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Vertical shear observed at contrasting sites over the continental slope off NW Africa

NW Africa
Slope undercurrent
Small scale shear
Thermohaline structure
Dynamic stability

Afrique Nord Ouest
Pente continentale
Cisaillement
Structure thermohaline
Stabilité dynamique

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ABSTRACT

Two 12 hour time series of vertical small scale shear and hydrographic profiles were made with Protas and STD probes over the continental slope off NW Africa as part of the Upwelling 75 programme. Instrument drops to 300 m were made close to current meter moorings situated in 2 000 and 500 m bottom depth. A preponderance of North Atlantic Central Water carried equatorward in the Canary Current was evident at the offshore site. Its influence weakened with depth because poleward flow below 150 m introduced South Atlantic Central Water into the column. The influence of the southern water mass was stronger at the slope site where poleward flow occurred throughout the upper 300 m. The maximum of poleward flow was associated with a minimum of salinity near 200 m depth.

Levels of square shear were more than twice as high at the slope station than offshore, while the density stratification was weaker. Values of square shear were correlated with square Brunt-Vaisala frequency at the offshore site but not at the slope site. Whereas internal waves represented the dominant contribution to the observed shear offshore, over the upper slope turbulent contributions appeared more important. Thermohaline steps were apparent below 150 m at the offshore site but were well developed only when the overall level of shear was low. The interfaces of the step structures, which were associated with maxima of the shear vector modulus, were of marginal dynamic stability at all times. The poleward flow over the upper slope exhibited numerous dynamic instabilities on vertical scales of metres. The region of the salinity minimum, which was closely associated with the minimum of large scale vertical shear (core of the poleward current), was more stable dynamically.

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RÉSUMÉ

Cisaillement observé en différents sites sur la pente continentale au large du nord-ouest de l'Afrique

Pendant le programme Upwelling 75 des profils verticaux hydrologiques et de cisaillement à petite échelle ont été établis avec des sondes Protas et STD au cours de deux séries de 12 heures sur la pente continentale au large de l'Afrique du Nord-Ouest. Les mesures furent faites jusqu'à une profondeur de 300 m à proximité des lignes de courantomètres mouillés sur des fonds de 2 000 et 500 m. La prépondérance de l'Eau Centrale de l'Atlantique Nord transportée vers l'Équateur dans le Courant des Canaries était manifeste au site le plus au large. Son influence diminuait vers la côte à cause de l'Eau Centrale de l'Atlantique Sud transportée par le courant qui s'écoule vers le pôle en dessous de 150 m de profondeur. L'influence de la masse d'eau du Sud était plus forte à la station située sur la pente où le flux vers le pôle se manifestait dans les 300 premiers mètres. Le maximum de ce sous-courant était associé à un minimum de salinité voisin de la profondeur 200 m. Les valeurs du carré du cisaillement étaient plus de deux fois plus élevées à la station de la pente qu'à celle du large alors que le gradient vertical de densité y était plus faible. Elles étaient corrélées au carré de la fréquence de Brunt-Vaisala à la station du large mais non à celle de la pente. Alors qu'au large la contribution des ondes internes au cisaillement observé était dominante, sur la pente la turbulence paraissait plus importante. Les étages thermohalins étaient apparents en dessous de 150 m à la station du large, mais n'étaient bien développés que lorsque globalement la valeur du gradient vertical de vitesse était faible. Les interfaces entre ces étages, associées aux valeurs maximum du cisaillement étaient toujours à la limite de la stabilité dynamique. Le sous-courant à la partie supérieure de la pente continentale montrait de nombreuses instabilités dynamiques à une échelle de quelques mètres. Le minimum de salinité étroitement associé au minimum du gradient vertical de vitesse au cœur du sous-courant était dynamiquement plus stable.

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INTRODUCTION

The ocean off NW Africa is best known as one of the major areas of coastal upwelling. Considerable observational effort has been devoted to examining the complexities of the upwelling process in the region. The upper layers over the continental slope and offshore are also known to be characterized by widespread interleaving between the North and South Atlantic Central Water masses which come together in the region of 20-22°N to form a large scale frontal zone. During the Upwelling 75 cruise, short time series of hydrographic and small scale shear observations were made at two sites over the continental slope. One site was 130 km offshore, outside the region directly affected by upwelling, where interleaving was observed earlier in the cruise. The other was 70 km offshore over the upper continental slope where it was expected a poleward undercurrent opposed to the general flow would dominate. Both sites had been instrumented with moored current meters as part of the main programme.

It was believed that there would be a strong contrast in conditions between the offshore site and the undercurrent site. The aims of the study were to establish the differences in the hydrographic and current regimes and, in the light of those results, examine the observations for differences in the properties of the shear at the two locations. Particular goals were to investigate the differences in mean levels of shear, the degree of correlation of shear and hydrographic structure, and the dynamic stability.

The results have shown that there was indeed a strong contrast between the sites but, contrary to expectation, there was little evidence of interleaving at the offshore site. The water column was instead dominated by a thick temperature and salinity maximum below which evidence of thermohaline steps similar to those beneath the Mediterranean salinity maximum was found. The investigation of the dynamic stability of the steps, relationship of the small scale shear to the general conditions, and the differences between the two sites are reported here.

