EXCHANGES WITH THE MEDITERRANEAN, LATERAL AND VERTICAL FLUXES, AND MIXING PROCESSES IN THE BLACK SEA

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Abstract

The two-layer flows through the Bosphorus determine the fluxes transported to the Black Sea by the 'Mediterranean effluent', and those exported out into the Marmara Sea. Estimates of the fluxes for a number of important properties are made, based on long-term measurements in the region.

Investigations of the spreading of the Mediterranean effluent into the Black Sea have shown a very particular pattern of boundary mixing. The Mediterranean water first spreads on the shelf and becomes diluted by entraining the overlying Cold Intermediate Water, then descends the continental slope, where it generates a pattern of intrusions and secondary circulations up to a depth of 500m, aided by the double diffusive ambient environment and the temperature-salinity anomalies of the sinking slope water. This in turn sets up a larger scale vertical circulation contributing to the interior mixing. The cross-shelf exchanges determine the domain of influence of the intrusions. The filaments of anomalous water thus spread horizontally into the interior carrying the fluxes of various properties with them.

The Black Sea Circulation is dominated by a coherent current system along its periphery, i.e. the 'rim' current, and meso-scale eddies and meandering motions superposed onto this basic pattern. The influence of buoyancy input into the northwestern shelf by major rivers, among which the Danube is the largest, contributes to the instabilities of the rim current, which transports the river inputs along the periphery of the western Black Sea. Another mechanism generating intense meandering is the interaction with the abrupt topography of the Sakarya canyon along the southwestern shelf area near the Bosphorus. Strong cross-shelf exchanges driven by these mechanisms redistribute the lateral fluxes originating from the major rivers and straits which contribute significantly to the budget of water, nutrients, organic and inorganic particulates and pollutants. A synthesis of the scales and signatures of these circulation features is made, based on oceanographic surveys and satellite data.

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1. Fluxes Through the Bosphorus

1.1 Volume Fluxes

The two-layer flow through the Bosphorus has been investigated since the 17^{th} century, when Marsigli established the basic principles involved in its dynamics (Deacon, 1971). Measurements made early in this century by Merz and Möller (Defant, 1960), and later in 1940's to 1960's (Ünlüata and Oğuz, 1992) helped define the characteristics of the two-layer exchange between the Black Sea and the Mediterranean. Systematic measurements in the 1960's have provided the necessary detail (DAMOC, 1971, Gunnerson and Özturgut, 1974) to demonstrate the variability of the exchange flows.

Recent data gathered from 1986 to the present by the Institute of Marine Sciences in a number of continuing studies (Özsoy *et al.*, 1986, 1988, Latif *et al.*, 1990,1991,1992a), and the published results based on them (Oğuz *et al.*, 1990, Ünlüata *et al.*, 1990; Latif *et al.*, 1992b) have provided the most detailed information on the hydrochemistry and flow regimes of the Turkish Straits System, including the Bosphorus and Dardanelles Straits and the Marmara Sea. More recently, a continuing program to monitor the Bosphorus with current-meter and acoustic Doppler current Profiler (ADCP) measurements has provided the necessary detail in the velocity distributions to yield better estimates of the net fluxes (Latif *et al.*, 1992a). Some current meter measurements were also made separately in the Bosphorus and at its junction with the Marmara Sea by De Filippi *et al.*, (1986) and Arısoy and Akyarlı (1990).

The average fluxes of water through the Bosphorus, shown in Figure 1, have been calculated from steady state water mass and salt conservation equations, based on budgets of the net freshwater inflow, and the long term average salinity values at the strait entrances ((Özsoy *et al.*, 1986, 1988; Ünlüata *et al.*, 1990; Latif *et al.*, 1991). Based on four years of observational data, the average fluxes at the Black Sea end of the Bosphorus were computed to be ~600 km^3/yr ($\simeq$20000 m^3/s, outflowing from the Black Sea) and ~300 km^3/yr ($\simeq$10000 m^3/s, inflowing ino the Black Sea). These estimates are found to be considerably higher than the previous ones appearing in the literature, mainly due to an underestimation of the net freshwater input in the previous computations (Ünlüata *et al.*, 1990).

An important result from the recent observations is the transience and significant variability of the exchange flows through the Bosphorus. Tides in the region are insignificant; yet Özsoy *et al.* (1986, 1988), and Latif *et al.* (1991) provide ample evidence to show that the flow regimes can differ from one day to the next in response to meteorological and hydrological conditions in the adjacent seas.

Fluxes computed by ADCP surveys (Latif *et al.*, 1992) are based on repeated cross-sectional measurements at a number of locations along the Bosphorus. Due to limitations in the measurement technique, and the short-term changes in the physical factors influencing the flows, variations were often found in the fluxes measured along the strait, and depending on the time of measurement. The average fluxes computed from repeated surveys of the Bosphorus are listed in Table 1. It can be verified that the two-way average fluxes have large variations with respect to time. The average upper layer flux is of the same order as the flux computed from steady mass balance; however the measured lower layer fluxes seem to be much lower than the estimates. The ADCP measurements (Table 1) confirm the variability of Bosphorus fluxes, indicating that the upper layer flow can change by more than a factor of two within a single day.

Normally, the Bosphorus is characterized by exchange flows of Black Sea and Mediterranean waters separated by a density interface (Figure 2). However, it has been demonstrated that either one of the exchange flows can be blocked. The lower layer flow becomes blocked (Figure 3a) when the net flux through the Bosphorus increases; a typical event lasts only for a couple of days (Latif *et al.*, 1989, 1992). During conditions of upper layer blocking (Özsoy *et al.*, 1986,1988 and Latif *et al.*, 1992b) showed an anomalous three-layered stratification with saline waters surfacing in the southern part of the Bosphorus (Figure 3b), but found the typical duration of the events to be less than a few days.

ADCP measurements of fluxes in Table 1 show blocking in the lower layer on 9 March and 15 May 1992; especially in the first case, the flux through the Bosphorus increased enormously. Current-meter measurements during 1992 (Figures 4a,b) revealed short term blocking of the lower layer flow, in agreement with the hydrographic measurements.

The upper layer blocking typically occurs in the autumn and winter months, when the setup created by south winds preceeding atmospheric depressions reverses the surface flow, leading to increased salinity in the surface waters (an event locally called *Orkoz*). These characteristics are evident in the current data of DAMOC (1971), Gunnerson and Özturgut (1976), and Arısoy and Akyarlı(1990). Long-term (8 years) salinity and temperature measurements in the Bosphorus surface waters (Figure 5) indicate significant salinity increases in winters (Artüz and Uğuz, 1976).

The Bosphorus is the foremost example of a strait with maximal exchange (Özsoy *et al.*, 1986, Ünlüata *et al.*, 1990). This basic character of the Strait derives from the fact that the combination of a constriction and a sill leads to supercritical flow on entrance to both of the adjoining basins (Figure 6), as confirmed by numerical computations (Oğuz *et al.*, 1990) (Figure 7). Provided that the interface depths in both of the basins are suitable to create dissipative transitions, the existence of two hydraulic controls isolates the mechanics governing the exchange from those occuring in the basins (Farmer and Armi, 1986; Armi and Farmer, 1987). Moreover, when the sill is located on the side of the lower density basin

(relative to the constriction), the control at the contraction modifies the sill control and leads to exchanges which are highly assymmetrical with respect to barotropic flows and more sensitive to geometrical parameters (Farmer and Armi, 1986). The above concepts have been applied to the Strait of Gibraltar (Armi and Farmer, 1986, Bryden and Kinder, 1991), which marginally satisfies maximal exchange (Garrett *et al.*, 1990).

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 typical meteorological events (several days), and seasonal and interannual variations of the fluxes. Curiously, some interannual variability is detected in Figure 5, with higher surface salinities occurring every two years. Such a subharmonic oscillation is not likely to be present in the meteorological forcing, and may suggest the effects of nonlinear functional dependence of the seasonal exchanges.

The net freshwater inflow into the Black Sea, i.e. the net flux driving the Bosphorus, appears to be variable on seasonal and interannuual scales. Although we do not have reliable information on the variability of the atmospheric components, information on the river runoff component exists scattered in the literature (Serpoianu, 1973; Özturgut, 1966; Tolmazin, 1985; Bondar, 1989; Bondar *et al.*, 1991). The Danube river accounts for about 50 % of the total river inflow. Its annual mean flux varies from 4000 m^3s^{-1} to 9000 m^3s^{-1} during long-term observations covering more than a century (Figure 8), and is well correlated with sea-level changes on the interannual time-scales. The seasonal changes in the Danube water flux are about ±30 % of the annual mean value (Serpoianu, 1973; Bondar, 1989). When the seasonal and interannual variability are combined, one can therefore expect a ratio of $\sim$ 3 between the minimum and maximum Danube fluxes. This large variability in the seasonal and longer time-scales is reflected in the sea-level data (Figure 8), emphasizing the control exerted by the Bosphorus exchanges.

Motivated by this functional variability of the fluxes, the exchange through a strait with two-controls has been studied by Ozsoy (1990), who modified the Farmer and Armi (1986) model to include finite depth at the constriction, blocking of the layers, and seasonal variations of the Black Sea sea-level and net fresh water influx. Due to the basic nonlinearity of the system and the sensitivity to geometrical parameters, multiple-valued solutions and seasonal transitions between states are found when friction effects are neglected (Figure 9). The phase diagram shows that the system oscillates about two fixed points, and moves from one to the other due to variable forcing. When friction is included, the solution becomes single valued, but the nonlinear behaviour survives. The sea-level in the Black Sea changes as a nonlinear function of the net barotropic flow, indicating that the average fluxes computed from the seasonal, time-dependent variations could be in variance from estimates based on average values of the net influx or sea-level. This is consistent with the variability of the Bosphorus flow regimes, and the measured fluxes.

1.2 Nutrient and Organic Carbon Fluxes

The major source of nutrients entering the photic zone in the Black Sea is the reserve of nutrients in the the oxic and anoxic waters below the photic zone (Deuser, 1971; Fonselius, 1974; Sorokin, 1983). However, in recent years, the nutrient inputs by rivers have caused eutrophication in the brackish waters of the broad northwestern shelf (Chirea and Gomoiu, 1986; Bologa, 1986; Mee, 1992). Thus, the Danube now introduces 60,000 tons/year of total phosphorus and about 340,000 tons/year of total inorganic nitrogen to the Black Sea (Mee, 1992). In comparison, major Turkish rivers are estimated to contribute 1700 tons/year of o-PO4 and 25,000 tons/year of total inorganic nitrogen. When the main circulations of the Black Sea is taken into account, the brackish surface waters of the broad northwest shelf, contaminated with inorganic and organic chemicals of land-based origin, flow in a north-south direction towards southwestern Black Sea and some of these waters reach the upper layer of the Marmara Sea through the Bosphorus.

Interacting biogeochemical processes modify the chemical pollutants in the northwestern shelf before they eventually get incorporated in the circulation. For example, inorganic nutrients are consumed by phytoplankton to produce dissolved and particulate organic matter during photosynthesis. This organic matter is then utilized by bacteria and other organisms. Some of the biogenic organic matter containing nitrogen and phosphorus is deposited in the coastal margin. Similarly, toxic metals are accumulated by various living organisms during the flow of the northwestern shelf waters towards the Bosphorus. Thus, the amount of chemical pollutants carried to the southwestern region by surface currents is expected to be much lower than the total load introduced by the rivers to the estuarine waters of the Black Sea. However, the net effect of these chemical pollutants is the alteration of the Black Sea ecosystem in recent decades (Tuğrul *et al.*, 1992; Mee, 1992). Changes most probably may have occurred in the Marmara Sea ecosystem as a result of the transport of the nutrients from the northwestern shelf into the Black Sea basin and then into the Marmara Sea, but these effects are not sufficiently documented at present.

