DOUBLE DIFFUSIVE INTRUSIONS, MIXING AND DEEP SEA CONVECTION PROCESSES IN THE BLACK SEA

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ABSTRACT. Hydrographic measurements obtained during Leg 4 oceanographic expedition of the RV Knorr in the Black Sea point to important processes deserving scientific attention. The destabilizing effects of the cooling near the surface and the influx of geothermal heat at the bottom combined with the stable salinity gradients provide an environment suitable for double-diffusion in the water column. The hydrographic data do not provide any evidence for the replenishment of the bottom water by the inflowing Mediterranean waters. On the other hand, there is clear evidence that the renewal of intermediate waters takes place at or below the pycnocline level by the transformed intrusion waters. Temperature-salinity anomalies at the shelf break demonstrate that the Mediterranean water mixes with the ambient cold intermediate waters and then sinks in the form of a plume with high aspect ratio. Later, horizontal transport of water in the form of multiple layers with anomalous properties is often evident and is also traced by the transport of suspended matter from the continental slope towards the interior region of the Black Sea. The geothermal heating gives rise to the convective turnover of the deep waters in a bottom mixing layer. The extent and features of this convective layer are quite unique. On the other hand, models derived from laboratory experiments and the available theory appear to be insufficient to describe its evolutionary aspects. The identification of such unique physical processes in the Black Sea make it an ideal environment for scientific studies of these processes, as well as providing new insights into some of its chemical, and sedimentological puzzles.

1. Introduction

One of the most extensive hydrographic data sets of the 1988 Black Sea expedition have been collected during the Leg 4 of the RV Knorr cruise. Although the station spacing is uneven due to the multidisciplinary orientation of the expedition, data of essentially continuous nature have been obtained at a number of shelf break and deep stations covering the full water column. The topography of the basin and the station positions

E. Izdar and J. W. Murray (eds.), Black Sea Oceanography, 17–42.

during leg 4 are shown in Figure 1. A total of 20 stations were occupied in the Black Sea, and a single profile was obtained in the Sea of Marmara for reference.

We describe the hydrographic structure during the Leg 4 observations, which were obtained mainly at the continental slope or deep basin regions. A companion paper (Oğuz *et al.*, 1990) provides background on the oceanography of the southern Black Sea in relevance to the present observations. Another one (Latif *et al.*, 1990) describes the results of an experimental program carried out in the vicinity of the exit region of the Bosphorus for identifying the distribution and mixing properties of the Mediterranean effluent on the shelf region before it plunges down the continental slope.

A systematic survey by the Turkish ship RV Bilim of the Institute of Marine Sciences, Middle East Technical University, preceded the Leg 4 surveys of the RV Knorr, aimed at locating the plunging point of the Mediterranean plume along the shelf break so that the Leg 4 stations in the region could be relocated most efficiently. These measurements are a subset of the observations reported by Latif *et al.* (1990); the data indicated that the maximum salinity of the thinly spread out plume occurred at the head of a canyon feature of the slope around 41° 35' N and 29° E about 35 km northwest of the Bosphorus exit.

By the time the plume reaches the shelf edge, its thickness becomes about 1-2 m, and the length of the shelf break covered by the plume is on the order of several tens of kilometers, although this latter dimension can hardly be defined due to the diffuse filaments of the anomalous plume waters. The maximum salinity at the shelf break (100 m contour) is about 23 against a background salinity of about 18. Because the plume thickness is so small, every effort was made to obtain data close to the bottom, often by letting the CTD touch the bottom (Latif *et al.*, 1990).

The general outline of the observations is given in the next section, followed by a discussion of the anomalous intrusions in section 3. The features of the bottom convective layer are reviewed in section 4 and conclusions are provided in section 5.

2. The θ-S Relationship and Mediterranean Water Anomalies

The potential temperature - salinity relationship for all of the stations is shown in Fig. 2. The warm surface waters of the summer season join with the Cold Intermediate Water (CIW) at depths of about 50-75m where the minimum temperature is slightly less than 7°C. This layer is known to be formed in winter when the cooling reaches from surface down to the depth of the CIW, although variations in the efficiency of cooling makes the northwestern shelf to be the main source of this water type. The signature of the same water exists also in the Marmara Sea, partially advected there by the upper layer flow of the Bosphorus.

In the Marmara Sea, below the cold layer of about 11°C, a warmer layer

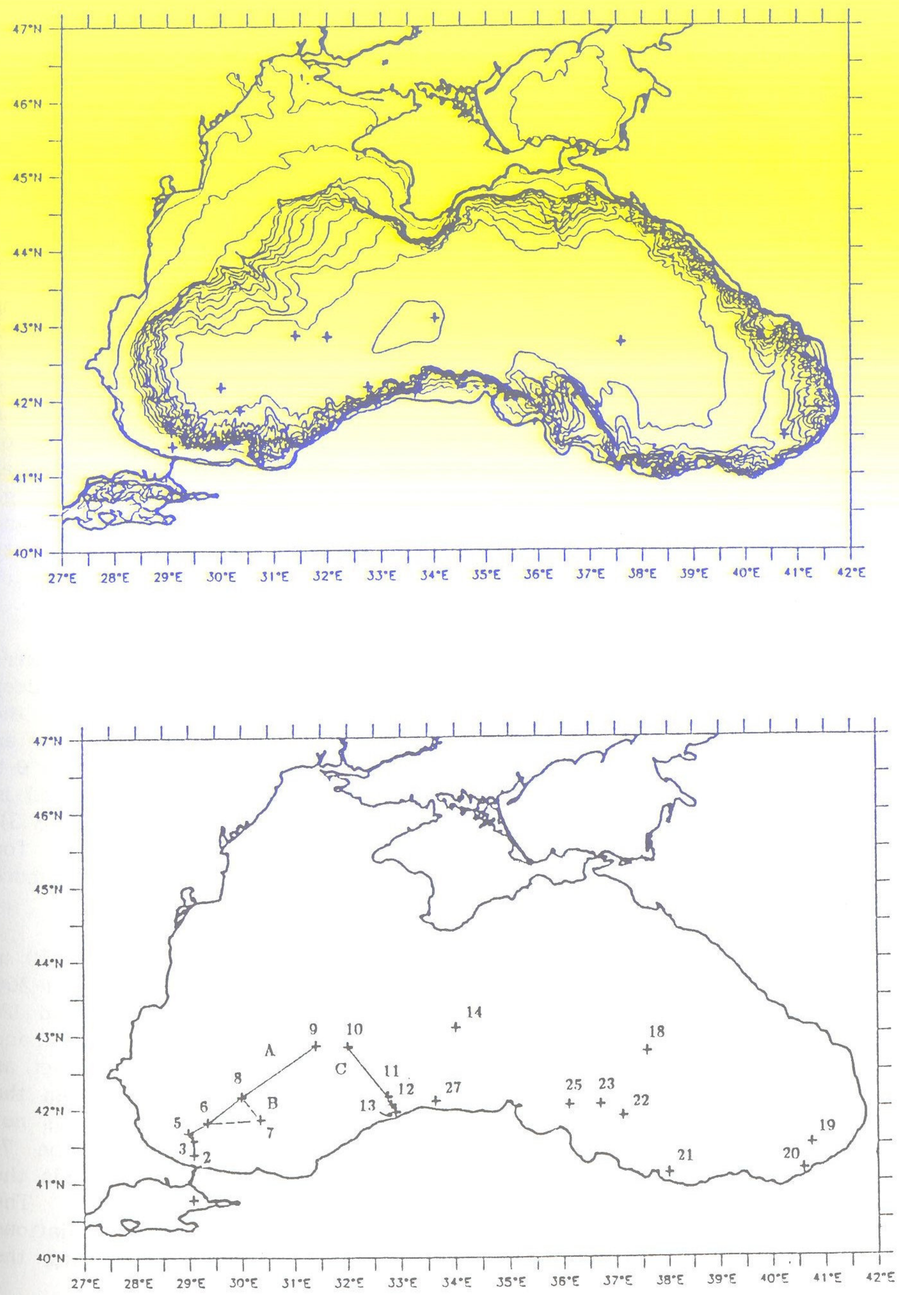

Figure 1. (a) Bottom topography of the Black Sea with superposed station positions, (b) Station identifiers for Leg 4 of the RV Knorr Black Sea Expedition.

of about 15°C appears in the subhalocline waters. The subhalocline waters are essentially of Mediterranean origin, with a salinity of about 38.5. The temperature of the halocline waters below the 15°C layer are about 14.2-14.5°C.