DATA

The hydrographic, wind and current meter data from the Upwelling 75 cruise have been compiled by Brockmann *et al.* (1977). As part of the experimental programme two current meter moorings, BCM2 and BCM3, were emplaced on the NW African continental slope in 515 m and in 2 015 m depth respectively near latitude 22°50'N (Fig. 1). Both moorings carried Aanderaa current meters at 75, 165, 290, 365 and 505 m (and 815 m on the deeper mooring). The two time series stations were situated close to the moorings. A salinity-temperature-depth (STD) probe was used from RRS Discovery to obtain hourly profiles to 300 m at each station. The STD data were calibrated by comparison with the results of water bottle casts and were corrected for mismatch of the temperature and conductivity sensor time constants by a numerical routine.

At both stations, a free fall probe for the measurement of velocity shear (Protas) was launched simultaneously with each STD cast. Protas design and performance are

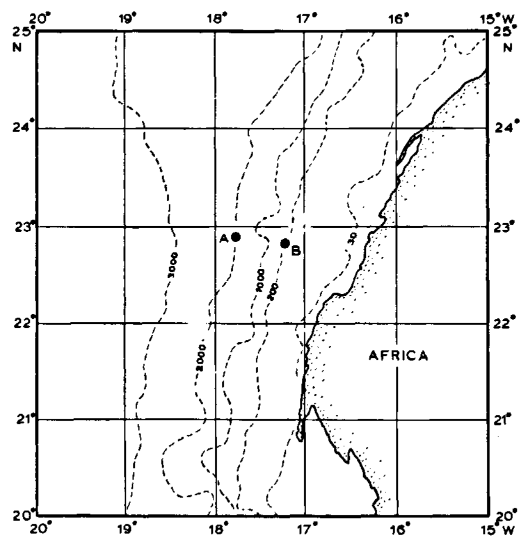

Figure 1

Location of offshore Site A (Discovery Station 8765 and current meter mooring BCM3) and slope Site B (Discovery Station 8772 and mooring BCM2). Isobaths are marked in metres.

described by Simpson and Stratford (1975). Essentially Protas measures the two horizontal components of water velocity relative to the body of the probe, which falls freely through the water column at a drop speed close to 40 cm sec.$^{-1}$. Velocity measurements are recorded roughly every 15 cm. From the vertical gradients of the velocity components, the shear vector modulus may be calculated :

$$S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2,$$

where u and v are the horizontal components of velocity and z is depth. In practice, the shear is not calculated on the smallest possible depth interval but over a depth increment of roughly 1 m to suppress noise contributions. The nature of Protas is such that the velocity measurements are band pass filtered representations of the total velocity profile (Simpson, 1975). Very high wavenumber contributions are smoothed out because of the finite size of the velocity sensor and low wavenumber contributions are lost because of the limited length of the probe itself. The low wavenumber cutoff corresponds to a length scale of 6 m and the high wavenumber cutoff to 11.5 cm. For this reason, Protas shears cannot be related to large scale shears defined for example by the current meters. Protas also recorded temperature and conductivity to provide a knowledge of the salinity and density profiles simultaneous with the shear observations. Unfortunately, problems were experienced with the conductivity records and it was necessary to rely on the almost simultaneous STD data for hydrographic information.

The first time series was carried out at station 8765 between 0639 and 1831 24 February 1975 in 2 000 m of water. Twelve STD casts and 9 Protas casts were successfully obtained. The second series took place in 500 m depth at station 8772 from 0640 to 1843 26 February 1975. Thirteen STD casts and 8 Protas casts were obtained. For convenience, the offshore site (station 8765 and mooring BCM3) will be referred to as site A, and the upper slope site (station 8772 and mooring BCM2), as site B. The position of site A was 22°53.7′ ± 2′N, 17°48.4′ ± 3′W while that of site B was 22°45.8′ ± 4′N, 17°15.1′ ± .7′W.

RESULTS

Hydrographic features and mean currents

There was a strong contrast in conditions between the two sites. The water masses dominant in each location were clearly different (Fig. 2). The temperature-salinity curves, plotted for all the STD profiles, showed virtually no overlap between the two series. The offshore station, Site A, was more saline at all levels than Site B. The higher offshore salinities are indicative of waters strongly influenced by the North Atlantic Central Water mass (NACW), whereas the lower salinities over the slope indicate a stronger influence of South Atlantic Central Water (SACW). The latter are advected northwards close to the continental slope by a poleward undercurrent centred at about 200-300 m, which occasionally may extend up as far as the surface or extend outwards from the slope to encompass more offshore waters.

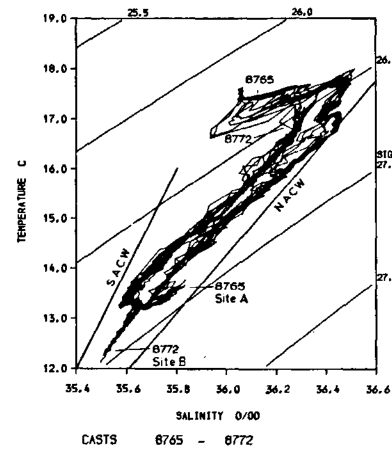

Figure 2

Temperature-salinity curves for all STD casts at offshore Site A (8765) and slope Site B (8772). SACW and NACW indicate the typical characteristics of South and North Atlantic Central Water masses as found in the region. Sigma-t isolines are shown.

Both sets of temperature-salinity curves show a persistent salinity and temperature minimum near the surface of sigma-t 26.8. This is the same feature traced by Hughes and Barton (1974) from 15 to 28°N along the continental slope and interpreted as evidence of poleward flow centred near the level of the minimum. The currents averaged over the period 23 February to 1 March 1975 (Fig. 3) around the time of the Protas and STD time series showed poleward flow at both sites at all but the near surface (75 m depth) meter at Site A. The currents are here referred to axes with alongshore flow positive (poleward) towards 20°T, the trend in direction of the continental slope over the surrounding two degrees of latitude. At Site A poleward flow was strongest at 365 m, below the level of the time series observations, while at the slope site it was strongest at 165 m. In the upper 300 m, the poleward flow was stronger at Site B than at Site A. Below 300 m the alongshore flow was similar at both sites.

