Sources of Double Diffusive Convection and Impacts on Mixing in the Black Sea

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The Black Sea is a uniquely stratified environment supporting double diffusive convection in most of its interior. Originating from the Bosphorus, and modified by entrainment of Cold Intermediate Water on the continental shelf, the inflowing Mediterranean Water drives double diffusive intrusions penetrating horizontally into the interior of the Black Sea from the continental slope. Intrusions aided by the inherent double diffusive instability of the ambient stratification drive a vertical circulation, creating ventilation across the halocline. The intrusions are also significant in transporting shelf-derived materials into the interior of the basin. Various scales of convection are indicated, with increasing amplitude near the basin boundaries. The relatively smaller scale disturbances are confined above the halocline, possibly driven by atmospheric forcing and buoyancy inputs. Double diffusive intrusions occur at or below the halocline, up to a depth of $\sim 500m$, where a peculiar zone of vanishing temperature gradient exists. A bottom convection layer occupying several hundred meters near the bottom is driven by geothermal heat fluxes. The slow but efficient convection in this layer homogenizes the water properties across the basin. The transports of heat and salt upwards from the bottom convective layer are most likely determined by double diffusive fluxes.

1. INTRODUCTION

With a maximum depth of $\sim 2200m$, a surface area of $4.2 \times 10^5\ km^2$ and a volume of $5.3 \times 10^5\ km^3$, the Black Sea is a unique marine environment, representing the largest land-locked basin in the world (Figure 1). Its positive water budget, with total freshwater input largely in excess of evaporation [*Ünlüata et al.*, 1990], is balanced by the two-way exchange through the Turkish Straits System (the Bosphorus, Dardanelles Straits and the Sea of Marmara). Almost complete isolation from the world ocean, except for the exchanges controlled by a shallow (60 m) sill, has resulted in a strong density stratification to be developed in the Black Sea.

As a result, the Black Sea deep waters have become stagnant, with renewal time scales of a few thousand years [*e.g., Boudreau and Leblond*, 1989; *Östlund*, 1974; *Grasshoff*, 1975; *Tolmazin*, 1985]. The basin is almost completely anoxic, containing oxygen in the upper $\sim 150m$ depth (13% of the sea volume) and hydrogen sulphide in its deep waters. A permanent halocline separates the oxic and anoxic waters. On the other hand, the ventilation of the deeper layers and the structure of the halocline essentially depend on the inflow of Mediterranean water through the Bosphorus.

It is important to understand processes contributing to pycnocline and deep mixing, and the three-dimensional transport of materials in the Black Sea, because it is being seriously threatened by environmental degradation [*e.g., Mee*, 1992] in recent years, as a result of man's activities around this enclosed region. Very little is known of the relative roles of the various trans-

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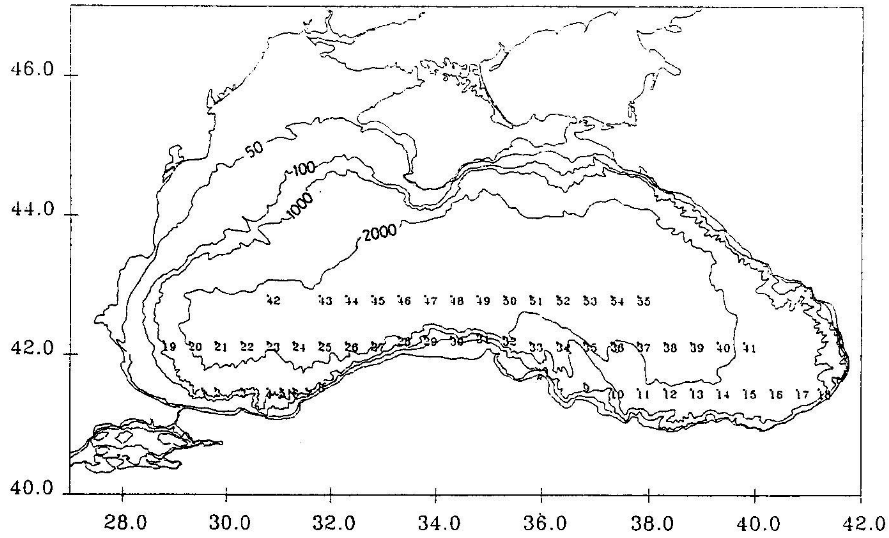

Fig. 1. The regional map and bottom topography of the Black Sea. Also shown are the locations of the three east-west transects for which station data are displayed in Figures 6, 7, 8 and 10.

port and ventilation mechanisms. On the other hand, the Black Sea is one of the primary areas of the world ocean where small-scale processes such as double diffusive convection can have a significant impact on the large scale properties of a system.

Although the present review derives largely from our earlier publications [*Özsoy et al.*, 1991; *Murray et al.*, 1991; *Latif et al.*, 1991; *Özsoy et al.*, 1993]), further discussion has been added, based on some recent observations.

2. HYDROGRAPHIC DATA

Our analyses are largely based on hydrographic data of high resolution and accuracy, collected by RV BİLİM of the Institute of Marine Sciences, Middle East Technical University during 1986-1993, and by RV KNORR during 1988 [*Murray et al.*, 1991; *Özsoy et al.*, 1993]. The temperature and salinity measurements were obtained with Seabird 9/11 CTD profilers in all cruises. In 1988 the KNORR, and in July 1992 the BİLİM collected light transmission data with a Sea-Tech transmissometer with a 25*cm* optical path, interfaced with the CTD systems. After 1990, the data have been obtained collaboratively with the riparian countries of the Black Sea, in an international, interdisciplinary program presently known as CoMSBlack (Cooperative Marine Science Program for the Black Sea) [*Ünlüata et al.*, 1993]. Although these data cover the entire basin with a nominal horizontal resolution of 30 *km*, we only use data from BİLİM, because only these data were suitable for studies of fine structure. However, the analysis showing the depth distribution of the bottom diffusive interface in Figure 13 have been constructed using the entire data set.

3. DOUBLE DIFFUSIVE INTRUSIONS

3.1. *Shelf Modification of the Mediterranean Water*

The cross-shelf spreading of the Mediterranean Water into the Black Sea has been described to some extent [*Tolmazin*, 1985; *Yüce*, 1990], including a more complete, recent description [*Latif et al.*, 1991]. The warm, saline Mediterranean Water enters the Black Sea through the lower layer of the Bosphorus, overflowing a sill and following a bottom channel till the middle of the wide shelf region. From then on, the Mediterranean Water spreads out to form a thin sheet of warm and saline anomalous bottom water on the shelf [*Latif et al.*, 1991]. The overlying Cold Intermediate Water (CIW) is a product of winter convection (temperature less than $\sim 8°C$) in the Black Sea. The intruding Mediterranean Water is rapidly mixed (Figures 2 and 3), and diluted by a factor of 3-6 by entraining the CIW on the shelf. As a result, the shelf-mixed water becomes relatively colder, yet remains more saline than the Black Sea waters off the shelf edge [*Özsoy et al.*, 1993]. The cold anomaly of the shelf-mixed water (relative to the interior water