In contrast to the Marmara Sea, the Black Sea is continuously stratified in temperature and salinity. During the recent evolutionary history of the Black Sea basin, the dense, saline waters from the Mediterranean Sea have fed the deep waters through the lower layer flow of the Bosphorus. The inflowing waters are also warmer than the waters locally formed in the Basin (e.g. CIW); as a consequence, warm salty water underlies less saline but cold water in the Black Sea. The resulting stratification is gravitationally stable, but it favors double diffusive instabilities in the 'diffusive' regime.

The geological record indicates that the Black Sea has evolved from a slightly brackish lake to the present salty conditions as a result of recent sea level rise (Stanley and Blanpied, 1980). It is estimated that the replacement of the deep waters by the saline waters flowing in through the Bosphorus has taken several thousands of years (e.g. Boudreau and Leblond, 1989). Because of the slow rate of replacement, it is not easy to identify the intruding waters in the practically stagnant deep waters of the Black Sea.

Figure 2 indicates that the θ-S properties of the Black Sea deep waters approximately lie along a straight line connecting the Mediterranean (deep water of Marmara) and the CIW θ-S characteristics, which testifies to the origin of the deep waters of the Black Sea, i.e. of them being formed by an admixture of these two water types. However, the actual shape of the θ-S curve is more complex. In general, a nonlinear relationship is observed in Figure 2. When we enlarge the lower portion ofthe θ-S diagram (Figure 3), we observe a general curvature, and as the deeper part is expanded for another time, the nonlinearity in the θ-S relationship becomes more prominent (Figure 4).

We note the anomalous water types in Figure 3. They occur in a 50 m thick layer near the bottom at station 3 (total depth of the station is 200 m), and at various intermediate depths of 60-200 m at stations 7 and 12. Station 3 is close to the plunging point of the Mediterranean 'plume', and it was located there for that purpose. Station 7 lies more to the east as compared to the general direction of stations 2-6 going offshore from the Bosphorus (Figure 1). The fact that the intermediate depth anomaly is not observed at some stations (e.g. station 6), but at others (station 7) suggests that after the shelf break the plume turns east as it descends the slope, and shows up as lenses of anomalous water to the east. The anomalies observed further east at station 12 are much smaller deviations from the cluster of θ-S data, but are perhaps significant in showing the evolution of the anomalous waters along the continental slope.

It is of interest to note that the characteristics of the anomalous waters observed by Bogdanova *et al.* (1967, cited in Tolmazin, 1985) do not match the above description. The lens they observed about 150 m had a

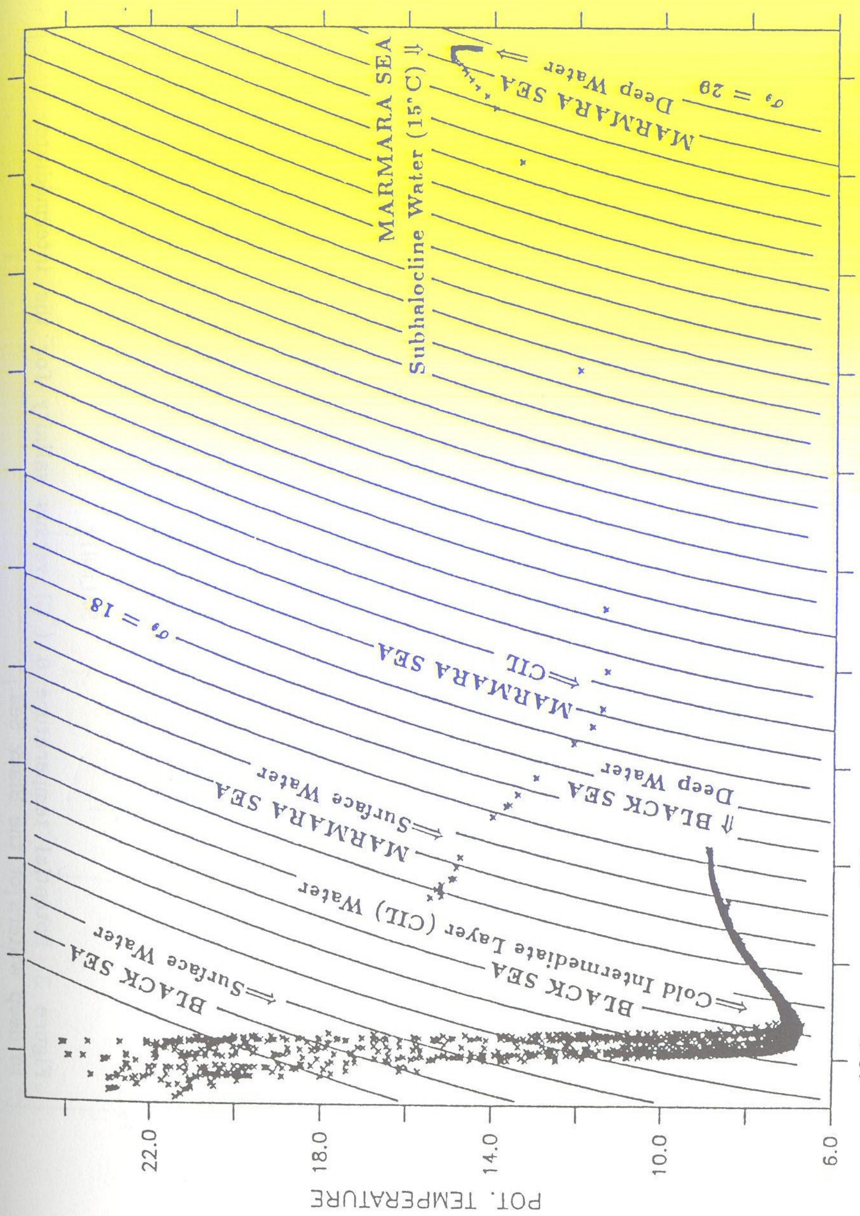

Figure 2. Potential temperature θ (°C) versus salinity for all Leg 4 stations including the Black Sea stations 2-27 and the Marmara station 1.