The variability of the currents was greater offshore where there was marked subtidal variation superimposed on the tidal fluctuations which were strong at both

Figure 3

Mean alongshore (V) current-depth profiles 23 February to 1 March, 1975 at the offshore Site A and slope Site B. Alongshore flow is positive towards 20°T. The standard deviation about the mean is indicated by the broken line. Observation levels are marked 0.

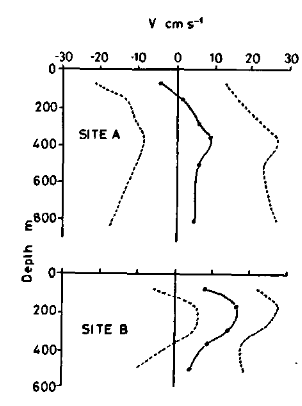

Table 1

Mean velocity and shear, 23 February to 1 March 1975, at the current meter sites.

Current meter depth m.	$\bar{u}$ cm sec.$^{-1}$	$\Delta\bar{u}$ cm sec.$^{-1}$	$\bar{v}$ cm sec.$^{-1}$	$\Delta\bar{v}$ cm sec.$^{-1}$	Δz m	$S^2 x10^{-6}$ sec.$^{-1}$
BCM3						
75	17.90		− 11.06			
		5.54		8.19	90	1.21
165	12.36		− 2.87			
		1.71		5.43	125	0.20
290	10.65		− 2.56			
		1.63		3.92	75	0.32
365	9.02		6.48			
BCM2						
75	2.65		7.75			
		0.19		9.04	90	1.01
165	2.46		16.79			
		1.12		2.12	125	0.04
290	1.34		14.67			
		0.39		5.82	75	0.60
365	0.95		8.85			

sites. In the upper layers, the large scale shear of the mean currents in both locations was similar in magnitude (Table 1). At the slope site the shear passed through a minimum at the level of the core of the undercurrent.

The variation of temperature, salinity, sigma-t and percentage of NACW at 8765 as a function of depth and time is plotted in Figure 4. The calculation of water mass proportions, explained in detail by Tomczak and Hughes (1980), assumes isopycnal mixing between the two water masses NACW and SACW depicted in Figure 2. For the purposes of the calculation these water masses have been defined by observed temperature-salinity relationships at locations sampled during Upwelling 75. The calculation results do not represent therefore the proportions of "true" NACW and SACW in the area, rather those of the locally important modified versions of the true water masses.

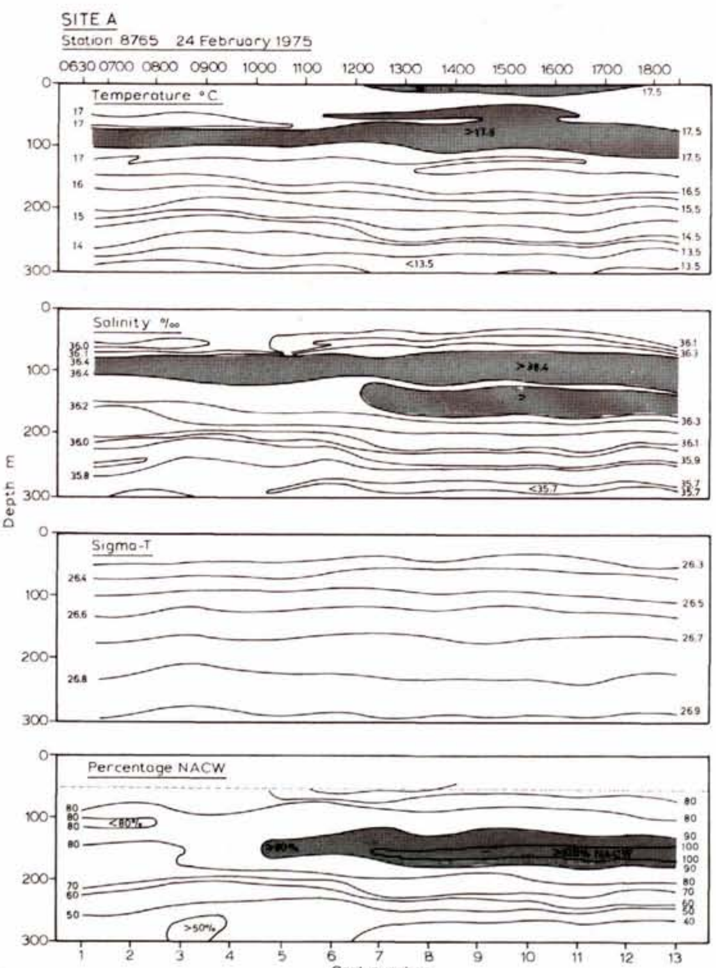

Figure 4

Depth-time variation at the offshore Site A of, from top to bottom: temperature, salinity, sigma-t and percentage of NACW (as defined by Fig. 2).

