Bottom Nepheloid Layers and Bottom Mixed Layers Observed on the Continental Shelf off Oregon

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One hundred and seventy pairs of temperature and light transmission profiles were obtained by simultaneous conductivity-temperature-depth (CTD) and light transmissometer casts in three cruises on the R/V *Yaquina* over the continental shelf off Oregon. These were analyzed for bottom nepheloid layers (BNL) and bottom mixed layers (BML). Supplementing these data were 1177 CTD profiles taken during the Coastal Upwelling Ecosystems Analysis (Cuea) program and time series current data obtained under the Winter-Spring Transition Experiment on the Oregon Continental Shelf program. Frequencies of BML occurrences obtained from Cuea data taken during July and August 1972 and July and August 1973 were 52.9 and 53.3% for the respective years. Frequency of BNL occurrences for each of the three *Yaquina* cruises was consistently higher than that of BML. Large temporal variations in bottom layers are attributed to advection of different water types there. Frequency of BNL and BML is clearly associated with coastal upwelling intensities; under intense coastal upwelling, BNL and BML tend to be dissipated, and under weak coastal upwelling, they tend to be thick.

INTRODUCTION

Bottom nepheloid layers (BNL) have been observed in all the major oceans of the world [*Ewing and Thorndike*, 1965; *Hunkins et al.*, 1969; *Eittreim et al.*, 1969; *Plank et al.*, 1973; *Drake*, 1974; *Biscaye and Eittreim*, 1974]. Bottom layers have often been observed in temperature profiles as mixed layers in the western Atlantic, on the continental shelf off Florida [*Millard*, 1974; *Weatherly and Niiler*, 1974], and on the continental shelf off Oregon [*Huyer and Smith*, 1972]. Knowledge of the mechanisms that generate and maintain these layers and the processes that cause large temporal variations [*Plank et al.*, 1973] is still very meager. The lack of field measurements of environmental parameters still appears to be the most serious obstacle. Since both the bottom nepheloid layers and the bottom mixed layers (BML) are found in bottom waters, their formation, dissipation, and time variation may be controlled by common processes. Studies of the bottom layers, especially if they are measured simultaneously, should help us to understand the processes. In this paper we present simultaneous measurements of suspended particles, temperature, and current to describe BNL and BML on the continental shelf off Oregon during the spring and summer seasons. On the basis of these observations, supplemented by a large number of conductivity-temperature-depth (CTD) profiles obtained during the Coastal Upwelling Ecosystems Analysis (Cuea) program, we discuss the processes of generation and dissipation of BNL and BML.

DATA

Data analyzed in this study include salinity-temperature-depth (STD) measurements from Cuea data reports 4 [*Halpern and Holbrook*, 1972] and 12 [*Holbrook and Halpern*, 1974] and nephelometer profiles taken during three cruises on Oregon State University (OSU) research vessels (Table 1). Cuea data report 4 contains STD profiles taken during July and August 1972. They extend to within 5 m of the bottom in a region from 44°10.0'N–45°05.0'N latitude to 125°00.0'W longitude. Cuea data report 12 contains STD profiles taken during July and August 1973. They extend to within 5 m of the bottom and along two zonal sections (45°15.0'N and 45°19.0'N) to 125°30.0'W longitude. The STD measurements were made with a Hytech model 9006 salinity-temperature-depth-sound velocity instrument.

Station locations for the three cruises on the OSU research vessels listed in Table 1 are shown in Figure 1. The STD used during the C7308-E cruise was a Plessy self-contained STD unit. The STD data are reported by *Curtin et al.* [1975]. The 'Scout' nephelometer is an in situ self-contained light-scattering meter, designed and built at OSU. It measures the forward scattering at 45° from a collimated light beam of a tungsten lamp. The STD and Scout nephelometer were tied side by side and lowered simultaneously to within about 5 m of the bottom.

The nephelometer, used in the two other cruises, contains a Geodyne CTD unit, a light transmissometer, and a 12-bottle Niskin sampler mounted on a single cage. Data from the CTD and the transmissometer were sent to a shipboard recording system through a cable by using frequency modulation. The transmissometer, designed and constructed by the Optical Oceanography Group at OSU, uses a light-emitting diode in a pulsed mode as the light source and has 0.5% stability over the temperature range of 0°–25°. The nephelometer was lowered to within 5 m of the bottom during most casts.

The data obtained by both nephelometers are described and interpreted as a parameter indicative of concentration of suspended particulate matter (spm). Such a conversion is certainly valid for a first approximation. Suspended particulate matter determinations using such approximations have been attempted by *Jerlov* [1968], *Gibbs* [1974], *Biscaye and Eittreim* [1974], and others.

RESULTS

The BML is a vertically homogeneous layer in temperature immediately above the bottom, usually identified from temperature profiles. The BML usually are indicated concurrently in both temperature and salinity profiles. *Weatherly and Niiler* [1974] report that the layers appear in both temperature and salinity profiles with mutually consistent thickness. Because we found that the thicknesses of BML were not always consistent in temperature and salinity profiles, as is indicated in Figure 3, we used temperature profiles only as the criteria of BML in this study. According to the scales of temperature and salinity

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TABLE 1. Station Locations, Time, and Instruments of OSU Cruises

Cruise	Time	Instrument
C7308-E	August 23–31, 1973	STD and Scout nephelometer
Y7408-B	August 19–28, 1974	nephelometer
Y7504-C	April 23 to May 2, 1975	nephelometer

used in plotting STD data in the Cuea data reports, vertical gradients of salinity were generally less than the vertical gradient of temperature, and salinity profiles showed nearly constant salinities in the bottom boundary layers. At depths corresponding to the top of BML in temperature profiles, salinity profiles did not show any recognizable mark, such as a sharp change in gradient or break in the profile. Hence an objective determination of BML thickness in salinity profiles was often impossible.

Cuea Data

Frequencies of BML and BNL occurrences determined from the Cuea data reports and the three optics cruises are shown in Table 2. The frequency of BML occurrence versus water depth (in meters) indicates a slight depth dependence (Table 3). The maximum frequency can be found in the depth range of 50–200 m.