Recent findings of the IMS-METU (Latif *et al.*, 1990 and 1992; Beşiktepe, 1991; Baştürk *et al.*, 1990; Polat and Tuğrul, under preparation) indicate that both the flow of the Black Sea brackish water towards the Marmara Sea through the Bosphorus Strait and its associated nutrient and organic carbon contents vary significantly with season. The inorganic nutrient concentrations of the Black Sea surface waters at the northern entrance to the Bosphorus were observed to increase markedly in winter and decrease steadily from the early spring to the autumn (Figure 10a). The nitrate concentrations, for example, were measured to be as large as 4.5 and 7.6 μM in February 1987 and in December 1991 respectively, whereas the May data has varied between 0.2 and 2.0 μM since 1986. A peak

value of 7.6 μM observed in December 1991 implies that a significant fraction of nutrients introduced by the major rivers to the the northwestern coastal margin of the Black Sea reached as far as the Bosphorus without being consumed by photosynthesis. Nevertheless, the nitrate concentration of the Black Sea surface water at the northern entrance of the Bosphorus was observed to be consistently low during the summer, ranging only from ¡0.05 to 0.3 μM during the 1986-1991 period; the August values were mostly less than 0.05 μM. A concomitant seasonal variation, as expected, appeared in the ortho-phosphate concentrations; the lowest concentrations, as low as 0.02 μM, were always observed during the July-September period whereas the highest values were recorded in the winter months, ranging from 0.3 to 0.6 μM (see Figure 10a).

Because of the large interannual variations in the the nutrient contents of the surface waters (0-30m) of the southwestern Black Sea, it is rather difficult to assess the annual means of the nutrient concentrations of the surface waters leaving the Black Sea through the Bosphorus. For this calculation, we first determined the mean concentrations for each month of the year by taking arithmetic mean of the data obtained during the last 6 years. The annual means of the nitrate and phosphate concentrations estimated from the monthly averages for the 1986-1991 period are 1.55 ± 1.63 μM and 0.17 ± 0.17, respectively.

Figure 11 demonstrates that the nutrient concentrations of the lower layer waters of the Marmara Sea near the southern entrance of the Bosphorus vary seasonally by at most 40 % . The concentrations range only between 8-11 μM for nitrate and from 0.8 to 1.0 μM for phosphate throughout the year, with a molar ratio of about 10. These values are very similar to those for the deep basin waters of the eastern Marmara Sea (Baştürk *et al.*, 1990).

Unfortunately we have no ammonia data from which to estimate the total concentrations of inorganic nitrogen in the surface waters of the Black Sea and the lower layer waters of the Marmara at the Bosphorus exits. Nevertheless, previous studies performed in the 1980s (Sapozhnikov, 1990; Codispoti et al., 1991) indicate the ammonia concentrations in the brackish surface waters of the western Black Sea to have been less than the nitrate values by, on average, 50 %. The winter values were observed to exceed 1μM in the coastal waters of the northwestern region. Thus, the annual mean of ammonia concentration for the Bosphorus upperflow is assumed to be 0.5 μM. According to the limited ammonia data (Sen Gupta, 1971; Friederich *et al.*, 1989), the ammonia content of the basin waters of the Marmara Sea ranges from 0.2 to 0.4 μM, which appears to be much lower than the nitrate concentrations of the deep basin waters.

Particulate organic carbon (POC), nitrogen (PON) and total particulate phosphorus (PP) data for the upper and lower layer currents in the Bosphorus are very limited. The annual means of 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 Tuğrul (unpublished) in 1991. As seen in Figure 10b, the POC concentrations in the inflowing Black Sea waters varied seasonally between 0.12 and 0.43 ppm with an annual mean of 0.25 ppm for 1991 whereas the lower layer waters of the Marmara at the southern entrance of the Bosphorus contained only 0.02-0.05 ppm of POC throughout the year (Polat and Tuğrul, unpublished). The seasonal variations of the PON and PP contents of the surface currents in the Bosphorus are very similar to that for POC (see Figure 10b); the largest values, 4.8-5.0 μM for PON and 0.2 μM for PP were observed in January and March 1991.

The dissolved organic carbon (DOC) concentrations of the surface waters leaving the Black Sea vary seasonally between 2.0 and 2.6 ppm (Figure 10b) whereas the lower layer waters of the Marmara Sea flowing into the Black Sea through the Bosphorus contained 0.5-0.7 ppm of DOC throughout the year (Polat, 1989; Baştürk *et al.*, 1990; Tuğrul, 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.

The total nutrient and organic carbon fluxes through the Bosphorus Strait, estimated from the annual means of the concentrations measured in the upper and lower layer waters at the Bosphorus entrances and the net water influxes to the Marmara or to the Black Sea through the Bosphorus counter currents, are presented in Table 2. Considering the seasonal and annual variations in both the flow rate and the chemical contents of the brackish surface waters leaving the Black Sea, the total annual fluxes of the nutrients, particulary the ones estimated for the upperflow, show only the order of magnitude of the total nutrient inputs to the Marmara through the Bosphorus and permit one to compare these values with the other nutrient fluxes in the Black Sea system. We should also note that the disssolved organic nutrient (DON and DOP) contents of the surface waters of the southwestern Black Sea are not taken into account in estimating the total nutrient fluxes through the Bosphorus. No data exists to assess what percentage of the total dissolved organic matter (DOM) is biochemically available for bacteria as organic sources of nitrogen and phosphorus to produce inorganic nutrients in the ambient waters. Previous findings suggest the concentrations of the total dissolved organic nitrogen, mainly of humic origin, are relatively large in the surface waters of the Black Sea (Sorokin, 1983), which is resistant to biochemical oxidation by bacteria. Nevertheless, during bloom times, DOM (thus DON and DOP) content of the productive surface waters is known to increase significantly (Sharp, 1977; Legendre and Gossalin; Kirchman *et al.*, 1991; Wenhao and Wangersky, 1992). Because of the lack of data for the biochemically labile DON and DOP in the surface waters of the Black Sea, the total nutrient loads of the outflowing Black Sea waters through the Bosphorus have been estimated from the total concentrations of the nutrients in the particulate organic and inorganic forms only (e.g. total-N= PON + nitrate + nitrite + ammonia; t-P= t-PP + PO_4).

Comparison of the monthly inorganic and organic nutrient contents of the surface waters depicted in Figure 10 suggests that nutrients (N, P) are transported from the Black Sea to the Marmara Sea mainly as organic particles in the productive seasons during which the inorganic nutrient contents of the surface waters in the Black Sea are consumed by photosynthetic reactions to yield organic matter containing nitrogen and phosphorus. For example, in summer, the PON content of the outflowing Black Sea surface waters contained 0.8-1.2 $\mu g-at$ N/L while the nitrate concentrations were less than 0.5 μM (see Figure 10). In the bad winter conditions, algal growth in the surface waters is limited significantly by insufficient solar irradiance. Thus, the inorganic nutrients fed to the the northeastern shelf waters of the Black Sea by the major rivers and resulting partly from bacterial decomposition of organic matter accumulate significantly in these brackish surface waters; the concentrations, as observed in December 1991, may exceed those in particulate form (PON or PP). In the lower layer waters leaving the Marmara Sea through the Bosphorus, the inorganic nutrients constitute the majority (over 90 %) of the total nutrient concentrations in the waters throughout the year.

The examination of the flux data presented in Table 2 reveals that the total amount of phosphorus leaving the Black Sea through the Bosphorus is about 5300 tons/year, which is in good agreement with the annual transport (5600 tons of total-P) estimated by Fonselius (1974). However, our estimate for the lower layer current is 7600 tons/year, three times larger than the load suggested by Fonselius (1974), who used a concentration value of 10 μg-P/L for the lower layer waters of the Marmara whereas the real phosphate content of these waters exceeds 25 μg-P/L (see Figure 11). The phosphorus and nitrogen influxes to the Marmara Sea through the Bosphorus are about 10 % of the nutrients introduced by the Danube to the Black Sea.

As seen in Table 2, the annual amounts of both the total phosphorus and nitrogen leaving the Black Sea through the Bosphorus are very close to the annual influx through the lower layer counter current in the strait. These findings suggest that the organic and inorganic nutrients leaving the Black Sea through the Bosphorus upperflow are almost completely returned to the intermediate waters of the Black Sea by the underflow. However, the DOC and POC fluxes through the Bosphorus show a different behaviour; there exists a net input of organic matter to the Marmara Sea. The annual amount of the DOC transported from the productive Black Sea to the surface waters of the Marmara Sea is about 1.3 x 10^6 tons-C/year, which is about 8 times larger than the annual DOC load of the saline waters of the Marmara flowing into the Black Sea intermediate layers through the Bosphorus undercurrent. A similar ratio can be obtained from the particulate organic carbon (POC) fluxes through the Bosphorus; the outflowing Black Sea surface waters introduce 1.4 x 10^5 tons of POC/yr to the Marmara Sea whereas the Bosphorus undercurrent carries only 0.17 x 10^5 tons of POC/yr to the Black Sea. Put simply, the majority of the DOC load of the outflowing Black Sea waters reaches the Aegean Sea through the Dardanelles to the southwest of the Marmara while the particulate organic matter of the Black Sea origin are oxidized biochemically in the Marmara Sea basin.

2. The Fate of the Mediterranean Influx and Effects on the Black Sea Interior

2.1 Shelf Mixing and Entrainment of the Mediterranean Effluent

The warm, saline Mediterranean water entering the Black Sea from the lower layer of the Bosphorus first overflows an exit sill, then follows a bottom channel to mid-shelf, where it spreads to form a thin sheet of anomalous bottom water crossing the shelf region (Latif *et al.*, 1991). A typical situation is shown in Figure 12, along a section following the core of the outflow. The warm saline bottom waters are rapidly mixed with overlying cold waters (Latif *et al.*, 1992; Özsoy *et al.*, 1992), to become colder though more saline than the adjacent waters off the shelf edge (Figure 13), so that the shelf-modified waters sinking along the continental slope are later identified by cold anomalies at deeper levels (section 2.2).

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.*: with 3.3 used by Murray *et al.* (1991), 2.7 estimated by Ünlüata *et al.* (1989), 4.4 used by Swart (1991), and a ratio of 4-5 suggested Koczy and Östlund (1966, quoted by Buesseler *et al.*, 1992). We should note that the first one of above estimates is based on the shelf mixing alone, but the other estimates from mass balances are usually made for the entrainment flux carried below the halocline. The net entrainment should be modified further by the continental slope mixing processes to be dwelled on in the next section. However, we do not have quantitative estimates at present.

2.2 Intermediate Depth Double Diffusive Intrusions

The sinking shelf-modified cold, dense water often leads to a series of intrusions spreading horizontally into the interior at intermediate depths. Based on the horizontal distribution and the hydrochemical structure of these layers, Özsoy *et al.*, 1992) showed that the intrusions resulted from a unique convective process driven by the Bosphorus and shelf sources of anomalous water, and supported by the double diffusive instabilities of the interior stratification.

The perfect correlations (*e.g.* Figure 14) between the anomalies of temperature and the other seawater properties (light transmission, nutrients, sulfide, radiotracers, etc.) suggest horizontal transport by intrusions. The most direct evidence of such transport is given by measurements of shelf-derived particulates (light transmission profiles), and have been verified by independently filtered samples of seawater (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) 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 source region near the southwest margin of the Black Sea and the adjoining continental slope (Figures 15 and 16). However, diluted imprints can also be found in the mid-basin area (Kempe *et al.*, 1991).

Özsoy *et al.* (1992) showed short term variability and intermittency to be basic features of the intrusions, and established similarity between the advecting layers and double diffusive intrusions, which are often triggered by two-dimensional effects (e.g. lateral boundaries) in stratifed environments, and characterized with a series of alternating diffusive/fingering interfaces (Turner, 1973, 1978, Huppert and Turner, 1980). In Figure 17, a potentially unstable double diffusive regime in the diffusive range is shown to exist in the entire Black Sea water column below the CIW core (depth $\geq$ 50-100m), with possible effects of increasing the efficiency of the intrusions (Turner, 1978).