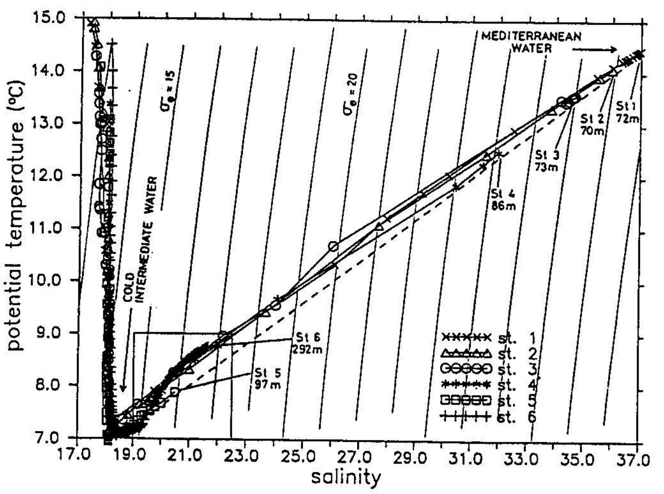

Fig. 2. Evolution of temperature - salinity across the shelf. Stations 1-5 extend from the Bosphorus to the shelf break. Station 6 is a deeper station immediately offshore. The dashed line models the changes in the 'Mediterranean effluent' at the bottom. At the shelf break (station 5), the modified bottom waters are colder than the waters at comparable depths of the continental slope (station 6). After Özsoy *et al.* (1993).

mass at the same depths) is then used to identify its intrusion into the interior at intermediate depth.

3.2. *Intermediate Depth Intrusions and Double Diffusive Instability*

The introduction at the shelf edge of shelf-mixed (cold, saline) water into a doubly stratified interior immediately leads to convection along the southwest margins of the Black Sea [*Özsoy et al.*, 1993]. The shelf-mixed water sinking along the continental slope drives double diffusive convection with a series of intermediate depth, horizontally spreading intrusions, as schematized in Figure 3. In the potential temperature versus salinity ($\theta - S$) diagram (Figure 4), the intrusions are identified first in the form of a cold sheet of water on the continental slope (dashed lines), then as discrete layers of anomalous characteristics (solid lines) spreading into the interior. The intrusions are characterised by a series of cold anomalies in the 100-500m depth range.

Two-dimensional effects created by a buoyancy source located on the lateral boundary of a stratified or a doubly stratified fluid environment often generates similar

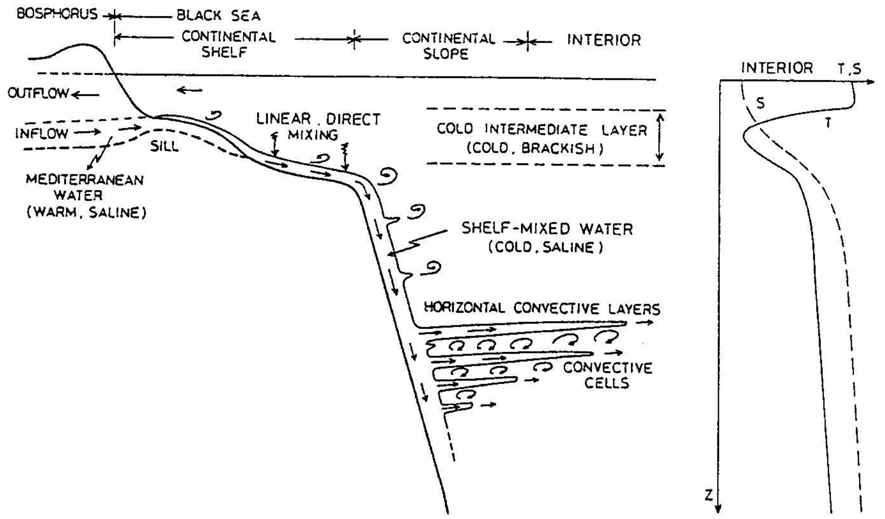

Fig. 3. Schematization of the boundary mixing processes driven by the Mediterranean Water issuing from the Bosphorus. Linear, direct mixing occurs on the shelf region and on part of the slope. At intermediate depths, double diffusive instabilities are generated due to the temperature and salinity contrasts of the intrusions and the potential instability of the interior. After Özsoy *et al.* (1993).

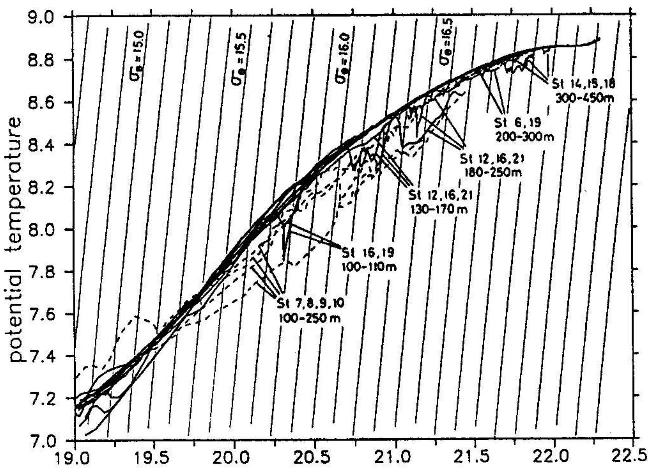

Fig. 4. The potential temperature - salinity relationship for stations near the southwestern shelf of the Black Sea. Dashed lines represent stations closest to the continental slope, *i.e.* within the boundary layer. The intrusive features at other stations offshore of the shelf region occur in the form of discrete layers spreading into the interior. After Özsoy *et al.* (1993).

convection patterns [*e.g.*, *Turner*, 1973, 1978; *Huppert and Turner*, 1980].

The essential element in the case of the Black Sea is a source of buoyancy with two diffusive components introduced into doubly stratified water which is potentially unstable. The vertical profile of Turner angle $Tu = tan^{-1}\{(1 + R_\rho)/(1 - R_\rho)\}$ [*Ruddick*, 1983], and density ratio $R_\rho = (\beta \partial S/\partial z)/(\alpha \partial T/\partial z)$ (where z is depth and α and β are the respective expansion coefficients for temperature, T, and salinity, S) plotted in Figure 5 indicates that almost the entire depth of the Black Sea is stratified in the double diffusive sense and in the diffusive range, a fact which can considerably increase the mixing efficiency of the intrusions [*Turner*, 1978]. (Note that the density ratio is defined following the convention used in the diffusive regime. In some references [*e.g.*, *Ruddick*, 1983], as well as in our earlier work [*Özsoy et al.*, 1993], it has been defined in the salt fingering sense, which is the inverse of the present definition. The inverse definition is easier to plot in the case of the Black Sea, because $R_\rho \to \infty$ at mid-depth in Figure 5a.)