The vertical structure of temperature and salinity at Site A was complicated and rather variable in detail (Fig. 4). Although a thick layer of maximum temperature and salinity persisted at 80 m throughout the series and a thinner minimum was apparent near 300 m, many smaller extrema appeared and disappeared. The variation of sigma-t showed these temperature and salinity structures were mutually compensating, that is, gravitationally stable. It is evident there was little variation in the depth of the structures. The plot of percentage of NACW demonstrates the high proportion of this water mass at the offshore station. The >100% NACW is an artefact of the definition of NACW. Near 300 m depth, close to the salinity minimum the proportion of NACW was low and fell to about 40% toward the end of the series, showing the stronger influence of SACW at this level.

The corresponding plots for Site B (Fig. 5) are quite different in nature. There were far fewer inversions at the slope station but one well-defined minimum of salinity persisted for most of the period at about 200 m, or more precisely on the surface σ_t = 26.8. This is the same feature noted in Figure 2. There was more variation in depth of the isopleths at this station, although the more abrupt changes can be ascribed to differences in position. The slope area is one of strong horizontal gradients in the hydrographic fields (Tomczak, Hughes, 1980) and the onshore-offshore range of about 5 km in station positions is sufficient to explain, for instance, the 110 m rise in the isotherms around 1 400 hrs. The proportion of SACW at the slope station was considerably higher than offshore. Values as high as 80% SACW (20% NACW) occurred in con-

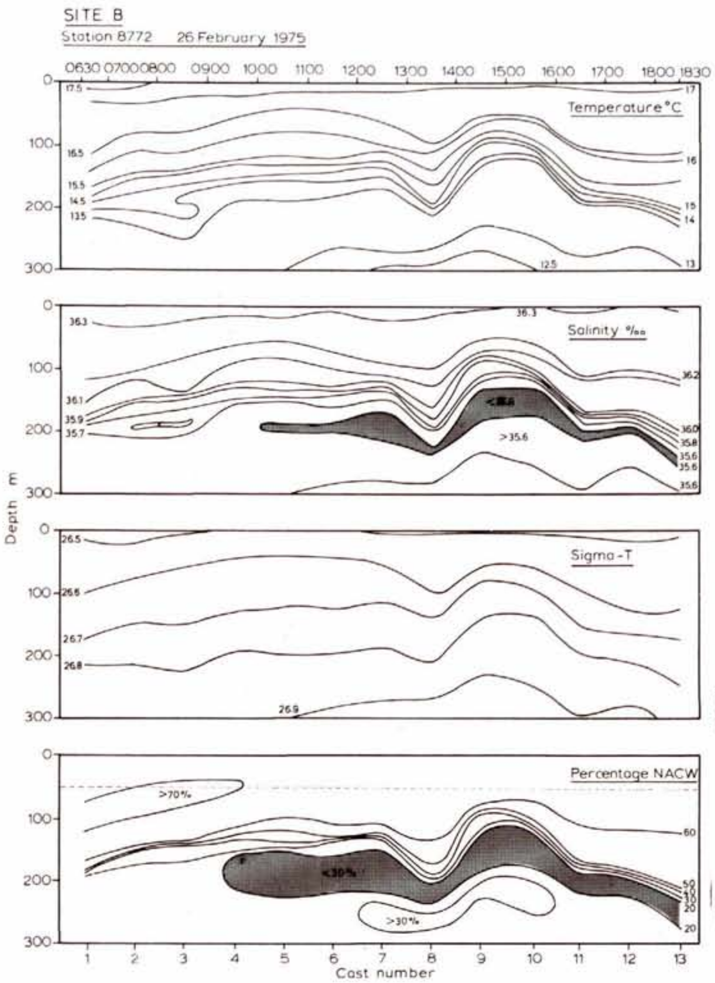

Figure 5

Depth-time variation at the slope Site B of, from top to bottom: temperature, salinity, sigma-t, and percentage of NACW (as defined by Fig. 2).

junction with the salinity minimum. The stratification at the slope station was considerably weaker than at the offshore station, as may be seen by comparing the contour plots of sigma-t in Figures 4 and 5.

The data show that the slope station was dominated by poleward flow, strongest around 200 m, which resulted in the presence of high proportions of SACW in the water column. A distinct minimum of salinity was associated with the core of the poleward current. The offshore station presented equatorward flow near surface and consequently higher proportions of NACW, but the concentration of SACW increased with depth in accord with the weak poleward flow at deeper levels. The magnitude of the vertical shear of the mean currents was similar in the upper 300 m at both sites, but at the slope station both components of velocity were maximal between 165 and 290 m. The large-scale shear must have been close to zero between these levels.

General characteristics of the shear

In Figures 6 and 7 selected profiles of the square shear vector modulus, temperature, salinity and sigma-t from Sites A and B, respectively, are plotted. Although not all of the profiles are shown, the same general features were apparent in the complete data set. Detailed comparison of the shear and hydrographic profiles has to be made with some caution since they are not strictly simultaneous. Horizontal separations of several hundred metres and time lags of several minutes resulted in discrepancies of up to 5 m in the depth of recognizably the same features in Protas and STD temperature profiles. The otherwise excellent agreement between Protas and STD temperatures leads to the conclusion that the lack of exact simultaneity does not invalidate a general comparison of the features on the scale of 5 m and more.

