Exchanges with the Mediterranean, fluxes, and boundary mixing processes in the Black sea

by

E. ÖZSOY, M. A. LATIF, S. TUĞRUL and U. ÜNLÜATA

Institute of Marine Sciences, Middle East Technical University, P.K. 28, Erdemli, Içel, 33731 Turkey.

ABSTRACT

The two-layer Bosphorus flows transport materials from the Mediterranean into the Black Sea, and export materials from the Black Sea into the Marmara Sea. Estimates of water, nutrient and carbon fluxes through the Bosphorus are essential for understanding the Black Sea budgets, but complicated because of the dynamic variability in these flows. The Bosphorus flows depend on the short term and seasonal variability of the strait dynamics, operating in the full range of possible forcing and flow configurations, i.e. blocked flows of the upper and lower layers, short term transients, and seasonal and interannual response to the net water budget of the Black Sea, which in turn is highly variable. The net fluxes of nutrients carried both ways through the Bosphorus are of the same order, and are much smaller than the nutrients introduced by the river Danube alone. On the other hand, dissolved and particulate carbon leaving the Black Sea are much larger than the lower layer inputs.

The spreading of the Mediterranean effluent into the Black Sea follows a very particular pattern of boundary mixing. The Mediterranean water first spreads onto the shelf and becomes diluted by entraining the overlying Cold Intermediate Water. Then, descending the continental slope, the anomalous water generates a pattern of intrusions and secondary circulations up to a depth of 500 m, aided by the double diffusive instability of the Black Sea interior. This, in turn, sets up a larger scale vertical circulation of the interior, contributing to the mixing across the halocline. Boundary mixing

appears to be an important element contributing to the Black Sea interior balances. Intrinsic properties of the Mediterranean and Intermediate waters are thus transported in three dimensions, and occur simultaneously with the transport of shelf-derived materials into the interior. Instability in the Black Sea currents enhances the transport of materials from the basin periphery into the interior through fluctuating components of cross-shelf exchanges.

A bottom convection layer of several hundred meters thickness is driven by geothermal heat fluxes. The slow but efficient convective motions homogenize the bottom properties across the basin. The deep vertical structure is dominated by the convective layer interface and double diffusive fluxes.

FLUXES THROUGH THE BOSPHORUS

Volume Fluxes

The Black Sea is by large a landlocked basin, whose overall mass budget and hydrochemical structure critically depend on the exchange through the Bosphorus. An accurate knowledge of the transport through the Bosphorus is therefore essential.

The Bosphorus transports can only be quantified by detailed observations, in view of the transient and dynamic nature of the flows through it. Although a number of earlier observations have been made in the past, those made by the Institute of Marine Sciences are the only set of long-term, systematic measurements to date, yielding results to define the hydrochemistry and flow regimes of the Bosphorus and Dardanelles straits, and the Marmara Sea (ÖZSOY *et al.*, 1986, 1988; LATIF *et al.*, 1990, 1991, 1992; OGUZ *et al.*, 1990; ÜNLÜATA *et al.*, 1990). The Bosphorus fluxes are estimated from these data. More recently, current-meter and acoustic Doppler current profiler (ADCP) based measurements of the fluxes have also been carried out (LATIF *et al.*, 1992).

Based on the long term averages of salinity at the strait entrances and the steady-state mass and salt balances, the average fluxes at the Black Sea end of the Bosphorus (fig. 1) have been computed to be ~ 600 km^3/yr (≈ 20 000 m^3/s, outflowing from the Black Sea) and ~ 300 km^3/yr (≈ 10000 m^3/s, inf-

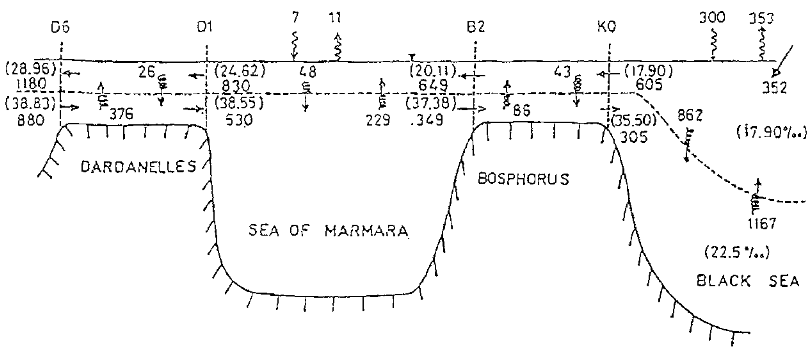

Fig. 1 – Mean annual volume fluxes in the Turkish Straits System, after ÜNLÜATA *et al.* (1990), and LATIF *et al.*, 1991. The fluxes are given in units of km^3/yr (1 km^3/yr = 31.7 m^3/s). Numbers in parentheses are average salinity values used.

lowing into the Black Sea) respectively. These estimates are considerably higher than others given in literature, mainly due to underestimation of the net freshwater input in the previous computations (ÜNLÜATA *et al.*, 1990). The steady-state salt budget of the Black Sea requires that the ratio $Q_{1b}Q_{2b} = S_{2b}S_{1b} = 35.5/17.9 \approx 2$, where Q_{1b}, S_{1b} and Q_{2b}, S_{2b} are the upper (1) and lower (2) layer volume fluxes and salinities defined at the Black Sea entrance of the Bosphorus.

The ADCP surveys are made at cross-sections along the Bosphorus (LATIF *et al.*, 1992). The average fluxes computed from repeated surveys are listed in Table I, representing nominal values subject to limitations in the measurement technique, along-strait variations, and short-term variability. The average upper layer fluxes are found to be of the same order as the average fluxes computed from mass balances. On the other hand, the lower layer fluxes are found to be much lower than the other estimates. Moreover, these measurements show that the transient Bosphorus fluxes can change significantly, even within a single day.

TABLE I

Volume Flux Computations Based on ADCP Measurements in the Bosphorus

Date	**Upper Layer Flux** $m^3 s^{-1}$	**Lower Layer Flux** $m^3 s^{-1}$
1 Apr 1991	22 200	950
21 Aug 1991	22 200	3 200
2 Oct 1991	4 000	9 500
29 Oct 1991	14 300	9 500
20 Dec 1991	19 000	4 400
21 Dec 1991	11 100	4 800
24 Dec 1991	17 400	4 800
5 Mar 1992	20 700	1 700
9 Mar 1992	50 700	0
14 Mar 1992	14 800	2 500
14 May 1992	32 000	1 000
15 May 1992	30 000	0
18 May 1992	19 000	4 000
28 Aug 1992	16 000	6 000
29 Aug 1992	7 500	7 500
31 Aug 1992	5 000	10 000
1 Sept 1992	5 000	12 000
2 Sept 1992	4 000	15 000

Tides in the region are insignificant; yet ÖZSOY *et al.* (1986, 1988), ÜNLÜATA *et al.* (1990), and LATIF *et al.*, (1991) have shown that transience on various time scales, in response to meteorological and hydrological conditions in the adjacent seas, are typical of the exchange flows. Normally, the Black Sea and Mediterranean waters are separated by a density interface which becomes shallower from north to south (fig. 2 above). Blocking of the flows in either layer occurs during extraordinary, though not entirely infrequent, events. The lower layer flow blocking (fig. 2 middle) typically lasts for a few days (LATIF *et al.*, 1989, 1991). Likewise, the upper layer flow blocking (ÖZSOY *et al.*, 1986, 1988 and LATIF *et al.*, 1991), during which an anomalous three-layered stratification develops and the salinity is increased in the southern Bosphorus (fig. 2 below), also lasts for only a few days.

The lower layer flow is typically blocked during the spring and summer months when the net freshwater influx to the Black Sea increases. The

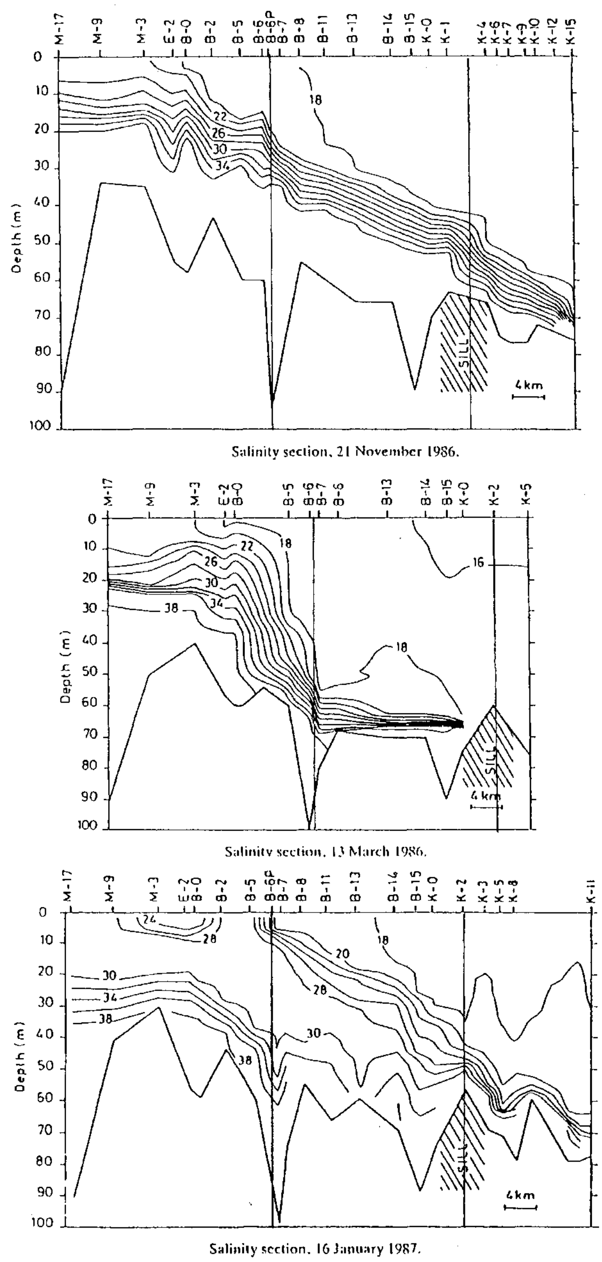

Fig. 2 – The salinity distribution in the Bosphorus: (above) during 'normal' two-layer exchange, (middle) lower layer flow blocked at the northern sill, (below) upper layer blocked, with a resulting three-layer situation. Hydraulic controls apply at the northern sill (station K-2), and at the southern Bosphorus contraction (station B-7).