It is expected that a lateral buoyancy source located in a stratified medium (characterized with two diffusive properties of either the source or the ambient fluids) can create complicated convection patterns. These effects are best illustrated in experiments on sidewall heating or cooling applied to a salinity gradient [*e.g.*, *Turner*, 1978; *Huppert and Turner*, 1980; *Tanny and Tsinober*, 1988; *Jeevaraj and Imberger*, 1991]. Accordingly, the critical Rayleigh number for layered convection is $Ra_c = 1.5 \times 10^4$. Computation of the Rayleigh number $Ra \equiv g\alpha\Delta T\eta^3/\nu\kappa_h$ (g being the gravity, ΔT the temperature difference at the sidewall, ν the kinematic viscosity, κ_h the thermal diffusivity, and $\eta \equiv \alpha\Delta T/\phi_0$, with $\phi_0 = -\beta dS/dz$, a length scale proportional to the vertical spacing of the convecting layers) for typical parameters of the Black Sea yields $Ra \simeq 10^{11} - 10^{13}$, exceeding the critical values of $Ra = Ra_c$ for convection. The estimated layer thicknesses of 20 - 40 m [*Özsoy et al.*, 1993] were also consistent with the observations.

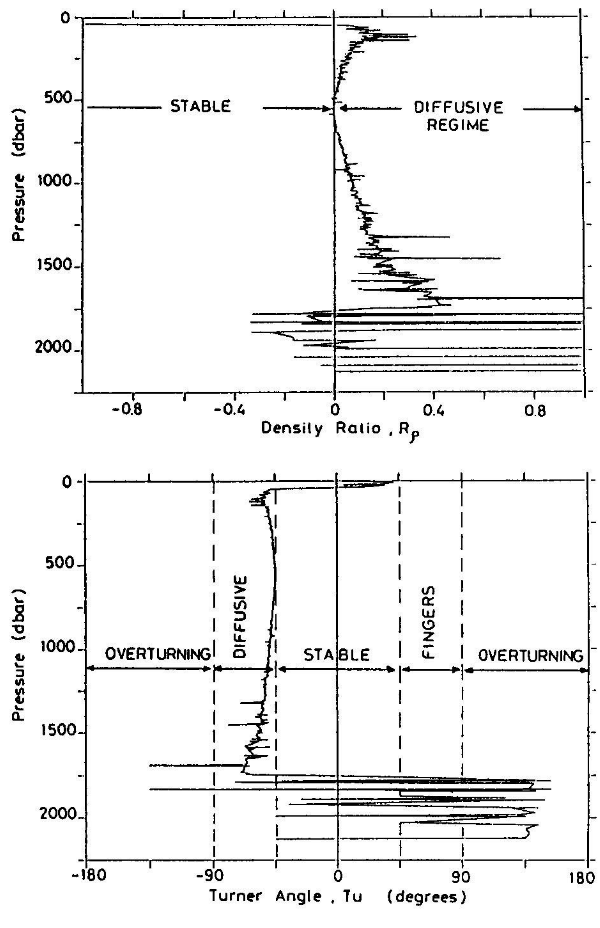

Fig. 5. The average stratification parameters computed from an ensemble of Black Sea deep water profiles: (a) the inverse density ratio $R_\rho^{-1} = \{(\beta dS/dz)/(\alpha dT/dz)\}^{-1}$, and (b) the Turner angle $Tu = tan^{-1}\{(1+R_\rho)/(1-R_\rho)\}$, where α and β are coefficients of expansion for temperature and salinity. The ranges for stable, statically unstable, and double diffusively unstable regimes are indicated. After Özsoy *et al.* (1993).

Short term variability and intermittency were found to be basic features of the intrusions. Part of the intermittency and filamentation was interpreted to be a result of the interaction of the sinking, dense, shelf-mixed water with ambient currents and the major topographic features in the region, such as Sakarya Canyon [*Özsoy et al.*, 1993; *Sur et al.*, 1994].

Based on data sets from a number of different cruises, it was shown [*Özsoy et al.*, 1993] that the anomalies could be traced back to a main source region in the southwest margin of the Black Sea, although much diluted imprints, in the form of smaller amplitude cold temperature anomalies and suspended material concentrations, can be found further east along the Anatolian coast [*Kempe et al.*, 1991].

More recent surveys covering the entire basin consistently indicate the southwestern shelf region to be the source for the intermediate depth intrusions. Figure 6 shows a series of temperature profiles in the southern Black Sea along 41°30'N, for repeated surveys of September 1990, September 1991 and July 1992. Note that in all of the cases, the intrusions with relatively larger cold anomalies are detected in the southwest, in the vicinity of the Bosphorus. The Turner Angle computed for the July 1992 profiles (Figure 7) show rapid fluctuations in the southwestern Black Sea, caused by alternating diffusive and fingering interfaces of the intrusions.

Along 42°10'N (Figure 8), only slightly north of the section in Figure 6, intermediate depth cold anomalies (at depths of 100-500m) are less prominent, but it can be verified that the cold anomalies have moved further east following the coast along the main direction of cyclonic circulation.

3.3. *Material Transport from the Continental Shelf and Slope Regions*

Intermediate depth inorganic particulate maxima near the basin boundaries are well known in the Black Sea [*e.g., Brewer and Spencer*, 1974; *Spencer et al.*, 1972]. Earlier sediment-trap measurements in the open waters of southwestern Black Sea have also identified large quantities of shelf-derived materials reaching their locations [*İzdar et al.*, 1986; *Hay, 1987; Honjo et al.*, 1987; and *Kempe et al.*, 1991].

A significant part of the transport of materials from the continental shelf and slope region into the interior is driven by the horizontally spreading intrusions. The most direct evidence of such transport is given by light transmission measurements [*Özsoy et al.*, 1993]. The perfect coincidence of seawater, particulate and nutrient anomalies [*Codispoti et al.*, 1992; *Özsoy et al.*, 1993], such as shown in Figure 9, indicate a common source of the materials. This pattern of transport, derived from the shelf and occurring across the halocline, is verified by independent measurements of Iron, Manganese and Chernobyl radiotracers [*Buesseler et al.*, 1991].

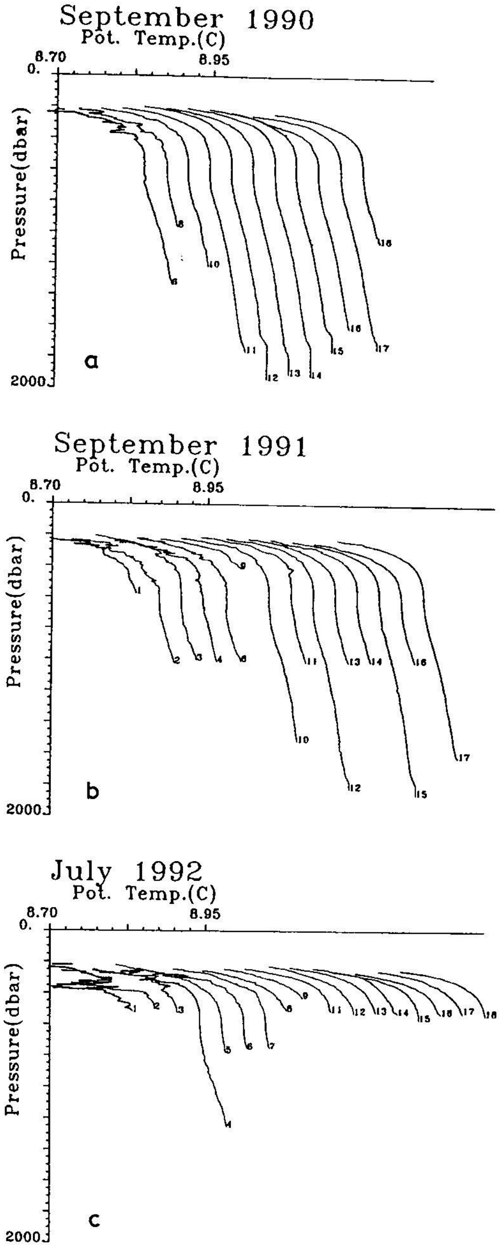

Fig. 6. Temperature profiles along 41° 30' N (Figure 1) in (a) September 1990, (b) September 1991, and (c) July 1992. Consecutive profiles are offset by 0.03°C in temperature units.