A scatter diagram of depth versus thickness of BML (Figure 2) shows a large scatter of points, which indicates a low correlation between them. An envelope of the points shown by the dashed curve in Figure 2, however, shows a positive correlation with a peak thickness at about the 200- to 250-m depth. The peak value of thickness is approximately 70 m. Because of

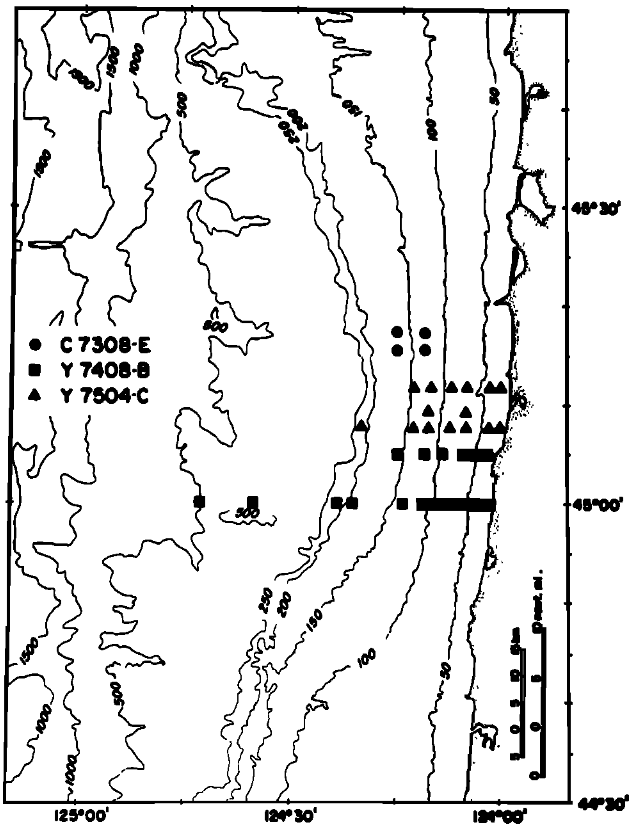

Fig. 1. Bathymetry and approximate locations of stations occupied during the three cruises listed in Table 1.

TABLE 2. Frequencies of BML and BNL Occurrences Determined From Cuea Data Reports and Optics Cruises

	Total Profiles	Frequency of Occurrence, %	
		BML	BNL
C7308-E	47	96	100
Y7408-B	68	97	99
Y7504-C	55	40	72.7
Cuea report 4	726	52.9	
Cuea report 12	451	53.3	

the small number of deeper sample points, the envelope at those depths is not certain; therefore statistical significance of the shape of the envelope may also be uncertain in deeper water.

Effects of the density stratification on BML occurrence were examined by *Weatherly and Niiler* [1974], who reported that in shallow waters the occurrence of BML was not as frequent and that the thickness was not as large as that in deep waters. They suggested that 'additional damping of turbulent motions due to stronger, positive stratification' may be responsible for the low frequency and small thickness in shallow waters. According to our analysis, however, a high frequency of BML occurrence is associated with a strong thermocline in the surface layer. Figure 3 shows profiles of temperature, salinity, and density from two time series observations during the Cuea experiments at a station within 7 km of anchor station A8. Twenty-six profiles observed at 1-hour intervals are plotted on top of each other. Figure 3*a* shows a weaker thermocline ($\Delta T < 1.5°C/20$ m) in the surface layer with no BML in the bottom water, while a stronger thermocline ($\Delta T > 6°C/10$ m) with BML is shown in Figure 3*b*. It should be remembered that the strong thermoclines are observed under a weak upwelling or nonupwelling condition, while the weak thermoclines are observed under a strong upwelling condition. The vertical variation in Brunt-Väisälä frequency during strong thermoclines is different from that during weak thermoclines: the Brunt-Väisälä frequency increases steadily upward under strong thermoclines (Figure 4, bottom panel) and increases slightly upward under weak thermoclines (Figure 4, top panel). The absolute value of Brunt-Väisälä frequency was smaller in the bottom water when the BML was present.

Millard [1974] and *Weatherly and Niiler* [1974] reported a trend of thicker BML associated with cooler water, and from it they suggested a possible BML formation process through Ekman veering. When data in the Cuea data reports were examined, no clear correlation was found between the thickness of BML and the bottom temperature. Hence the absolute value of the bottom water temperature at 5 m above the bottom is not simply related to the thickness of BML on the continental shelf off Oregon.

Data From the Optics Cruises

The frequencies of BML and BNL occurrence observed during the three optics cruises are also listed in Table 2. The BNL is defined, similarly to the BML, as a layer immediately above the bottom in which concentration of spm is larger than that in the water above and the concentration generally increases with depth within the layer; occasionally, the concentration can be vertically homogeneous, like the BML in a temperature profile. Frequency of BNL was not measured during the Cuea cruises. The frequencies of occurrence of BML differ significantly during the two optics cruises C7308-E

TABLE 3. Frequency of BML Occurrence Versus Water Depth

	Depth Interval, m														
	<30	31–40	41–50	51–60	61–75	76–100	101–150	151–200	201–250	251–300	301–350	351–400	401–500	500–1000	1001–1500
Profiles	0/5	1/27	1/18	13/28	14/68	38/145	241/221	59/43	13/16	1/24	8/24	27/21	27/35	5/37	2/1
BML	0/0	0/3	0/8	8/15	11/44	19/97	144/149	36/33	6/7	1/7	4/8	8/3	3/3	0/6	0/0
Frequency of BML	0/0	0/11	0/44	61.5/54	78.6/65	50/67	60/67	61.0/77	46/44	100/29	50/33	29.6/14	11.1/9	0/16	0/0

Frequencies of BML occurrence in the numerators were determined from Cuea data report 12, and those in the denominators from Cuea data report 4.