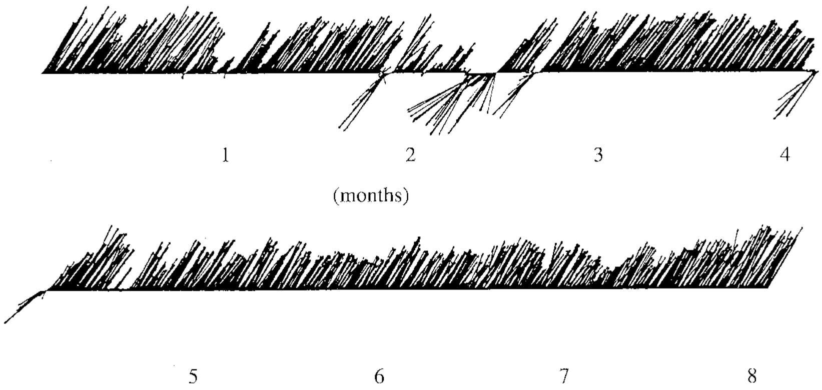

Fig. 3 – North end of Bosphorus, bottom velocity vector January – August 1992. Time series of current-meter measurements in the lower layer of the Bosphorus. Location: Anadolukavagi, depth: ~ 60 m. The reduced or reversed currents are characteristic of the lower layer blocking events. Velocity scale: 0,5 cm = 20 cm/s.

ADCP derived fluxes in Table I show the blocking of lower layer flows on March 9 and May 15, 1992. Current-meter measurements (Fig 3) also reveal several blocking events.

The upper layer blocking events (identified locally as *Orkoz),* occur in the autumn and winter months, when the surface flow reverses, and the surface salinity increases in response to the setup caused by southwesterly

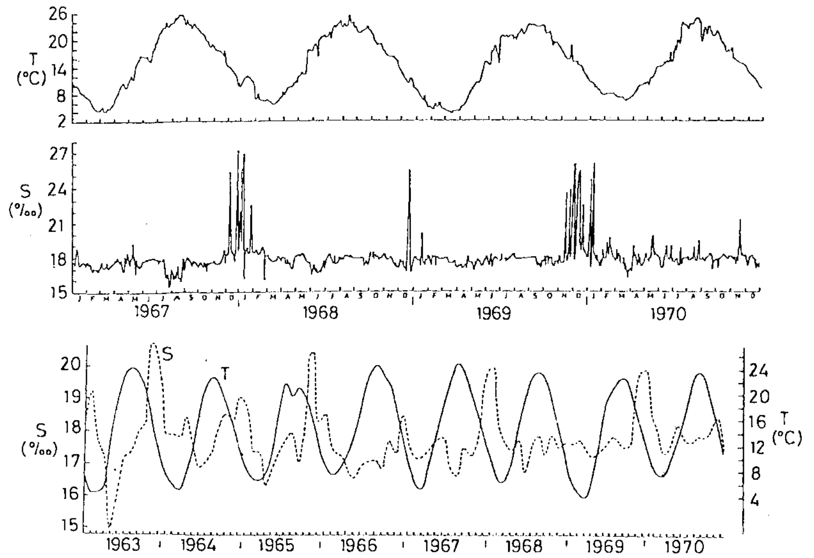

Fig. 4 – Long-term time series of daily surface salinity and temperature measurements at Baltalimani, Bosphorus: (a) daily values during 1966-1970, (b) monthly averaged values during 1962-1970. After ARTÜZ and UGUZ (1976).

winds, evident in the earlier data of DAMOC (1971), GUNNERSON and ÖZTURGUT (1976), and ARISOY and AKYARLI (1990). Long-term measurements of daily salinity and temperature in the Bosphorus (fig. 4) indicate increased surface salinity during these events (ARTÜZ and UGUZ, 1976).

Due to the combination of a contraction and a sill, and the supercritical transitions at these control sections (Fig. 5 top), the Bosphorus is the foremost example of a strait with maximal exchange (ÖZSOY *et al.*, 1986; ÜNLÜATA *et al.*, 1990). Provided that the reservoir conditions in the adjacent basins are suitable, the existence of two hydraulic controls, by efficiently isolating the mechanics of the strait from the basins, leads to maximal exchange

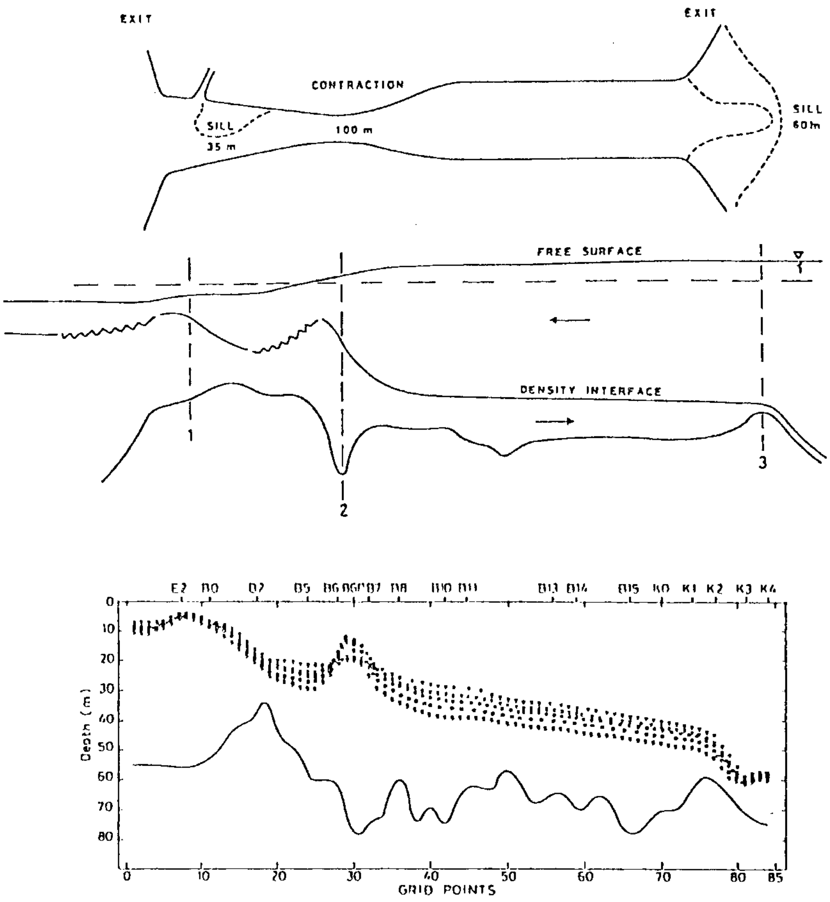

Fig. 5 – Elements of the Bosphorus two-layer flow hydraulics proposed by ÖZSOY *et al.* (1986), based on observations. Hydraulic controls exist at sections 1, 2 and 3. Subcritical to supercritical transitions occur at a contraction (section 2), and a sill (section 3). South of the contraction, the flow goes through a dissipative transition (a hydraulic jump) and re-organises to pass through a third hydraulic control (section 1) at exit to the Marmara Sea. (b) the interface depth computed from a numerical model (ÖZSOY *et al.*, 1990), indicating the same features as the observations. At sections 1, 2, and 3 the Froude number exceeds 1.

(FARMER and ARMI, 1986; ARMI and FARMER, 1987). These basic features are confirmed by numerical computations (Fig. 5 bottom, after OGUZ *et al.*, 1990). Moreover, when the sill is located nearer to the smaller density basin (relative to the contraction, as in the case of the Bosphorus), the exchanges become asymmetric with respect to barotropic flows and the relative geometrical dimensions of the control sections (FARMER and ARMI, 1986).

In summary, the Bosphorus responds rapidly to changes in the forcing conditions (net barotropic flow, wind setup, or inverse barometric effects in the adjacent basins), and operates in the full range of weak to strong barotropic forcing in either direction. The nonlinear character of the controlled flows makes its response to these forcings rather complex on time scales of several days to a few years. Curiously, a two-year subharmonic signal can be detected in Fig. 4, and is not likely to be the result of seasonal meteorological forcing.

The net freshwater inflow into the Black Sea has large seasonal and interannual variability. Although we do not have reliable information on the variability of the atmospheric components, the river runoff component (SERPOIANU, 1973; ÖZTURGUT, 1966; TOLMAZIN, 1985; BONDAR, 1989; BONDAR *et al.*, 1991) indicates such variability. The Danube river accounts for about 50% of the total freshwater inflow, and its annual mean discharge monitored for more than a century shows large natural variations (Fig. 6).