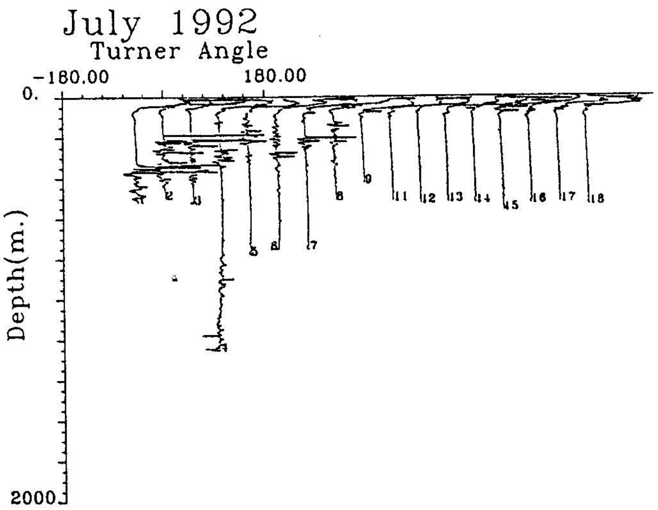

Fig. 7. Computed Turner angle (Tu) profiles along 41° 30' N (Figure 1) in July 1992. Consecutive profiles are offset by 90° in Turner angle units. In the western part of the transect, intrusions with alternating interfaces are identified by Tu fluctuating between the ranges of $-90° < Tu < -45°$ (diffusive regime) and $45° < Tu < 90°$ (salt finger regime) of double diffusive instabilities (Ruddick, 1983).

Light transmission measurements, repeated during the July 1992 survey (Figure 10), showed intermediate depth particulate maxima covering a large area of the basin. The peaks were prominent in the southwest Black Sea (Figure 10a), but also reached the central parts of the southern coast (Figure 10b) where the transect of profiles approaches the coast.

4. BOTTOM CONVECTION

Deep CTD casts in the Black Sea indicate constant temperature and salinity in a 300-400m thick layer above the bottom (Figures 6, 8 and 11). The perfect vertical and horizontal homogeneity of the properties across the basin within this layer suggest homogenization by convectively driven motions, believed to be formed by geothermal heating working against the existing gravitationally stable gradient of salinity [*Özsoy et al.*, 1991; *Murray et al.*, 1991]. Even the low level of geothermal heat fluxes in the Black Sea ($H \simeq 40\ mW\ m^{-2} = 0.9\ \mu cal\ cm^{-2} s^{-1}$), as compared with the relatively higher values in some neighboring seas [*Zolotarev et al.*, 1979; *Haenel*, 1979], are sufficient to drive convective motions in the otherwise stagnant waters of the deep Black Sea.

The thickness of the convective layer varies across the basin (Figure 12), possibly in response to the variable geothermal heat flux, modalities of the convection or other interior balances.

Laboratory convective layers under similar conditions of a salinity gradient heated from below have been studied extensively [*e.g., Turner*, 1968; *Huppert and Linden*; 1979, *Fernando*, 1987], and many oceanographic and

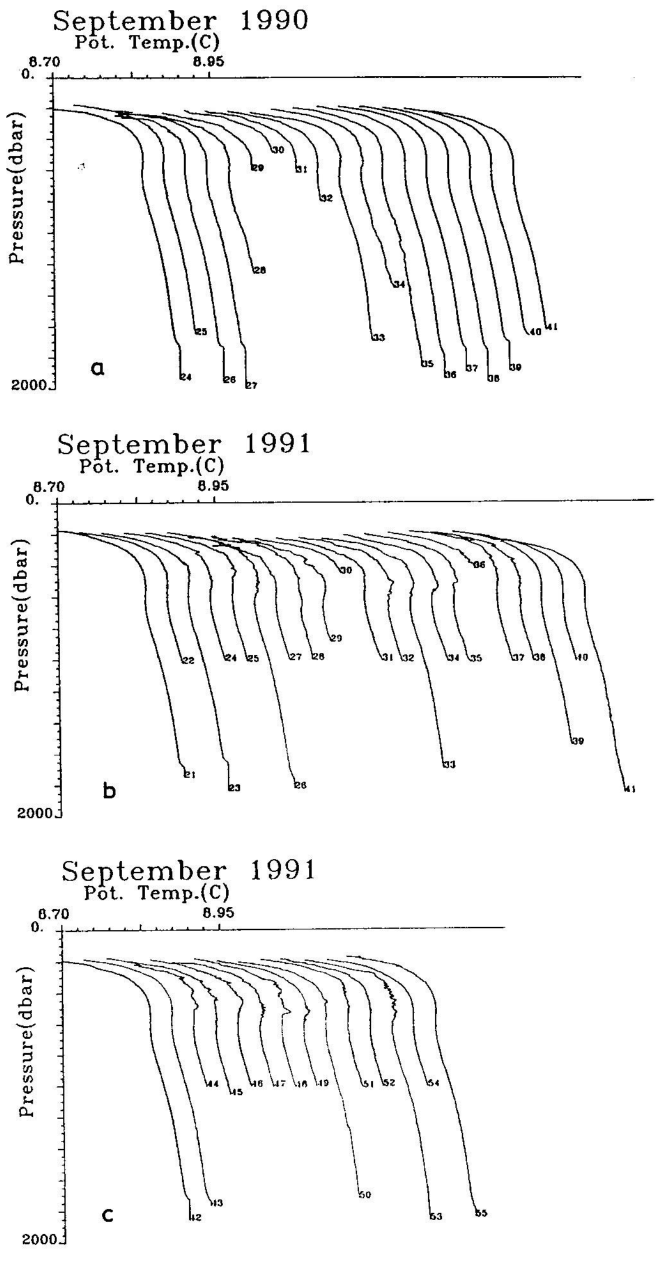

Fig. 8. Temperature profiles (a) along 42° 10' N in September 1990 and (b) along 42° 10' N in September 1991, and (c) along 42° 50' N in September 1991. Consecutive profiles are offset by 0.03°C temperature units.

