movements tend to overshadow on-offshore transport and serve to make the determination of these transports more difficult. For example, the monthly current observations determined from ships drift (16, p. 28) show currents differing more than 15^{o} from the north-south direction only two months of the year, January and October. Thus, a method of determining latitudinal flows, different from ordinary path and flow methods, is useful.

Kinematics of the Surface Layer

In order to determine flows within the upper zone, a kinematic model was constructed. This model was based on three axioms:

(1) No water entered or left the region through the sea-air interface or through the sea-land interface.

(2) Sigma-t surfaces 25.5 and 26.0 were conservative, i.e., mass was not transported across them.

(3) No north-south gradients existed.

These axioms were idealized from conditions which are approximated by nature.

With this model, it is possible to interpret volumetric changes as flow across the vertical offshore boundary due to translation of the sigma-t surface(s). The author selected for the offshore vertical boundary station NH 145. To obtain the flow across this boundary, three quantities are required: (1) the change in area in the xz plane of the surface layer between two cruises (ΔA); (2) the time lapse between the cruises (t); (3) the mean depth of the surface layer at NH 145 during the observation period ($\bar{z}$). The flow rate, v, is determined by:

$$(4\text{-}1) \qquad v = \frac{\Delta A}{(t)(\bar{z})}$$

Flow rates determined in this manner will be termed "volumetric" flow rates.

Table 4 contains a computation of the volumetric flow rates at NH 145 for the hydrographic data collected by the ACONA from June 1961, through May 1963. The volumetric flow velocities obtained in Table 4 indicated offshore currents during the upwelling season (June-October), onshore flows immediately following upwelling (October-January), and variable currents during the remainder of the year.

Table 4. Volumetric onshore flow rates through a plane at NH 145 for the surface layer.

Date	Flow cm/sec	Date	Flow cm/sec
1961: 26 Jun-21 Aug	-0.77	1962: 3 May-6 Jun	-1.08
21 Aug-30 Oct	0.70	6 Jun-27 Jul	-0.26
30 Oct-2 Dec	0.31	27 Jul-5 Sep	-0.47
2 Dec 1961-9 Jan 1962	0.25	5 Sep-16 Oct	-0.34
1962: 9 Jan-4 Feb	0.48	16 Oct-17 Dec	1.90
4 Feb-3 Apr	-0.58	17 Dec 1962-22 Feb 1963	0.30
3 Apr-3May	1.03	1963: 22 Feb-25 May	0.16

It is to be emphasized that volumetric flow rates only represent average flows across NH 145. Also, since this is a difference method, one inaccurate frontal profile would affect two velocity determinations.

Table 5 offers a comparison of the on/offshore currents obtained by the volumetric method (Table 4) with the latitudinal components of the velocity obtained from drogue data and a current summary based on considerations of drogue data, drift bottle data, and ship's drift data after Maughan (16, p. 33). There are appreciable discrepancies between speeds. However, the drogue data presented is for current velocities at ten meters depth while that obtained by the volumetric method assumes that each particle of the entire surface layer had the same velocity. This may explain some of the velocity discrepancies. Furthermore, the drogue data were taken during a single two-day period in each case, while the volume changes were the net between cruises. One would surely expect the average flow in a month or two to be smaller than the "instantaneous" currents which vary in direction as well as speed.

In comparing the direction of flow, it is seen that discrepancies exist in February, May, and September. The volumetric method has indicated offshore flow for these months, and the drogue data and the surface current summary onshore current.

Table 5. Comparison of onshore surface currents, 1962.

Month	Flow rate, cm/sec Volumetric	10-meter drogue	Maughan's surface current summary
Jan	0.5	8.72	strong, onshore
Feb	-0.6	13.05	moderate, onshore
Mar	-0.6		weak, onshore
Apr	1.0		weak, onshore
May	-1.0	1.18	weak, onshore
June	-0.3		weak, transitional
July	-0.3	-5.36	moderate, offshore
Aug	-0.5		weak, transitional
Sep	-0.3	25.23	weak, onshore
Oct	-0.3		moderate, onshore
	1.9		
Nov	1.9	12.98	strong, onshore
Dec	1.9		strong, onshore
	0.3		

For these months the ship's drift observations averaged over previous years (16, p. 28) indicate offshore flow; 1.2 cm/sec in February, 0.2 cm/sec in May, and 2.7 cm/sec in September. The drift bottle data indicate an offshore flow only by absence of recoveries on the beach. This makes their results difficult to evaluate, especially during a period of variable flow. It would appear the current summary for these months was weighted on the basis of the drogue measurements.

Since the drogue data were obtained over a short period of time (2 days), they are greatly affected by local transitory disturbances. On the basis of the volumetric and ship's drift flow rates, the drogue measurements do not appear to be representative of net flow within the surface layer during February, May, and September.