Boundary mixing processes resulting from the Bosphorus inflow, including shelf-mixing and intrusions along the continental slope are schematized in Figure 18. An important outcome of these processes is the transport and recirculations generated in the Black Sea, reviewed in the following.

2.3 Effects on Mixing in the Black Sea Interior

Material transported from the shelf regions to the interior has always been a puzzling aspect of the Black Sea. In addition to the surface sediments originating from rivers and coasts and reaching the interior parts, Brewer and Spencer (1974) and Spencer *et al.* (1972) indicated a secondary particulate maximum composed mainly of inorganic materials and particulate trace metals near the anoxic interface, with increased concentrations near the southwest continental shelf. Based on sediment-traps deployed in the southwestern Black Sea, İzdar *et al.* (1986), Hay (1987), and Honjo *et al.* (1987) have shown a vertical flux of particulates resuspended from the shelf and slope regions and transported offshore. Similarly, Kempe *et al.* (1991) indicates transport of fine particulates (including particulate Manganese) from the shelf into the central region.

Buesseler *et al.* (1991) found lateral injection of materials below the anoxic interface, marked by coinciding peaks of particulate materials including particulate Iron, Manganese and radiosotopes (Figure 19). He also demonstrated rapid depletion and deepening of the Chernobyl outfall in the Black Sea, implying rapid ventilation due and vertical exchange across the halocline as a result of recirculations driven by the lateral injections.

The maximum depth of penetration of Bosphorus intrusions driving this important component interior mixing is estimated as ~500m (Özsoy *et al.*, 1992). This is consistent with the ^{14}C age distribution (Figure 20) given by Östlund (1974, 1986), who found that the mean residence times of intermediate waters (depth $\leq$ 500m) were consistently smaller than the uniform values of deep water age. The penetration of Tritium (Figure 21) was also found to reach similar depths by Top *et al.* (1992). Interestingly, Grashoff (1975) attributed the inferred ventilation of the upper water column to mixing along the Anatolian coastal margin. It is also interesting to find a layer with vanishing potential temperature gradients at depths of about 500m (Figure 22), which agrees with the limit of vanishing vertical double diffusive fluxes (Özsoy *et al.*, 1992).

The structure of the Black Sea interior stratification appears strongly linked to boundary transport mechanisms. Density currents along the continental slope disintegrate into double diffusive intrusions spreading horizontally into the interior, and thereby generate a recirculation in the upper part of the ocean. Buesseler *et al.* (1991) and Özsoy *et al.* (1992) suggest that the Bosphorus outflow could be a major factor driving such a boundary transport. The vertical recirculation driven by the boundary transports of the southwestern shelf/slope region are schematized in Figure 23.

The need to explain relatively large effective vertical diffusivities (much larger than the molecular diffusivity) measured in the deep ocean have prompted the development of boundary mixing theories (Garrett, 1979,1990; Ivey and Corcos, 1982; Phillips *et al.*, 1986; Woods, 1991; Salmun *et al.*, 1991), which attempt to explain the interior mixing by boundary transports. Accordingly, turbulent side boundary layers with variable properties generate secondary and tertiary circulations which are most effective in the case of variable stratification (near the pycnocline).

The boundary mixing concepts may be analogous to the proposed intrusion-driven vertical ventilation processes in the Black Sea. There are additional factors involved in the case of the Black Sea. Double-diffusive instability leading to increased interior mixing is one of the important consequences of lateral fluxes introduced to stratified environments (Huppert and Turner, 1980), and seems to increase significantly when the ambient waters are double-diffusively stratified (Turner, 1978).

The net entrainment of the surrounding fluid into the continental slope boundary layer flow joining the intrusions is difficult to estimate, but should considerably increase the entrainment ratio found for the shelf mixing.

The time-dependent random termination of boundary currents is consistent with the ventilation model of Rooth (1986), and consistent with a similar model proposed by Stigebrandt (1987) for the Baltic. The continuous increase of salinity with depth in the Black Sea halocline as shown in Figure 22 (also cf. Murray *et al.*, 1991) could be explained by similar factors.

In their numerical model studies, Friedrich and Stanev (1988) and Stanev (1990) found the boundary transport driven by the Boshorus inflow to be important, and attempted parameterization of vertical mixing, which they found to be remarkably different from other seas of the world ocean.

In addition to the above processes, wind mixing and winter convection are important processes determining the upper ocean mixing. However, they do not seem to penetrate deeper than the base of the Cold Intermediate Water (CIW), *i.e.* a maximum of $\sim$ 200m. Averages formed from cruises covering the Black Sea over a period of more than 40 years, shown in Figure 24, indicate that the CIW joins the surface during the cold season, confirming its convective origin. There are, however, strong climatic changes in its features, with the thickness of the layer increasing and its base deepening during extreme winters. Such deepening is evident in 1987 from two independent sets of measurements, apparently a year when similar effects were evident in the surrounding seas as well, *e.g.* dense water intrusion into the Marmara Sea from the Aegean (Beşiktepe, 1991), deep water formation in the Rhodes Gyre area in the Eastern Mediterranean (Gertman *et al.*, 1990), and possibly linked basin-wide circulation changes (Özsoy *et al.*, 1992). It is tempting to note that an extraordinary productivity event occurring between May 1986 and July 1988 was detected from radioactive dating of fresh bottom sediments in the 'fluff layers' (Moore and O'Neill 1991). The increase in production could be related to the mixing event in 1987. A separate deep mixing event during the winter of 1992 is also detected in Figure 24. In this case, as well as in the 1987 case, deep water formation ocurred in the Rhodes Gyre region of the Eastern Mediterranean (Sur *et al.*, 1992), possibly due to analogous climatic interactions.

3. Bottom Fluxes and Bottom Convection

Geothermal heat fluxes acting on an otherwise tranquil deep water mass drive a bottom convective layer (Özsoy *et al.*, 1991, Murray *et al.*, 1991). Laboratory experiments and available theory are far from explaining its evolution, but the time of origin of the convective layer is inferred to be of the same age as the formation of bottom waters. The absolute homogeneity of the properties of this layer everywhere in the Black Sea suggests efficient mixing by turbulent eddies. The characteristic time scale of overturning implies a homogenisation period of at least several hundreds of years, required for the entire basin. This may explain the observed continuity of bottom sediment layers within the basin.

The transports between the bottom and the upper layer waters appear to be determined by a diffusive interface at the top of the convective layer, and double diffusion in the water column. A peculiar thermostad separates the pycnocline region from the deep waters. Anomalous temperature fine structure can be observed at all depths in the water column, and appears to be larger near the basin lateral boundaries.

4. The Role of Sakarya Canyon Topography and Coherent Circulation Features in the Dispersal of Intrusions

Continental shelf dynamics and coherent structures of the Black Sea circulation locally modify the transport by the intrusions. The interaction of cyclonic boundary currents with the abrupt topography of Sakarya Canyon, and instabilities of the boundary currents motivate cross-shelf transport of the shelf sediments and water anomalies via intrusions and filaments.

The wide continental shelf in the northwestern region of the Black sea extends to the south-west, where it becomes narrower and approaches an abrupt termination at the Sakarya Canyon (Figure ***). This abrupt topography has a singular effect on the boundary currents of the Black Sea (Oğuz *et al.*, 1991) Satellite data indicates instabilities of the current system developing exactly at the abrupt topography of the Sakarya Canyon (Figures ***).

Table 1
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	22200	950
21 Aug 1991	22200	3200
2 Oct 1991	4000	9500
29 Oct 1991	14300	9500
20 Dec 1991	19000	4400
21 Dec 1991	11100	4800
24 Dec 1991	17400	4800
5 Mar 1992	20700	1700
9 Mar 1992	50700	0
14 Mar 1992	14800	2500
14 May 1992	32000	1000
15 May 1992	30000	0
18 May 1992	19000	4000

Table 2
Annual Mean Nutrient and Organic Carbon Concentrations and Fluxes Through the Bosphorus

	Upper Layer Concentration (g/m^3)	Lower Layer Concentration (g/m^3)	Influx into the Marmara Sea (tons/year)	Influx into the Black Sea (tons/year)
PO_4-P	0.005	0.028	3.0 x 10^3	7.50 x 10^3
t-PP	0.0045	0.0014	2.7 x 10^3	0.55 x 10^3
o-PO_4+PP			5.7 x 10^4	7.70 x 10^4
NO_3-N	0.021	0.126	1.2 x 10^4	3.30 x 10^4
NH_4-N	0.007	0.005	0.4 x 10^4	0.16 x 10^4
NO_3+NH_4			1.6 x 10^4	3.45 x 10^4
PON	0.037	0.006	2.1 x 10^4	0.31 x 10^4
PON+NO_3+NH_4			3.8 x 10^4	3.76 x 10^4
DOC	2.3	0.6	1.3 x 10^6	2.55 x 10^5
POC	0.25	0.065	1.5 x 10^5	0.28 x 10^5
DOC+POC			1.5 x 10^6	2.83 x 10^5

Notes:

1) Annual water fluxes of $q_{UN} = 6.0 \times 10^{11} m^3/yr$ (upper layer) and $q_{LN} = 3.0 \times 10^{11} m^3/yr$ (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_{UN} of the upper layer waters measured at the northern end of the Bosphorus (first column) by the upper layer flux q_{UN}. The lower layer flux entering the Black Sea is computed from the annual mean concentration c_{LS} measured in the lower layer at the southern entrance of the Bosphorus (second column), and by making the correction to the flux so that it becomes $c_{LS}q_{LS} - c_{LS}q_U + c_{UN}q_D$, where $q_{LS} = 3.5 \times 10^{11} m^3/yr$ is the water flux of the lower layer at the Marmara end, and $q_U = 8.6 \times 10^{10} m^3/yr$ and $q_D = 4.3 \times 10^{10} m^3/yr$ are the upward and downward entrainment fluxes in the Bosphorus respectively.

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Figure Captions

Figure 1. Volume fluxes in the Turkish Syraits System, computed from Mass and Salinity conservation, after Ünlüata *et al.* (1990), and Latif *et al.* (1991).

Figure 2. The salinity distribution in the Bosphorus during 'normal' two-layer exchange. Hydraulic controls apply at the northern sill (station K-2), and at the southern Bosphorus constriction (station B-7).

Figure 3. The salinity distribution in the Bosphorus during blocked flow conditions, (a) lower layer flow blocked at the northern sill, (b) upper layer blocked, with a resulting three-layer situation.

Figure 4. Time series of (a) current vectors, (b) salinity obtained from current-meter measurements in the lower layer of the Bosphorus. Location: Anadolukavağı , depth: ~60 m. The lowered or reversed currents and lowered salinities (lower than sensor range) are characteristic of lower layer blocking events.

Figure 5. Long-term time series of daily surface salinity and temperature measurements at Baltalimanı , Bosphorus: (a) daily values during 1966-1970, (b) monthly averaged values during 1962-1970. After Artüz and Uğuz (1976).

Figure 6. Schematization of the Bosphorus two-layer flow hydraulics: Hydraulic controls exist at sections 1, 2 and 3. A constriction (section 2), and a sill (section 3) located between the constriction and the lower density Basin (the Black Sea) satisfy the maximal exchange conditions by creating supercritical flows on the outer domains (Farmer and Armi, 1986). South of the constriction, 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.

Figure 7. Computed lengthwise variations of (a) the two-layer composite Froude number, and (b) the interface depth, obtained from numerical solutions, with the net Black Sea outflow specified in the range of 4380-21765 m^3s^{-1}. After Oğuz *et al.*, 1990).

Figure 8. 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).