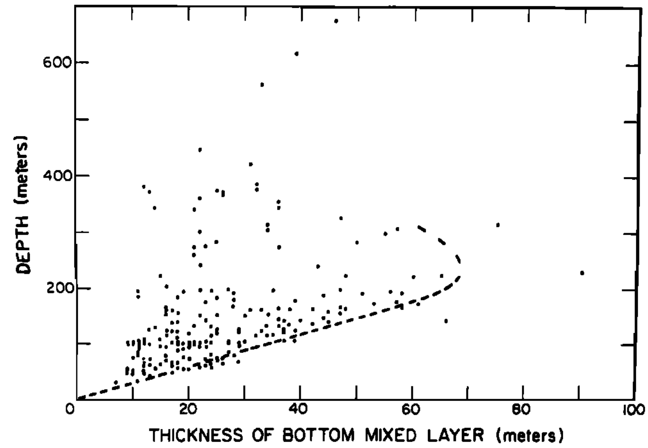

Fig. 2. Thickness of the BML plotted against water depth. Data are from Cuea data reports 4 and 12. Many overlapping points are omitted. The dashed curve is an envelope of the points determined by a freehand approximation.

and Y7408-B as compared to those of the Cuea and Y7504-C cruises; the frequency of BNL ranged from 100 to 73%, while the BML frequency varied from 97 to 40%. The two optics cruises with the high frequencies of BML and BNL (Y7408-B and C7308-E) were in August 1974 and August 1973, respectively. Each cruise was about a week long. The third cruise, with a low frequency (Y7504-C), was in April 1975 under moderate to strong upwelling conditions. As was described earlier with reference to Figure 3, coastal upwelling appears to be related to a lower frequency of BML occurrence, and the Y7504-C cruise took place during a coastal upwelling period. Strong coastal upwelling is indicated by wind, CTD profiles, and strong southward current. During the Y7504-C cruise, sea surface temperatures were often below 9° within 15 km from the coast. The seasonal variation of the BML and BNL frequencies described above would nevertheless require further verification, since we had only one spring cruise.

During the Y7504-C cruise we made time series of BML and BNL observations at two anchor stations located approximately 15 and 7 km offshore. They are designated as A8 and A4. Each profile made at the anchor stations is indicated by a number after the station designator, i.e., A8-1, A8-2, A4-3, etc. Observations were made at approximately 3-hour intervals. Temperature and light transmission profiles taken at station A8 are shown in Figure 5. Wind speed and direction at the two anchor stations are shown in Figure 6. A sharp increase in northerly winds (upwelling favorable wind) was observed at station A8, and the corresponding changes in BNL and BML are described below:

1. At the beginning of the anchor station the upwelling wind was on the increase from a relatively low speed of 10 kn (5 m/s). During this period the thickness of the BNL decreased from 64 to 12 m, and the BML was absent. Although no BML was present, there was a layer of homogeneous water at a middepth in the temperature profiles A8-1, A8-2, and N-8 (profile N-8 was taken approximately 5 hours before A8-1 at a station located 3 km to the north of A8). It appears that the middepth homogeneous water is the remnant of a BML which existed earlier as indicated in an earlier profile, S-8 (profile S-8 was taken 23 hours before A8-1 at a station located 3 km to the south of A8), and the BML was subsequently modified at both bottom and top ends. During the increase of the upwelling wind the remnant of the BML was also destroyed in the same

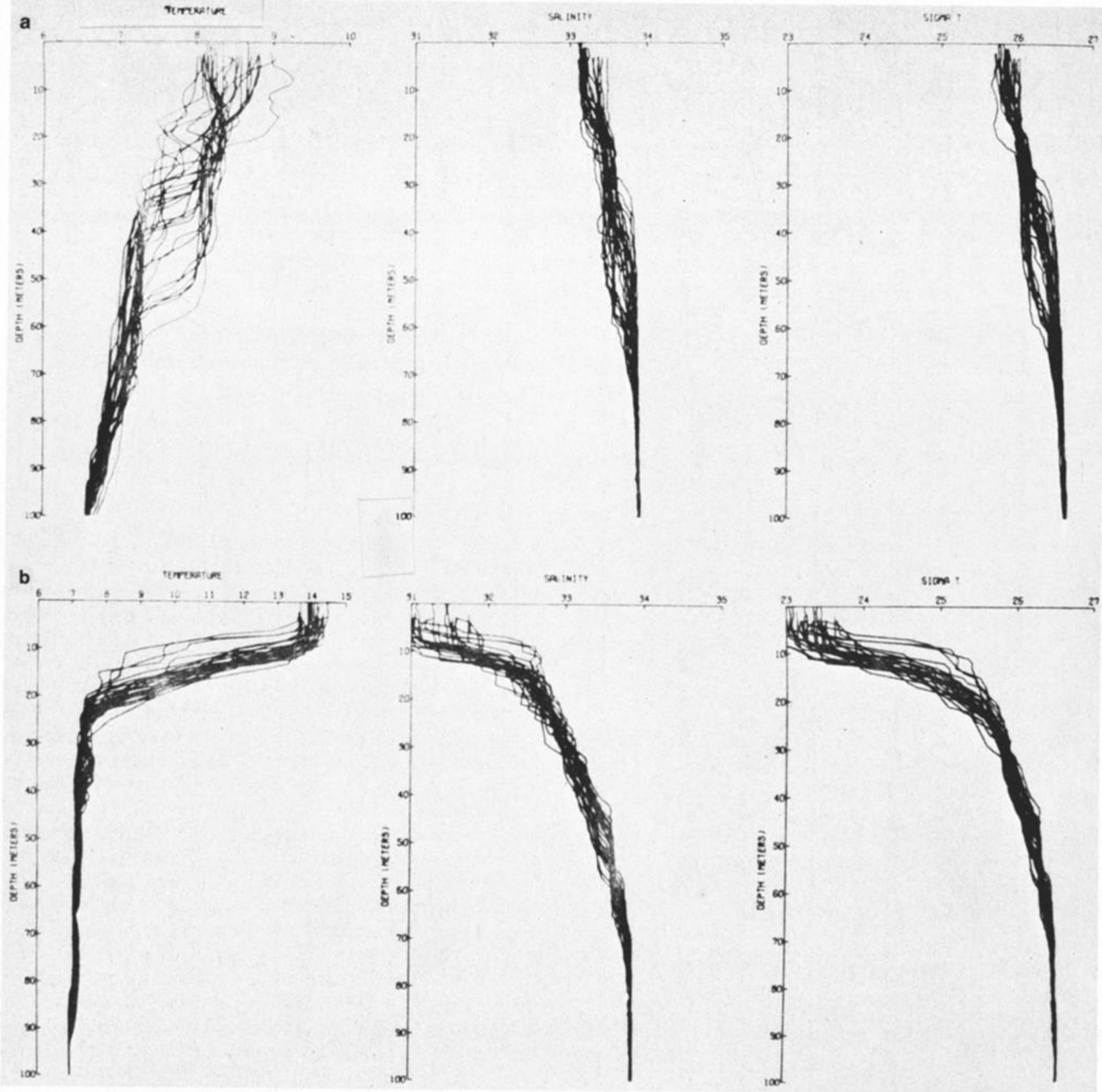

Fig. 3. Temperature, salinity, and sigma *t* profiles from two time series observations ((*a*) CUE-2-OC-179-204, and (*b*) CUE-2-OC-414-439) in August 1973 located at 45°15.6'N, 124°08.0'W on the continental shelf off Oregon. Figure 3*a* is from a strong coastal upwelling period, and Figure 3*b* is from a nonupwelling period [*Holbrook and Halpern*, 1974].

manner as the BNL; an advection of warm water eroded the homogeneous layer from its top downward.