As a summary of the results obtained by the author's analysis of latitudinal flows, the following three periods are distinguished:

(1) A period of net offshore flow occurring from May to the middle of October. This coincides with the upwelling season.

(2) A relatively short period of large onshore currents which takes place during late October, November, December, and possibly January.

(3) A somewhat "neutral" period in which no large net flow occurs. This period occurs during the months of February, March, and April, and may extend into May. The oceanographic data on which this summary is based were all collected during the period June 1961, to May 1963. However, the ship's drift data represent a cumulative mean of many years.

Kinematics of the Frontal Layer

On the assumption that all changes in volume of the frontal layer were also the result of flow across a vertical plane, NH 145, the magnitude and direction of these flows were computed. The results are listed in Table 6.

Table 6. Volumetric onshore flow rates through a plane at NH 145 for the frontal layer.

Date	Flow cm/sec	Date	Flow cm/sec
1961: 26 Jun-21 Aug	-0.97	1962: 3 May-6 Jun	-0.16
21 Aug-30 Oct	-1.54	6 Jun-27 Jul	0.52
30 Oct-2 Dec	2.73	27 Jul-5 Sep	-0.02
2 Dec 1961-9 Jan 1962	0.53	5 Sep-16 Oct	0.63
1962: 9 Jan-4 Feb	2.23	16 Oct-17 Dec	-1.20
4 Feb-3 Apr	-0.22	17 Dec 1962-22 Feb 1963	0.34
3 Apr-3 May	-0.97	1963: 22 Feb-25 May	0.08

On the basis of the statistical relationships obtained in Chapter three, one would expect agreement between surface and frontal flow. During 1961 the volumetric flows which occurred within the front were in good agreement with the surface flows for the period, i.e. an offshore flow during upwelling, and a large onshore flow immediately following. However in 1962 the agreement between frontal and surface volumetric flow is not so clear-cut. In fact, in four cases the direction of the frontal flow was contrary to that obtained for the surface flow. Principally these disagreements involved onshore flow within the pycnocline during upwelling.

To this point, only conservative flows have been considered. However, it was stated earlier (p. 31) that a characteristic of a surface front is the sinking of water at the surface front and its subsequent offshore flow.

Three possibilities can be presented to explain the increase of the volume of the frontal layer during upwelling in 1962. The first possibility is that the increase of volume of the frontal layer is a result of onshore flow across NH 145. That is, the front participated with the lower layer in upwelling.

The second possibility is that convergent flow at the surface front resulted in mixing and an increase in volume of the frontal layer. Although this process violates axiom two of the kinematic model, assume that this is the only such violation and that the axioms are true otherwise. It is now possible, if there is no flow across the NH 145 plane, to compute the mixing rates required by the surface front to account for the change in volume.

Assuming that the convergence at the surface front extended to a depth of 20 meters, the mixing rate was computed. The mixing rate is expressed as the velocity difference across the front. For

June-July 1962, mixing required that the velocity normal to the surface front change by eight cm/sec as one proceeded across the surface front. As the front was approximately 5000 meters in width (Fig. 5), this would require water to sink at the rate of 0.04 cm/sec. These velocity values appear to be within the realm of possibility for the Oregon coastal waters, although vertical speeds associated with mixing have never been measured here.

The third possibility is that both horizontal flow at NH 145 and frontal mixing were occurring. If there were <u>outward</u> flow through NH 145, the mixing rates given in Figure 6 would be minimum values. On the other hand, if there were <u>onshore</u> flow, the values listed would be too high.

Now consider the frontal flow for the upwelling period, 1962, in more detail.

May-June. As the first frontal profile that showed a surface front in 1962 was the June profile, the first period which frontal convergence could have affected was the May-June period. To determine if upwelling was the predominant process over such a time interval, a simple hypothesis was used:

(Test for the Predominance of Upwelling)

> If the surface layer shows a net offshore flow across the vertical offshore boundary during the time inteval between two frontal profiles, upwelling was the predominant process during the period.

Since offshore flow existed in the upper layer, upwelling predominated during the entire period for May to October. During May-June offshore volumetric flow in the front was a small value.

June-July. It is probable that the volume increase of the frontal layer during June-July 1962, can be ascribed to the third possibility, i.e. frontal flow acting jointly with flow through NH 145. It cannot be determined whether flow through NH 145 is onshore or offshore.

July-September. As it is unreasonable to assume that frontal convergence occurs at a surface front one month and no frontal convergence occurs at a surface front the next month, the front's failure to show a significant accumulation of volume is interpreted to show that some volume was transported offshore beyond NH 145 during the period. If the surface front maintained the same rate of mixing during the July-September 1962, period as that computed during the June-July period of the same year (p. 40), an offshore flow of 0.50 cm/sec occurred within the pycnocline.