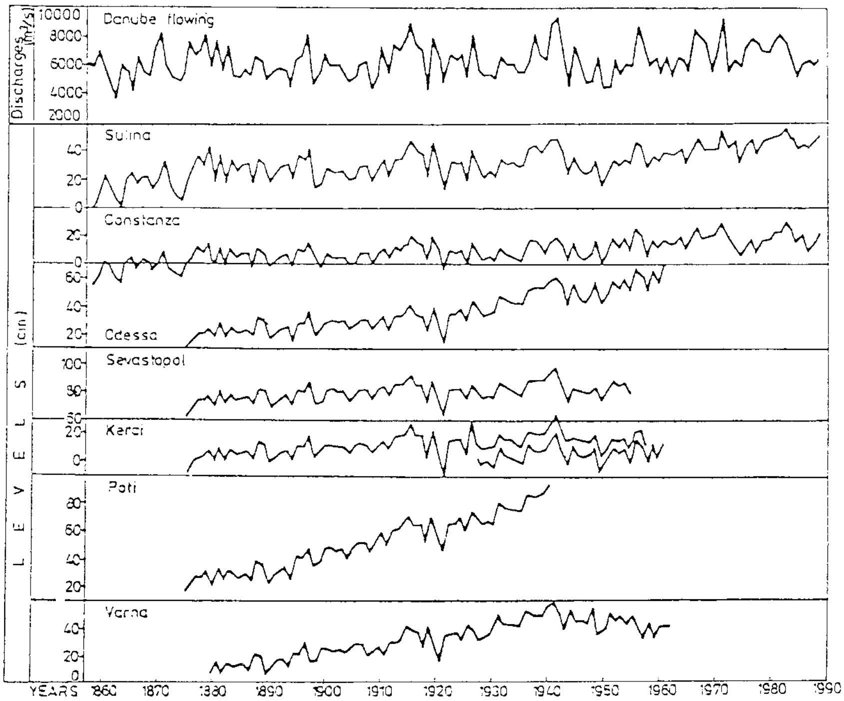

Fig. 6 – Long-term time-series of the annual mean Danube freshwater flux, and the sea-level at various stations in the Black Sea. (After BONDAR, 1989).

The seasonal changes in the Danube water flux are about ± 30% of the annual mean (SERPOIANU, 1973; BONDAR, 1989). In short, the combined seasonal and interannual variations account for a ratio of ~ 3 between the minimum and maximum of Danube flows over a period of several years. More significantly in Fig. 6, the Danube influx appears well correlated with the sea-level changes on interannual time-scales, as a result of the controls exerted by the Bosphorus.

Motivated by this functional variability of the fluxes, the exchange through the two controls has been studied by ÖZSOY (1990), through a model modified after FARMER and ARMI (1986) to include Black Sea storage, finite depth at the contraction, and time-dependent barotropic forcing. Multiple-valued (inviscid) or nonlinear (frictional) solutions with seasonal to interannual responses were found (Fig. 7). These solutions illustrate the expected differences between fluxes based on average sea-level or net flux values and those computed by averaging the time-dependent seasonal variations. This is consistent with the observed variability of the Bosphorus fluxes and flow regimes.

Nutrient and organic carbon fluxes

The surface waters of the broad northwest shelf, contaminated with land-based inorganic and organic chemicals, flow south with the main circulation of the Black Sea, and reach the southwestern shelf, partly to become exported to the Marmara Sea through the Bosphorus. Biochemical interactions modify the materials, and some biogenic organic matter is deposited on the coastal margins. As a result, the chemical pollutants reaching the southwest region is expected to be greatly reduced. The net effect of these chemical pollutants is the alteration of the Black Sea ecosystem in recent decades (MEE, 1992). Changes in the adjacent Marmara Sea ecosystem are also evident.

The recent findings of the IMS-METU (LATIF *et al.*, 1990 and 1992; BESIKTEPE, 1991; BASTÜRK *et al.*, 1990; Polat and Tugrul, under preparation) indicate significant seasonal variability in the nutrient and organic carbon contents at the northern entrance of the Bosphorus. The inorganic nutrients markedly increase in winter and then steadily decrease from early spring till autumn (Fig. 8a). The nitrate concentrations were 4.5 and 7.6 µM in February 1987 and in December 1991 respectively, compared to 0.2-2.0 µM in May. The 7.6 µM peak in December 1991 implies a significant invasion of waters from the northwest region, carrying nutrients to the Bosphorus, without being consumed by photosynthesis. The nitrate in the surface waters was observed to be consistently low during summer, from < 0.05 to 0.3 µM. Likewise, low values (e.g. 0.02 µM) of ortho-phosphate were always observed from July to September, and the highest values of 0.3-0.6 µM occurred in winter (Fig. 8a).

The annual mean concentrations of the nitrate and phosphate in the Black Sea waters entering the Bosphorus are estimated to be 1.55 ± 1.63 µM and 0.17 ± 0.17 µM , respectively for the 1986-1991 period.

The nutrients in the lower layer flow, e.g. near the southern entrance of the Bosphorus, are relatively more stable and display a seasonal variation of less than 40% (Fig. 9), with nitrate and phosphate in the ranges of 8-11 µM and 0.8-1.0 µM respectively, yielding a molar ratio of about 10. These

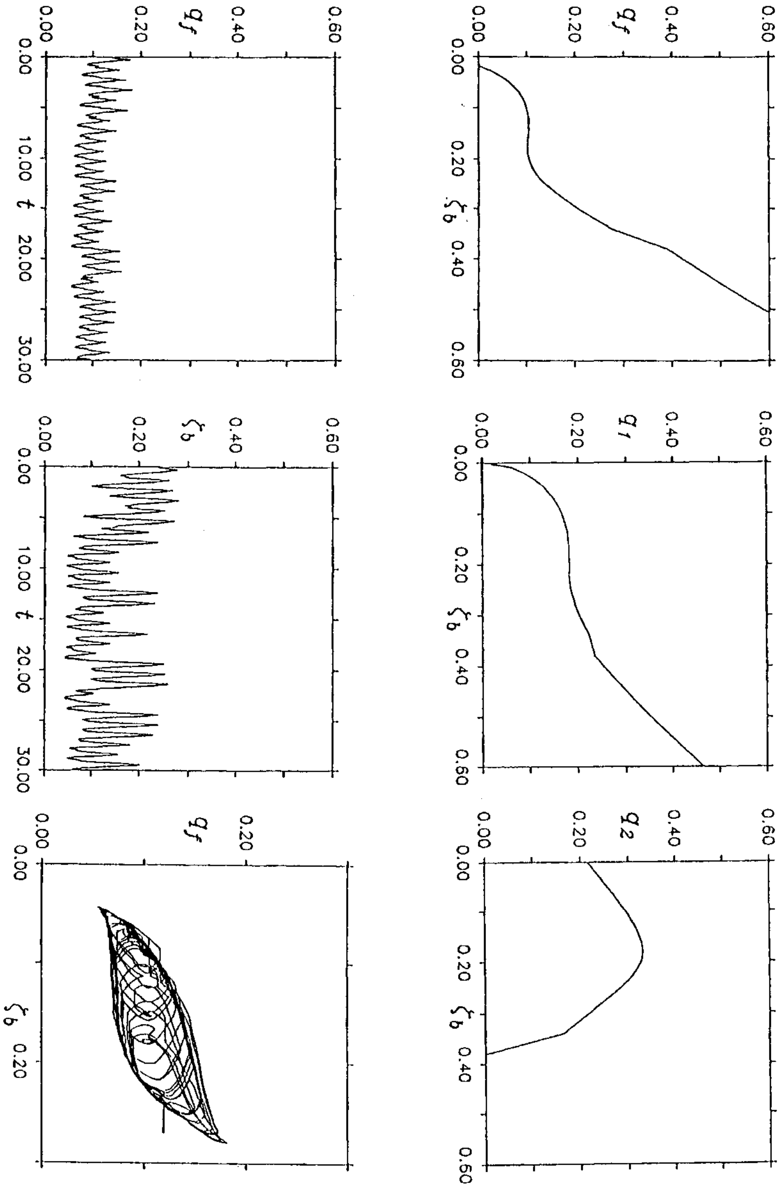

Fig. 7 – The results of a hydraulic model incorporating controls, seasonal variations, and blocking of the upper and lower layers (ÖZSOY, 1990). The top row shows the net volume flux q_f through the Strait, and the upper (q_1) and lower (q_2) layer fluxes, as a function of Black Sea sea-level (ζ_b). The bottom row shows a 30 year synthetic q_f, the response ζ_b and a phase diagram q_f versus ζ_b. q_f, q_1, and q_2 are nondimensionalized with $(b_{1c}b_{2c})^{1/2}$, Λb_{1c}, and Λb_{2c} respectively, and ζ_b with $\varepsilon y_0/2$ ($\Lambda = (\varepsilon g y_0^3)^{1/2}$, g is the gravity, $\varepsilon = \Delta\rho/\rho$, y_0 the depth at the contraction, b_{1c}, b_{2c}, b_{1s} and b_{2s} the upper and lower layer widths respectively at the contraction and the sill, and H_s is the sill height. Parameters values are $B_1 = b_{1c}/b_{1s} = 0.07$, $B_2 = b_{2c}/b_{2s} = 0.5$, $\beta = b_{2c}/b_{1c} = 0.6$, $h_s = H_s/y_0 = 0.2$, and $\varepsilon = 0.015$).

values are typical of the subhalocline waters of the eastern Marmara Sea (BASTÜRK *et al.*, 1990).

Although no ammonia data exists in the Bosphorus, previous studies in the 1980s (SAPOZHNIKOV, 1990; CODISPOTI *et al.*, 1991) indicate ammonia levels in the surface waters of the western Black Sea to be about 50% smaller than the nitrate. Winter values exceeding 1 μM were observed in the coastal waters of the northwest region. The annual mean ammonia concentration for the Bosphorus upper layer flow is assumed to be 0.5 μM. According to the limited available data (SEN GUPTA, 1971; FRIEDERICH *et al.*, 1989), ammonia levels in the subhalocline waters of the Marmara Sea are 0.2-0.4 μM which are much lower than nitrate in the same waters.