2. As a result of dissipation of the BNL, the entire water column reached maximum clarity.

3. When the upwelling wind decreased to about 15 kn (7.5 m/s), approximately 5 hours after the peak upwelling wind of about 25 kn (12.5 m/s), a BML emerged, the BNL gained its thickness, and a distinct cold advection took place in the bottom water (Figure 7).

4. After the peak upwelling wind the entire middepth clean water was gradually replaced by more turbid water; the light transmission profiles indicate several layers of minimum light transmission, and the number of the minimum increased from 1 to 3 by the end of anchor station A8 (Figure 5).

A time series observation made at station A4, at approximately 7 km offshore, is shown in Figure 8. During the station A4 observations the BNL was not observed except possibly at the end of the station, and the BML was not observed at any time. Instead, a well-defined maximum in suspended particles was found at a middepth where clean water is normally found; moreover, the bottom water was clean. Gradually, the turbid water embedded in the middepth clean water descended during the period of observation, and at the end it appeared to have reached the bottom. Such a vertical movement of the turbid water from the middepth to the bottom suggests that the turbid water has been advected from an elevated source of such water, and an elevated source could be found in the nearshore water (to the east of station A4), since the bottom is

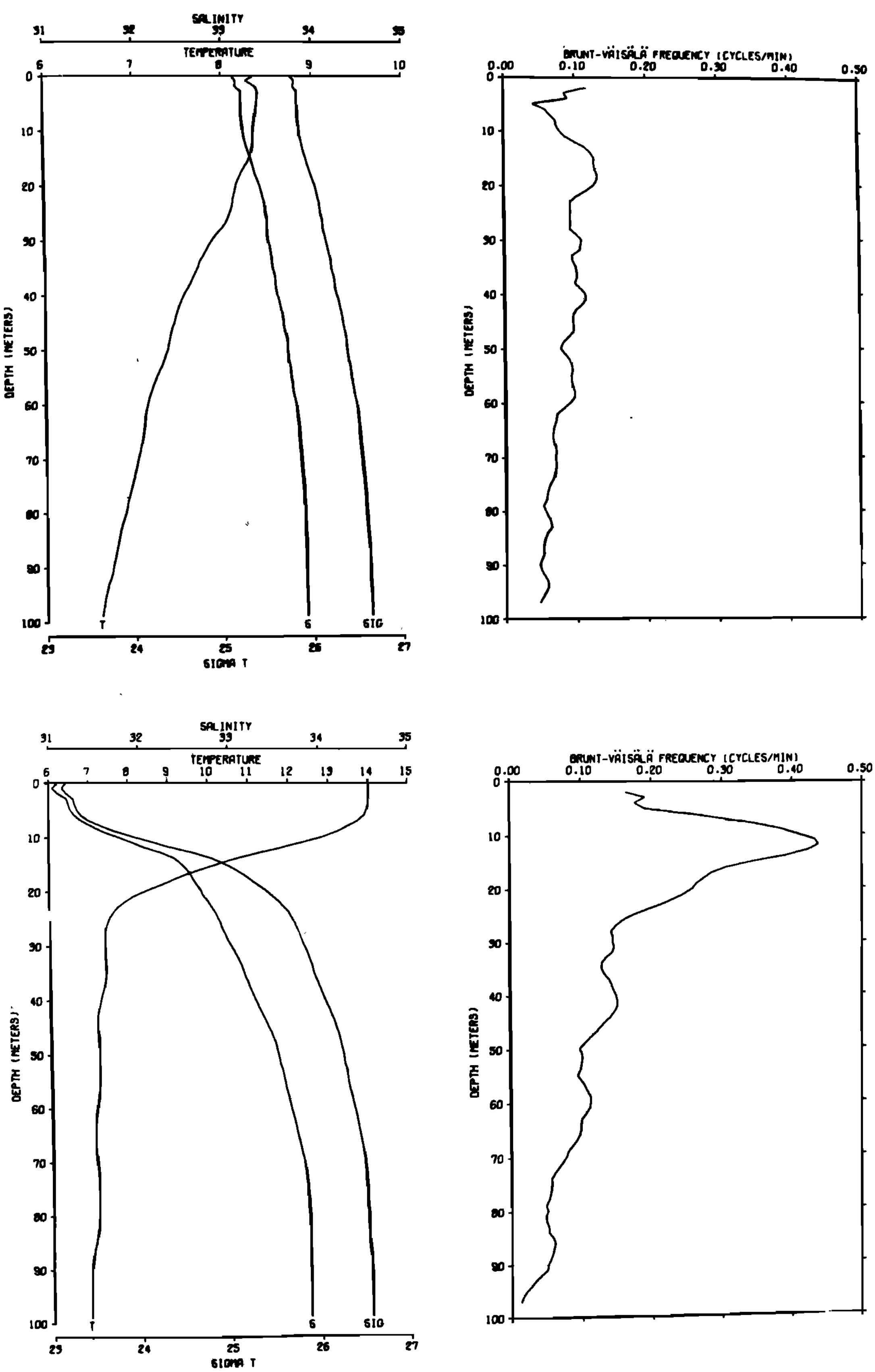

Fig. 4. Mean profiles of temperature, salinity, sigma t, and Brunt-Väisälä frequency for the two time series observations shown in Figure 3 [*Holbrook and Halpern,* 1974].