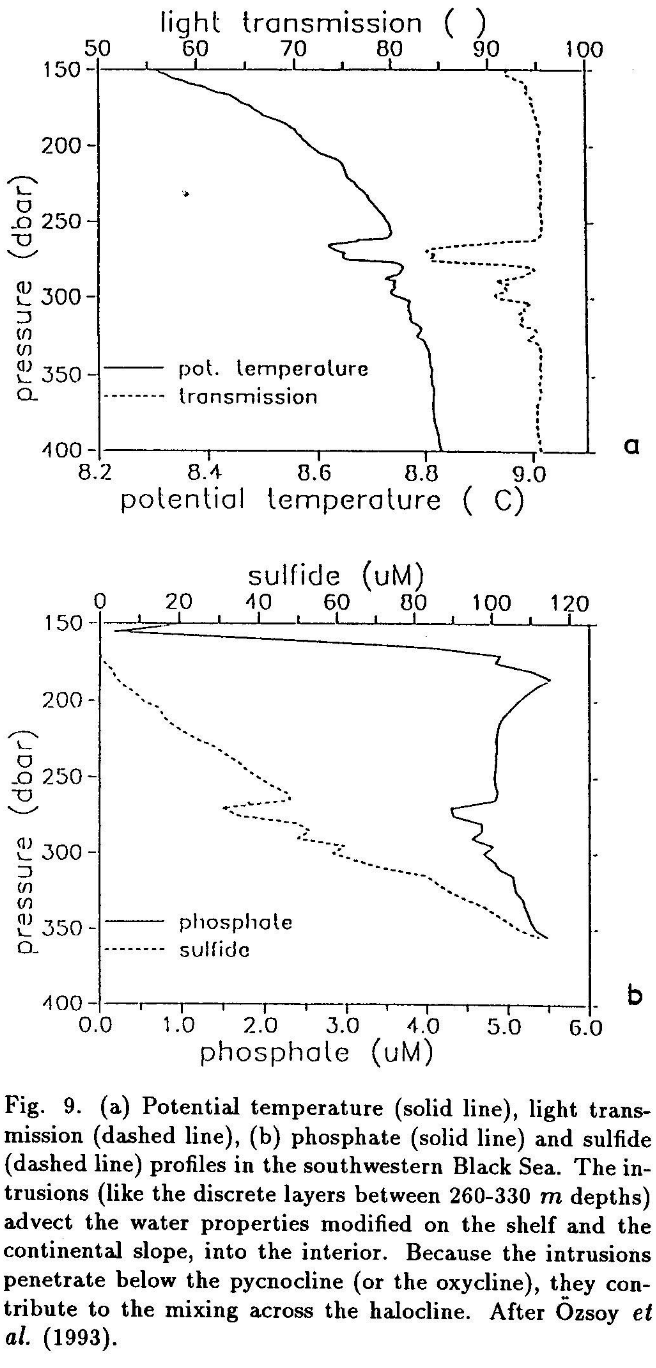

Fig. 9. (a) Potential temperature (solid line), light transmission (dashed line), (b) phosphate (solid line) and sulfide (dashed line) profiles in the southwestern Black Sea. The intrusions (like the discrete layers between 260-330 m depths) advect the water properties modified on the shelf and the continental slope, into the interior. Because the intrusions penetrate below the pycnocline (or the oxycline), they contribute to the mixing across the halocline. After Özsoy *et al.* (1993).

limnological examples are known [*Turner*, 1969, *Fernando*, 1989]; yet the available theory is far from fully explaining the time evolution of the convective layer in the Black Sea.

Based on the earlier results [*Turner*, 1968; *Huppert and Linden*, 1979], and for given values of geothermal heating, the time required for the formation of a layer with the present thickness is estimated to be on the order of 34 *years* or less. On the other hand, the maximum thickness at which the diffusive interface would split into a second convective layer is estimated to be 43 m, that would occur in less than a year after the initiation of the heat flux [Özsoy *et al.*, 1991]. Since there is no reason to suspect such rapid changes in the system, the age of the convective layer is expected to be on the same order as the deep water itself. (The convective layer is the bottom layer with uniform properties below $\sim 1700m$; the deep water is the water below $\sim 500m$). On the other hand, these comparisons indicate that there are large discrepancies between the predictions and the observations.

The observed structure can not be scaled with laboratory experiments, except with those in a limiting case [*Fernando*, 1987]. Recent experiments and a survey of oceanographic applications [*Fernando*, 1987, 1989] have indicated the possibility of different regimes in the development of the convective layer. In the 'low stability' regime, the eddies from the convection region initially penetrate into the interfacial layer, preventing its splitting into many layers; however, the growth of the layer slows down in the long time limit, when the kinetic energy of the eddies can no longer overcome the potential energy of the buoyancy jump across the interface. In particular, the layer thickness initially increases as $h \sim t^{1/2}$, until a critical thickness $h_c = C(HN^{-3})^{1/2} = cH_*^{1/2}S_*^{-3/4}$ is reached at time $t_c \simeq 860N^{-1}$ (where $N^2 = 2S_*$, $S_* = -(1/2)g\beta(dS/dz)$, $H_* = -g\alpha H/\rho c_p$, where H is the bottom heat flux, ρ and c_p are respectively the density and specific heat of sea water). It is found that $h_c = 20m$ and $t_c \simeq 1$ month in the case of the Black Sea [*Özsoy et al.*, 1991; *Murray et al.*, 1991].

The existence of a single mixed layer much thicker than h_c suggests that the Black Sea bottom convection is in the long time limit of the 'low stability' regime. By comparing the calculated value of the Rayleigh Number $Ra_h = g\alpha\Delta T h_s^3/\kappa_h\nu = 4\times10^{15}$ (ΔT is the temperature difference across the interface, and h_s is the convective layer thickness) versus the density ratio $R_\rho \simeq 2$ at the interface, and making use of the classification of various regimes [*Fernando*, 1989], we verify that the Black Sea interface is potentially in the 'low stability' regime. The fact that the effects of eddy entrainment have become vanishingly small in the long time limit can be verified by comparing the interface Richardson Number, $Ri_\star = \Delta b h w_\star^{-2}$ (where $\Delta b \equiv g\alpha\Delta T - g\beta\Delta S$ is the buoyancy jump defined by the temperature and salinity differences ΔT and ΔS at the interface, $w_\star$ is the *r.m.s.*