Figure 9. The results of a Bosphorus internal hydraulics model incorporating Bosphorus hydraulic control geometry, a free surface, barotropic flow, seasonal variations, and blocking of the upper and lower layers (Özsoy, 1990). The results are for the frictionless case. The top row shows the net fresh water influx q_f into the Black Sea (the barotropic flow through the Strait), and the upper (q_1) and lower (q_2) fluxes as a function of the Black Sea sea-level (ζ_b). The bottom row shows simulations with a 30 year synthetic q_f (modeled after time variations of the Danube flux), the sea-level ζ_b response showing transitions between multiple states, and the corresponding phase diagram of forcing q_f versus response ζ_b. All plots are nondimensional: fluxes in the top row are nondimensionalized with $\Lambda(b_{1c}b_{2c})^{1/2}$, Λb_{1c}, and Λb_{2c} respectively, and sea-level is nondimensionalized with $\varepsilon y_0/2$, where $\Lambda = (\varepsilon g y_0^3)^{1/2}$, g is the gravity, $\varepsilon = \Delta\rho/\rho$ the normalized density difference, y_0 the depth at the constriction, and b_{1c} and b_{2c} are the channel widths of the upper and lower layers at the constriction. The geometrical and density parameters used were $B_1 = b_{1c}/b_{1s}$=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 ε=0.015, where b_{1s} and b_{2s} are the upper and lower layer widths at the sill, and H_s is the sill height measured relative to the bottom at the constriction.

Figure 10. Monthly variations of chemical 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).

Figure 11. Depth distributions at different times of measurement, of phosphate, nitrate+nitrite, dissolved organic carbon (DOC) and salinity at the southern entrance of the Bosphorus.

Figure 12. Salinity and temperature distribution along a section following the Mediterranean effluent across the southwest Black Sea Shelf. After Özsoy *et al.* (1992).

Figure 13. Evolution of the temperature - salinity relationship across the shelf, corresponding to Figure 12. Stations 1-5 are on the continental shelf and follow a sequence from the Bosphorus to the shelf break. Station 6 is a deeper station immediately offshore, on the continental slope. The characteristics of the Mediterranean effluent are shown by the linear change in the bottom water characteristics (dashed line). 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).

Figure 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).

Figure 15. Light transmission profiles show anomalous intermediate depth layers with the most pronounced peaks near the southwest continental shelf (dashed lines). Residual features are seen elsewhere. The near surface particulate maxima (light transmission minima) are due to production of planktonic organisms.

Figure 16. 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).

Figure 17. The average stratification parameters computed from an ensemble of Black Sea deep water profiles: (a) the density ratio $R_\rho = (\alpha dT/dz)/(\beta dS/dz)$, and (b) the Turner angle $Tu = (R_\rho + 1)/(R_\rho - 1)$, 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).

Figure 18. 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 initiated due to the temperature and salinity contrasts of the intrusions and the potential instability of the interior. After Özsoy *et al.* (1992).

Figure 19. Correlation of the particulate iron and manganese and Chernobyl derived Thorium isotopes with the light transmission anomalies. The intrusions transport shelf particulates and surface fluxes of isotopes into the interior. The existence of particulate Mn and Fe below the oxic-anoxic interface and radioisotopes suggest efficient ventilation across the halocline After Buesseler *et al.* (1991).

Figure 20. 14^C data in the Black Sea and estimated renewal time distributions. After Östlund and Dryssen (1986).

Figure 21. Recent Tritium measurements in the Black Sea. After Top *et al.*, (1991a,b).

Figure 22. Expanded scale displays of potential temperature, salinity, and σ_θ density in the halocline region and the deep waters. After Özsoy *et al.*, (1992).

Figure 23. Schematization of Boundary Driven Recirculation in the Black Sea.

Figure 24. Mean temperature profiles of the Black Sea from various cruises covering a span of ~ 40 years. Each profile is an average of the station data during a particular survey.

Figure 25.

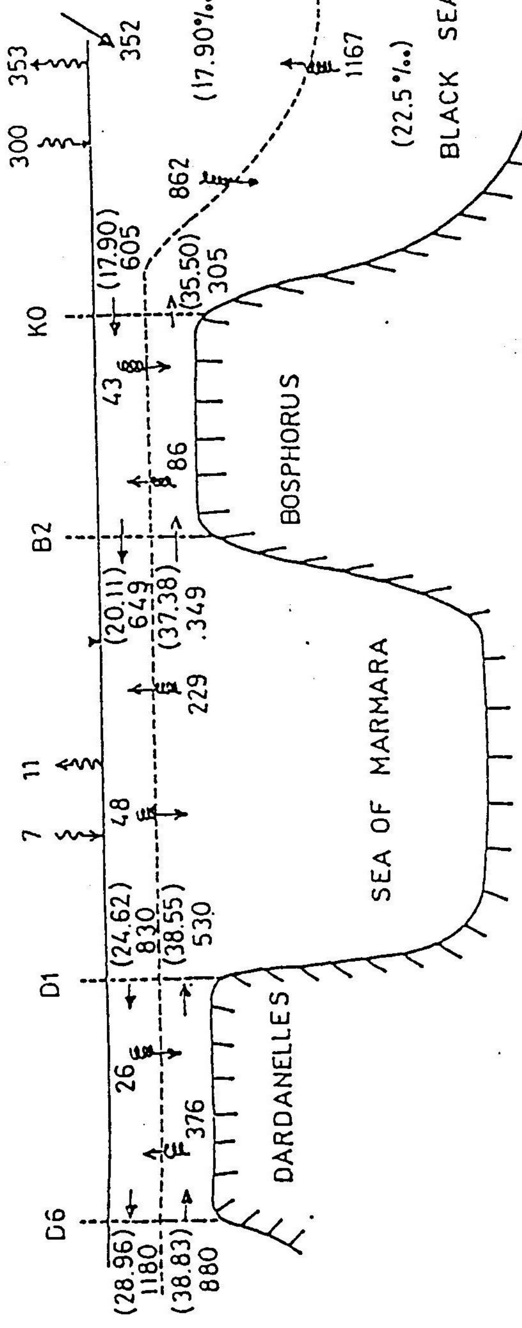


Figure 1.43. Volume fluxes for 1989, using salinity at station B-2 at the Bosphorus-Marmara Junction. Numbers in parenthesis indicate salinities in ppt and the accompanying numbers give flows in km^3/yr.

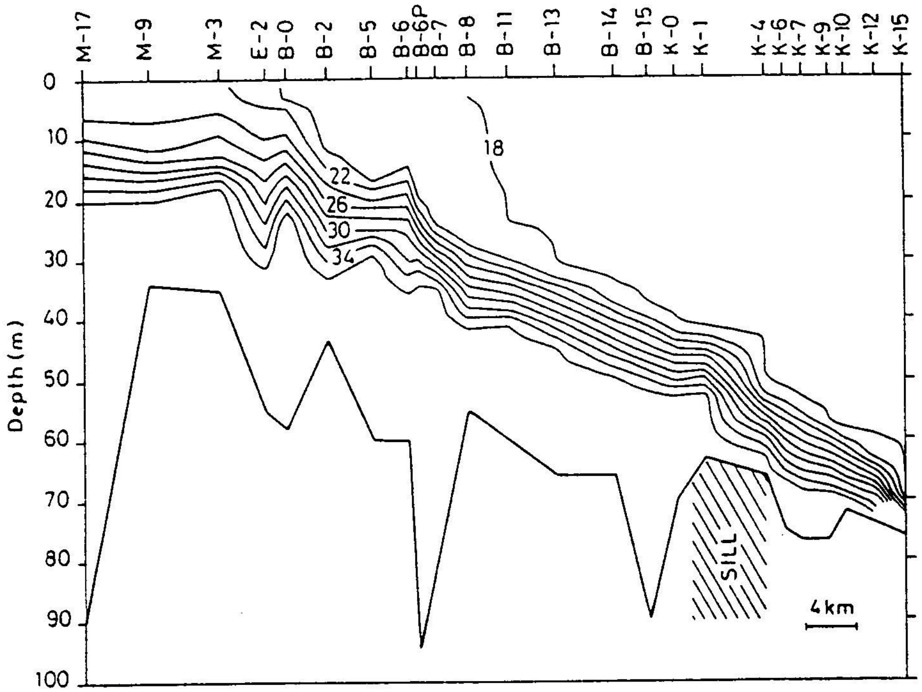


Fig. 6. Salinity section, 21 November 1986.

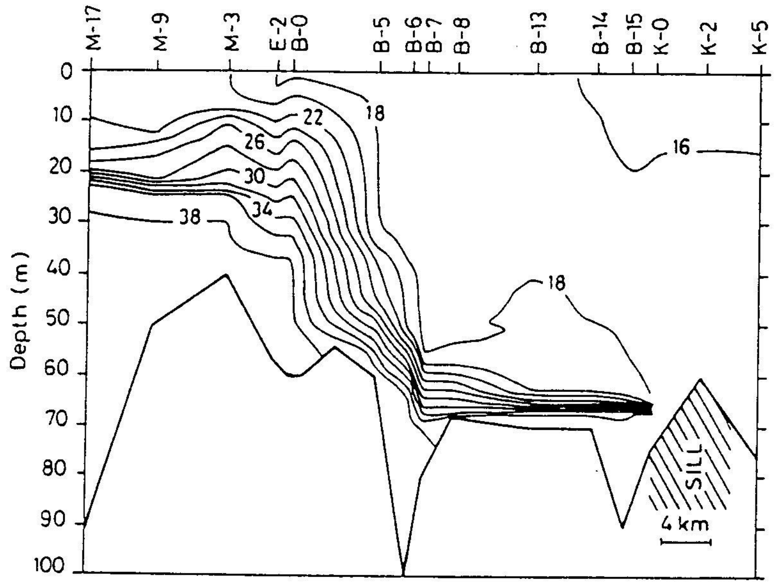


Fig. 9. Salinity section, 13 March 1986.

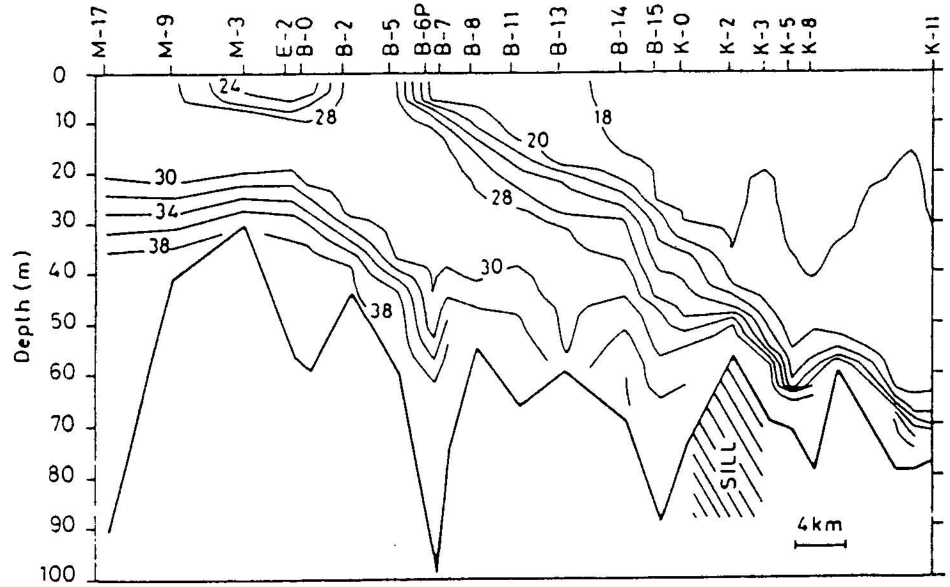
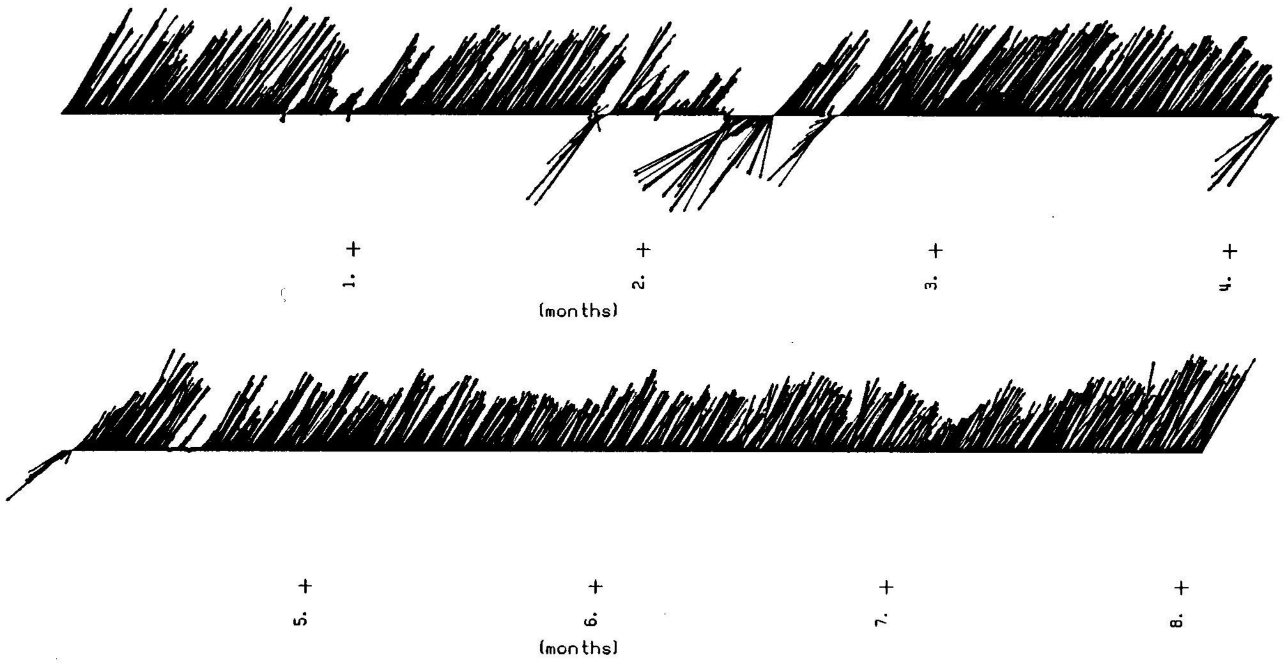