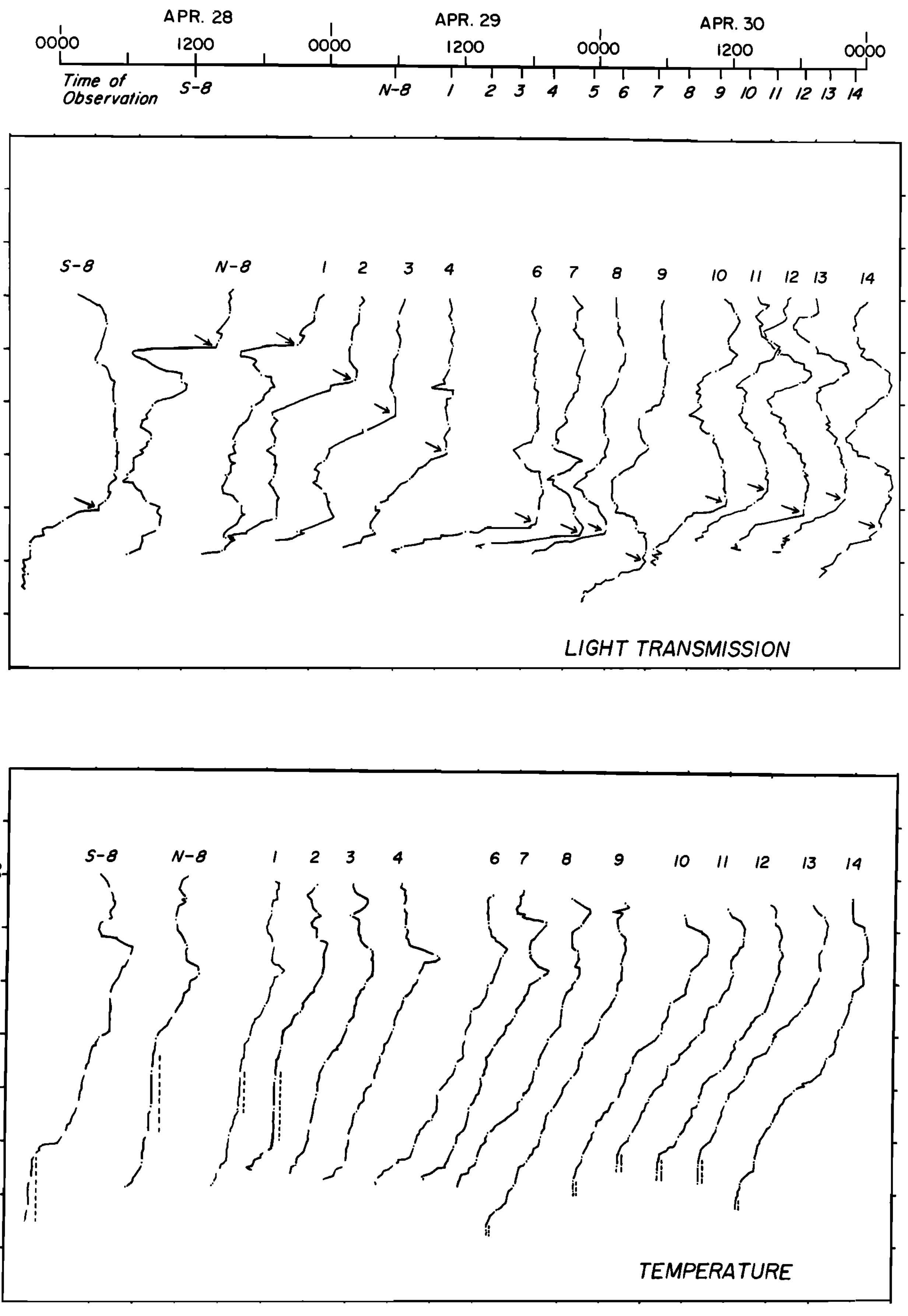

Fig. 5. Profiles of light transmission, in percent, and temperature, in degrees Celsius, at anchor station A8. Arrows indicate the tops of BNL, and broken lines on the right side of the temperature profiles indicate the mixed layers. Time of each profile is indicated at the top of the figure.

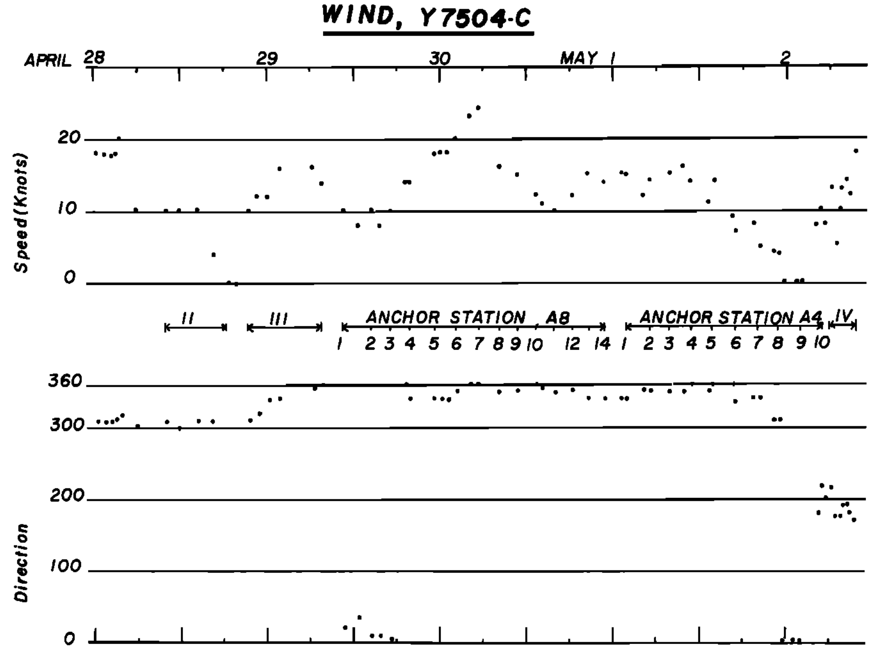

Fig. 6. Wind speed and direction observed during the Y7504-C cruise. Times of observation at stations A8 and A4 are also indicated.

sloped in this area. Furthermore, the temperature at the middepth turbid layer was nearly conserved for the 12 hours prior to the end of the station A4 observations, from 10 A.M. to 10 P.M., May 1, 1975, so the BNL at the end of station A4 may be interpreted as the turbid water derived from the same source of water found earlier in the middepth turbid layer.

In the later part of the time series observations at station A4 the upwelling wind subsided to a calm; then it reversed its direction, to the southerly wind, which is the opposite wind to the upwelling wind. Under the nonupwelling condition the BNL was formed at the end of station A4, a finding which was further confirmed by profiles measured a few hours later, i.e., stations S-4 and S-6 in Figure 9. Emergence of the BNL in this case also supports the relation between BNL and weak upwelling or nonupwelling conditions.