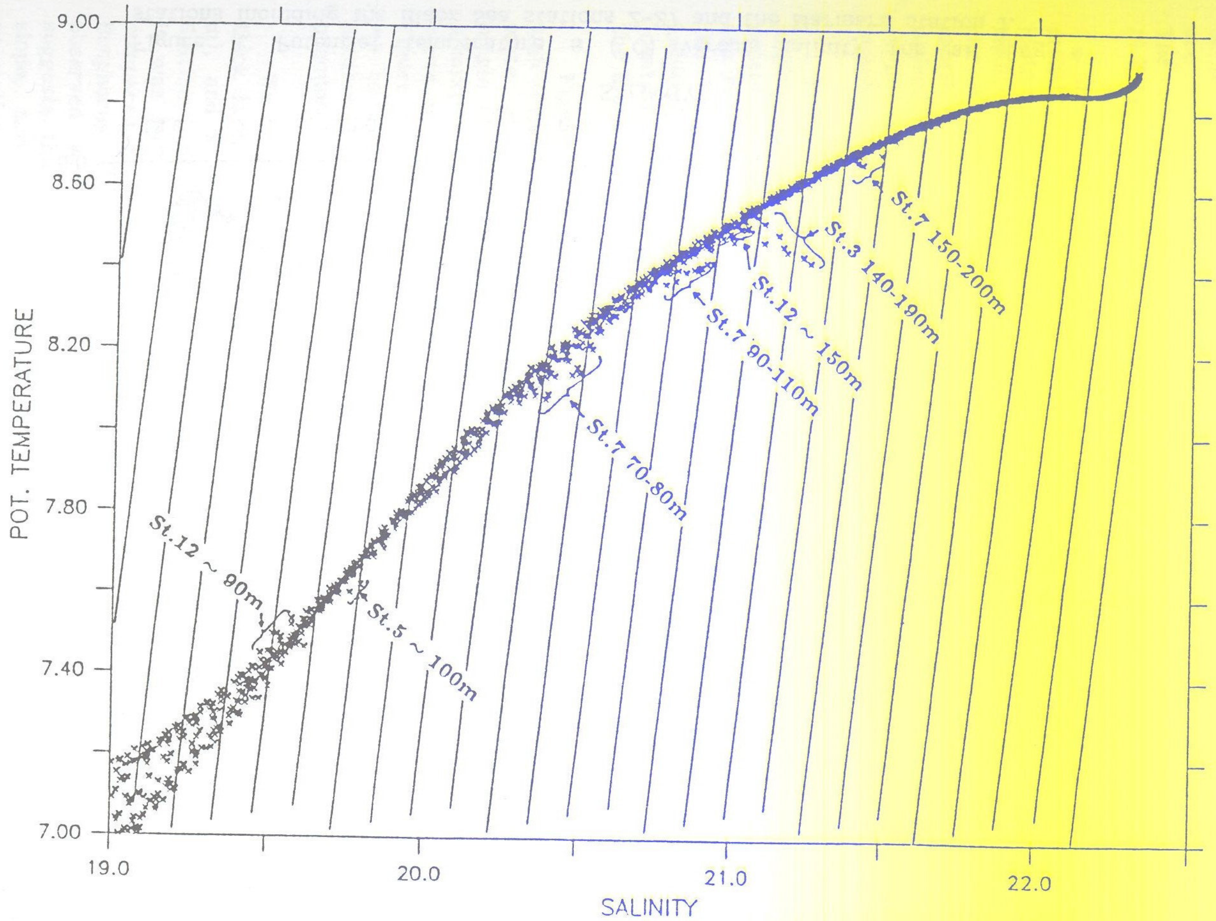

Figure 3. Potential temperature θ (°C) versus salinity for the intermediate to deep waters of the Black Sea.

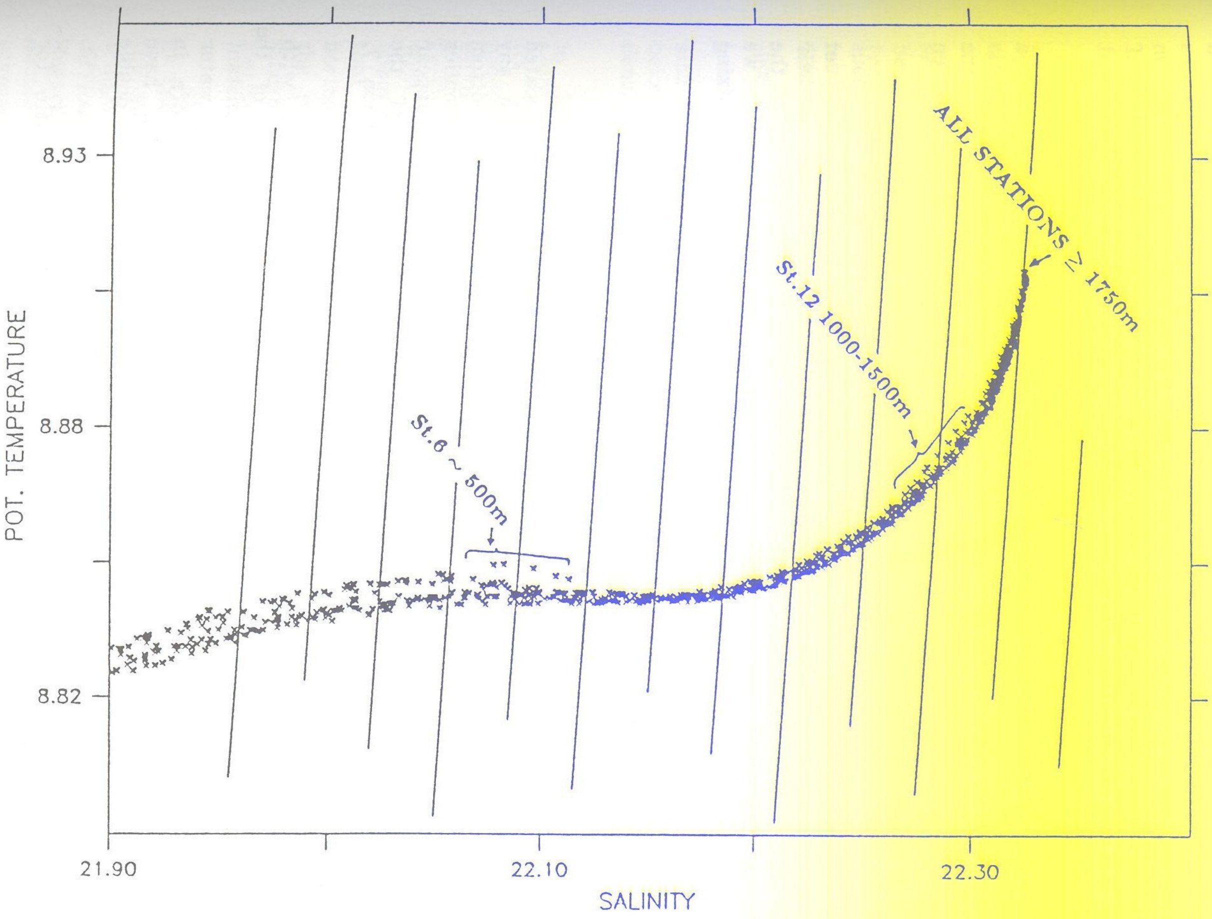

Figure 4. Potential temperature θ (°C) versus salinity for the deep waters of the Black Sea.

positive temperature anomaly of about 3°C and a salt anomaly comparable to the present case. The negative temperature anomaly we are observing is possibly due to a greater contribution of the CIW to the lens mixture. On the other hand, the lenses they observed at 300-500 m had anomalies of 0.5°C and 0.1 in salinity, which appear in discord with most of the present day observations.

Finally, in the expanded θ-S diagram of Figure 4, we can identify a positive temperature anomaly at about 500 m depth at Station 6. This feature cannot be explained and does not appear to be related to the Mediterranean plume, because the evolution at the shallower depths has been shown to be towards negative temperature anomalies.

Evidence suggests that the intermediate depth intrusions of anomalous water are quite common near the Bosphorus (Oğuz *et al.*, 1989; Codispoti *et al.*, 1989), although it is not always easy to locate them due to their patchy distribution. On the other hand, large horizontal excursions of the anomalous features indicate unique processes. In the following, we emphasize the role of a double diffusive ambient environment on the mixing processes.

3. Double Diffusive Intrusions of the Mediterranean Waters

In reviewing the distribution of the anomalies, the observation of anomalous properties in the form of multiple layers at station 7, located at some distance from the continental slope, contradicts strongly with any preconceptions of the Mediterranean plume being attached to the bottom after it descends the continental shelf. The Mediterranean water anomalies manifest themselves as various layers at intermediate depths which appear to extend offshore from the shelf region. The offshore extent of the anomalous water originating from the Bosphorus goes as far as station 7, and perhaps further.

A nonlinear θ-S relationship (Figures 2-4) is often associated with double diffusive regimes (e.g. Schmitt, 1981), due to the adjustment of the ratio of the temperature and salinity fluxes to an approximately constant value. Temporarily turning our attention to Figure 11 where the deep water enlarged profiles of temperature and salinity are displayed, we note in particular that the deep water temperature and salinity profiles have different features, testifying to different rates of diffusion, i.e. double diffusion.

The double diffusive regime is characterised by the density ratio (or the stability ratio, which is inversely defined in some literature)

$$R_\rho = \alpha \frac{\partial T/\partial z}{\partial S/\partial z}$$

or the Turner angle

$$Tu = \tan^{-1} \frac{R_\rho + 1}{R_\rho - 1}$$

(Ruddick, 1983). The mean profiles, obtained by averaging the above quantities horizontally over the Leg 4 stations are shown in Figure 5. For the diffusive regime $0 < R_\rho < 1$, or $-90 < Tu < -45$ are the ranges satisfied, which are shown to be the conditions throughout the water column below the CIW core. The spikes in the figures are due to noise resulting from the method of computation, and should be disregarded. As $R_\rho \Rightarrow 0$, a marginally stable regime is reached (it is seen that this happens at about 500 m), and as $R_\rho \Rightarrow 1$, the potential for double diffusive instabilities increases (immediately above the convective layer $R_\rho \approx 0.5$, and at the CIW level $R_\rho \approx 0.2$). It appears that the intermediate depth CIW acts a heat sink from above, and the convective bottom layer acts as a heat source from below, with respect to the water column sandwiched between the two. The density ratio reflects the effects of these source and sink regions.