Fig. 7. Salinity section, 16 January 1987.

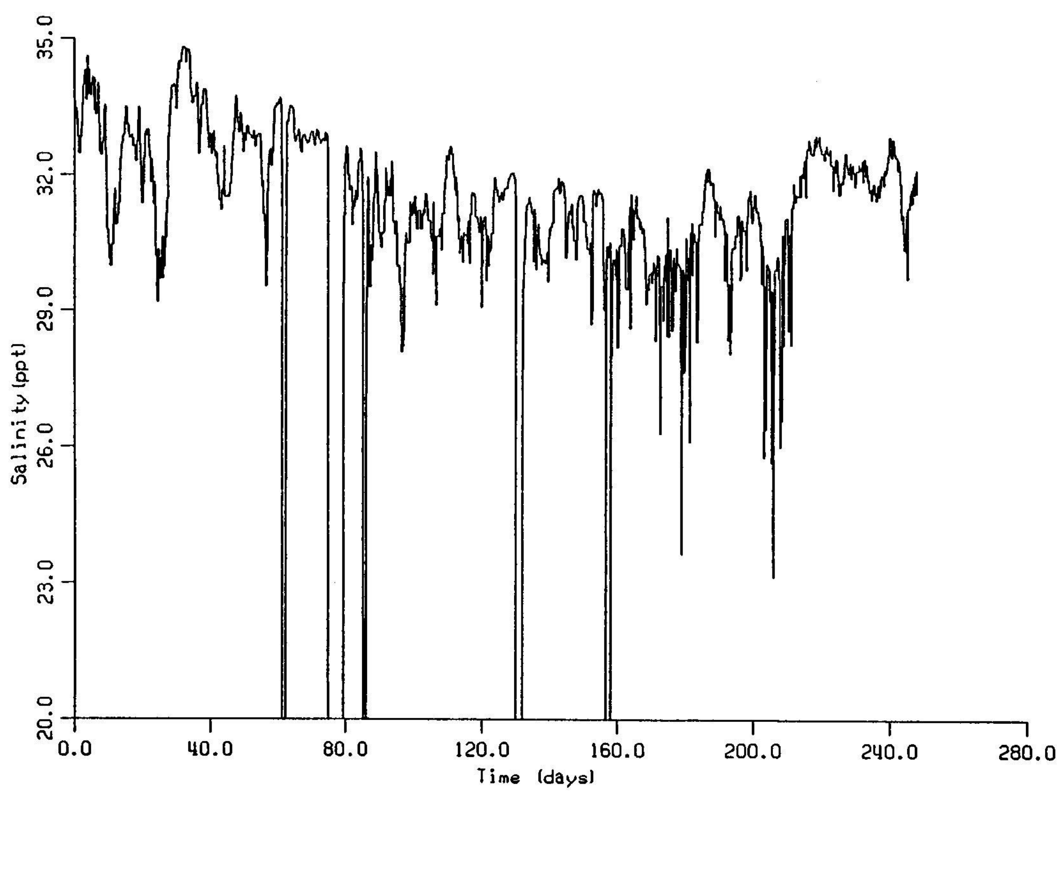
2

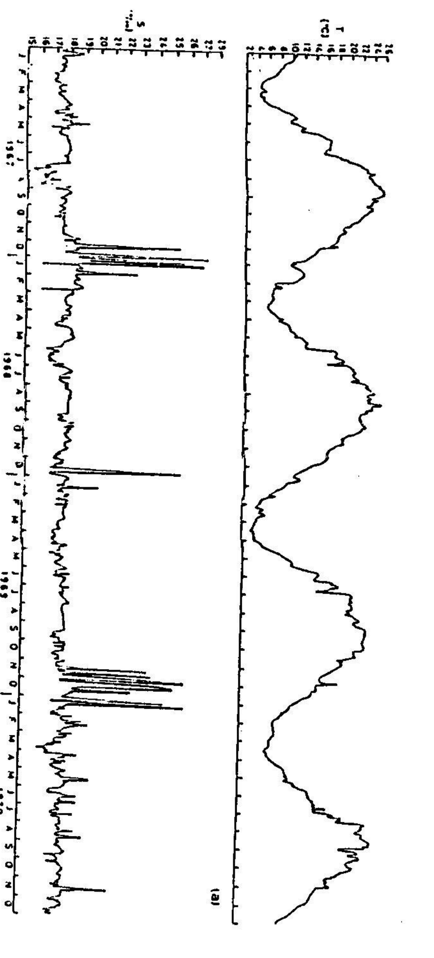
3

North end of Bosphorus, bottom vel vector Jan-Aug 1992
vel scale: 1 cm = 20. cm/s.

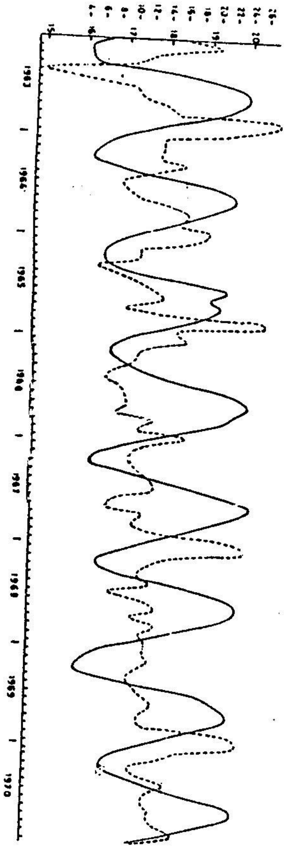


Anadolu Kavak bottom sal 24 Dec 1991-28 Aug 1992 (rcm 4016)





Time series of daily surface (a) temperature and (b) salinity during 1966-1970 at Baltalimanı (Bosphorus).



Time series of monthly averaged surface temperature and salinity during 1962-1970 at Baltalimani (Bosphorus).

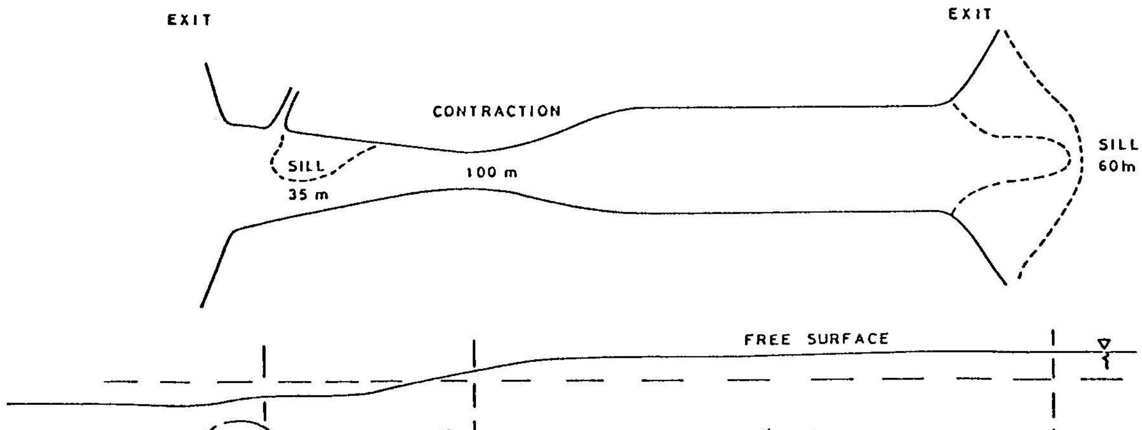


Figure 3.46. The two-layer controlled flow schematization of the Bosphorus.

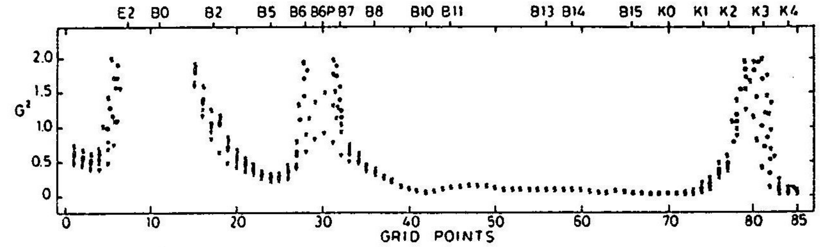


FIG. 5a. Computed variations of the composite Froude number for various values of q_0: 4380 $m^3 s^{-1}$ (∇), 10 500 $m^3 s^{-1}$ (×), 12 350 $m^3 s^{-1}$ (●), 16 600 $m^3 s^{-1}$ (O) and 21 765 $m^3 s^{-1}$ (s).