September-October. The September-October period is one of net upwelling. In this case, rates of mixing can be obtained from volumetric data in the same manner as was used during June-July 1962 (p. 40). The mixing rate, so obtained, requiring an algebraic difference in normal velocities of 11.0 cm/sec, is similar to that obtained for June-July. Offshore flow could have existed in the frontal layer.

In summary, the observed flows within the frontal layer had the same direction as the flows within the upper layer in ten of the fourteen observation periods. If during periods of upwelling, mixing at the surface exists, offshore flow somewhere within the front is required. This would increase the number periods in which surface and frontal flows agreed to twelve. No correlation was observed between the magnitude of flow in the front and surface layer flow. A mean magnitude of 0.85 cm/sec was observed for volumetrically determined frontal flows, that is, assuming no mixing. Since mixing probably occurred, this magnitude is probably too small.

Evaluation Principles for the Frontal Profiles

For the upper layer, the axioms left only one surface through which changes in characteristics could be effected - the vertical offshore boundary. The only boundary of this layer which varied in position with time was sigma-t surface 25.5. Therefore, the following principles may be used to estimate flow direction within the upper layer:

(1) Downward translation with time of the upper boundary of the front indicates a shoreward flow within the upper layer (and vice versa).

(2) Rotation with time of the sigma-t surfaces indicates flow in the direction of relative deepening of the sigma-t surface.

For the frontal layer a similar situation exists. However, in this case two surfaces vary in position - the upper and lower boundaries of the front. The following principles may be used to evaluate flow direction within the frontal layer:

(3) A vertical translation of one or both frontal boundaries with time that thickens the front requires a shoreward flow within the front.

(4) A rotation of one of the frontal boundaries relative to another with time indicates a flow in the direction of relative divergence of the sigma-t surfaces.

It is difficult to generalize the relationships governing the flow magnitudes. However, if the change in area is the predominant factor in velocity determination, the following generalities may be used to estimate flow magnitudes within the layer:

(5) Flow at the vertical offshore boundary required by translation must decrease to zero at the coast.

(6) Flow which is the result of rotation only will have a maximum magnitude halfway to shore; the magnitude must decrease to zero at each vertical boundary.

If the sigma-t surfaces are linearized, i.e. represented by a straight line, the frontal profiles are represented schematically. With a schematic representation it is possible to simplify and quicken the velocity determination process using the above generalities.

DYNAMIC CONSIDERATIONS

Turbulence

The second axiom of the kinematic model was that no mass was exchanged across sigma-t surfaces. However, if turbulent flow existed, this axiom would not be correct and the kinematic model would need modification.

It is possible to determine the existence of turbulence by an examination of the velocity and density gradients. The condition for the suppression of turbulence (4, p. 392) is:

$$\frac{gE}{\left(\frac{\partial u}{\partial z}\right)^2} > 1 \qquad (5\text{-}1)$$

u = horizontal velocity
z = depth
g = gravitational acceleration
E = stability, i.e., the rate of change of density with depth

The expression on the left hand side has been termed the Richardson number, Ri.

Proudman (17, p. 102, 112, 160) has provided useful numerical steps for the calculation of the Richardson number which have been utilized, slightly modified, to obtain Table 7. As Maughan (16, p. 13) has stated that the drogue measurements of September 1962 (6209), are most reliable, these were utilized with the velocity vectors resolved into the east-west plane. The hydrographic data from the 6209 hydrographic cruise are also utilized to provide the necessary density gradients.

The results of these calculations (Table 7) indicate Richardson numbers equal to 10 to 100 for the frontal layer. It would appear that the flow is laminar (nonturbulent) and that therefore the second axiom of the kinematic model is a valid approximation.

Table 7. Values of the coefficients of vertical eddy diffusion (K_z), vertical eddy viscosity (N_z), and of the Richardson number (Ri) at NH 50 during September 1962.

z	K_z	N_z	Ri
m	cm^2/sec	$10^2\ cm^2/sec$	--
50	-5.91	-49.2	14.2
100	-13.40	-62.6	11.6
150	-53.50	-743.	303.
200	-211.4	1180.	-173.

However, Defant states for a similar case (4, p. 393) that:

> The Ri-numbers...are so high that...a turbulent flow can hardly be present. However, the measurements indicated still a small, though very weak, turbulence with a friction coefficient between 1.9 and 3.8 $cm^{-1}\ sec^{-1}$. According to these investigations, other factors seem also to be involved in the appearance and maintenance of turbulence.