Intrusions in a double diffusive medium are implied in the Black Sea. Laboratory experiments of Turner (1978) has shown that fluid injected at its neutral density level into a stably stratified fluid (which is not necessarily in the double diffusion regime itself) often produces double diffusive stairs and interleaving, as it intrudes horizontally into the fluid. In other experiments, when the ambient fluid was initially set up with double diffusive temperature and salinity gradients (i.e. with opposing contributions to the density gradient), Turner (1978) has shown that the mixing becomes significantly more efficient and rapid both horizontally and vertically. In this case, the intrusion releases some of the potential energy of the ambient fluid in addition to its own, and the kinetic energy ensuing from the conversion is spent in horizontal shearing motions.

It seems likely that various types of mechanical forcing, in the form of buoyancy and momentum perturbations of the sinking plume, wind mixing on the shelf, or interactions of the shelf edge currents with topography can trigger the instabilities. This may be one of the reasons why it is difficult to trace the Mediterranean water anomalies in deep water. Regardless of the forcing mechanism, it seems that as a result of the double diffusive ambient conditions, the Mediterranean 'plume' splits into several layers which spread horizontally into the interior of the basin before reaching abyssal depths.

The plume structure originating from a source of heat in a stable salinity gradient has been studied by Tsinober *et al.* (1983). Even in the relatively simple case they considered (much simpler than the geometrical features of the Mediterranean effluent in the Black Sea), they

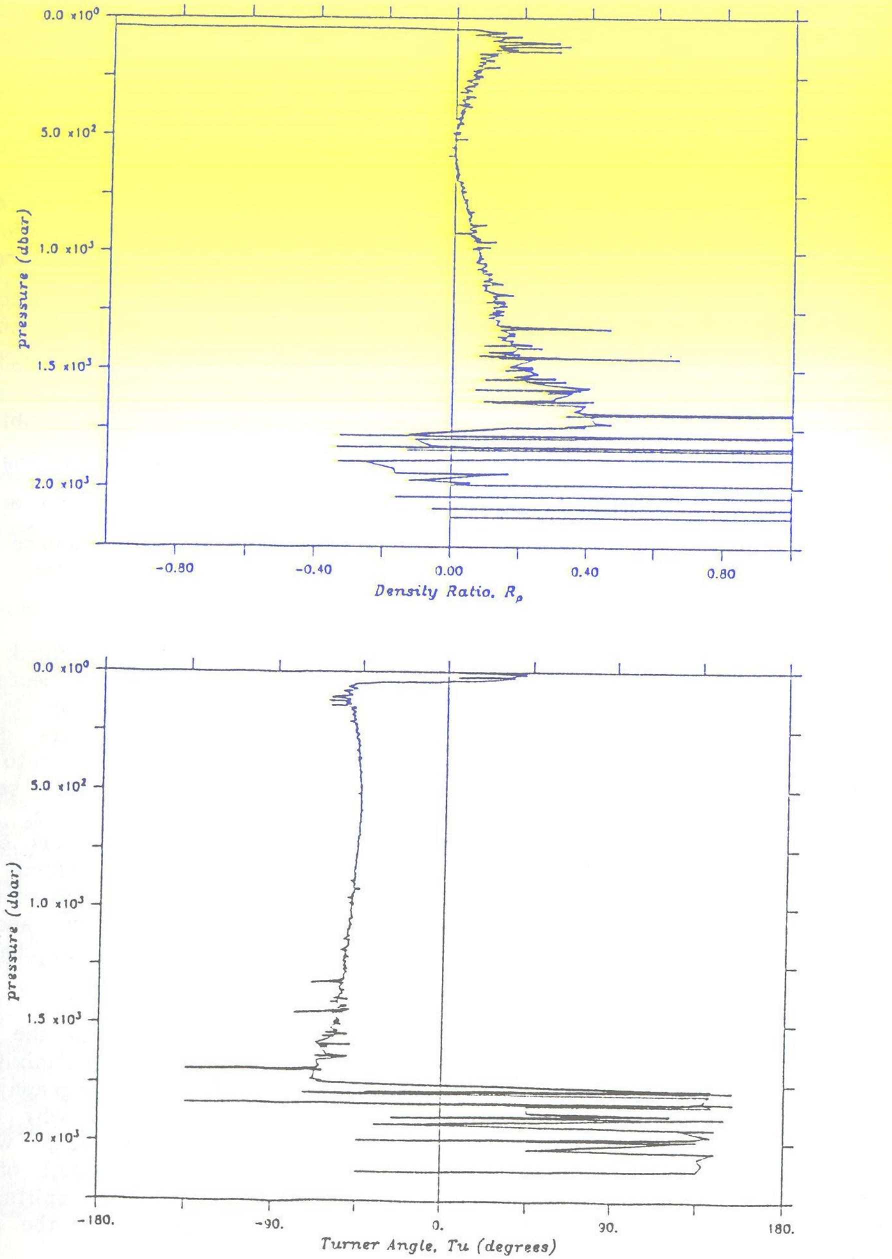

Figure 5. (a) Density ratio, R_ρ, and (b) Turner angle, Tu, versus pressure (decibar) calculated from an average of all Leg 4 stations, the Black Sea.

distinguished three types of horizontal layers according to the mechanisms of their generation: the first type was driven by vertical heat transport above the heat source, the second type was associated with horizontal heat transfer from the plume, and the third type directly carried the source characteristics as in the case of double diffusive intrusions. All three types were superimposed on a basic plume and located at different vertical distances from the source. Vortices between the horizontal layers were reportedly some of the common features observed.

Given the double diffusive environment, the evolution of the Mediterranean plume descending along the continental slope is more complicated than it would be anticipated. On the wide shelf region, the Mediterranean plume is an elongated horizontal source with an excess of both heat and salinity, and after the shelf edge it sinks vertically due to its excess density, while turning eastwards along the slope region.

On the grounds of the time dependence of the Bosphorus lower layer flow, and the shelf mixing, a further complication could potentially influence the plume induced intermediate depth mixing processes. The time dependent temperature and salinity anomalies and the resulting transient nature of the buoyancy flux of the 'plume' (e.g. Killworth and Turner, 1982) are expected to determine the penetration depths, as well as the depths and hydrographic characteristics of the intrusive layers at different times.

The effect of rotation on the double diffusive mixing processes constitutes one of the less explored areas of the science. The numerical experiments of Hyun and Kwak (1989) seem to indicate that a 'fountain effect' can be responsible for relatively intense downwelling regions near the boundaries of a rotating basin. It is, at this time, early to make any further statements, before further studies of the double diffusive processes specific to the Black Sea could be made.

Of the various anomalies in Figure 3, the ones at station 3, near the Bosphorus are the most prominent, followed by the ones at the nearby station 5. Immediately after reaching the shelf edge (station 5), the 'plume' turns east and is next detected at station 7 in the east, which is far from the shelf edge, suggesting that it is injected offshore immediately after it has turned to the east. Indeed, the distribution of the anomalous water masses is in the form of interleaving filaments extending offshore. Oğuz *et al.* (1990) have found a number of such filaments being injected offshore in a region with relatively small east-west extent at a location nearer to the shelf break and not far from station 7.

Station 7 is revisited in Figure 6 to show the layered structures. Three casts repeated within a total duration of 6 hours at the same station are superposed in the figure, showing the short term variations in the fine structure features. The signature of the anomalous (transformed Mediterranean) waters is in the temperature. A series of cold anomalous layers appear down to a depth of about 200 m. The light transmission profile has well correlated anomalies, indicating that the sheared layers