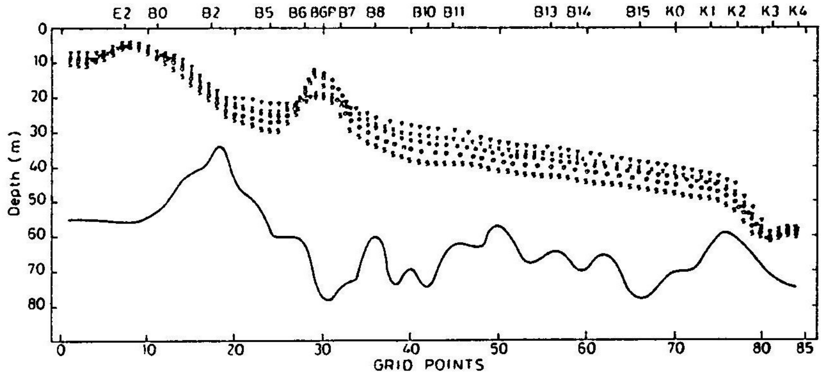
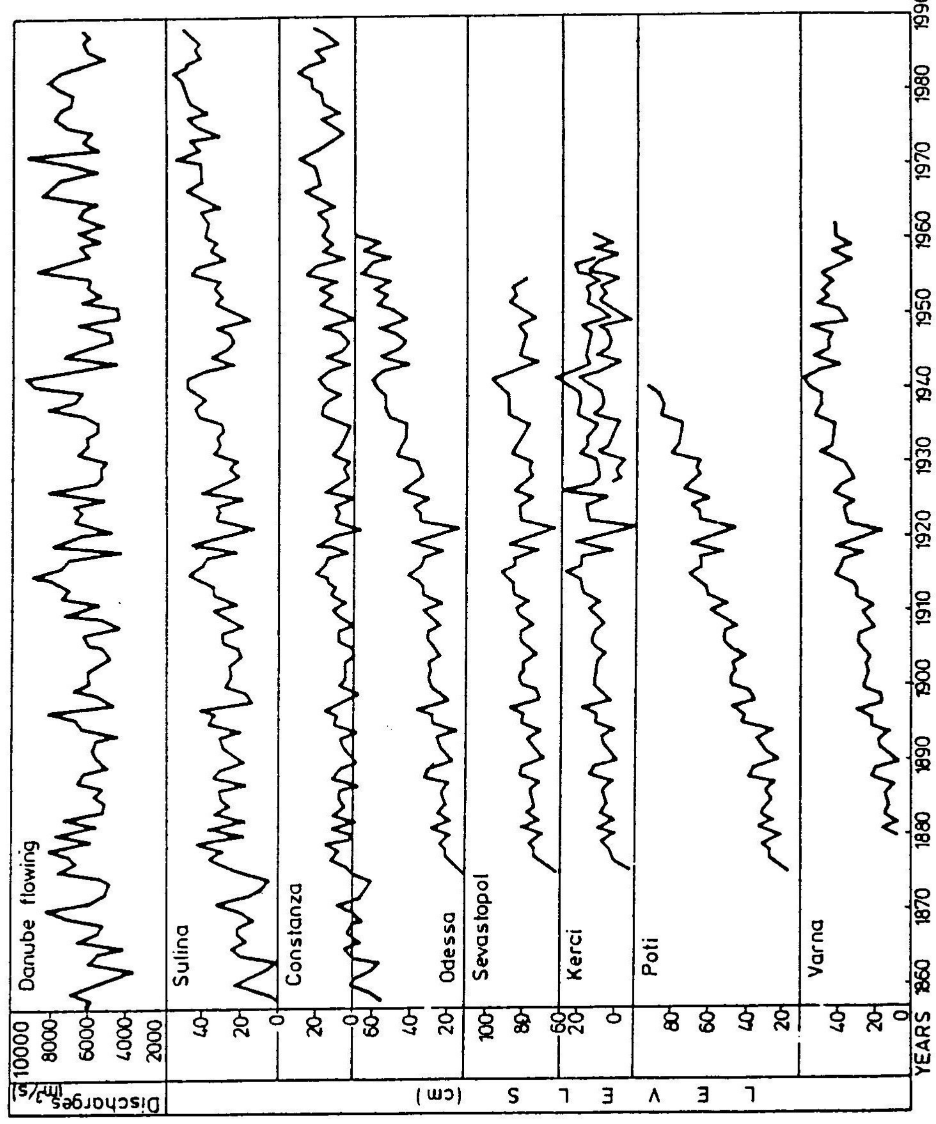
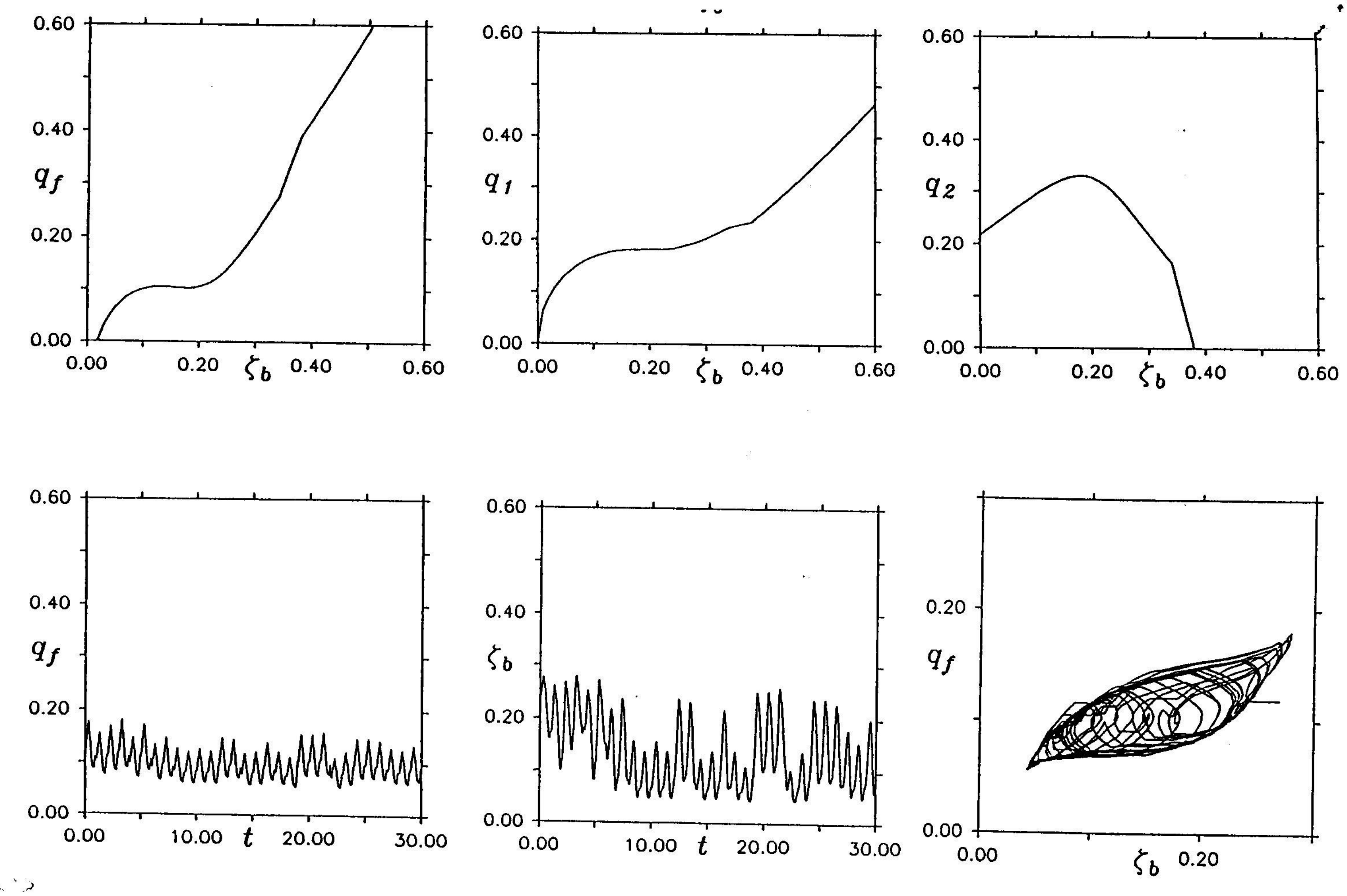


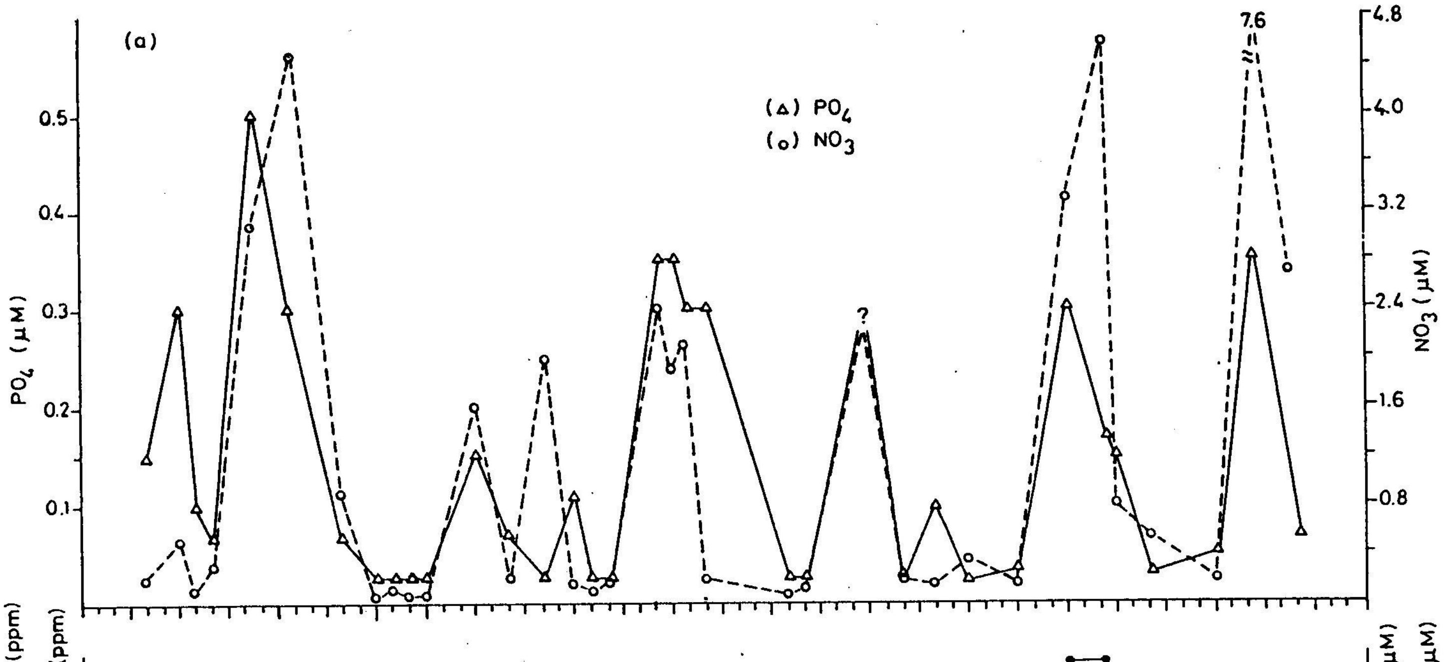
FIG. 5b. Computed variations of the interface depth for various values of q_0: 4380 $m^3 s^{-1}$ (∇), 10 500 $m^3 s^{-1}$ (×), 12 350 $m^3 s^{-1}$ (●), 16 600 $m^3 s^{-1}$ (O) and 21 765 $m^3 s^{-1}$ (s).