Particulate organic carbon (POC), nitrogen (PON) and total particulate phosphorus (PP) data for the upper and lower layer flows in the Bosphorus are very limited. The annual mean POC, PON and PP for the Black Sea and Marmara Sea waters flowing into the Bosphorus were estimated from the seasonal data measured by Polat and Tugrul (unpublished) in 1991. The inflowing Black Sea waters carried POC of 0.12-0.43 ppm with an annual mean of 0.25 ppm, and dissolved organic carbon (DOC) of 2.0-2.6 ppm. The seasonal variations of the PON and PP in the surface currents in the Bosphorus are very similar to that of POC (Fig. 8b); the largest values, of 4.8-5.0 μM for PON and 0.2 μM for PP were observed in January and March 1991. The lower layer waters at the southern entrance of the Bosphorus contained 0.02-0.05 ppm of POC (Polat and Tugrul, unpublished data), and the waters flowing into the Black Sea at the northern end of the Bosphorus contained 0.5-0.7 ppm of DOC throughout the year (POLAT, 1989; BASTÜRK *et al.*, 1990; TUGRUL, 1992). The annual mean concentrations of DOC estimated from the monthly data are 2.3 ppm and 0.6 ppm for the upper and lower layer currents of the Bosphorus, respectively.

Total nutrient and organic carbon fluxes through the Bosphorus, estimated from the annual mean upper and lower layer concentrations measured at the Bosphorus entrances and the net water fluxes of each layer are presented in Table II.

Only the organic and inorganic particulate forms of the nutrients have been included in the calculations (e.g. total-N = PON + nitrate + nitrite + ammonia; t-P = t-PP + PO_4), excluding the dissolved organic nutrients (DON and DOP), due to insufficient data on the latter. The uncertainties arising from the sampling frequency and the method of calculation (*i.e.* average values of the fluctuating nutrient and volume fluxes being used) also yield nutrient fluxes which should at best be considered as order of magnitude estimates.

The nutrients (N, P) are transported from the Black Sea to the Marmara Sea mainly as organic particles in the productive season. In summer, the PON content of the outflowing Black Sea surface waters is 0.8-1.2 μg – at/l while its nitrate is < 0.5 μM (Fig. 8). In winter, algal growth is much reduced, and the inorganic nutrients accumulated in the surface waters of the Black Sea may exceed those in particulate form (PON or PP). In the lower layer waters flowing into the Black Sea, inorganic nutrients constitute over 90% of the total nutrient throughout the year.

The total phosphorus exported through the Bosphorus is about 5300 t/yr, which agrees well with the estimate of FONSELIUS (1974). On the other hand, our lower layer flux of 7600 t/yr is three times larger than that suggested by

FONSELIUS (1974), who used a value of 10 µg/l for the lower layer. We find phosphate concentrations of > 25 µg/l in the same waters (Fig. 9).

TABLE II

Annual Mean Nutrient and Organic Carbon Concentrations and Fluxes through the Bosphorus

	Upper Layer Concentration	Lower Layer Concentration	Influx into the Marmara Sea	Influx into the Black Sea
	(g/m^3)	(g/m^3)	(t/yr)	(t/yr)
PO_4-P	0.005	0.028	3 000	7 500
t-PP	0.0045	0.0014	2 700	550
o-PO_4+PP			5 700	7 700
NO_3-N	0.021	0.126	12 000	33 000
NH_4-N	0.007	0.005	4 000	1 600
NO_3+NH_4			16 000	34 500
PON	0.037	0.006	21 000	3 100
PON+NO_3+NH_4			38 000	37 600
DOC	2.3	0.6	1 300 000	255 000
POC	0.25	0.065	150 000	28 000
DOC+POC			1 500 000	283 000

1 – Annual water fluxes of Q_{1b} = 6.0 x 1011 m^3/yr (upper layer) and Q_{2b} = 3.0 x 10^{11} m^3/yr (lower layer) at the Black Sea entrance of the Bosphorus have been used to estimate the chemical fluxes through the Bosphorus.

2 – The chemical flux leaving the Black Sea is calculated by multiplying the annual mean chemical concentration c_{1b} of the upper layer waters measured at the Black Sea entrance of the Bosphorus (first column) by the upper layer flux Q_{1b}. The lower layer flux entering the Black Sea is computed from the annual mean concentration C_{2m} measured in the lower layer at the Marmara entrance of the Bosphorus (second column), and by making the correction to the flux so that it becomes $c_{2m}Q_{2m} - c_{2m}Q_u + c_{1b}Q_d$, where Q_{2m} = 3.5 x 10^{11} m^3/yr is the water flux of the lower layer at the Marmara end, and Q_u = 8.6 x 10^{10} m^3/yr and Q_d = 4.3 x 10^{10} m^3/yr are the upward and downward entrainment fluxes in the Bosphorus respectively.

The phosphorus and nitrogen exported through the Bosphorus are about 10% of the nutrients introduced by the Danube alone into the Black Sea. At present, the Danube introduces 60,000 t/yr of total phosphorus and about 340,000 t/yr of total inorganic nitrogen to the Black Sea (MEE, 1992). In comparison, major Turkish rivers are estimated to contribute 1700 t/yr of o-PO_4 and 25,000 t/yr of total inorganic nitrogen.

According to Table II, the annual fluxes of total phosphorus and nitrogen exported are of the same order as the fluxes imported from the Bosphorus. On the other hand, the DOC and POC fluxes through the Bosphorus indicate a net input of organic matter from the Black Sea into the Marmara Sea. The annual transport of DOC from the productive Black Sea to the Marmara Sea is about 1.3 x10^6 t/yr, which is about 8 times larger than the annual DOC influx from the Strait. A similar ratio exists for the particulate organic carbon (POC) fluxes. Apparently, the majority of the DOC from the Black Sea reaches the Aegean Sea through the Dardanelles Strait, while the POC is oxidized biochemically in the Marmara Sea basin.

THE MEDITERRANEAN WATER INFLUX AND THE EFFECTS ON THE BLACK SEA INTERIOR

Shelf Mixing and Entrainment of the Mediterranean Effluent

The warm, saline Mediterranean water entering the Black Sea through the lower layer of the Bosphorus initially overflows a sill located at the exit,

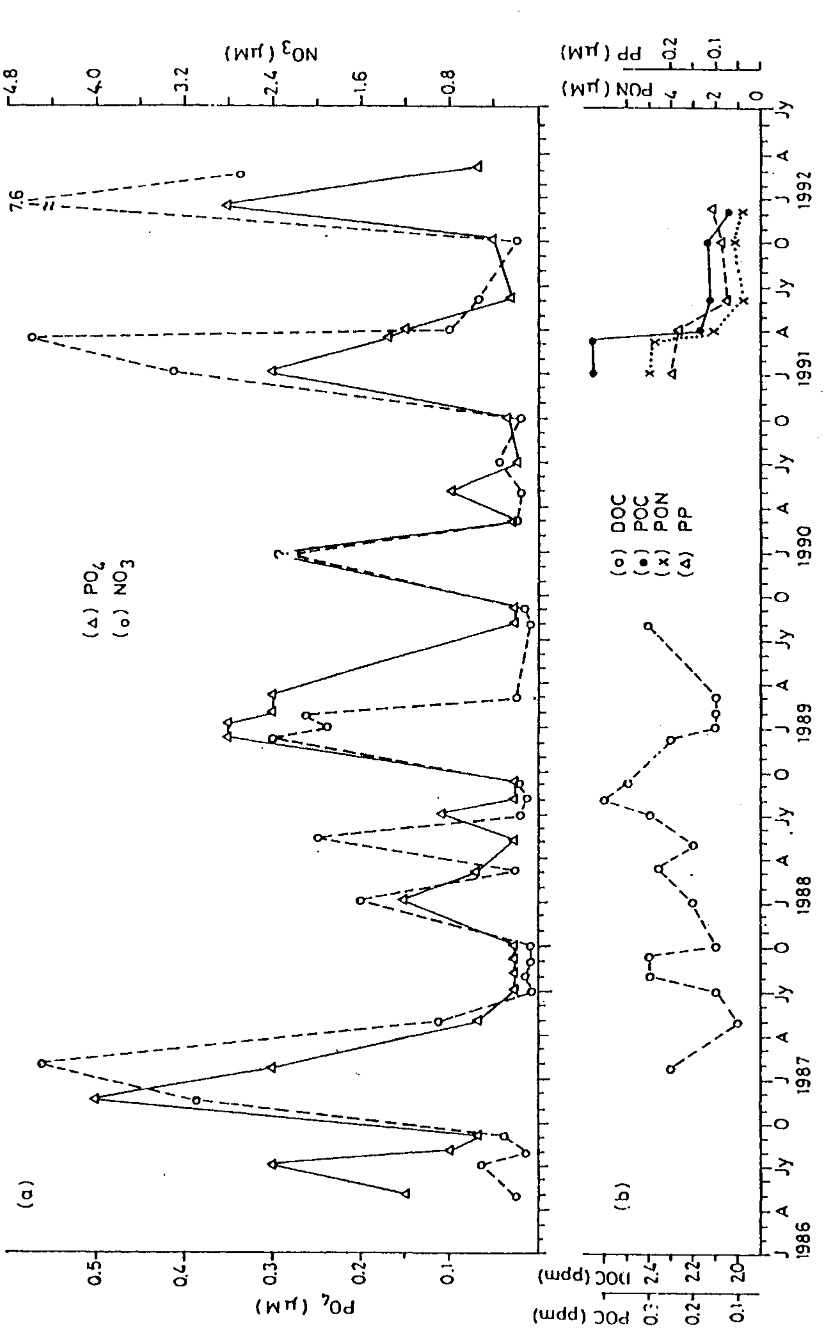

Fig. 8 – Monthly variations of concentrations in the outflowing waters of the Black Sea (0-30m averages) through the Bosphorus: (a) nutrients (o-PO_4 and NO_3+NO_2), (b) dissolved organic carbon (DOC), particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP).