The initial impression is one of great variability in shear from one profile to another and the lack of any obvious

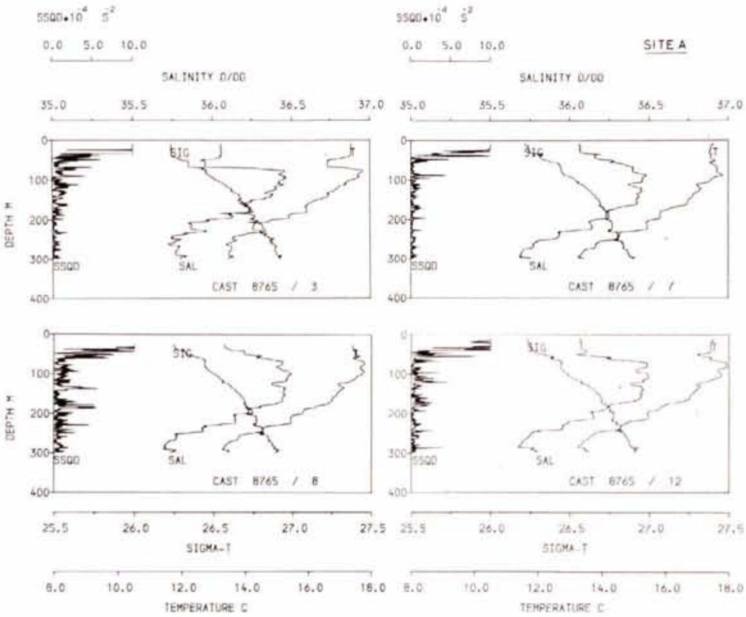

Figure 6

Profiles of square shear from Protas, temperature, salinity and sigma-t from STD probe at the offshore Site 8765 (Site A).

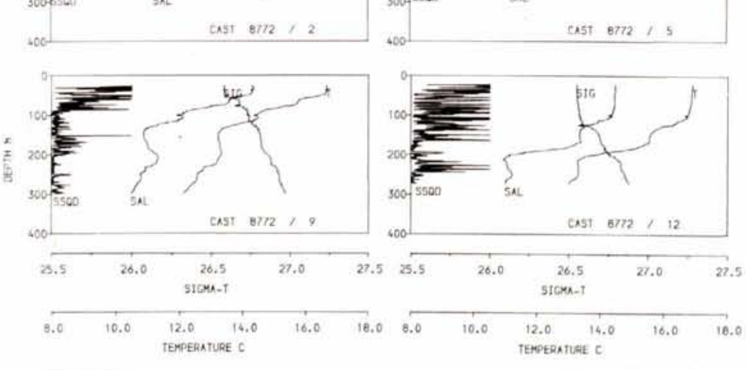

Figure 7

Profiles of square shear from Protas, temperature, salinity and sigma-t from STD probe at the slope Site 8772 (Site B).

relation between shear and other parameters. Inspection of the profiles makes it possible to identify a number of features of interest. Referring first to the offshore station Site A the following characteristics are found:

a) a tendency for the appearance of regular steps of temperature and salinity below the depth of the salinity maximum and some association of high shear with the interfaces of the steps (strongly pronounced in 8765/7 but much less clear in the other profiles);
b) the occasional coincidence of higher shears with strong gradients above and below temperature and salinity inversions, *e.g.* 8765/7 at 120 m, 8765/12 at 100 m and 130 m;
c) the extrema of inversions, if uniform over some vertical extent appear to coincide with layers of little or no shear, *e.g.* 8765/3 at 60 m, 8765/12 at 70-80 m and at 125 m;
d) a tendency for high shears to occur in the shallow pycnocline although these are shallow enough to be due to the effect of surface waves.

At the slope station notable features were (Fig. 7):
a) a region of high and variable shears in the layer above about 100 m in association with weak vertical gradients of temperature, salinity and sigma-t;
b) a level of shear generally higher than at 8765 by a factor of two or more;
c) a region of reduced shear in the upper part of the salinity minimum, especially notable in profiles 8772/9 and 8772/12 where the minimum was quite pronounced;
d) a general lack of correlation between shear and the small scale features of the hydrographic profiles, *i.e.*, no coincidence of high shears with regions of strong gradient.

The only evidence of the interleaving expected at the offshore Site A was confined to the few small intrusions of less than 20 m thickness noted above. It seemed that the intrusive layers were regions of low shear bounded by higher shears at the interfaces with the surrounding water mass. However, the present data do not allow any firm conclusions in this respect.

The general levels of shear found at the two stations were comparable to results reported by Simpson (1975) in the Straits of Gibraltar and by Simpson and Stratford (1975) in the upper 300 m of the tropical Atlantic, and were greater than values reported for the deeper layers in the Rockall Trough and the Bay of Biscay. Simpson (1975) found that the shear was related in a gross manner to the density stratification. The latter was expressed by the Brunt-Vaisala frequency, which is defined by :

$$N^2 = g\left(\frac{1}{\varrho}\frac{\partial \varrho}{\partial z} - \frac{g}{c^2}\right),$$

where ϱ is the density, g the acceleration due to gravity and c the velocity of sound. He concluded that $< s^2 >$ where the brackets signify a 50 m average, was positively correlated with $< N^2 >$ and tentatively suggested that this relationship may hold for stratified shear flows in general. The data from the offshore station conform to this hypothesis, but the slope station appears to be exceptional.