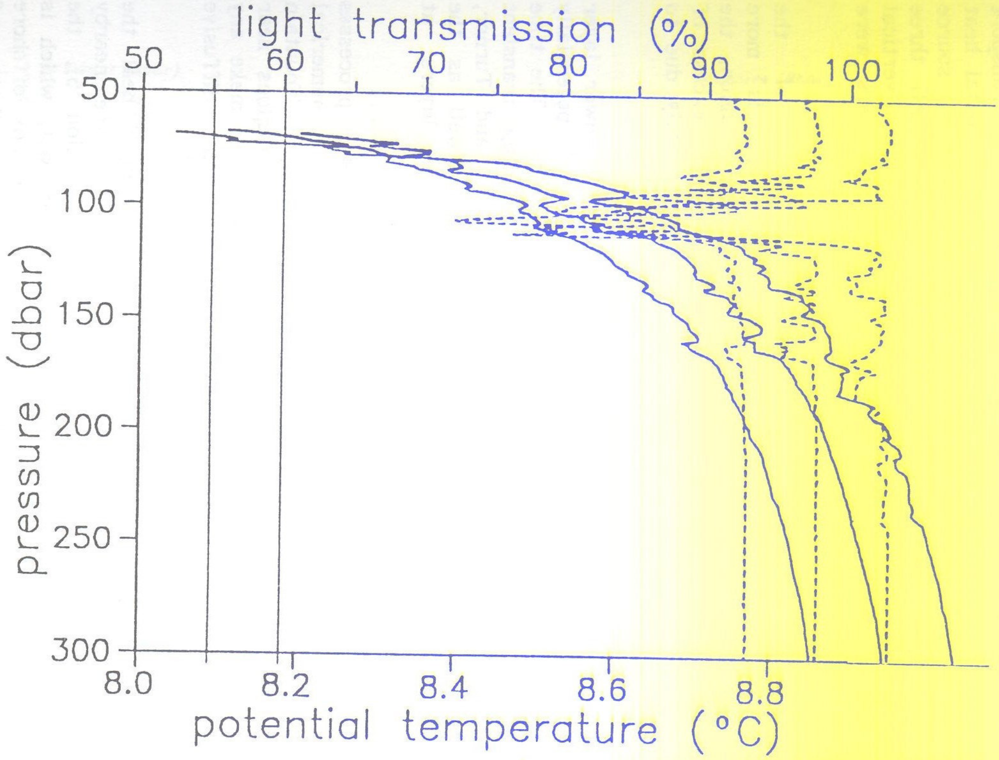

Figure 6. Potential temperature θ (°C) (solid lines) and light transmission (%) (dashed lines) versus pressure (decibar) at Station 7, Leg 4. Data from three repeated casts at the same station are superposed with shifted profiles (the amount of shifting for each set of profiles are indicated by the thin vertical lines on the left).

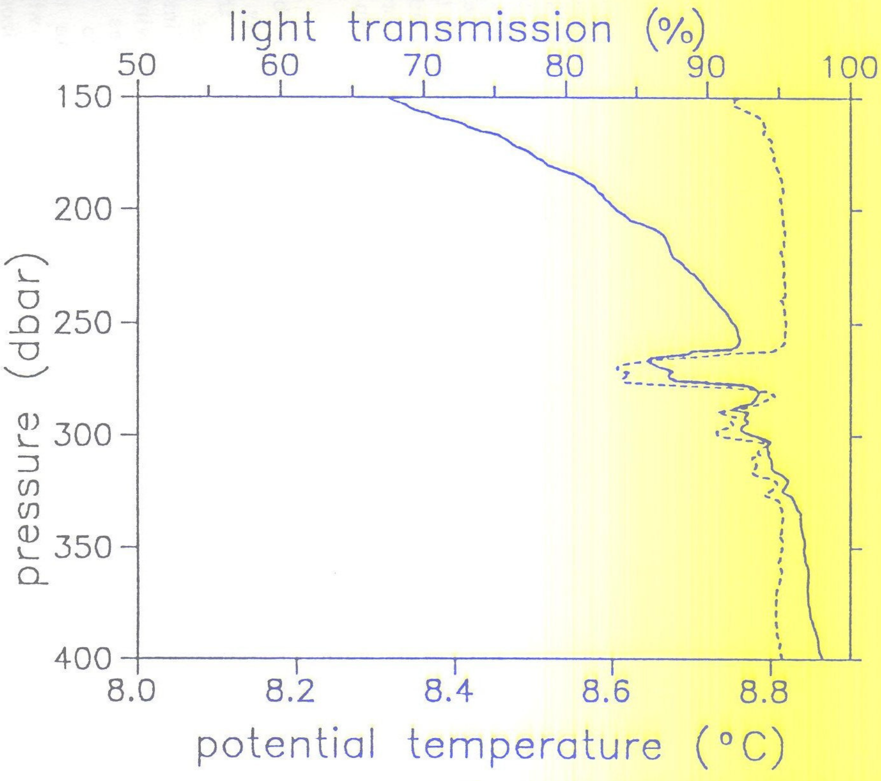

Figure 7. Potential temperature θ (°C) (solid line) and light transmission (%) (dashed line) versus pressure (decibar) at Station 1, Leg 3.

formed by the plume sinking in the double diffusive environment also carry with them the suspended matter originating at the shelf region. Indeed, large volume sampling at this station has shown the presence of anomalously high concentrations of suspended matter at the depths of the intrusions; the chemical composition of the particulates indicate the shelf region as the possible source of the load (K. Buesseler, personal communication). On the other hand, a review of all of the RV Knorr light transmission profiles indicates that the largest suspended sediment concentrations at intermediate layers consistently occur in the southwestern part of the Black Sea.

During the Leg 4 observations, the largest detectable temperature anomalies were observed at Station 7, as already seen in the θ-S diagrams. An example of the variations in the features and the depth of horizontal intrusions is given in Figure 7, which shows a marked anomaly at Station 1 (located ≈ 30 km to the east of station 3 of Leg 4) visited during Leg 3 of the Black Sea cruises. A layer with considerably larger temperature anomalies than those observed in Leg 4 stations is observed at a depth of 280 m, with a coincident light transmission minimum. This is much deeper than the anomalies observed in Leg 4 stations. The fact that Station 1 is located closer to the continental slope perhaps makes it a better candidate to observe the plume anomaly at a deeper level. The observations reported in Oğuz *et al.*,(1990) also indicate the presence of such features down to depths of about 300 m.

The presence of intermediate depth layers of suspended matter have been a puzzling aspect of the Black Sea in the past. Their capacity to transport suspended matter into the interior of the basin and in their subsequent sedimentation has been implied by the studies of Honjo *et al.*, (1987) and Buesseler *et al.*, (1989), who have related the initial suspension to wind stirring of the shelf sediments predominantly in winter. An additional mechanism proposed by Özsoy *et al.* (1990) relates the suspended matter in the intermediate depth nepheloid layers to the disturbances created by the nearby Sakarya Canyon. They demonstrate that the abrupt topography creates strong anomalies in the hydrography, which could be partially responsible both for the suspension and the horizontal spreading of shelf derived sediments. Although wind mixing on the shelf and canyon disturbances can be of importance in the resuspension and in the horizontal advection of the materials, both descriptions would be incomplete without invoking the effects of the intrusions entering into a double-diffusively unstable environment.

The distribution of properties at a section extending offshore from the Bosphorus is shown in Figure 8 to emphasize some of the previous points. The isolines sloping towards the coast correspond with the cyclonic rim currents along the periphery of the Black Sea basin. The CIW becomes markedly sharper (with lower temperatures at its core) at the offshore stations near the center of the basinwide gyres. The temperature and salinity anomalies at station 3 near the continental slope mark the evolving Mediterranean plume at about 175 m depth. The last section in Figure 8 is the percent light transmission, and it shows that the Mediterranean plume carries suspended material with it. The general

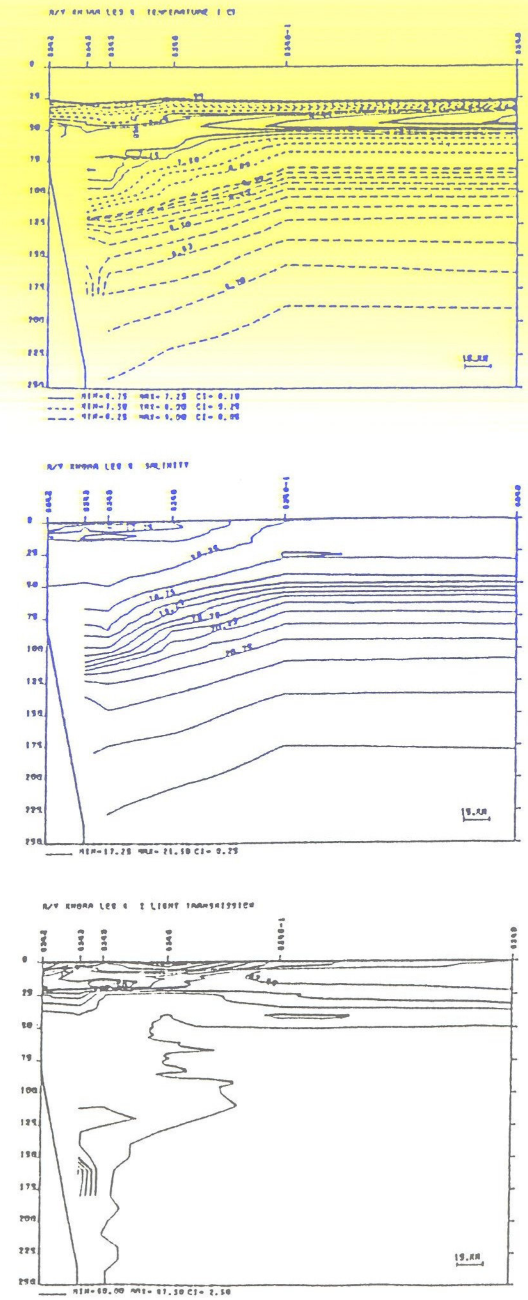

Figure 8. Distribution of (a) temperature (°C), (b) salinity, and (c) light transmission (%) along transect A, including stations 2,3,5,6,8,9.