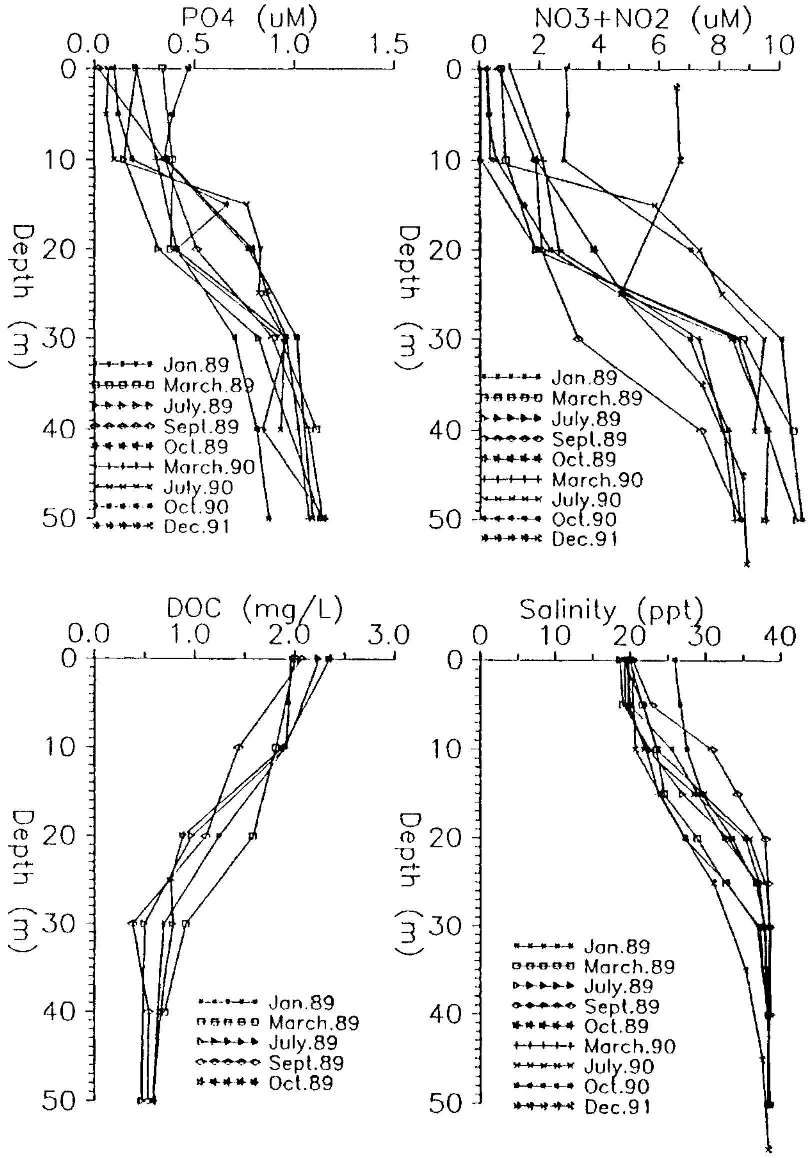

Fig. 9 – Profiles of phosphate, nitrate + nitrite, dissolved organic carbon (DOC) and salinity at the southern entrance of the Bosphorus.

then follows a bottom channel to mid-shelf, where it spreads to form a thin sheet of anomalous bottom water (LATIF *et al.*, 1991). The warm saline bottom waters are thus rapidly mixed with the overlying cold waters (LATIF *et al.*, 1991; ÖZSOY *et al.*, 1992), to become colder than the adjacent waters off the shelf edge (Fig. 10), and to be identified by cold anomalies as they sink along the continental slope.

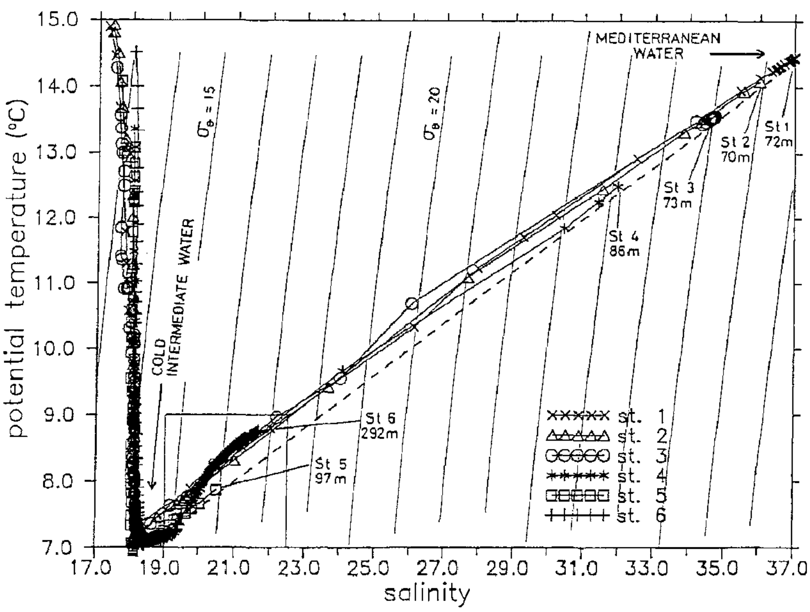

Fig. 10 – Evolution of the temperature – salinity relationship across the shelf. Stations 1-5 extend from the Bosphorus to the shelf break. Station 6 is a deeper station immediately offshore, on the continental slope. The dashed line models the changes in the 'Mediterranean effluent' at the bottom. At 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.* (1992).

Based on salinity changes across the shelf, the ratio of the entrainment flow (Q_I) to the Bosphorus outflow (Q_B) is estimated to be $Q_I/Q_B \sim 3 - 6$ (ÖZSOY *et al.*, 1992). This entrainment flux ratio differs from the ratio of 0.25 employed by BOUDREAU and LEBLOND (1989), but is consistent with other estimates, *e.g.* MURRAY *et al.* (1991), ÜNLÜATA *et al.* (1989), SWART (1991), and Koczy and Östlund (1966, quoted by BUESSELER *et al.*, 1991). Our estimate is for the shelf mixing only, and would increase further by including the contributions on the continental slope. The other estimates include the latter, because they are based on mass balances for the Black Sea interior.

Double Diffusive Intrusions

The sinking of the shelf-modified cold dense water along the shelf slope results in a series of intrusions. The intrusions are aided by the double diffusive instabilities of the interior stratification, and a unique convective process is generated adjacent to the southwest margins of the Black Sea (ÖZSOY *et al.*, 1992).

The advecting layers are in many ways similar to double diffusive intrusions often triggered by two-dimensional effects (e.g. lateral boundaries) in stratified environments, and characterized with a series of alternating diffusive/fingering interfaces (TURNER, 1973, 1978; HUPPERT and TURNER, 1980).

A potentially unstable double diffusive regime (diffusive range) exists (Fig. 11) in the entire Black Sea water column below the CIW core (depth

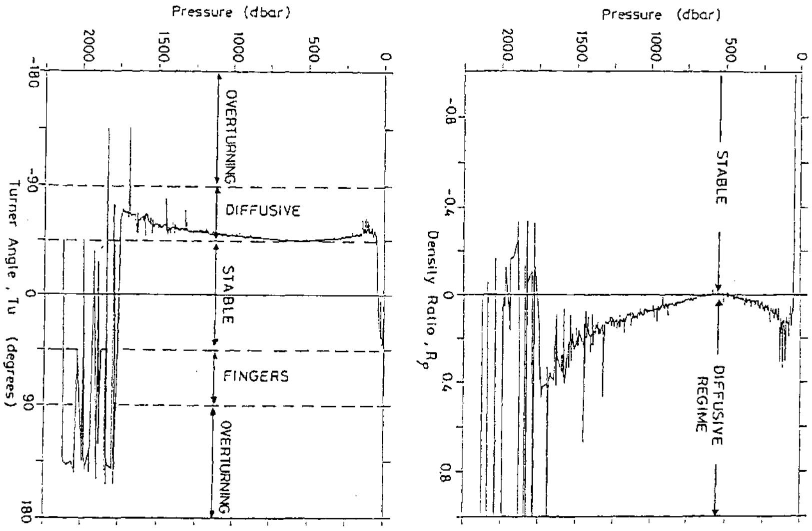

Fig. 11 – The average stratification parameters computed from an ensemble of Black Sea deep water profiles: (a) the density ratio $R\rho = (\alpha dT/dz)/(\beta dS/dz)$,
(b) the Turner angle $Tu = \tan^{-1}[(R\rho + 1)/(R\rho - 1)]$, where α and β are coefficients of expansion for temperature and salinity. The ranges for stable, statically unstable, and double diffusively unstable regimes are indicated. After ÖZSOY *et al.* (1992).

≥ 50-100m), and this ambient stratification can increase the efficiency of the intrusions (TURNER, 1978).

Short term variability and intermittency are basic features of the intrusions (ÖZSOY *et al.*, 1992). The intermittency and filamentation can result from the interaction of the sinking flow with many canyon features and local currents in the region. For example, the interaction of the currents with the abrupt topography of Sakarya Canyon has a singular effect on the cross-shelf transports in the immediate vicinity (SUR *et al.*, in press).

In the temperature versus salinity diagrams (Fig. 12), the intrusions are identified first as a cold sheet of water on the continental slope (dashed lines), then as discrete layers of anomalous characteristics.

The boundary mixing processes resulting from the Bosphorus inflow, including shelf-mixing and horizontally penetrating intrusions along the continental slope are schematized in Fig. 13.

Transport is motivated by the horizontally spreading intrusions. The most direct evidence of transport originating from the shelf is given by light transmission measurements, and has been verified by independent measurements of Chernobyl radiotracers and shelf-derived particulates (BUESSELER *et al.*, 1991; ÖZSOY *et al.*, 1992). The perfect coincidence of seawater, particulate and nutrient anomalies (CODISPOTI *et al.*, 1992; ÖZSOY *et al.*, 1992), such as shown in Fig. 14, indicate a common source of the materials. Based on data sets from different cruises, ÖZSOY *et al.* (1992) showed that the anomalies could be traced back to a main source region in the southwest margin of the Black Sea. Much diluted imprints are found further along the Anatolian coast (KEMPE *et al.*, 1991).