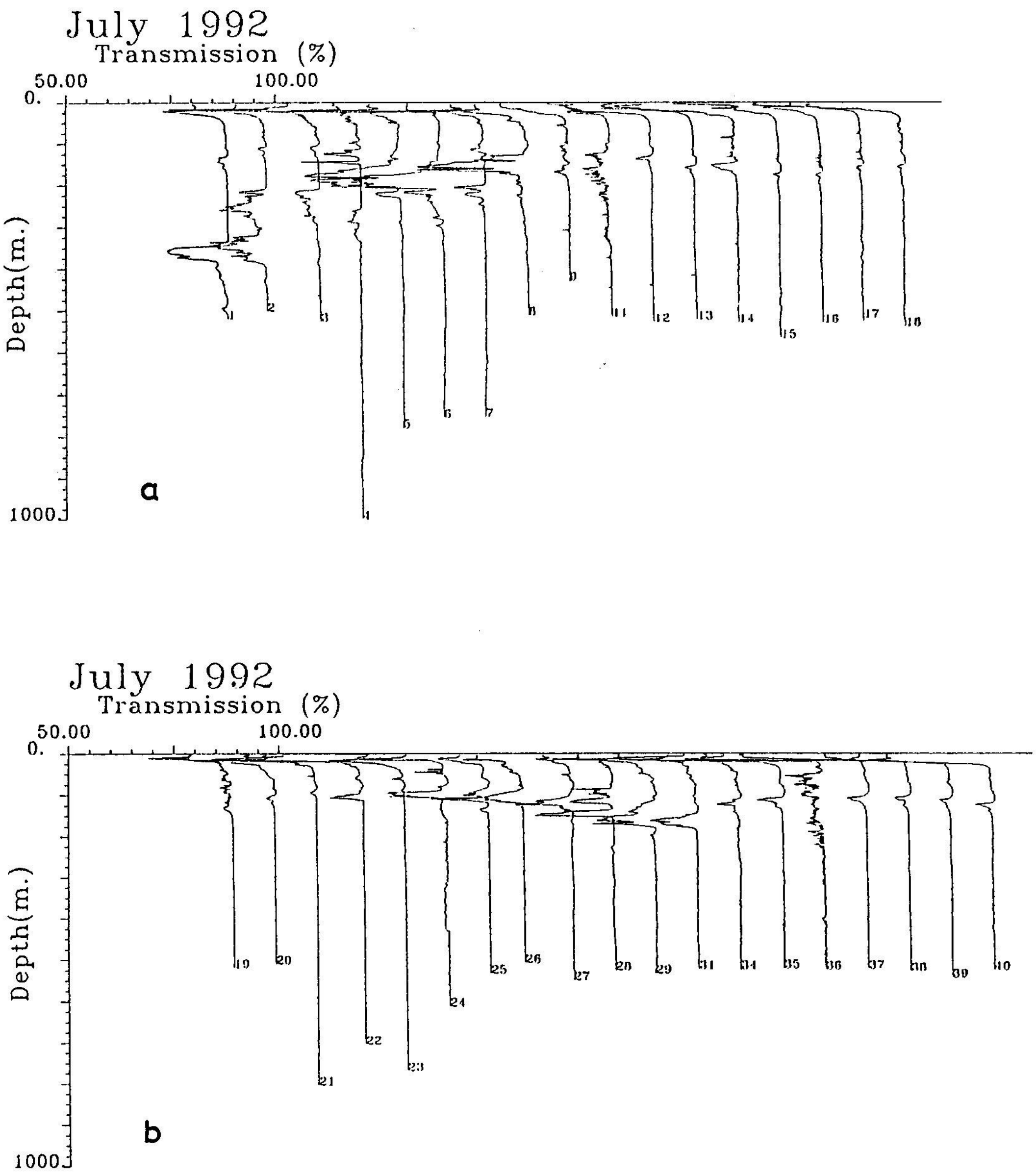

Fig. 10. Light transmission profiles along (a) 41° 30' N and (b) 42° 10' N (Figure 1) in September 1990. Consecutive profiles are offset by 10 % in light transmission units.

convective velocity), with the values reported for other cases [*Fernando*, 1989]. For $Ri_\star > 240$, the entrainment is expected to become vanishingly small; this is certainly true in the Black Sea, since the interface Richardson Number has a value of $Ri_\star \simeq 600$, the largest reported so far. This is not surprising, because the Black Sea also has the largest convective layer thickness among known examples in the world.

On the other hand, another criterion was found [*Fernando and Ching*, 1991] to differentiate between the cases with multiple splitting of the diffusive interface and a single layer development. According to this scheme, if $R_\rho > \tau^{1/2}$ ($\tau = \kappa_s/\kappa_h$ is the ratio of salt / heat diffusivities), the convection would continue to grow as a single layer because the interface would be a non-entraining (or detraining) type. With τ=0.01, and $R_\rho = 2$ at the diffusive interface, this criterion is satisfied in the Black Sea. Experiments indicate that, in this regime, the convective layer growth almost comes to a stop after the depth h_c is reached; *i.e.* the thickness of

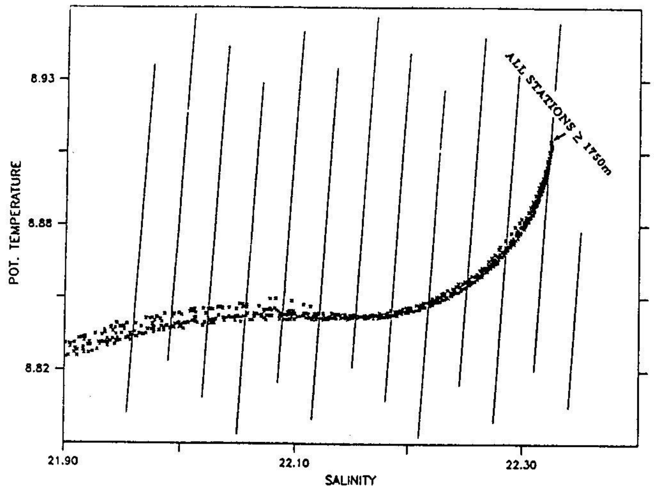

Fig. 11. The potential temperature - salinity relationship for the deep waters of the Black Sea. All the data with uniform properties within the bottom convective layer converge to a single point in potential temperature - salinity space.

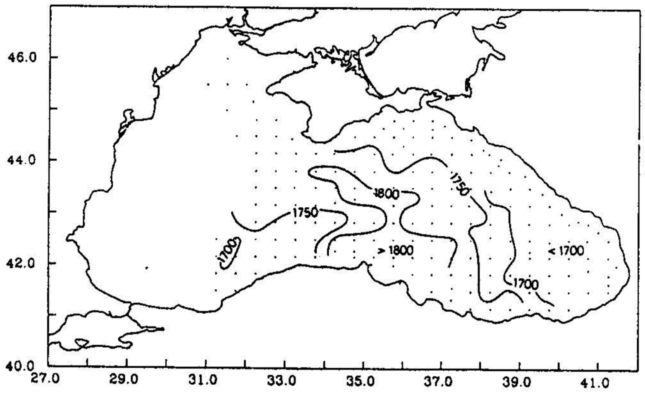

Fig. 12. The depth (m) of the diffusive interface bounding the bottom convective layer in September 1990.

the convective layer increases at a much slower rate as compared to the earlier regime. This is why we believe that the age of the Black Sea convective layer (time for the layer to reach the present thickness) must be comparable to the mean residence time of 1000 - 2000 years reported for the deep waters of the Black Sea below a depth of $\sim 500m$.