Specific determination of similar friction coefficients has not been undertaken for the Oregon Coastal waters.[1] Since the second axiom

[1] For the area 44°-46°N, 125°-129°W, Pytkowicz (18) has calculated from oxygen distribution the following values for A_z (i.e., ρN_z) at 10, 20, and 30 meters depth: 2.3, 1.3, and 0.1 gm/cm-sec, respectively.

need only be an approximation, the existence of small, very weak, turbulence would not be a sufficient basis to invalidate the kinematic model or the results obtained through its use.

Ekman Transport

Earlier a relationship between wind direction and sigma-t depth was noted (p. 3-12). Freeman (11) has established, for sufficiently small accelerations, that

(5-2) $$\frac{\partial H}{\partial t} = \left(\frac{1}{\rho f}\right)\left(\frac{\partial \tau y}{\partial x} - \frac{\partial \tau x}{\partial y}\right)$$

where "H" represents the thickness of the upper layer, "f" the Coriolis force, τ the wind stress, and ρ the density of the surface layer (11). Since

(5-3) $$fV_E = - \tau x, \; fU_E = \tau y$$

where "U_E" is the zonal component of Ekman transport and "V_E" is the meridional component of Ekman Transport (8, p. 4), equation 5-2 becomes

(5-4) $$\frac{\partial H}{\partial t} = \left(\frac{1}{\rho}\right)\left(\frac{\partial U_E}{\partial x} + \frac{\partial V_E}{\partial y}\right)$$

Using Fofonoff's data (8, 9, 10) values of $\partial H/\partial t$ have been determined for a position 45°N, 130°W. Note that Δx is 788 km, and Δy is 1111 km (2, Table 6). Also, the value of U_E at 45^oN, 125^oW was assumed always zero due to its proximity to shore. Finally, a positive $\partial H/\partial t$ indicates shallowing of the surface layer.

Table 8 indicates that divergence due to Ekman transport would result in shallowing of the surface layer during the upwelling season, rapid deepening immediately thereafter, and a period of little frontal movement. However, the magnitudes of $\frac{\partial H}{\partial t}$ obtained from divergence of the wind differ by a factor of ten from those obtained by use of the frontal profiles (Fig. 5).

Table 8. Change in depth of the frontal layer due to Ekman transport at 45^oN, 125^oW.

Month	Mean 1950-1959 cm/day	Mean 1950-1959 m/mth	May 1961-June 1962 cm/day	May 1961-June 1962 m/mth
Jan	-0.6	-0.2	-7.9	-2.5
Feb	-3.5	-1.0	3.1	0.9
Mar	-1.0	-0.3	4.2	1.3
Apr	-0.6	-0.2	-6.8	-2.0
May	-0.1	0	3.1	1.0
Jun	1.8	0.5	-0.3	-0.1
Jul	3.1	0.9	2.8	0.8
Aug	3.5	1.0	0.9	0.3
Sep	0.6	0.2	0.5	0.2
Oct	-4.4	-1.3	-3.6	-1.1
Nov	-5.6	-1.6	-0.9	-0.3
Dec	-10.4	-3.1	-1.8	-0.5

SUMMARY

In 1962 the Oregon coastal front was primarily the result of a permanent halocline which usually extended from 50 to 150 meters depth. During the heating season, a thermocline developed, extending the front upward to within 10 meters of the surface. Sigma-t surfaces 25.5 and 26.0, which always fell within the front, were chosen to describe the front.

The major changes in frontal shape were due to upwelling. Upwelling caused the shoreward portion of the front to curve upward, intersect the surface, and form a surface front. Upwelling also resulted in an average upward translation of the frontal layer of approximately twenty meters.

The depth of each sigma-t surface (25.5 and 26.0) was related to the depth of the other with resulting correlation coefficients having a magnitude greater than 0.90.

Frontal depth appeared to be related to geostrophic winds.

Assuming conservative sigma-t surfaces and complete absence of north-south gradients, volume changes in surface frontal layers were interpreted as the result of flow perpendicular to the coast. Surface currents appeared to fall within three periods: (1) a period of offshore flow occurring from May to the middle of October;

(2) a relatively short period of large onshore currents which took place during late October, November, December, and possibly January; and (3) from February to April a somewhat "neutral" period in which no large flow took place.

The direction of frontal flow coincided with that of the surface flow in ten of the 14 observation periods. If appreciable mixing occurred at the front with resultant increase in volume of frontal type water, agreement in flow direction would occur in 12 of the observation periods. Flow agreement for these two additional periods would have required sinking rates of approximately 0.04 cm/sec for a surface front of 5000 meters width.

Richardson numbers ranging from ten to three hundred were obtained for the frontal layer in September 1962.

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