Current in the Bottom Layer

Current data from a string of bottom-moored current meters located about 10 n. mi. (18.52 km) to the south of station A8 are presented in Figure 10. The current meters were installed under the Winter-Spring Transition Experiment on the Oregon Continental Shelf (Wisp) program funded by the NSF [*Gilbert et al.*, 1976]. The data presented in Figure 10 are from two current meters placed at 75 and 90 m in water of 100-m depth. The current records are reduced by low-pass filter, and the u and v components are hourly values. At both depths a strong southward current was observed under the strong northerly wind. During the same period the u component varied from offshore flow at 75 m to onshore flow at 90 m. The onshore flow at 90 m is in the direction of the expected Ekman transport owing to bottom friction experienced by the strong southward flow in the bottom water. Much to our surprise the BML and BNL were both dissipating during the period of the maximum alongshore v component and the onshore u component in the bottom water. BNL have been attributed to a balance between particle settling and upward diffusion by turbulence in deep oceans [*Ewing and Connary*, 1970; *Eittreim and Ewing*, 1972]; the turbulence is supposed to cause vertical mixing in the bottom water and resuspension of bottom sediments. More upward diffusion is expected in the areas with high currents [*Eittreim and Ewing*, 1972; *Eittreim et al.*, 1975], but the time series observations at station A8 do not indicate any increase in intensity or thickness of BNL under the highest current that we measured during the time series observations.

The current records were not obtained at the same stations where temperature and light transmission were observed, so coherence of the current signals over the distance of 10 n. mi. (18.52 km) is required to support the interrelation between current and temperature or light transmission. Comparing current observations made on the continental shelf off the Oregon-Washington coast, separated by 200 km in the alongshore direction, *Huyer et al.* [1975*a*, *b*] found significant coherence in frequencies less than 1 cpd, and coherence was higher for alongshore separations as compared to offshore separations, even with much greater alongshore separations. They

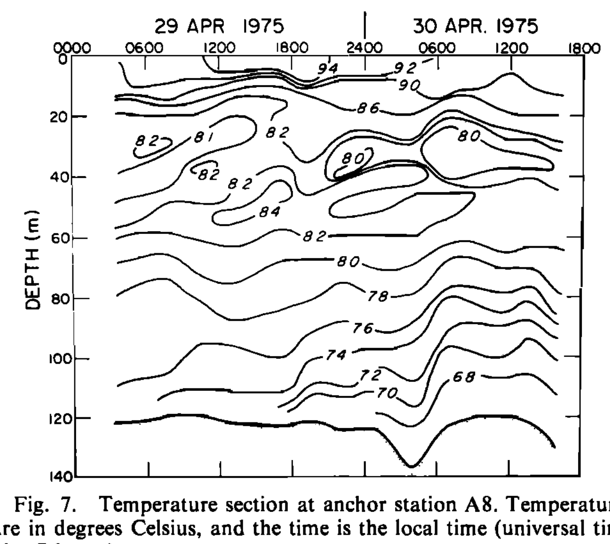

Fig. 7. Temperature section at anchor station A8. Temperatures are in degrees Celsius, and the time is the local time (universal time plus 7 hours).

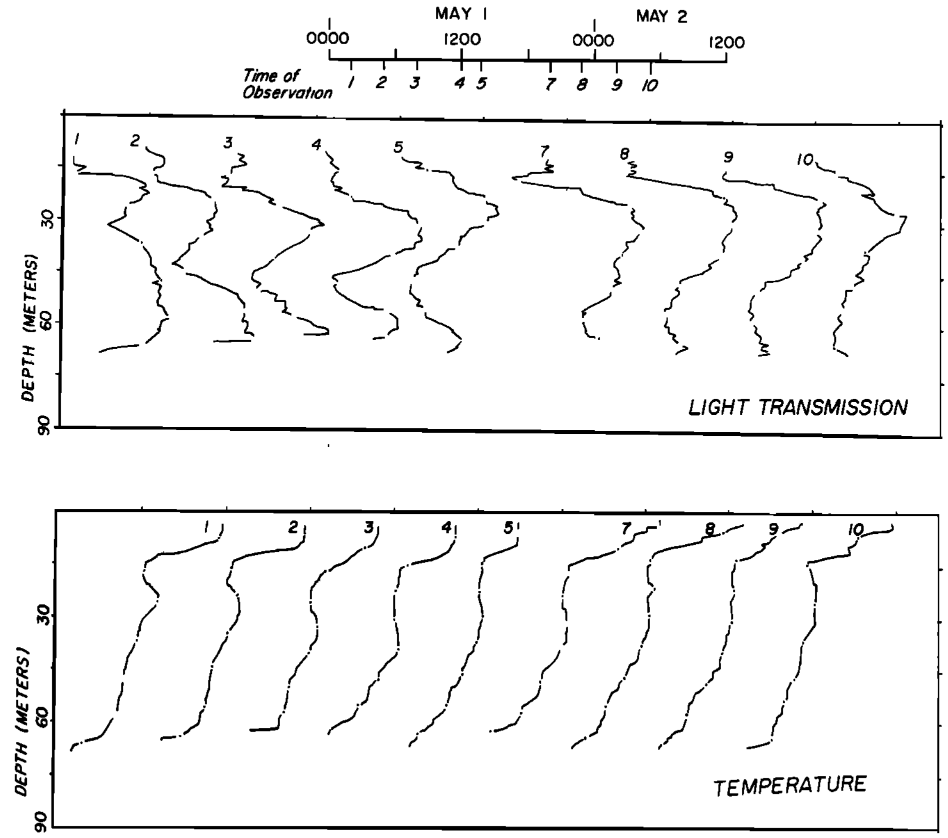

Fig. 8. Profiles of light transmission (in percent) and temperature (in degrees Celsius) at anchor station A4. Time of each profile is indicated at the top of the figure.

concluded that the alongshore correlation length is more than 300 km for the low-frequency fluctuations. In light of these findings we can assume homogeneous currents over a 10 n. mi. (18.52 km) distance for the significant temporal variations of currents discussed in this paper.