As for the thermal part of the buoyancy flux, q_h, across the diffusive interface, the [*Huppert and Linden*, 1971] formula $q_h = c_6(\kappa_h^2 \nu^{-1})^{1/3}(g\alpha\Delta T)^{4/3}R_\rho^2$ yields $q_h = 0.61 \times 10^{-6} cm^2 s^{-3}$. Similarly, the [*Fernando*, 1989] formula for the 'low stability' regime, $q_h = c_{11}(g\alpha\Delta T)w_\star$, is found to yield $q_h = 0.9 \times 10^{-6} cm^2 s^{-3}$. (Both c_6 and c_{11} are empirical constants). Both estimates of the thermal buoyancy flux are greater than the measured thermal buoyancy flux of $H_* = -g\alpha H/\rho c_p = -0.12 \times 10^{-6} cm^2 s^{-3}$ corresponding to the geothermal heat flux H. The disparity between calculated and measured fluxes is most probably associated with the long time limit of convection, for which none of the models are appropriate. We note that this result is consistent with [*Fernando*, 1989], who suggests an overestimating tendency in the flux computations in the long time limit, *i.e.* with large values of $Ri_\star$.

5. IMPACT ON MIXING

The identification of various mechanisms of mixing in the Black Sea has not been straightforward. Because of its rather unusual setting as an enclosed basin with a specific form and history of stratification, it may have very little in common with oceanographic settings in other regions of the world.

The various possible mechanisms of mixing in the Black Sea are schematized in Figure 13. A rather unique combination of factors exists in the Black Sea: a double diffusive environment, wind stress forcing in a closed basin geometry and the resulting Ekman pumping, buoyancy-driven lateral boundary layers, and exchanges through the Bosphorus Strait. All these mechanisms lead to mass fluxes, which simultaneously have to be balanced by conservation arguments.

Typical values of effective vertical diffusivities in the deep ocean are often found to be much larger than the molecular values, in regions where direct turbulent mixing is not expected. This fact has been explained, with some success, by boundary mixing theories [*Garrett*, 1979, 1990; *Ivey and Corcos*, 1982; *Phillips et al.*, 1986; *Woods*, 1991; *Salmun et al.*, 1991], in which variable turbulent boundary layers drive a vertical circulation forced at the pycnocline. Boundary mixing, driven directly by the Bosphorus buoyancy source, as well as other sources appears to be an important component of the Black Sea vertical circulation. It has been hypothesized [*Özsoy et al.*, 1994] that the boundary layer structure along the continental slope region, and its subsequent disintegration, resulting in the intrusions of water from the boundaries towards the interior, could partially be responsible for driving a recirculation in the upper part of the Black Sea (Figure 13).

The lateral intrusions of shelf-mixed inflowing water from the continental slope region into the interior constitute a source of mass introduced into the interior region. The time and depth variability of the corre-

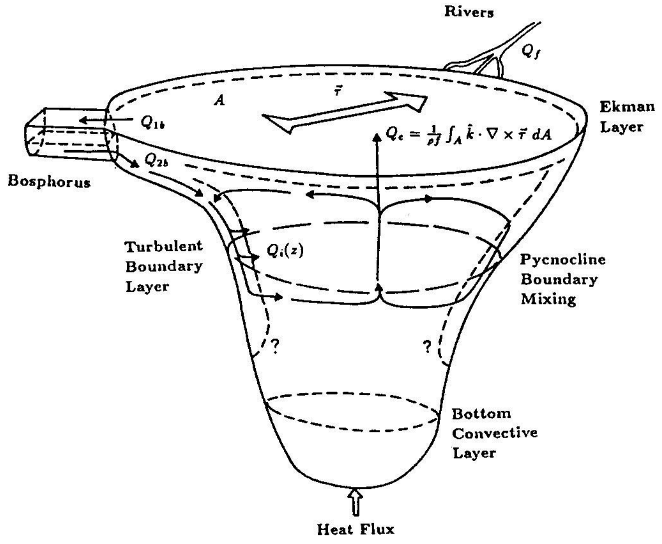

Fig. 13. Schematization of the recirculation driven by boundary mixing processes in the Black Sea. Mechanisms capable of driving a recirculation between boundary layers and the interior are emphasized. After Özsoy *et al.* (1993).

sponding source function at the halocline has important implications for the interior stratification in the upper part of the Black Sea, in which the vertical circulation may be dominated by the above mechanism of boundary transports. This conceptual model describing the upper ocean vertical recirculation in the semi-enclosed Black Sea basin is consistent with models of ventilation proposed earlier, based on the random termination depths of cascading water: *e.g.* the [*Rooth*, 1986] model for the Black Sea, and the Baltic model of [*Stigebrandt*, 1987].

It is possible that the zone of vanishing temperature gradient near a depth of $500m$ (Figures 4, 6 and 8) is linked with the observed ultimate depth of penetration of Bosphorus intrusions; the double diffusive fluxes likewise tend to vanish at the same depths corresponding to double diffusive marginal stability, $R_\rho \rightarrow \infty$ [*Özsoy et al.*, 1993]. This depth limit for efficient vertical mixing is consistent with other tracers, *e.g.* ^{14}C, showing smaller mean residence times of intermediate waters (depth $\leq$ 500m) compared to the more uniformly aged deep waters [*Östlund, 1974*, 1986]. Likewise, the Tritium penetration reaches similar depths [*Top et al.*, 1991]. Interestingly, the ventilation of the upper water column has been attributed [*Grasshoff*, 1975] to mixing along the Anatolian coastal margin; we suggest that a major source for the ventilation is the effects of the Bosphorus outflow.

Anomalous temperature fine structure is observed at all depths in the water column, and appears to be amplified near the basin lateral boundaries. For example, in Figure 8b, a variety of fine scale features appear at deeper depths, near the zone of vanishing temperature gradient at $\sim 500m$. Note, however, that these features are not characterised by cold anomalies as in the case of Bosphorus intrusions, but rather have temperature anomalies of both signs, with positive ones apparently dominating. Note also that these features were more common in September 1991 as compared to other surveys, at which time they also covered a larger area in the central parts of the basin. The origin of these features are therefore not clear, though they too are probably linked with double diffusive instabilities in the regime of high density ratio, possibly in response to cooling of the overlying CIW in the central regions. A number of other fine scale features are observed at the deeper depths. Deep features (500-2000m) are indicated in Figure 8a, especially near the central part, where the profiles were close to the basin boundary. These deep features provide clear evidence of boundary mixing in the deeper waters adjacent to the continental slope.

The transport between the bottom convective layer and the overlying waters occur through a diffusive interface between the two regions, where the fluxes are appropriate for a diffusive regime of double diffusion. In the deep water region above the interface, different types of assumptions could be made with regard to the fluxes. The deep water fluxes could either be related to double diffusion (with different diffusivities of salt and heat) or turbulent diffusion (with equal diffusivities of salt and heat). On the other hand, if the vertical transports of heat and salt were only related to one-dimensional diffusion (*i.e.* if lateral effects and variations in horizontal area were to be negligible), then we would expect the fluxes, and hence the flux ratio, to be constant throughout the deep waters.

One way to assess the regime of vertical transport in the deep water is to compare the computed flux ratios $R_f = q_s/q_h = \beta F_s/\alpha F_h$ (F_s and F_h respectively are the salt and heat fluxes) corresponding to the assumptions with regard to the form of vertical mixing.