For each profile, average values of the square shear and the Brunt-Vaisala frequency were calculated over adjacent 50 m depth intervals below 75 m. The two averaged quantities were found to be significantly correlated at the offshore station (Fig. 8) but at Site B they were not significantly correlated. The Garrett and Munk (1972) internal wave model predicted that $N^3 \alpha S^2$ (see also Munk, 1981). The data from the offshore station are consistent with this relation, although insufficient

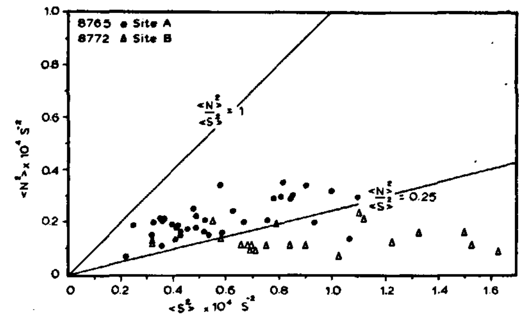

Figure 8
Plot of 50 m average squared Brunt-Vaisala frequency $<N^2>$ *against* $<S^2>$, *from both sites.*

to be definitive, supporting the idea that most of the observed shear is due to internal wave motions. The complete lack of correlation between N^2 and S^2 at the slope station must indicate that most of the shear is associated with processes other than internal waves. The low values of the ratio $< N^2 >/< S^2 >$ at this site suggest frequent dynamic instabilities on the small scale, perhaps turbulent in nature.

Evans *et al.* (1979) have reported first results of observations with Yvette, a shear and hydrographic profiler which samples a similar waveband to Protas. They stated without providing details that in regions of high stability there was a high correlation between strong density gradients and strong shear, but where the overall stability decreased the correlation appeared to degrade significantly. This would appear to be in accord with the results at the two sites discussed here.

Layer and interface structures

One of the major differences between the two stations was the presence of almost regular structures below the salinity maximum at Site A, where peaks in the shear were associated with the interfaces of temperature, salinity and sigma-t steps. The most orderly set of shear structures in the series was found in profile 8765/7. Although the tendency to step-like structures was obvious in the other hydrographic profiles, none of them showed as well defined a set of interfaces or shear maxima.

The layered structures were like those observed by Simpson *et al.* (1979) beneath the Mediterranean salinity maximum in the Atlantic. It is generally accepted that such features are caused by double diffusive convection or "salt fingering". Both a theoretical basis (Turner, 1973) and direct observational evidence (Williams, 1975) exist to support this view. The configuration of temperature and salinity at Site A is of the necessary form to allow the development of salt fingering activity, hence production of step structures. It has been suggested by Simpson *et al.* (1979) that a sufficiently high level of velocity shear may disrupt or prevent the formation of step structures. Their observations of shear in layered structures indicated marginal dynamic stabilities, which were interpreted as the reason for the limited horizontal extent of the layers at the time. It is therefore of some interest to investigate the dynamic stability of the steps at station 8765 in some detail.

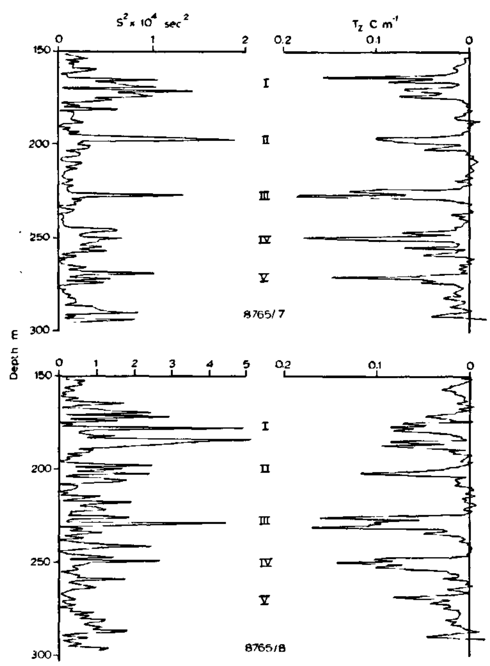

Figure 9

Depth profiles of square shear S^2 and temperature gradient T_z at the offshore site for cast 8765/7 (upper) and 8765/8 (lower). Note that the upper and lower shear scales are different.

The shear and temperature gradient profiles from cast 8765/7 over the depth range 150-300 m (Fig. 9) clearly show the correspondence of high shears to the layer interfaces. The peak values of square shear in the interfaces are around 1×10^{-4} sec.$^{-2}$ while between peaks the values average 1×10^{-5} sec.$^{-2}$ and individual values are as low as 1×10^{-6} sec.$^{-2}$. In Table 2 the results of a calculation of the interface Richardson number Ri_0 are shown. The thickness of the interfaces was estimated from the temperature gradient profile. The interface mean Brunt-Vaisala frequency $\overline{N^2}$ was estimated from the differences of temperature and salinity across the interface, and a mean value S^2 of the square shear was calculated by averaging across the thickness of the interface. The interface Richardson number was given by $Ri_0 = (\overline{N^2}/\overline{S^2})$.

The results for the five interfaces (Table 2) show that Ri_0 was less than unity in all but one case, and in general not much greater than the critical value of 0.25.

Table 2

Richardson number calculation for interfaces at station 8765/7 *and* 8.

Layer	Mean depth m	Thickness m	$N^2 \times 10^6$ sec.$^{-2}$	$S^2 \times 10^6$ sec.$^{-2}$	Ri
8765/7					
I	170	21	23.5	47.5	.49
II	201	12	18.9	41.5	.46
III	229	10	37.2	24.3	1.53
IV	254	17	25.1	33.8	.74
V	276	8	25.6	36.2	.71
8765/8					
I	179	10	14.4	166.6	.09
II	204	11	24.7	89.8	.27
III	230	14	25.1	81.7	.31
IV	253	14	27.2	71.0	.38
V	270	9	17.7	22.3	.79

Since Ri_0 represents the upper limit on the minimum gradient Richardson number within the interface it appears that the structures were only marginally stable in the profile where they were best defined.