DISCUSSION

Frequencies of BML and BNL

According to the frequencies of BNL and BML shown in Table 2, particularly the value from cruise Y7504-C, a BNL was observed whenever a BML was observed, but the reverse relation did not hold. This could be explained by the difference in their definitions; the concentration of particles is not required to be vertically homogeneous in the BNL, while vertical homogeneity in temperature is required in the BML. Even though the processes of BML and BNL generation are not well understood, the relation appears to be suggestive about the processes: while advection of turbid water in the bottom layer forms a BNL, a BML requires further development, perhaps vertical mixing, to produce vertical homogeneity.

The frequency of BML occurrence during two optics cruises, C7308-E and Y7408-B, was over 95%, which is considerably different from the 53% observed during the Cuea cruises. In addition to the seasonal changes of the frequency which were described earlier in connection with the seasonal changes of coastal upwelling, we found one other probable reason for such a difference. The Cuea data are from 2-month periods, and the occurrence of BML was noticed to be in a pattern rather than in a random distribution; in other words, they persisted as if they were generated by a storm type disturbance which occurs on a scale of days. The optics cruises were only about a week long, and they could have taken place during the period with conditions favorable for BML formation. On the basis of sea surface temperatures observed during the two optics cruises with high frequencies of BML the coastal upwelling was not very intense; the temperatures were in the range from 13° to 14.5°C beyond 7 km from the shore, typical sea surface temperature values under weak or nonupwelling periods. Thus the high frequencies of BML were expected during the two optics cruises from consideration of the upwelling conditions.

Bottom Friction

How the BML and the BNL are produced is the next question. BML must be caused by some environmental conditions yet unknown. A close examination of the anchor station data suggests one or possibly two different processes. Under strong upwelling winds, v components of the currents sharply increased at both 10 and 25 m above the bottom (Figure 10). While the wind and current were intensifying, the BNL dissipated from the top downward, and eventually, the thickness was reduced to less than 10 m. Considering that the change started at the top of the BNL and moved downward and that it was substantial (most of the water column was replaced by clean water, as is indicated by profile A8-5), taking only 6–9 hours after onset of the strong current, the changes in the BNL can only be attributed to advection of clean water, certainly not to settling of particles.

The changes in temperature profiles were not as dramatic as they were in the light transmission profiles. By comparing temperature and light transmission profiles from each observation (A8-1, A8-2, A8-3, and A8-4) when the large change in the

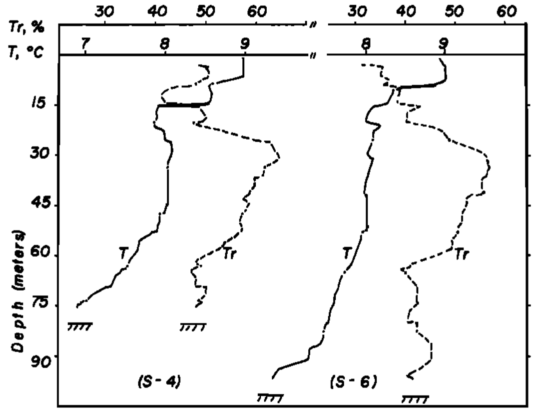

Fig. 9. Temperature *T* and light transmission *Tr* profiles at stations S-4 and S-6, which are located 4 and 6 n. mi. (25.92 and 29.63 km) offshore along a zonal section 2 mi south of the two anchor stations.

BNL took place we can recognize that the isothermal layer at the middepth changed in the same way that the BNL did; the quasi-isothermal layer was destroyed from the top downward, and the destruction apparently was caused by warm advection at the upper part of the layer.

During the next period from profiles A8-5 to A8-8 (from 2325 LT, April 29 to 0810 LT, April 30) the v component of the current in the bottom water remained almost at the peak speed (Figure 10), and temperature and light transmission profiles in the bottom water changed very little: the BNL maintained its thickness of about 10 m without appreciable gain in intensity. It appears that the current was not producing upward diffusion of particles more than 10 m from the bottom. The BML was not observed in this period.

At profile A8-9 (1055 LT, April 30) the thickness of the BNL increased by almost 10 m, and it was maintained for the rest of the station A8 observations (from A8-9 to A8-14). At the same time a BML appeared, shown in Figure 5 by dashed lines. Temperature of the BML is considerably lower than that of the bottom water before the appearance of the BML (profiles A8-3–A8-8), an indication of cold advection. According to *Wimbush and Munk* [1970] a thickness of frictional influence δ is proportional to a shear stress parameter U_* which is primarily related to bottom current velocity. Appearance of the BML and increase of the thickness of the BNL at A8-9, especially under a strong bottom current, are certainly suggestive of an increased δ. A closer examination of the data, on the other hand, presents the following facts: (1) the BML appeared 9 hours after onset of the peak current, (2) no appreciable change in the thickness of the BML was observed after the appearance of the BML, in spite of the sustained high current, and (3) cold advection accompanied the appearance of the BML. If the frictional influence of mixing were responsible for the changes in BML and BNL and 9 hours were required to make the observed changes, we would expect to see the changes continue as long as the current remained strong. The BML and BNL, however, did not appreciably change in the next 12 hours under the sustained current. In the Cuea data we found that BML thicknesses as large as 40 m in areas with depths similar to that at station A8 were observed during the summer seasons (Figure 2), when smaller currents prevailed [*Huyer et al.*, 1975*a*, *b*]. To account for the thickness of 40 m in light of the station A8 observations, either an enormously larger bottom current or an alternative process seems required.