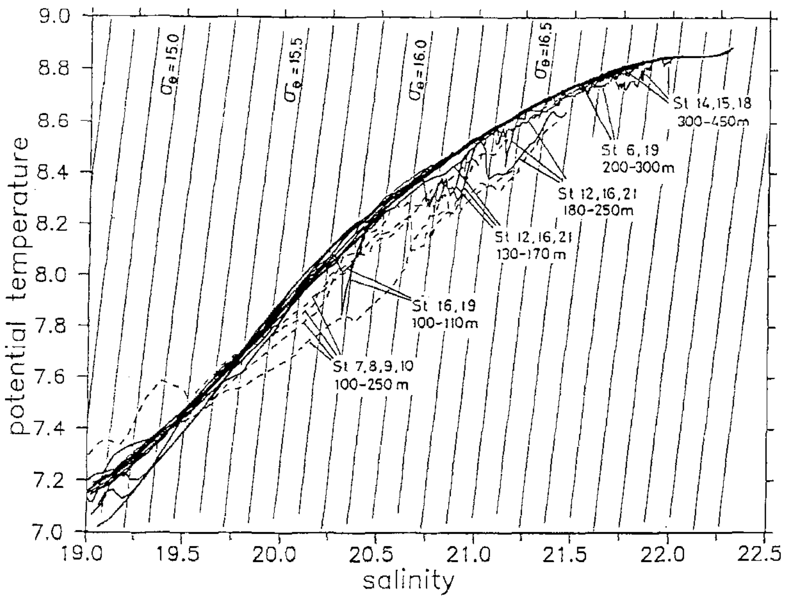

Fig. 12 – The potential temperature – salinity relationship for stations near the southwestern shelf of the Black Sea. Dashed lines represent stations closest to the continental slope, i.e. within the boundary layer. The intrusive features at other stations offshore of the shelf region occur in the form of discrete layers spreading into the interior. After ÖZSOY *et al.* (1992).

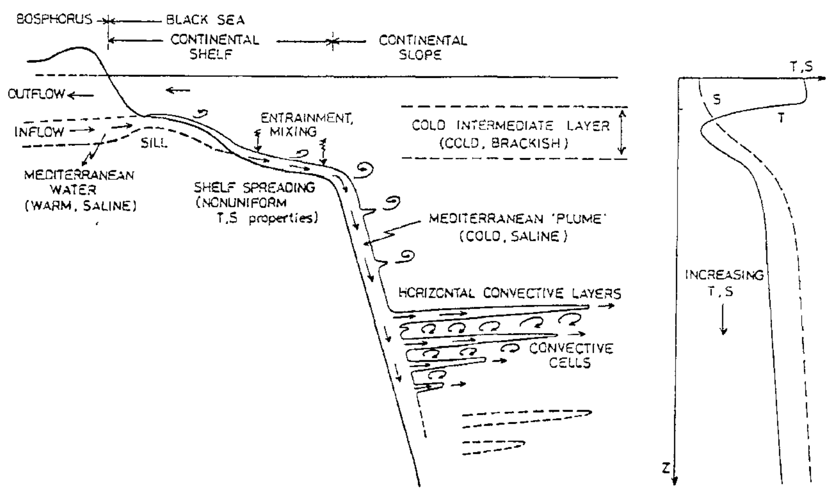

Fig. 13 – Schematization of the boundary mixing processes driven by the Mediterranean effluent issuing from the Bosphorus. Linear, direct mixing occurs on the shelf region and on part of the slope. At intermediate depths, double diffusive instabilities are generated due to the temperature and salinity contrasts of the intrusions and the potential instability of the interior. After ÖZSOY *et al.* (1992).

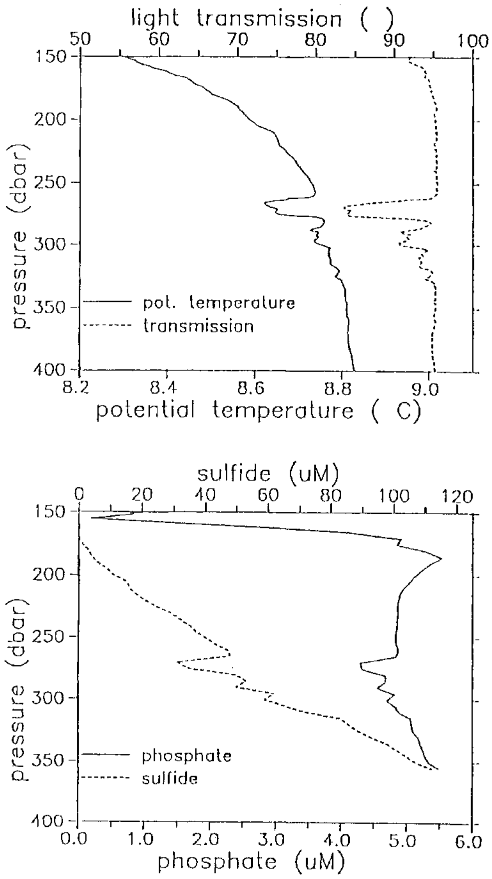

Fig. 14 – Imprints of anomalous water intrusions in the potential temperature, light transmission, sulfide and phosphate profiles. The intrusions advect the water properties modified on the shelf and the continental slope, into the interior. Because the intrusions are below the pycnocline and the oxycline, they are able to contribute to the mixing of subhalocline waters with the near surface and shelf waters. After ÖZSOY *et al.* (1992).

Mixing in the Black Sea Interior

An important outcome of the boundary mixing processes is the transport generated in the interior Black Sea. For example, the transport of particulates from the shelf to the interior has always been a puzzling aspect of the Black Sea. An inorganic particulate maximum near the anoxic interface, and vertical fluxes of shelf-derived materials have been consistently recognized in the southwestern Black Sea (e.g. BREWER and SPENCER, 1974; SPENCER *et al.*, 1972; IZDAR *et al.*, 1986; HAY, 1987; HONJO *et al.*, 1987; and KEMPE *et al.*, 1991). BUESSELER *et al.* (1991) found injections of particulate iron, manganese and some radioisotopes below the anoxic interface and a rapid deepening of fallout after the Chernobyll disaster, implying efficient ventilation across the halocline, in confirmation our results.

The maximum depth of penetration of Bosphorus intrusions is ~ 500 m, based on observations. It is possible that the vanishing gradient of potential temperature near depths of 500 m (Fig. 15) could be linked with this ultimate depth of penetration, and the double diffusive fluxes would likewise be expected to approach zero at this depth (ÖZSOY *et al.*, 1992). This limit on the depth of efficient vertical mixing is consistent with other indicators of interior mixing, e.g. ^{14}C age distribution, showing smaller mean residence times of intermediate waters (depth ≤ 500 m) compared to the more uniformly aged deep waters (ÖSTLUND, 1974, 1986). The tritium penetration reaches similar depths (TOP *et al.,* 1991). Interestingly, GRASHOFF (1975) attributed the inferred ventilation of the upper water column to mixing along the Anatolian coastal margin.

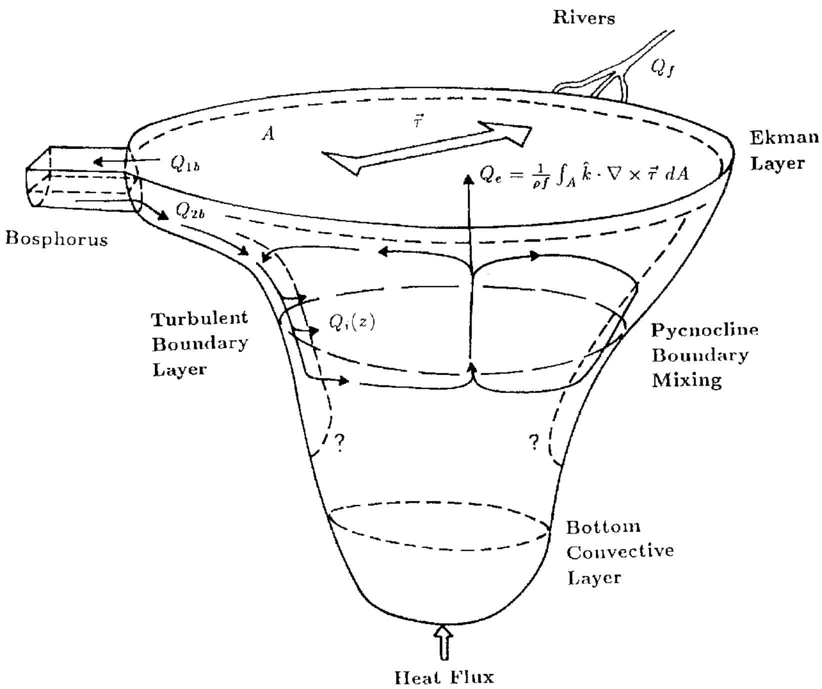

Fig. 15 – Schematization of the boundary mixing driven recirculation in the Black Sea. Other mechanisms capable of driving a recirculation between boundary layers and the interior, are also emphasized.