A similar calculation was made for the interfaces in cast 8765/8. The temperature gradient profile of this cast was very like that of 8765/7 and it was possible to identify the same layer and interface structure in both (Fig. 9). The shear profile, on the other hand, was markedly different. The shear in cast 8 was stronger by a factor of about two (note the difference in shear scales) and more irregular, though there was still an association of higher shears with the stronger temperature gradients. Results of the Richardson number calculation, included in Table 2, show even lower Ri_0 values than 8765/7. Layer I was unstable, layers II, III and IV were only slightly above critical values of Ri_0 and layer V had Ri_0 well below unity. Taking acount of the roughly 30 % error to which these estimates of Ri_0 may be liable does not alter the result that the layers in cast 7 were marginally stable and that those in cast 8 were unstable or only just stable.

These results are consistent with the idea that stronger shears break up or suppress the formation of step structures. Profiles 7 and 8 of the series provided the clearest examples of steps. Both earlier and later casts revealed thicker, less sharp interfaces with more intermediary structures or intrusive features. Furthermore, shear levels were higher than in cast 7 in all other profiles, which when coupled with the weaker vertical gradients of density across the interfaces indicates dynamic instability.

Shear in relation to the undercurrent

The magnitude of the shear at the slope station was greater than at 8765, especially in the upper levels (Fig. 6 and 7). Surface conditions were considerably less favourable at the time of station 8772. During the later part of the time series a 5 m swell of period about 8 seconds was evident. Simpson and Stratford (1975) stated that Protas, when falling through layers affected by surface wave motions, sensed a spurious component of shear s' given by

$$s' = \frac{a\sigma^4 L}{2gW} e^{kz},$$

where a is the wave amplitude, σ the angular frequency, k the wavenumber, L the length of Protas, W its fall speed at depth z, and g the acceleration due to gravity. It is found on substituting the appropriate values of the parameters that the spurious contribution to the square shear at 50, 75 and 100 m was 2.5×10^{-4}, 0.1×10^{-4} and 0.5×10^{-6} sec.$^{-2}$, respectively. Shear observations above 75 m at 8772 are therefore rejected for present purposes. Even so, the difference in shear magnitudes remains. In the layer 75-125 m, the mean square shear at 8772 was 3.4 times larger than at 8765, and in the layers 125-275 m, it was 2.0 times larger.

Although as noted earlier there was a distinct lack of correspondence between specific small scale features in the shear and the hydrographic profiles at Site B, it is clear that there existed a strong relation between shear and other variables on longer depth scales. In particular, the upper part of the salinity minimum was associated with unusually low shear values. Since it was shown in a previous section that the salinity minimum was situated close to the depth of the core of the slope undercurrent or maximum of poleward flow, the shear minimum is considered indicative of reduced turbulence in the core of the undercurrent (which was also a region of near zero large scale shear, see Table 1). The generally high levels of shear at this station might seem related to the overall large scale shears above and below the core of the undercurrent, but there was actually little difference between the shears observed between current meter levels at either site.

Estimates of Richardson number were made by combining the 1 m averaged values of square shear with Brunt-Vaisala frequency estimates derived from STD data interpolated to 1 m intervals. The slight differences in location and time of the Protas and STD observations can contribute to erroneous values of Ri calculated in this way. Furthermore, the ubiquitous salinity "spiking" problem of the STD makes calculations of the Brunt-Vaisala frequency noisy. For these reasons, the Richardson number estimates were not treated in a detailed manner. Instead, N_R the number of levels where Ri > 0.25 in each 10 m thick layer was calculated as an indicator of the dynamic stability on the 1 m scale within the layer. The results supported the proposition that the upper part of the salinity minimum was a location of relatively high dynamic stability. An example of the results (Fig. 10) illustrates the generally low proportion of stable Ri values at levels above and below the salinity minimum. Also shown are 10 m averages of the Brunt-Vaisala values and square shear values. The general disparity between the averaged N^2 and S^2 values emphasizes that, notwithstanding the large errors to which the Richardson number calculation may have been subject, dynamic instabilities on the 1 m scale were common. This result was typical of the Site B profiles.

It appears that the undercurrent over the upper slope was an area of strong turbulence on vertical scales of

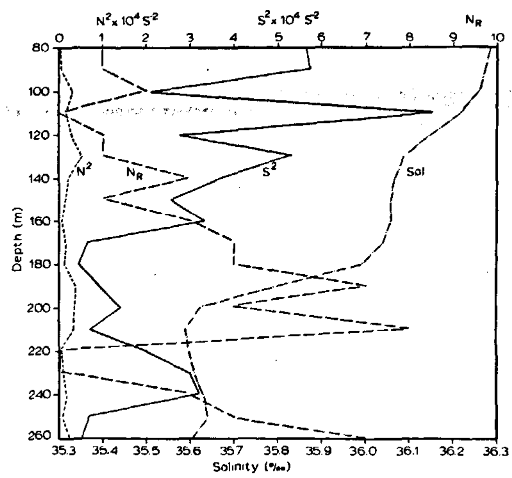

Figure 10

Depth profiles at Site B of N_R, the number of Richardson number values greater than 0.25 in each 10 m interval, salinity, SAL and 10 m block averaged squared Brunt-Vaisala frequency, N^2 and square shear, S^2.

metres. The actual core of the undercurrent, which appeared closely related to the salinity minimum, was more stable dynamically. The frequent occurrence of low Richardson numbers indicated that the instabilities happened on a more continuous basis than might be expected were they due to some intermittent process such as internal wave breaking. Although the large scale vertical shears from the moored current meters were not significantly higher at the slope station than offshore, it seems probable that the persistent shear above the core of the undercurrent was sufficient when associated with the reduced static stability there to produce the strong small scale shears observed with Protas.