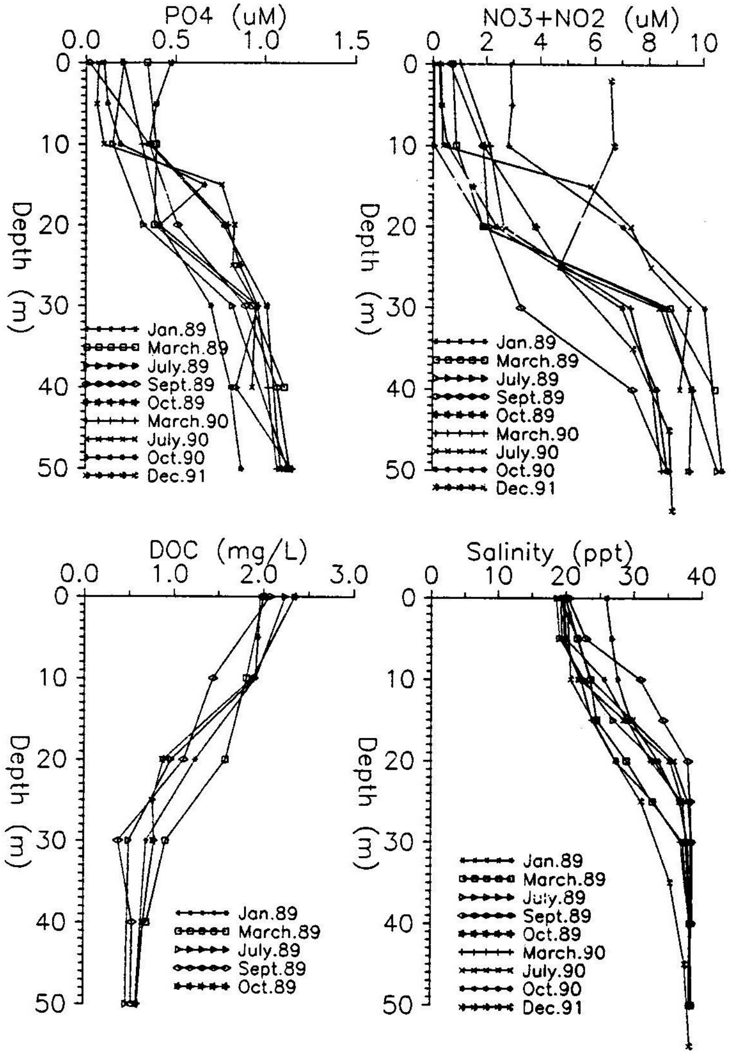
7

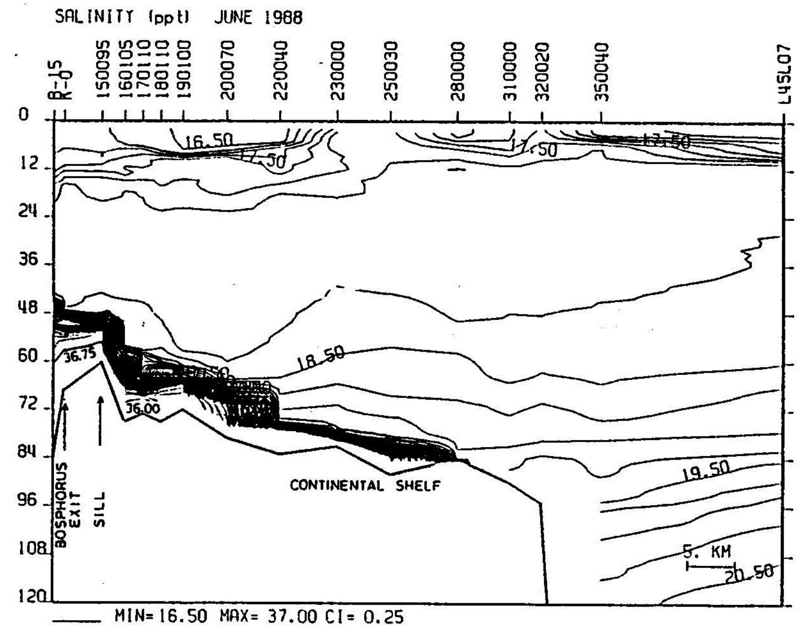


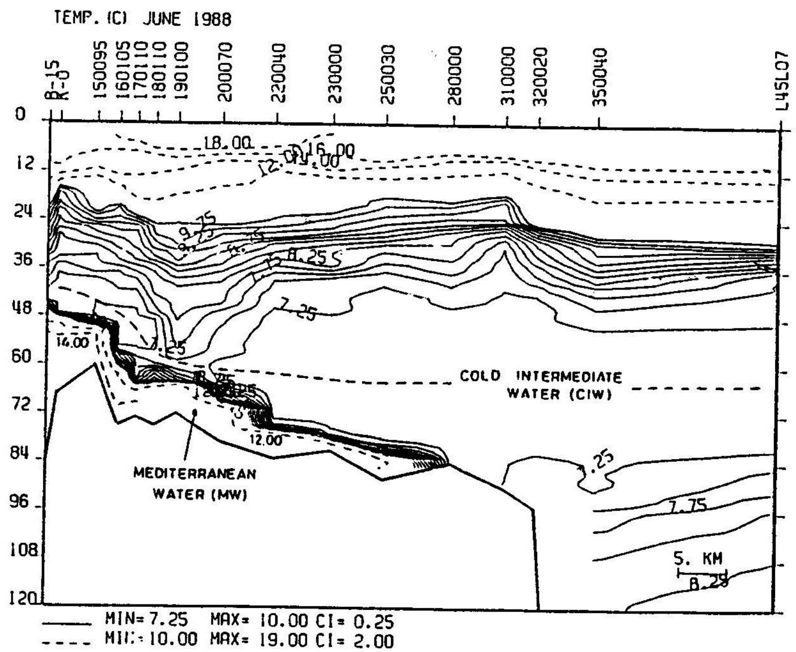
0.60
0.40
0.20
0.00
q_f
q_1
q_2
ζ_b
t
0.00
0.20
0.40
0.60
10.00
20.00
30.00



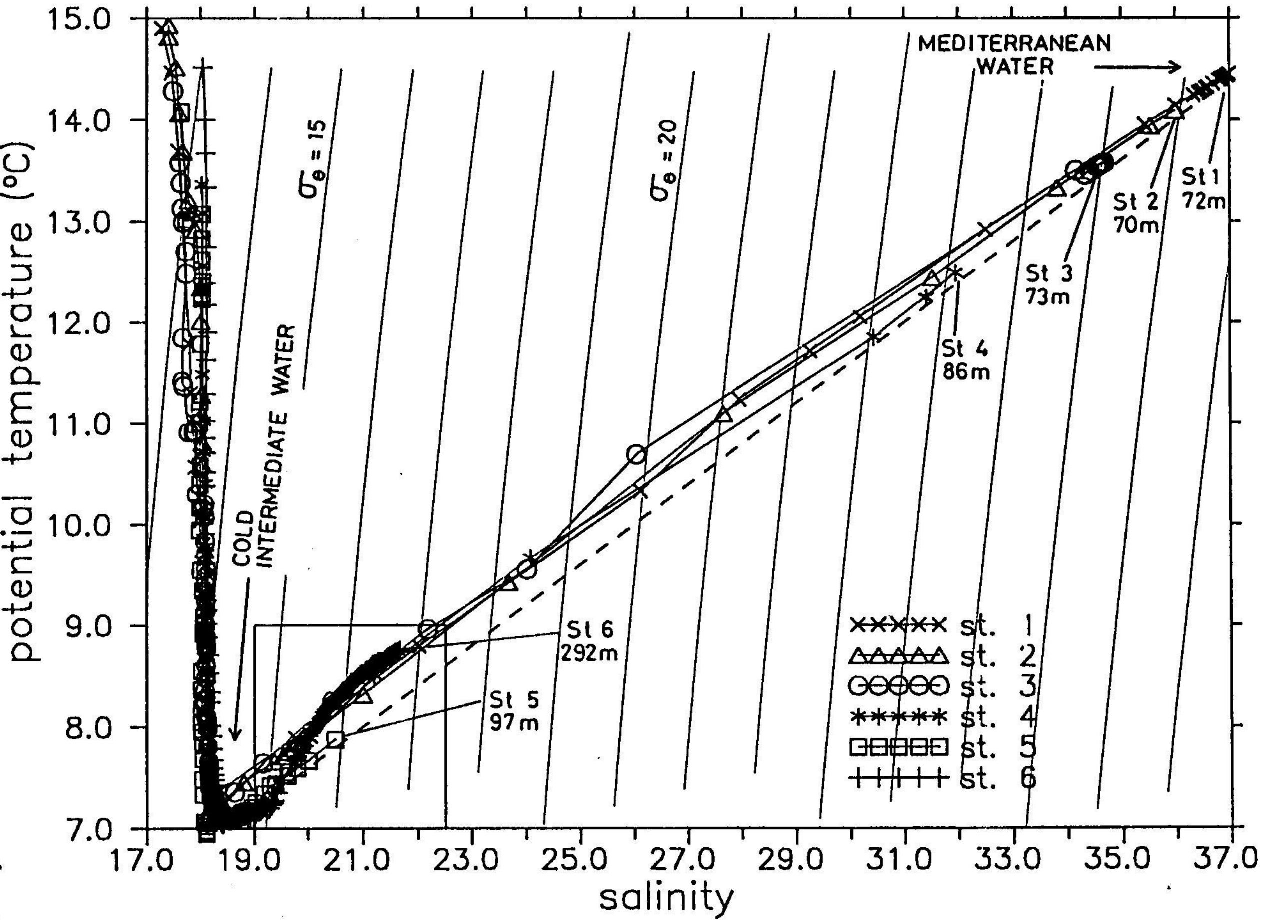
(a)
(△) PO_4
(o) NO_3
PO_4 (μM)
NO_3 (μM)
7.6
?
(b)
(o) DOC
(●) POC
(x) PON
(△) PP
POC (ppm)
DOC (ppm)
PON (μM)
PP (μM)
J A Jy O J A Jy O J A Jy O J A Jy O J A Jy O J A Jy O J A Jy
1986
1987
1988
1989
1990
1991
1992


PO4 (uM)
0.0 0.5 1.0 1.5
Depth (m)
Jan.89
March.89
July.89
Sept.89
Oct.89
March.90
July.90
Oct.90
Dec.91
NO3+NO2 (uM)
0 2 4 6 8 10
Depth (m)
Jan.89
March.89
July.89
Sept.89
Oct.89
March.90
July.90
Oct.90
Dec.91
DOC (mg/L)
0.0 1.0 2.0 3.0
Depth (m)
Jan.89
March.89
July.89
Sept.89
Oct.89
Salinity (ppt)
0 10 20 30 40
Depth (m)
Jan.89
March.89
July.89
Sept.89
Oct.89
March.90
July.90
Oct.90
Dec.91

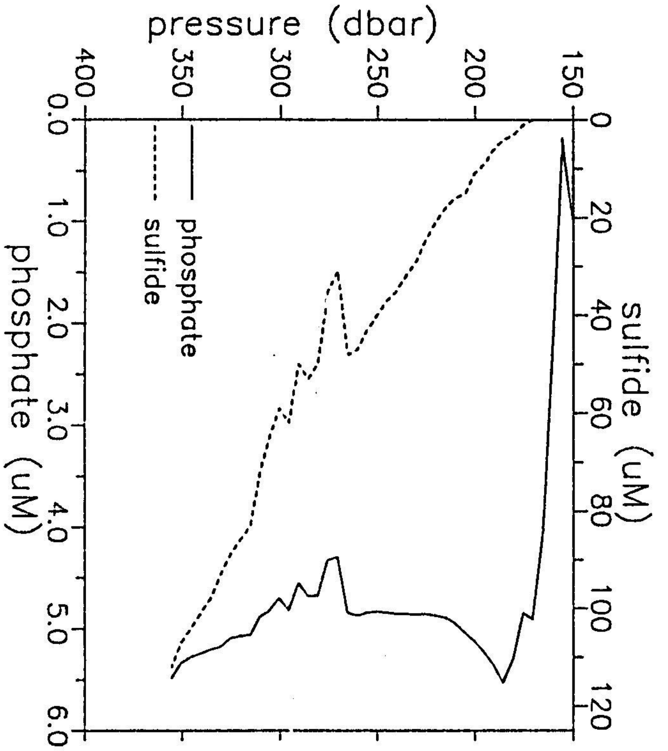

SALINITY (ppt) JUNE 1988
B-15
K-0
150095
160105
170110
180110
190100
200070
220040
230000
250030
280000
310000
320020
350040
L45L07
16.50
17.50
18.50
19.50
20.50
36.75
36.00
BOSPHORUS EXIT
SILL
CONTINENTAL SHELF
5. KM
MIN= 16.50 MAX= 37.00 CI= 0.25