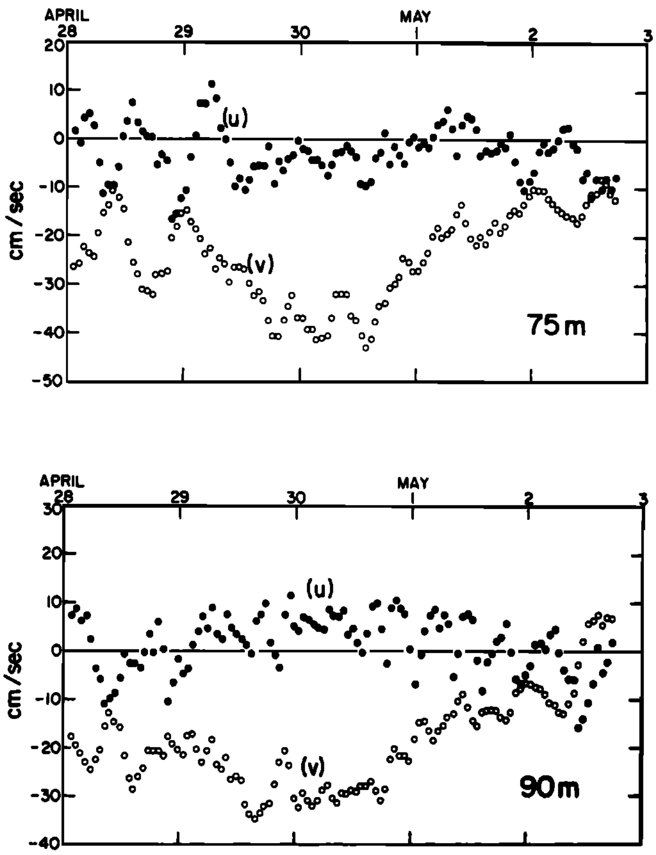

Fig. 10. Current observed at approximately 10 n. mi. (18.52 km) to the south of anchor station A8 during the A8 observations. The current was measured in water of 100-m depth, and the two depths are 25 and 10 m above the bottom, respectively. The u component is in the onshore-offshore direction, and the V component is in the alongshore direction.

Quasi-Horizontal Advection

As an alternative process to the frictional influence we consider advection of water with the required characteristics: vertical homogeneity in temperature and larger concentration of suspended particles. Assume that the BML and BNL are formed by an advection of water that is turbid and well mixed along the bottom layer. This advection, however, would require a source of water with such properties. Sources of turbid water are generally found in the nearshore water, where particles are added to the water from land sources, bottom sediments, and biological production. In particular, particles of small sizes have extremely small settling velocity, so they tend to stay in suspension. Advection in the bottom layer from nearby coastal sources, would therefore result in a BNL formation. In fact, most coastal regions are not experiencing accumulation of sediments, a condition which implies that sediment particles are carried away. On the basis of the widespread and persistent distribution of BNL, bottom layers appear to be important routes of particle transport in the ocean.

Is it possible to explain the widespread distribution of BML in the ocean simply by advection of BML from coastal sources? BML exist over the continental shelf in a wide range of temperatures according mainly to depth of water; in general, temperature is lower in deeper water to maintain the stratification. Since temperature is high in the bottom layers at shallow depths, offshore advection along the bottom layers would result in warm advection. Warm advection in bottom water would in turn generate convective overturning. Thus the bottom water would change its temperature as it mixes with water above it. Temperature of BML on the shelf is far from constant, and this indicates that the BML formation would take more than a simple advection. The advected water requires vertical mixing to form a BML. *Eittreim et al.* [1975] discussed how the Ekman thermal pump accounts for BNL 200 m thick or more on the continental rise and Blake-Bahama outer ridge off the coast of the eastern United States. The Ekman thermal pump requires a downslope movement of warm water (warm advection), and an Ekman veering was suggested as a possible cause for such an advection. On the continental shelf off Oregon the Ekman veering required to produce the offshore advection would occur in the northward-flowing bottom current. The northward bottom current prevails while upwelling is weak. Thus the necessary Ekman veering is expected more in nonupwelling seasons. The events that occurred at station A4, offshore advection (warm advection) and downwelling, were not quite a warm advection in the bottom layer; consequently, a BNL was formed, but a BML was not. On the other hand, a BML formation may require a time lag from a BNL formation. Advection of turbid water in the bottom layer would immediately be sufficient for a BNL, but a BML would require mixing after the advection. The reasons for the nonoccurrence of a BML at the end of station A4 can be, first, the time lag required for mixing and, second, unfavorable conditions for mixing. Quite likely the two reasons could be related; the time lag will be infinitely long if mixing conditions are not favorable.

A BML and a BNL may not necessarily be generated by the same processes; moreover, they may not be generated simultaneously. A BNL, for example, may be formed merely by advection of turbid water in the bottom layer, but local vertical mixing seems necessary for a BML formation. The local vertical mixing, which may not be required for a BNL formation, would make the BNL thicker than otherwise. Since the mixing occurs between turbid water in the BNL and cleaner water above it, the concentration of spm would decrease by the mixing, and the shape of the spm profile would become similar to the temperature profile (like station S-8 in Figure 5).

Hypothesis on Offshore Transport of Sediment Particles

The advection that is found to be an effective process of generating BNL must also be an effective process of horizontal transport of suspended particles. Particles found in the BNL are transported by the current in the bottom water. This process could have a far-reaching consequence on particle transfer from coastal sources to the nearby abyssal plain. Problems in interpreting sediment distributions, tracing sources of particles found in sediments, discussing environmental conditions from sediment characteristics, and zoning biological conditions from sediment distribution must consider the particle transport processes. Settling velocities of particles of a few microns in diameter may be less than 1 m/d, so they will take 10 yr to reach the bottom in 3600 m of water. A horizontal current of 1 cm/s would carry the particles 864 m in 1 day, 311 km in 1 yr, and 3110 km in 10 yr. Even at a 1-cm/s current, since settling velocities of the dominant particles in the ocean (small size particles) are low, dispersion during their settling by currents throughout the water column can be large. By advection through BNL, on the other hand, particle transfer from coastal waters to abyssal sediments seems possible without the vertical settling through water columns. Thus sediment distribution in a confined geographic pattern can be traced to a particle source region with minimum dispersing effect.

CONCLUSIONS

In summary, the following may be concluded:

1. The BNL is present at least as frequently as the BML on the shelf off Oregon during the spring and summer seasons.
2. BNL and BML were most frequently observed in the middle of the continental shelf in the depth range of 50–200 m.
3. A high frequency of BML and BNL occurrence was observed when winds were not favorable for coastal upwelling and when a strong thermocline existed in the nearshore water; the lowest frequency of BML occurrence was found in April–May 1975, when coastal upwelling was strong.
4. A major source of turbid water supplying spm to a BNL on the shelf appears to be the coastal source region. The turbid water spreads out by advection and diffusion processes in the bottom water.
5. Advection of turbid water from the coastal source appears to be one of the BNL forming processes. It is not certain that a BML is also formed by the advection from the coastal region; it is, however, certain that an extra process for vertical mixing is necessary to form a BML.
6. Large temporal variation in BML and BNL is associated with changes in horizontal advection; larger current speed in bottom waters did not accompany any appreciable increase in BML and BNL thicknesses.

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