Keunecke and Tomczak (1976) deduced from towed thermistor cable and CTD measurements that increased turbulent mixing occurred between the surface and 100 m over the upper continental slope at 15°N. They observed a thick isothermal surface layer, apparently similar to those seen at site B, e.g. profile 8772/12 in Figure 7, which they ascribed to vertical mixing in an assumed coastal jet (region of strong equatorward flow). The present results indicate that turbulent mixing over the upper slope occurs as a result of the strong shear above the core of the undercurrent, which would be enhanced by the presence of a coastal jet.

The situation at the slope station was reminiscent of conditions at the equator. In both cases an undercurrent moving counter to the prevailing surface flow is present, the region of maximum speed in the undercurrent is associated with a salinity anomaly, and enhanced vertical shear occurs between the undercurrent and the surface flow. During GATE, velocity and temperature microstructure measurements (Crawford, Osborn, 1980) indicated high turbulence levels above the core of the Atlantic Equatorial Undercurrent. The energy source for the turbulence appeared to be the shear above the undercurrent. Support for this conclusion was provided by independent estimates of layer Richardson numbers, which indicated that values of Ri <0.25 occurred frequently on the scale of 10 m.

Jones (1973) found very low Richardson numbers, again on the 10 m scale, beneath the core of the Pacific Equatorial Undercurrent and stable conditions in the core itself. The equatorial undercurrents are however much faster than the slope undercurrent off NW Africa, and have stronger large scale shears above and below. The slope undercurrent occurs in an area of unusually low static stability for the upper 300 m layer and it is this which appears to allow the development of turbulence.

GENERAL DISCUSSION

The upper continental slope off NW Africa in the area of investigation is a remarkable region of considerable dynamic interest. Barton *et al.* (1977) found that wind induced upwelling took place over the shelf-slope break during periods of strong equatorward winds, modifying the hydrographic fields down to at least 200 m depth. Mittelstaedt *et al.* (1975) concluded that wind variability evoked barotropic fluctuations in the poleward undercurrent. Tomczak and Hughes (1980) demonstrated rapid hydrographic changes in 300 m of water during Upwelling 75. Horn and Meincke (1974) found evidence of large amplitude internal tides over the upper slope. Huthnance and Baines (1981) investigated the occurrence of bottom trapped waves of tidal period over the critical bottom slope in 500 m. Barton and Hughes (1982) reported subsurface layers up to 150 m thick, mixed to within about ± .02C, of horizontal extent only a few kilometres in bottom depths between 400 and 800 m. The complexity and variety of these phenomena are impressive.

The present observations have demonstrated the contrast in shear and hydrographic signatures at two sites over the continental slope. It is of interest to find thermohaline steps at such shallow levels in an obviously energetic area, even though they were of apparent instability and short life. It seems possible that they would reform given less intense conditions of shear. Indeed, examples of isolated steps were observed in a number of other Upwelling 75 profiles. Rather than having seen formation and destruction of the layers during the time series, it is perhaps more likely that advection of a patch of layers through the observation site was taking place. The basic ambiguity of single oceanic time series makes it possible only to surmise on this point.

The most impressive result at the slope station was the apparent prevalence of dynamic instability on small vertical scales outside the core of the undercurrent. One is led to speculate that the decreased density stratification, due to the presence of SACW and the proximity of upwelling over the shelf and shelf break, allows the development of turbulence which itself acts to weaken vertical hydrographic gradients and so facilitates the continued production of turbulent shears. This may account for some of the difference between the upper slope and offshore sites since the latter was more statically stable. The greater dynamic stability at the level of the salinity minimum supports the conclusion that the minimum is intimately associated with the core of the undercurrent. Weak large scale shear near the poleward maximum appears to result in low levels of small scale shear. The consequent lesser degree of turbulence allows the perpetuation of the salinity minimum as a marker of the undercurrent.

CONCLUDING REMARKS

Two short time series of Protas, STD and moored current meter observations at two sites over the continental slope off NW Africa have demonstrated significant differences in the physical characteristics of the upper 300 m layer over a separation of about 60 km. Both sites were influenced by SACW transported northward in an undercurrent along the slope. Poleward flow was weaker at the more offshore site and was confined to levels below 100 m. The consequent greater proportion of saline NACW offshore led to a temperature and salinity configuration suitable for the production of double diffusive convection and "step" formation in the layers between 150 and 300 m. Over the upper slope, low static stabilities associated with the weakly stratified SACW and upwelling over the shelf resulted in production of small scale dynamic instabilities. These were prevalent throughout most of the water column, with the exception of the well defined salinity minimum (maximum concentration of SACW) at about 200 m depth.

The analysis of these observations leads to a number of conclusions :

1. Values of square shear and square Brunt-Vaisala frequency averaged over 50 m depth intervals were correlated offshore, consistent with the relation predicted by the Garrett-Munk internal wave model. They were not correlated at the slope site, where turbulent processes appeared to predominate over internal waves.

2. Despite hydrographic conditions favourable for the development of double diffusive layer and interface structures, the formation of clearly delineated thermohaline steps occurred only when shear levels were unusually low. This may be why few observations of such steps have been made in the upper ocean despite frequently favourable temperature and salinity profiles.

3. The region of the poleward undercurrent over the upper slope was one of prevalent dynamic instability on the scale of metres. Only the core of the undercurrent, which could be identified with the minimum of salinity was a location of relatively high dynamic stability.

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