The structure of the Black Sea interior stratification appears strongly coupled to the boundary transports. The termination of density currents in the form of intermittent and filamented intrusions, as schematized in Fig. 13, suggests a time and depth dependent source function for new water introduced into the halocline region. The termination of boundary currents in a wide area of the continental slope is consistent with the random termination ventilation model of ROOTH (1986). A similar model proposed by STIGEBRANDT (1987) was used to explain the wide halocline of the Baltic Sea. Renewals through the unique boundary transports could have important

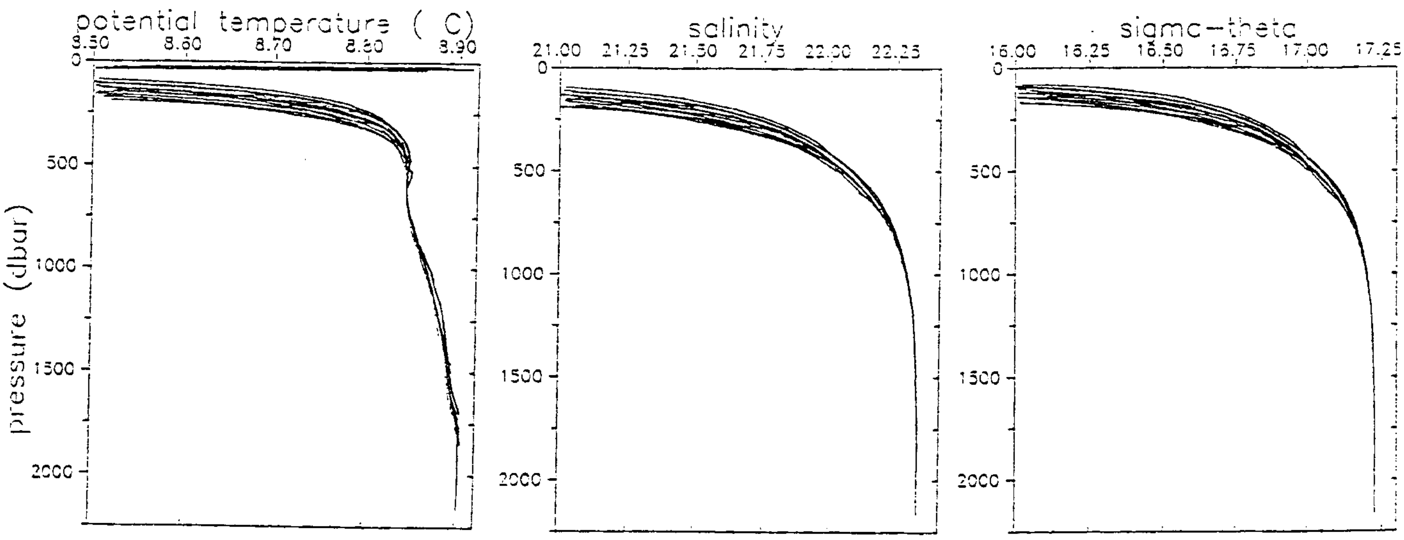

Fig. 16 – Expanded scale displays of potential temperature, salinity, and 60 density in the halocline region and the deep waters. After ÖZSOY *et al.* (1992).

implications for the structure of the Black Sea halocline with the monotonous increase of temperature, salinity and density with depth, displayed in Fig. 15.

More significantly, the sinking and the subsequent injection of water at intermediate depths implies a return flow in the interior, generating a recirculation in the upper part of the basin, schematized in Fig. 16.

The need to explain relatively large effective vertical diffusivities (much larger than the molecular diffusivity) measured in the deep ocean have prompted boundary mixing theories (GARRETT, 1979, 1990; IVEY and CORCOS, 1982; PHILLIPS *et al.*, 1986; WOODS, 1991; SALMUN *et al.*, 1991), in which turbulent boundary layers with variable properties set up circulations near the pycnocline.

Although the boundary mixing concepts could be applied to the ventilation process, there are important additional processes in the case of the Black Sea. For example, the increased interior mixing due to double-diffusive instabilities is one of its unique characteristics, and a consequence of lateral fluxes introduced into stratified environments (HUPPERT and TURNER 1980), increasing much further when the ambient waters are double-diffusively unstable (TURNER, 1978).

Wind mixing and winter convection are important processes in the upper part (depth < 200 m), where the Cold Intermediate Water (CIW) is formed. Long-term data (for more than 40 years) suggest strong climatic changes in the features of this convective region (SUR *et al.*, in press). Extreme cooling was evident in 1987, apparently when similar effects occurred in the surrounding seas, e.g. dense water intrusion into the Marmara Sea from the Aegean (BESIKTEPE, 1991), and deep water formation in the Rhodes Gyre region (GERTMAN *et al.*, 1990). It is tempting to note that an extraordinary productivity event between May 1986 and July 1988 was detected from radioactive dating of fresh bottom sediments in the "fluff layers" (MOORE and O'NEILL, 1991). CIW formation with extreme properties was repeated in 1992, when deep water formation was also recurrent in the Rhodes Gyre region (SUR *et al.*, 1992). All of these observations suggest important roles of climate, which should be investigated further.

BOTTOM FLUXES AND CONVECTION

Geothermal heat fluxes acting in the otherwise tranquil deep waters of the Black Sea drive a ~ 400 m thick bottom convective layer (Fig. 15) with homogenised properties throughout the sea. Similar convective layers are simulated in the laboratory (e.g. HUPPERT and LINDEN, 1979), but the available theory is far from explaining the time evolution of this layer. Since the observed structure can not be scaled with many of the laboratory experiments, except with those of FERNANDO (1987) in some limiting cases, the age of the convective layer is inferred to be on the same order as the deep water age (ÖZSOY *et al.*, 1991, MURRAY *et al.*, 1991). The characteristic time scale of overturning implies a homogenisation period of about a hundred years for the basin size. Scientific questions with regard to the redistribution of sediments settling on the bottom, *i.e.* its relation to the "fluff layers" and the observed continuity of sediment laminae throughout the basin are worthy of detailed examination.

The transport between the bottom convective layer and the overlying waters occurs through a diffusive interface, and double diffusion is likely to be the main transport mode in the deep waters (ÖZSOY *et al.*, 1991; MURRAY *et al.*, 1991). Anomalous temperature fine structure is observed at all depths in the water column, and appears to be amplified near the basin lateral boundaries (unpublished data).

REFERENCES

ARISOY Y. and AKYARLI A., 1990. — Long term current and sea level measurements conducted at Bosphorus. — *In:* The Physical Oceanography of Sea straits, L. J. Pratt (editor), NATO/ASI Series, Kluwer, Dordrecht: 225-236.

ARMI L. and FARMER D.M., 1987. — A generalization of the concept of maximal exchange in a strait. — *J. Geophys. Research*, **92**: 14679-14680.

ARTÜZ and UGUZ, 1976. — Daily observations on the hydrographic conditions of the Bosphorus during the period of 1967-1970. — Publications of the Hydrobiology Research Institute, Faculty of Science, University of Istanbul, **16**, 35 p. (in Turkish).

BASTÜRK Ö., TUGRUL S., YILMAZ A. and SAYDAM C., 1990. — Health of the Turkish straits: Chemical and environmental aspects of the sea of Marmara, METU-Institute of Marine Sciences, Tech. Rep. No. 90-4, Erdemli, ICEL, Turkey, 69 p.

BESIKTEPE S., 1991. — Some aspects of the circulation and dynamics of the sea of Marmara. — Ph. D. Thesis, METU, Institute of Marine Sciences, ICEL, Turkey, 226 p.

BONDAR C., 1989. — Trends in the evolution of the mean Black Sea level. — *Meteorology and Hydrology* (Romania), **19**: 23-28.

BONDAR C., STATE I., CERNEA D. and HARABAGIU E., 1991. — Water flow and sediment transport of the Danube at its outlet into the Black Sea. — *Meteorology and Hydrology* (Romania), **21**: 21-25.

BOUDREAU B. P. and LEBLOND P. H., 1989. — A simple evolutionary model for water and salt in the Black Sea. — *Paleoceanography*, **4**: 157-166.

BREWER P. G. and SPENCER D. W., 1974. — Distribution of some trace elements in Black Sea and their flux between dissolved and particulate phases. — *In:* The Black Sea – Geology, Chemistry and Biology, Degens, E. T. and D. A. Ross (editors), Am. Assoc. Pet. Geol. Memoir 20, Tulsa, Oklahoma: 137-143.

BUESSELER K. O., LIVINGSTONE H. D. and CASSO S., 1991. — Mixing between oxic and anoxic waters of the Black Sea as traced by Chernobyl cesium isotopes. — *Deep-Sea Res.*, **38**: S725 - S745.

CODISPOTI L. A., FRIEDERICH G. E., MURRAY J. W. and SAKAMOTO C., 1991. — Chemical variability in the Black Sea: Implications of data obtained with a continuous vertical profiling system that penetrated the oxic/anoxic interface. — *Deep-Sea Res.*, **38**: S691-S710.

DAMOC, 1971. — Master plan and feasibility report for water supply and sewerage for the Istanbul region. — v. III, DAMOC Consortium, Los Angeles.

FARMER, D. M. and ARMI L., 1986. — Maximal two-layer exchange over a sill and through the combination of a sill and contraction with barotropic flow. — *J. Fluid Mech.,* **164**: 53-76.

FERNANDO H. J. S., 1987. — The formation of layered structure when a stable salinity gradient is heated from below. — *J. Fluid Mech.*, **182**: 525-541.

FONSELIUS S. H., 1974. — Phosphorus in the Black Sea. — *In:* The Black Sea – Geology, Chemistry and Biology, Degens, E. T. and D. A. Ross (editors), Am. Assoc. Pet. Geol. Memoir 20, Tulsa, Oklahoma: 144-150.

FRIEDERICH G. E., CODISPOTI L. A., and SAKAMOTO C.M., 1989. — Bottle and pumpcast data from the 1988 Black Sea expedition. — Monterey Bay Aquarium Res. Inst., Tech. Rep. No. 90-3.

GARRETT C., 1979. — Mixing in the ocean interior. — *Dyn. Atmos. Oceans*, **3**: 239-265.

GARRETT C., 1990. — The role of secondary circulation in boundary mixing. — *J. Geophys. Res.*, **95:** 3181-3188.

GERTMAN I. F., OVCHINNIKOV I. M., and POPOV Y.I., 1990. — Deep convection in the Levantine sea. — *Rapp. Comm. Mer Medit.*, **32**: 172.