The interfacial flux ratio in the 'low stability' regime is estimated as $R_f = 0.15R_\rho = 0.3$ by the Fernando (1989) model, with a value of $R_\rho = 2$ at the interface. It should be reasonable to expect similar values of the flux ratio in deep water above the interface. If the vertical transport were to be by double diffusion across some staircase interfaces, then we could use either $R_f = \tau^{1/2}R_\rho$

[*Turner*, 1973], or $R_f = \tau^{1/2}$ [*Linden and Shirtcliffe*, 1978], to compute flux ratios of $R_f = 0.1 - 0.3$, immediately above the interface, and $R_f \rightarrow \infty$ near the zone of vanishing temperature gradient at about $500m$ depth. On the other hand, for $2 < R_\rho < 7$ (such as in most part of the Black Sea), it is often assumed that the flux ratio is constant, $R_f = 0.15$; at high values of density ratio, for $R_\rho > 7$, the dependence becomes $R_f = \tau R_\rho$ [*Newell*, 1984, cited in *Fernando*, 1989]. In contrast to the above, if we were to assume turbulent transport with equal eddy diffusivities for heat and salt, we should require $R_f = \{\beta(dS/dz)\}/\{\alpha(dT/dz)\} = R_\rho$, resulting in much higher values, increasing from $R_f = 2$ at the convective layer interface to $R_f \rightarrow \infty$ at about a depth of $500m$. Comparison of turbulent versus molecular diffusive fluxes therefore indicates that the double diffusive transport would be the more likely mechanism of vertical transport in deep water [*Özsoy et al.*, 1991; *Murray et al.*, 1991].

If the vertical transport in deep water was dominated by double diffusive fluxes we would expect to see staircase structures. However, our calculations show that even if layers were present, they could hardly be detected because of their size, and noise levels in the CTD measurements. For example, if the 'stairs' are formed by repeated splitting of the convective layer interface, we would expect the average thickness of staircases to be about $1m$ [*Özsoy et al.*, 1991; *Murray et al.*, 1991]. Another estimate, using the parameterization of Fedorov (1989), yields $h = 32.9\nu\kappa_h^{-1/2}(g\alpha\partial T/\partial z)^{-1/4} = 4m$ (taking an average temperature gradient of $\partial T/\partial z = 0.05°C/1000m$ in deep water).

A separate argument in favour of the role of double diffusive vertical fluxes in deep water derives directly from the typical 'S' pattern of the potential temperature versus salinity relationship. Curvilinear temperature - salinity relationships are typical of double diffusive regimes in other parts of the world (*e.g.* the salt-finger regime of [*Schmitt*, 1981]. In the case of the Black Sea, the different effective diffusivities of temperature and salinity could explain a curvilinear $\theta - S$ relationship, if two water masses separated by an initial discontunity were allowed to evolve by diffusion. In fact, if we assume that the Mediterranean Water reaching the bottom of the Black Sea several millenia before the present would initially form a discontinuous layer, the time evolution of the temperature and salinity structure would be analogous to the classical case studied in [*Mamayev*, 1975]. In his study, Mamayev (p. 189) showed that the resulting $\theta - S$ relationship would be 'S-shaped', as it happens to be the case in the Black Sea. Furthermore, for the infinite depth case studied, the shape of the $\theta - S$ curve is shown to be a function of the diffusivities and depth alone, and independent of time. This pattern of double diffusion could potentially explain the observed inflexion in the $\theta - S$ curve.

Turbulent convection seems to have an important impact on the homogenization of water properties across the basin within the bottom convective layer. The *r.m.s.* turbulent velocity, $w_\star$, within the convective layer is estimated to be $w_\star = c_2^{1/2}(H_* h)^{1/3} = 0.25\ cm\ s^{-1}$ [*Özsoy et al.*, 1993] (with c_2 defined as an empirical constant) [*Fernando*, 1989]. The characteristic time scale of overturning within the layer with thickness $h = 400m$ is then calculated to be $T_\star \equiv \pi h/w_\star \simeq 6\ days$. Since the east-west axis of the basin has a length of about $L = 1000\ km$, an assumption of exchange between eddies occurring on every cycle implies a basin-wide transport time scale, T_b, of about $T_b \equiv T_\star L/h = 40\ years$ for homogenization of properties across the basin. We should caution that this idealised estimate is based on an average velocity scale which may not be representative of the various length and time scales of turbulent convection modes in an enclosed domain [*e.g.*, *Knobloch et al.*, this volume].

The turbulent mixing within the bottom convective layer could have other important implications. In addition to its role in the observed homogeneity of water properties, we could hypothesize turbulent motions to have a similar effect on homogenization of sediment properties across the basin, although the faster rate of apparent mixing (in comparison to our estimate), yielding well correlated seasonal or annual varve structures across the basin, must be accounted for. A layer of organically rich, unbioturbated, high porosity (up to 99%) material, appropriately called the 'fluff layer', occupies the upper few centimeters of the Black Sea bottom sediments [*e.g. Moore and O'Neill*, 1991; *Lyons*, 1991] in the form of a fluid bed load. This unique layer contains freshly settled sediments preceeeding their conversion to varved bottom sediments by diagenesis, dissolution, and compaction processes. The origin of this floating material could in large be related to the bed load carrying capacity of the turbulent motions within the bottom convective layer. Despite large geographic differences in plankton blooms [*Sur et al.*, 1994], the sediment laminae (varves) resulting from the seasonal / interannual productivity cycles of the upper ocean display exceptional continuity across the basin [*Hay*, 1987, 1991; *Lyons*, 1991], suggesting that the homogenization could take place only after settling of the material near the bottom. These scientific questions with regard to the redistribution of bottom sediments are much worthy of further examination, because of the potential for sediment records in evaluating the history of hydrological, ecological and climatic changes in the region.

6. CONCLUSIONS

The peculiar temperature and salinity stratification of the Black Sea has great impact on its mixing characteristics. Double diffusion has primary importance in determining the mixing and transformation of its water masses. This setting of the Black Sea offers unique opportunities for observing double diffusive convection and for testing hypotheses in relation with such processes.

There are many areas of the world (*e.g.* the Mediterranean outflow and 'meddies' in the Atlantic Ocean, the Caribbean Sea and the Arctic Ocean staircases *etc.*) where small scale processes can determine ocean mixing in meso-scale and basin-scale dimensions. The Black Sea appears to be one of the unique areas of the world where double diffusive convection occurs on a large scale under restrictive conditions of a landlocked geometry.

The inflow of Mediterranean Water excites a large scale double diffusive convective pattern in this environment of potentially unstable double stratification. As a result, the inflow itself breaks up at intermediate depths, partially driving a basin-scale recirculation in the upper ocean, and transporting materials on the same scale.

Similarly, a relatively small geothermal heat flux at the bottom is sufficient to drive a bottom convective layer whose age is on the same order as the average age of the existing basin stratification. The convective layer homogenizes the bottom water mass, and could similarly play a major role in distributing bottom sediments across the basin. Features of this convective layer suggest a limiting case of convective layers studied in the laboratory, and could guide further studies on the possible regimes of convection.

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