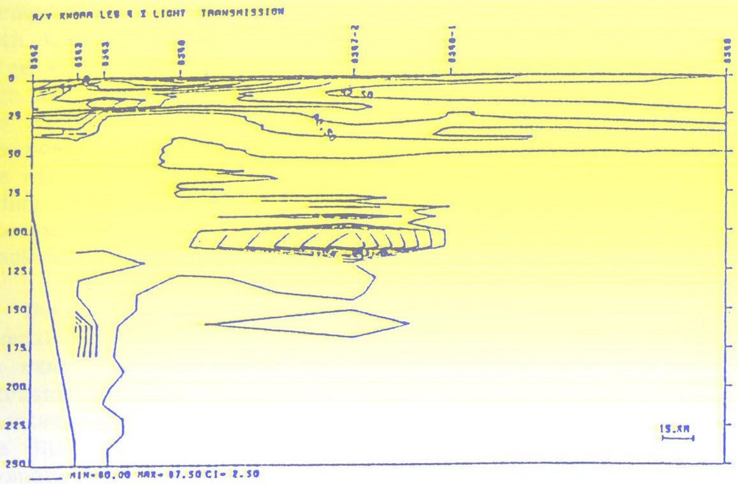

Figure 9. Distribution of light transmission (%) along transect B, including stations 2,3,5,6,7,8,9.

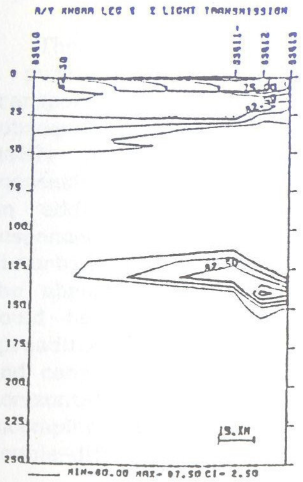

Figure 10. Distribution of light transmission (%) along transect C, including stations 10,11,12,13.

decrease of light transmission near the coast points to the importance of the shelf region as a source of suspended materials.

The light transmission section in the last figure is replotted in Figure 9, this time including station 7, where intermediate depth suspended matter is abundant. The light transmission minimum now extends to this offshore location. When it is remembered that various θ-S anomalies were observed at station 7 at intermediate depths of 100-200m, it becomes clear that the water marked by Mediterranean anomalies possibly spreads offshore as a layered structure much like predicted by the discussion of the double diffusive intrusions above.

Figure 10 shows another section of light transmission further east. Here too, we see the thin layer of suspended materials in the form of an intrusive layer extending offshore from the continental slope region. Previously, we have demonstrated weak anomalies of the θ-S characteristics (Figure 3) at station 12 located on this transect.

Although the temperature and salinity anomalies are observed in a region close to the Bosphorus, the layers of suspended matter are more common around the basin, indicating spreading from the shelf regions as indicated by the present data as well as data from other Legs of the Black Sea cruise (e.g. Realander *et al.*, 1988).

The presence of the lateral injections of material from the shelf region to the interior of the basin has profound implications in regard to the chemical structure of the basin as well as in its mixing and sedimentological aspects. For example, Buesseler (1990) demonstrates the rapid deepening of the Chernobyl radioisotope tracers due to their lateral injection at or below the anoxic interface, implying a mechanism for efficient ventilation down to intermediate depths and for the slower mixing between the surface and deep waters. It is of great importance to establish the exchanges between the deep and surface waters, because it is known that the Mediterranean water inflow alone can not explain the residence time of the intermediate to deep waters which appear shorter than the estimates based on the Bosphorus exchanges. The renewal time for waters shallower than a depth of 500m decreases sharply as compared to deep waters (Östlund, 1974, 1986). Grasshoff, (1975) has suggested that the difference in renewal rates due to the mixing generated between the surface and deep water masses especially along the Anatolian coastal margin.

4. The Bottom Convective Layer

An outstanding aspect of the observations is the detection of a bottom mixing layer in the Black Sea. The striking feature of Figure 11 is the layer with uniform properties at the bottom of the basin, covering a depth of about 400 m adjacent to the seafloor. We provide a review of the RV Knorr data indicating the presence of this layer in Murray *et al.* (1990). It appears reasonable to relate the bottom isothermal layer to geothermal heat fluxes at the bottom of the sea. It has been shown by Turner (1968), that a convecting layer of the type observed in Figure 11 would be formed

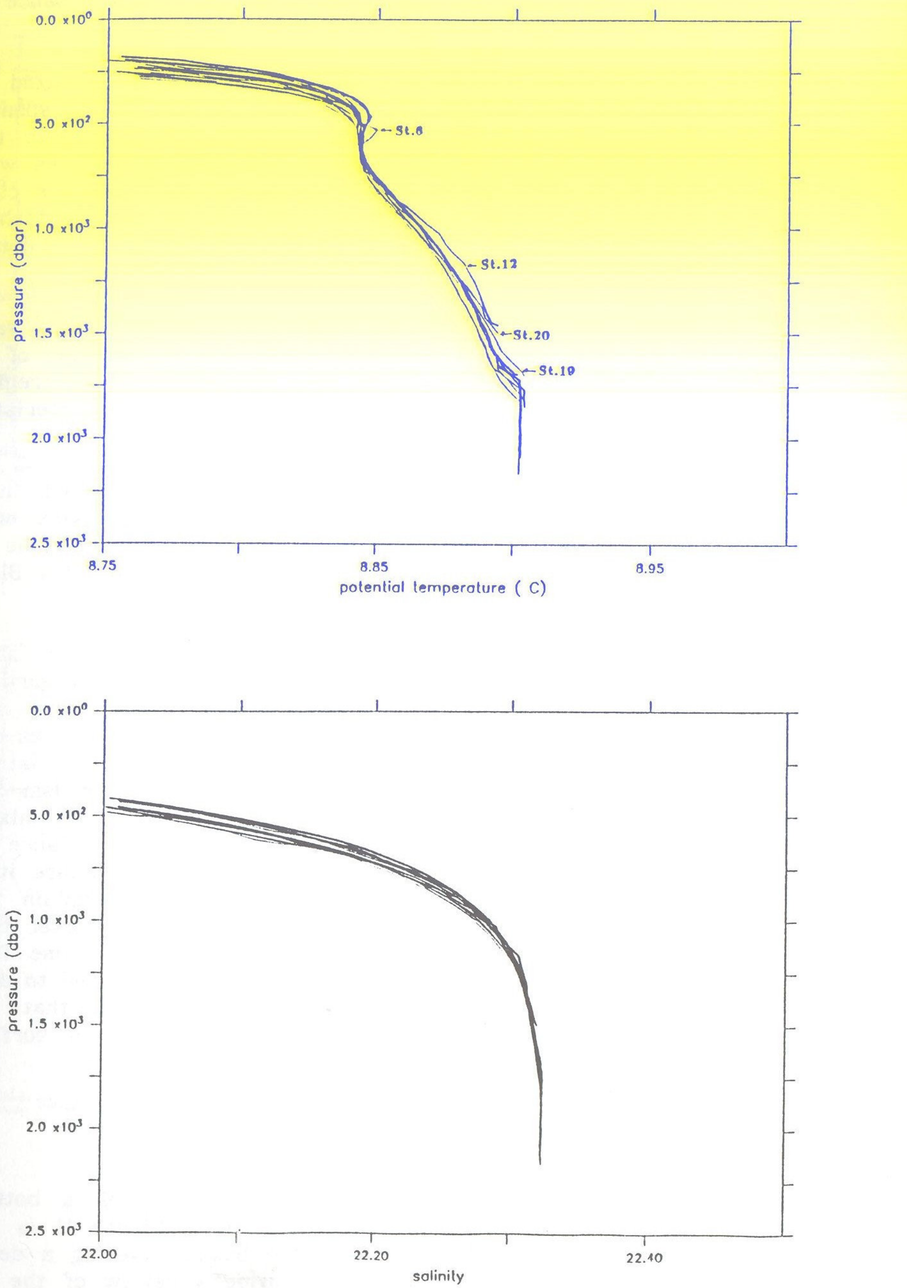

Figure 11. Profiles of (a) potential temperature θ ($^{\circ}$C) and (b) salinity versus pressure (decibar) in expanded scales to show the deep water characteristics. All Leg 4 stations are included.

if a gravitationally stable salinity stratified fluid is heated from below.