GRASSHOFF K., 1975. — The hydrochemistry of landlocked basins and fjords. — *In:* Chemical Oceanography, J. P. Riley and G. Skirrow (editors), Academic Press, New York, **2**, 647 p.

GUNNERSON C. G., and ÖZTURGUT E., 1974. — The Bosphorus. — *In:* The Black Sea — Geology, Chemistry and Biology. Degens, E. T. and D. A. Ross (eds), Am. Assoc. Pet. Geol. Memoir 20, Tulsa, Oklahoma: 99-113.

HAY B. J., 1987. — Particle flux in the western Black Sea in the present and over the last 5000 Years: Temporal variability, sources, transport mechanism. — Ph.D. Thesis, Joint Program M.I.T./Woods Hole Oceanographic Institution, 202 p.

HUPPERT, H. E. and LINDEN P.F., 1979. — On heating a salinity gradient from below. — *J. Fluid Mech.*, 95: 431-464.

HUPPERT, H. E. and TURNER J. S., 1980. — Ice blocks melting into a salinity gradient. — *J. Fluid Mech.*, **100**: 367-384.

IVEY G. N., and CORCOS G.M., 1982. — Boundary mixing in a stratified fluid. — *J. Fluid Mech.*, **121**: 1-26.

IZDAR E., KONUK T., ITTEKOTT V., KEMPE, S. and DEGENS E.T., 1987. — Particle flux in the Black Sea: nature of organic matter in the shelf waters of the Black Sea. — *In:* Particle flux in the ocean, E. T. Degens, E. Izdar and S. Honjo, (editors), Mitt. Geol. Paleont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderband, **62**: 1-18.

KEMPE, S., DIERCKS A. R., LIEBEZEIT G. and PRANGE A., 1991. — Geochemical and structural aspects of the pycnocline in the Black Sea (R/V Knoorr 134-8 Leg 1, 1988). — *In:* The Black Sea Oceanography, E. Izdar and J. M. Murray (editors), NATO/ASI Series, Dordrecht, Kluwer Academic Publishers: 89-110.

LATIF M. A., ÖZSOY E., ÖZSOY T., ÜNLÜATA U., BASTÜRK, O., SAYDAM C., YILMAZ A. and SALIHOGLU Iç., 1989. — Oceanographic characteristics of the region surrounding the northern entrance of the Bosphorus as related to planned sewage outfalls. — Final Report, Institute of Marine Sciences, METU, Erdemli, Içel.

LATIF M. A., ÖZSOY T., SUR H. I, BESIKTEPE S., ÖZSOY, E. and ÜNLÜATA U., 1990. — Oceanography of the Turkish straits. — Third annual report, Volume I. Physical oceanography of the Turkish straits, Institute of Marine Sciences, METU, Erdemli, ICEL.

LATIF M. A., ÖZSOY E., ÖZSOY T. and ÜNLÜATA U., 1991. — Observations of the Mediterranean inflow into the Black Sea. — *Deep Sea Research*, **38**, Suppl. 2: S711-S723.

LATIF M. A., ÖZSOY E., SALIHOGLU I., GAINES A.F., BASTÜRK Ö, YILMAZ A. and TUGRUL S., 1992. — Monitoring via direct measurements of the modes of mixing and transport of wastewater discharges into the Bosphorus underflow. — METU-Institute of Marine Sciences, Tech. Rep. No. 92-2, Erdemli, Içel, Turkey, 98 p.

MEE L. D., 1992. — The Black Sea in crisis: the need for concerted international action. (Submitted).

MOORE W. S. and O'NEILL D. J., 1991. — Radionuclide distributions in recent sea sediments. — *In*: The Black Sea Oceanography, E. Izdarand J. M. Murray (editors), NATO/ASI Series, Dordrecht, Kluwer Academic Publishers: 257-270.

MURRAY J.W., TOP Z. and ÖZSOY E., 1991. — Hydrographic properties and ventilation of the Black Sea. — *Deep Sea Research*, **38**, Suppl. 2: S663-S689.

OGUZ T., ÖZSOY E., ÖZSOY T., LATIF M. A. and ÜNLÜATA U., 1986. — Oceanography of the Turkish straits. — First annual report, Volume I, Physical Oceanography of the Turkish straits, Institute of Marine Sciences, METU, Erdemli, Içel, Turkey, 223 p.

ÖSTLUND H. G., 1974. — Expedition Odysseus 65: Radiocarbon age of Black Sea water. — *In:* The Black Sea – Geology, Chemistry and Biology. E.T. Degens and D. Ross (editors), The American Association of Petroleum Geologists, Memoir No. 20.

ÖSTLUND H. G. and DYRSSEN D., 1986. — Renewal rates of the Black Sea deep water. — *In:* The chemical and physical Oceanography of the Black Sea, Univ. of Göteborg, Rep. on the Chemistry of the Sea XXXIII. Presented in the Meeting on the Chemical and Physical Oceanography of the Black Sea, Göteborg, Sweden, June 1986.

ÖZSOY T., ÖZSOY E., LATIF M. A., and ÜNLÜATA U., 1990. — Modelling of hydraulically controlled exchange flow in the Bosphorus strait. — *J. Phys. Oceanogr.*, **20**: 945-965.

ÖZSOY E., ÖZSOY, T., LATIF M. A., ÜNLÜATA U., SUR H. I. and BESIKTEPE S., 1988. — Oceanography of the Turkish straits. — Second annual report, Volume I. Physical Oceanography of the Turkish straits, Institute of Marine Sciences, METU, Erdemli, Içel.

ÖZSOY E., 1990. — On the seasonally varying control of the Black Sea exchange through the Bosphorus. — AGU-ASLO Ocean Sciences Meeting, New Orleans, February 1990.

ÖZSOY E., TOP Z., WHITE G., MURRAY J. W., 1991. — Double diffusive intrusions, mixing and deep sea convection processes in the Black Sea. — *In*: The Black Sea Oceanography, E. Izdarand J. M. Murray (editors), NATO/ASI Series, Dordrecht, Kluwer Academic Publishers: 17-42.

ÖZSOY E., ÜNLÜATA U. and TOP Z., 1992a. — The Mediterranean water evolution, material transport by double diffusive intrusions, and interior mixing in the Black Sea. (Submitted).

ÖZTURGUT E., 1966. — Water balance of the Black Sea and flow through the Bosphorus. — CENTO Symposium on Hydrology and water resources development, Ankara, Turkey, Feb. 5-12, 1966: 107-112.

PHILLIPS O. M., SHYU J-H., and SALMUN H., 1986. — An experiment on boundary mixing: mean circulation and transport rates. — *J. Fluid Mech.*, **173**: 473-499.

POLAT S. C., 1989. — The supply, use and distribution of organic carbon in the sea of Marmara. — Ms. Thesis, Institute of Marine Sciences, METU, Içel, Turkey, 126 p.

ROOTH C. G. H., 1986. — Comments on circulation diagnostics and implications for chemical studies of the Black Sea. — *In:* The Chemical and Physical Oceanography of the Black Sea, Univ. of Göteborg, Rep. on the Chemistry of the Sea XXXIII. Also presented in the Meeting on the Chemical and Physical Oceanography of the Black Sea, Göteborg, Sweden, June 1986.

SALMUN H., KILLWORTH P. D., and BLUNDELL J.R., 1991. — A two-dimensional model of boundary mixing. — *J. Geophys. Res.*, **96**, 18447-18474.

SAPOZHNIKOV V. V., 1990. — Ammonia in the Black Sea. — *Oceanology*, **30**: 39-42.

SEN GUPTA R., 1971. — Oceanography of the Black Sea: inorganic nitrogen compounds. — *Deep-Sea Res.*, **18**: 457-475.

SERPOIANU G., 1973. — Le bilan hydrologique de la Mer Noire. — *Cercetari Marine*, IRCM, 5-6: 145-153.

SPENCER D. P., BREWER P. G. and SACHS P.L., 1972. — Aspects of the distribution and trace element composition of suspended matter in the Black Sea. — *Geochim. et Cosmochim. Acta*, **36**: 71-86.

STIGEBRANDT A., 1987. — A model for the vertical circulation of the Baltic deep water. — *J. Phys. Oceanog.*, **17**: 1772-1785.

SUR H. I., ÖZSOY E., and ÜNLÜATA U., 1992. — Simultaneous deep andiIntermediate depth convection in the northern Levantine Sea, Winter 1992. — (to appear in *Oceanol. Acta)*.

SWART P. K., 1991. — The oxygen and hydrogen isotopic composition of the Black Sea. — *Deep-Sea Res.*, **38**, Suppl. 2: S761-S772.

TOLMAZIN D., 1985. — Changing coastal oceanography of the Black Sea. — *In:* Northwestern Shelf. *Prog. Oceanog.*, **15**: 217-276.

TOP Z., ÖSTLUND H. G., POPE L. and GRALL C., 1991. — Helium and Tritium in the Black Sea: A comparison with the 1975 observations. — *Deep-Sea Res.*, **38**, Suppl. 2: S747-S760.

TUGRUL S., 1992. — Comparison of TOC concentrations by persulphate-

UV and HTCO techniques in the Marmara Sea and Black Sea. — Mar. Chem. (in press).

TURNER J. S., 1973. — *Buoyancy Effects in Fluids*. — Cambridge University Press, 367 p.

TURNER J. S., 1978. — Double-diffusive intrusions into a density gradient. — *J. Geophys. Res.*, **83**: 2887-2901.

ÜNLÜATA U., ÖZSOY T., LATIF M. A., and ÖZSOY E., 1990. — On the physical oceanography of the Turkish straits. — *In:* The physical oceanography of sea straits, L. J. Pratt (editor), NATO/ASI Series, Kluwer, Dordrecht, 25-60.

WOODS A. W., 1991. — Boundary-driven mixing. — *J. Fluid Mech.*, **226**: 625-654.