Measurements indicate that the Black Sea is a region of low geothermal heat fluxes as compared to most parts of the Mediterranean Sea (Haenel, 1979). The bottom heat flux is not uniform, but has an average value of about 40 mW m^{-2} = 0.9 μcal s^{-1} cm^{-2} (Zolotarev, 1979; Haenel, 1979). The latter author also quotes earlier work which would put the estimate at about three times this value, as a result of certain corrections to the measurements. The presence of a convection layer with a thickness of several hundred meters in spite of the weak fluxes gives a qualitative indication of the otherwise stagnant nature of the deep waters.

Figure 11 suggests a uniform distribution of properties both horizontally and vertically within the mixing layer, presumably homogenized by the convective motions. In principle, from given thermal fluxes at the bottom, it is possible to calculate the time required for the formation of the convective layer (time required for the propagation of the convection front from the bottom to its present position). Turner (1968) and Huppert and Linden (1979) give

$$t = (h/a)^2 \, H_*^{-1} \, S_*$$

where

$$H_* = - g \, \alpha \, H \, / \, \rho \, c$$

and

$$S_* = - (1/2) \, g \, \beta \, \partial S / \partial z$$

as the time required for the development of a layer of thickness h, given an initial salinity gradient of $\partial S/\partial z$ and a bottom heat flux of H. The proportionality constant is a=1 in Turner's (1968) analyses, but Huppert and Linden (1979) find better agreement with their experiments with a=1.7. Taking $H=0.9\times10^{-6}$ cal $cm^{-2}s^{-1}$, h = 400 m (the present thickness of the layer), and $\alpha = 0.13\times10^{-3}$, $\beta=0.78\times10^{-3}$ (thermal and salinity expansion coefficients appropriate for the bottom), and $\partial S/\partial z=0.02/1000$m (implying $H_*=0.12\times10^{-6} cm^2 s^{-3}$, $S_*=0.08\times10^{-6} s^{-2}$), we find that t=34 years or t=12 years, depending on whether the values a=1 or 1.7 are used respectively. Both estimates appear too young to be appropriate for the Black Sea bottom. The heat flux essentially has a geophysical time scale, and the age of the bottom waters is typically a few thousand years. On the other hand, Murray *et al.* (1989) report rapid changes in the upper part of the water column during the recent times. The only other alternative to our present interpretation would be to speculate on the possibility of rapid evolution in the deep water; we reject this hypothesis based on our present analyses.

Turner (1968) indicated that when the bottom layer reaches its maximum thickness, the diffusive layer immediately above the first convective layer becomes unstable and forms a second convecting layer. When this happens the maximum thickness reached by the bottom convective layer is

$$h_1 = (\nu R_c / 64 \kappa^2)^{1/4} H_*^{3/4} S_*^{-1}$$

where κ and ν are the heat conductivity and the molecular viscosity, g is the acceleration of gravity and R_c is a critical Rayleigh number. The critical Rayleigh number for the breakdown of the diffusion region existing above the bottom convection layer is given as an order of magnitude estimate by Turner (1968), and his experiments indicated that $R_c \approx 2.4 \times 10^{-4}$. Huppert and Linden (1979) established its value as $R_c \approx 10^{-4}$. Assuming this latter value applies also for the present situation and taking $\kappa = 10^{-3}$ $cm^2 s^{-1}$ and $\nu = 2 \times 10^{-2}$ $cm^2 s^{-1}$ respectively, we find $h_1 = 57$ m. This is much too small for the present case in which the convective layer depth is about 400 m. Due to the (1/4) power dependence on the first term, the role of the indeterminacies in R_c, κ and ν are only minimal. For example, to raise the estimate of h_1 by one order of magnitude would require a reduction by 10^{-4} in, say, the heat conductivity and viscosity. With the above values, the age of the layer would be estimated as less than a year, which also seems to be unrealistic.

It is obvious that the predictions based on the early laboratory studies do not appear to be realistic. Recent experiments by Fernando (1987) basically indicate that as the convective layer thickens the integral length scale of turbulence increases and the effects of buoyancy are increasingly felt. His model yields different results as compared to the above estimates. Most importantly, it is clear that the growth of the mixing layer does not proceed at the same rate for all times. Initially, the layer thickness increases as $h \sim t^{1/2}$ as given above, until it reaches a critical thickness of

$$h_c = C (H/N^3)^{1/2} = c H_*^{1/2} S_*^{-3/4}$$

which occurs at about $t \approx 860 N^{-1} = 610 S_*^{-1/2}$ where $N^2 = 2 S_*$ in the notation of Fernando (1987) and the constants in the above equation are $C \approx 41.5$ and $c \approx 34.6$ respectively. After that time, the growth is slowed down considerably, because the interfacial entrainment by eddies becomes inefficient and the only remaining component of transport is the molecular diffusion. In fact, the growth of the mixing layer almost comes to a stop in the limit of long times, where laboratory experimental coverage was also the least, nevertheless indicating a trend. For the Black Sea, the limiting depth of convection would be reached within less than a month after the process would have started, when the layer would have a thickness of 20 m. After this stage, the convective layer would still continue its thickening, but, only at a very slow rate.

The velocity scale for the convection is the r.m.s. vertical velocity w_*, is given by Fernando (1989) for the long time limit experiments as

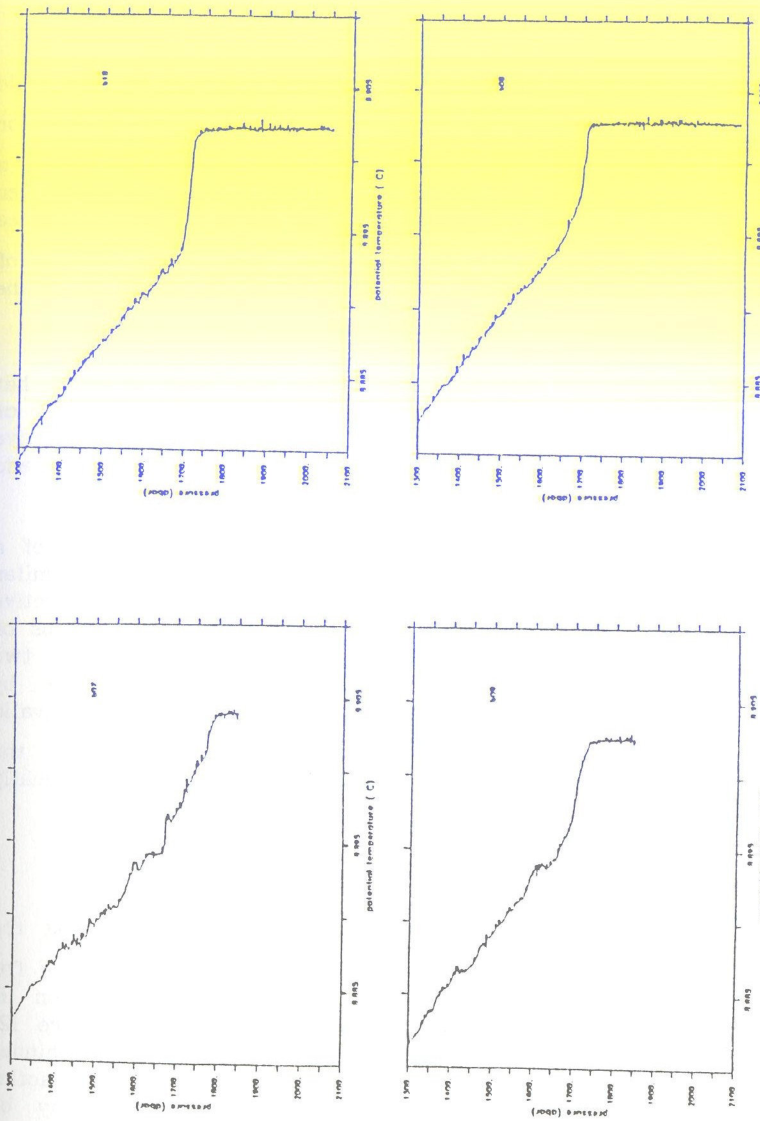

Figure 12. Potential temperature θ (°C) versus pressure (decibar) at the deeper parts (1300-2100 dbar) of (a) station 7, (b) station 18, (c) station 9, (d) station 8.

$$w_* = c_2^{1/2} (H_* h)^{1/3}$$

which yields $w_* = 0.15$ cm s^{-1} with the above values and c_2=1.8. This would correspond to an average turnaround timescale (h/w_*) of about 10 days for the convective layer. Taking δT=0.01°C and δS=0.003 yields a buoyancy jump of δb=0.001 cm s^{-2} at the convective layer interface. Then the Richardson number becomes $Ri_* = \delta b\ h/w_*^2 \approx 2000$ for the Black Sea convective layer. Fernando (1989) indicates that the effects of entrainment become vanishingly small for Ri_*>240, which seem to be the present case.

Based on the results of Fernando (1987), we can only conclude that probably a fair amount of time (on the order of the mean residence time of the basin) has passed since the time of initial formation of the convective layer. Since that time, the mixing layer has been growing slowly and mixing with the overlying waters only through molecular diffusion.

Experiments by Huppert and Linden (1979) indicate the development of a series of convective layers near the propagating front, in a similar fashion to the breakdown of the diffusive layer above the first convective layer. The number of layers formed increases as $t^{1/2}$ with the positions of the multiple interfaces constantly changing through the merging of two adjacent layers each time. The first layer depth also changes by occasional mergers with the layer above and the expression for h_1 is valid before the first time this ever occurs. The average thickness of the multiple layers at the front excluding the first layer which gradually thickens) is given by

$$h_{avg} = 43\ \kappa^{1/2}\ S_*^{-1/4}$$

and is calculated as h_{avg}=1 m for the present case. This is almost too small a scale to be detected in the present measurements, but evidence for layers with larger vertical scales with temperature homogenization is present at some distance above the bottom convective layer in Figure 12. Some of the layers may have been formed by several mergers of thinner layers, because the progression of the layering is expected to be chaotic. On the other hand, the horizontal variability in the layering may be associated with proximity to the continental slope (side heating) or uneven distribution of the bottom heat flux.

At some stations in Figure 12 only a single diffusive layer appears above the convective layer. According to the results of Fernando (1989), the long time limit of the 'low stability' regime differs from the chaotic layering of the 'diffusive' regime proposed by Huppert and Linden (1979) and is characterized by a single convective layer because of the engulfment the interfacial eddies by the eddies of the lower layer. In the long time limit, the eddies become too weak to entrain, and the development slows down. The fact that we see a dominant convective layer at the bottom of

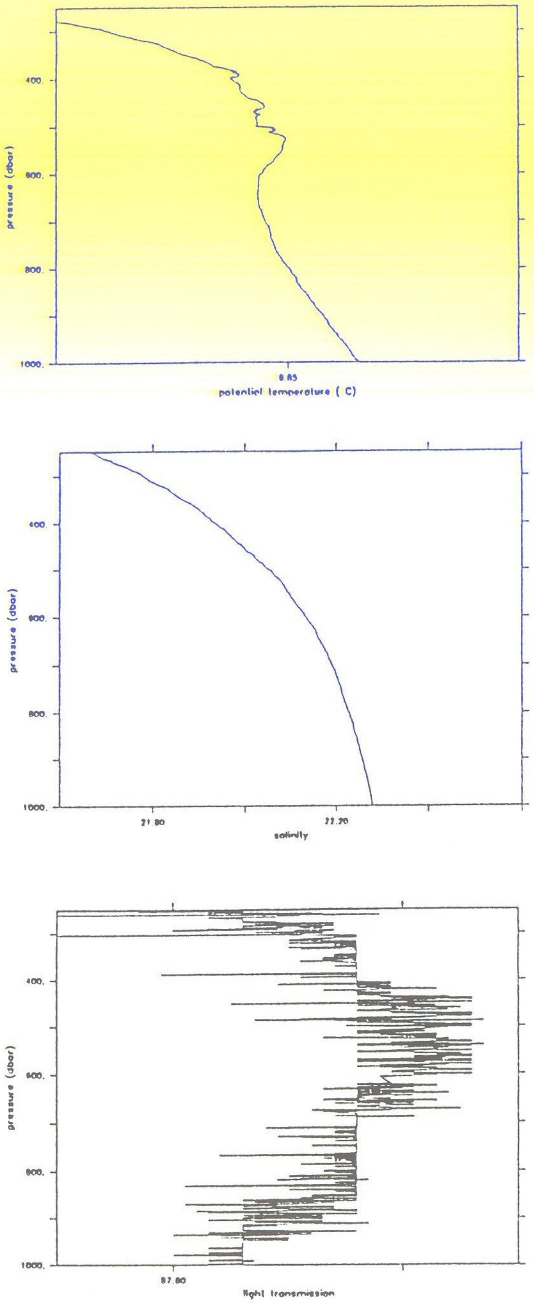

Figure 13. (a) Potential temperature θ (°C), (b) salinity and (c) light transmission (%) versus pressure (decibar) in the pressure range of (300-1000 dbar) at station 6.

the Black Sea suggests the long time limit of the Fernando 'low stability' regime.

One of the most puzzling aspects of the enlarged deep profiles (Figure 13) is the anomalous features observed at station 6 at about a depth of 500 m as previously displayed in Figures 4 and 11. An enigmatic feature is the maximum of temperature near 550 m with 'intrusive' features superposed on it. No evidence exists for accompanying salinity anomalies, but the light transmission indicates a minimum at these depths. Both the temperature maximum and the fine structure remains unexplained, because the Mediterranean water driven anomalies have up to now been observed more to the east and at shallower depths. In a larger context, we have seen that the density ratio $R_\rho \Rightarrow 0$ at depths of 500 m associated with temperature homogenisation. On the other hand, the generally uniform temperature at 500 m or the anomalous features of station 6 occur at the base of the CIW which is a negative buoyancy source for the deeper layers. The convection here differs from that at the bottom because of the complications presented by the large vertical salinity gradient and the vertical shears associated with the circulation.

5. Conclusions

The mixing and renewal mechanisms of the Black Sea waters appear to depend on a series of subtle processes. The intermediate waters are renewed by lateral injections of fluid from the basin periphery at or below the anoxic interface, which, by being replaced by the near surface waters, constitute an important mechanism for the vertical exchanges. The double diffusive environment of the Black Sea provides the suitable setting for these exchange processes. Various external driving factors, such as the intrusions of Mediterranean water, wind stirring and topographic effects at the shelf edge can trigger the proposed mechanism.

The intrusion of the Mediterranean waters and their subsequent evolution in the Black Sea are described. Although the inability of the observations to detect traces of the Mediterranean plume in deep water may just be due to the limits of the observation methods, the breakdown of the plume into horizontally advecting layers at intermediate depths leaves little to be sought for at deeper waters, and is thought to play an important part in its dispersal in the Basin. In addition, a basic difference exists with the typical plume dynamics used elsewhere to model the deep water renewal processes. The assumption of entrainment commonly used in plume models is modified by a combination of detrainment at the location of horizontally spreading layers and entrainment elsewhere; this could lead to a modified 'entrainment hypothesis' to be applied to the present case.

The bottom mixing layer driven by the sub-bottom heat fluxes appears to be unique in its features and age. Although none of the present laboratory models for the development of convective layers can predict its age, it is anticipated to be associated with the recent geological history of the

basin. It appears to be the thickest one of such mixing layers so far observed in the world ocean. Furthermore, the unique features of the bottom convective layer make it a perfect candidate for further scientific studies of convection processes in the nature under ideal conditions.

The Black Sea offers unique opportunities for observing and testing various mechanisms related to convective and double diffusive processes and the interaction of basin scale dynamics with the shelf regions. Many of the mysteries associated with various aspects of its oceanography can be explained by further multidisciplinary oceanographic studies.

Acknowledgements

This work has been completed during a visit by the first author to the Harvard University as a Fulbright scholar. The encouragement and suggestions received from Prof. Allan Robinson during the course of the studies, and the use of the facilities of his group at Harvard University in producing the results presented are gratefully acknowledged. We thank the Institute of Marine Sciences, METU, Turkey, for cooperating in data collection by the RV Bilim to aid in relocating some of the RV Knorr stations.

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