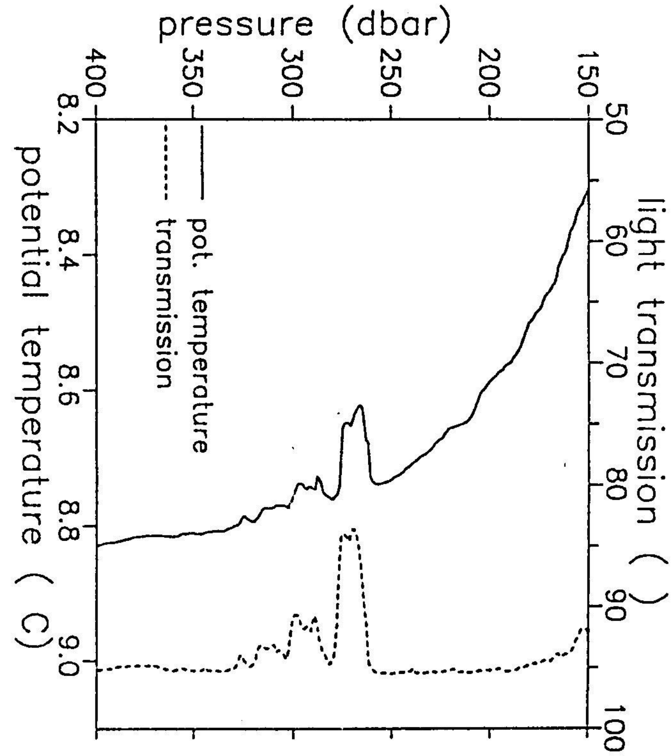

TEMP. (C) JUNE 1988
B-15
K-0
150095
160105
170110
180110
190100
200070
220040
230000
250030
280000
310000
320020
350040
L45L07
18.00
16.00
12.00
9.75
8.25
7.25
7.75
14.00
12.00
COLD INTERMEDIATE WATER (CIW)
MEDITERRANEAN WATER (MW)
5. KM
MIN= 7.25 MAX= 10.00 CI= 0.25
MIN= 10.00 MAX= 19.00 CI= 2.00

12

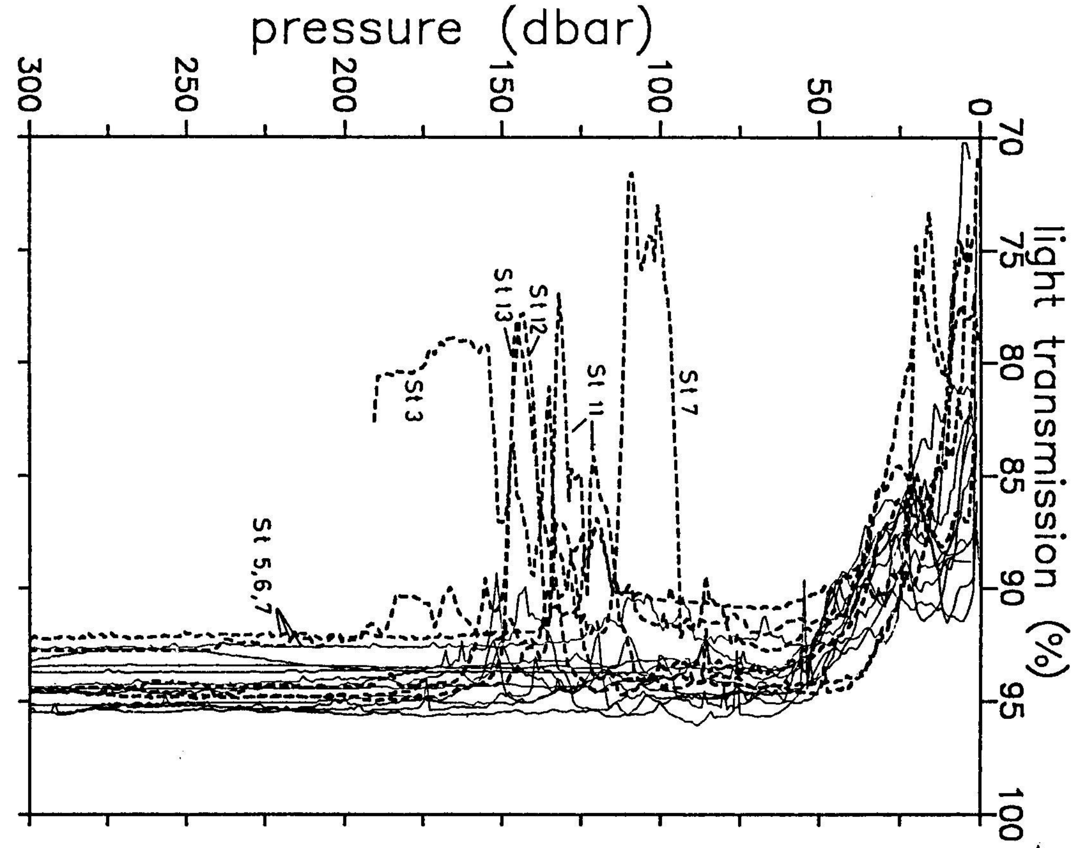

potential temperature (°C)
salinity
MEDITERRANEAN WATER
COLD INTERMEDIATE WATER
$\sigma_\theta = 15$
$\sigma_\theta = 20$
St 1 72m
St 2 70m
St 3 73m
St 4 86m
St 5 97m
St 6 292m
st. 1
st. 2
st. 3
st. 4
st. 5
st. 6
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
17.0
19.0
21.0
23.0
25.0
27.0
29.0
31.0
33.0
35.0
37.0

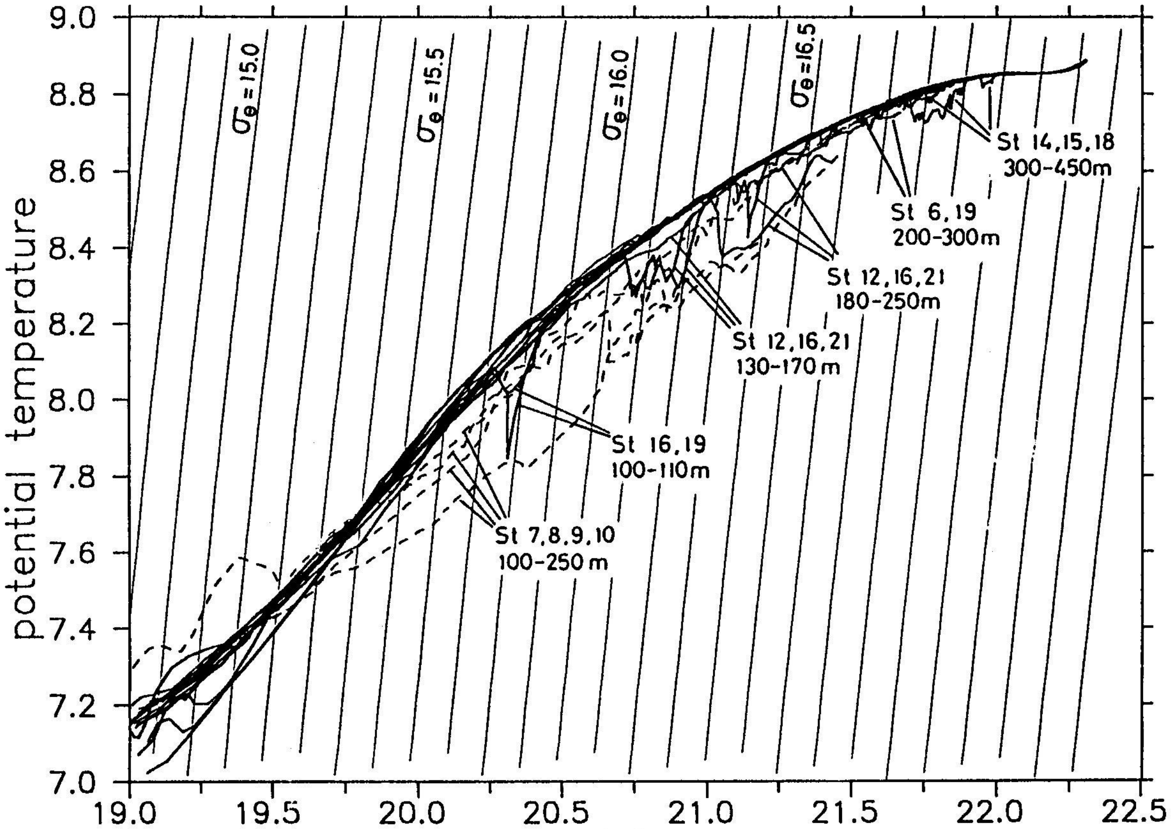
13

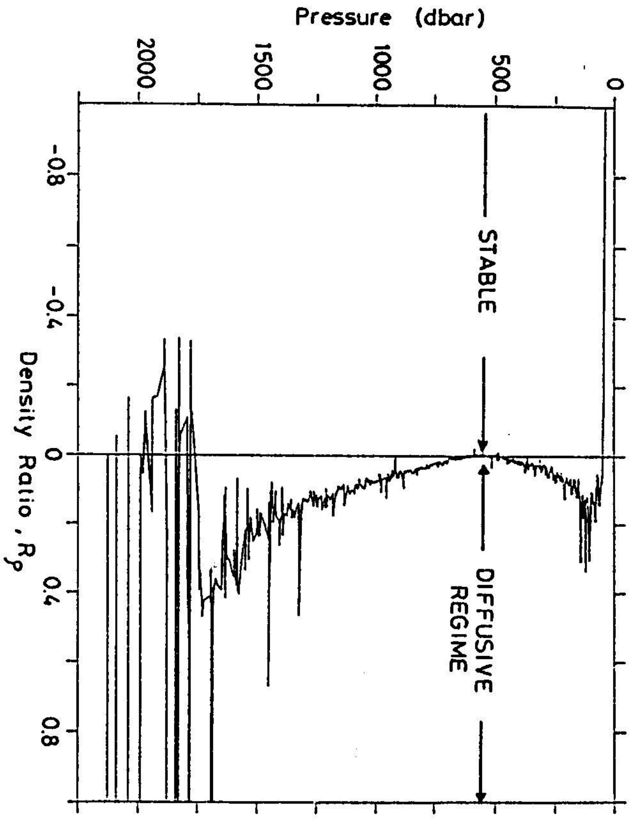

pressure (dbar)
sulfide (uM)
phosphate (uM)
phosphate
sulfide


pressure (dbar)
light transmission ( )
potential temperature (C)
pot. temperature
transmission

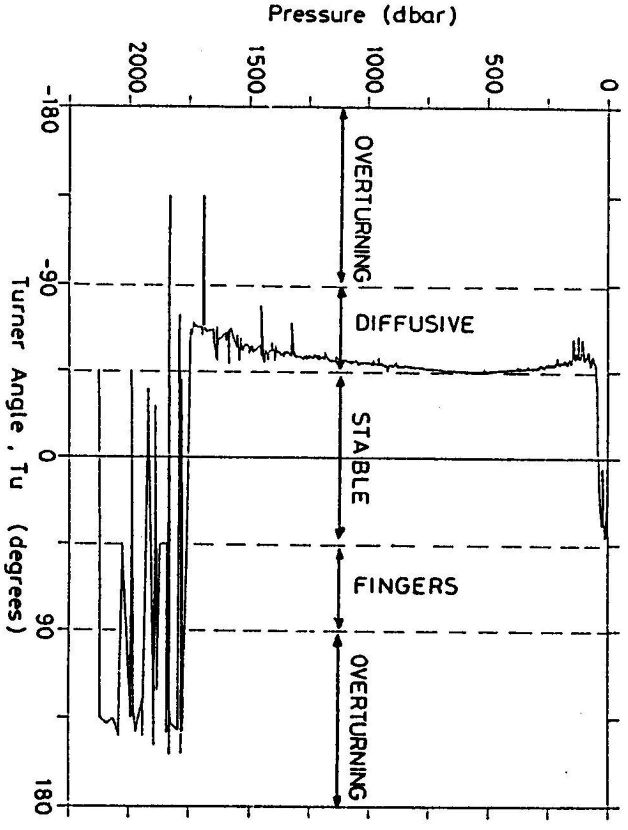
14 a, b


pressure (dbar)
light transmission (%)
St 3
St 13
St 12
St 11
St 7
St 5,6,7


potential temperature
salinity
σ_θ=15.0
σ_θ=15.5
σ_θ=16.0
σ_θ=16.5
St 14,15,18
300-450m
St 6,19
200-300m
St 12,16,21
180-250m
St 12,16,21
130-170m
St 16,19
100-110m
St 7,8,9,10
100-250 m

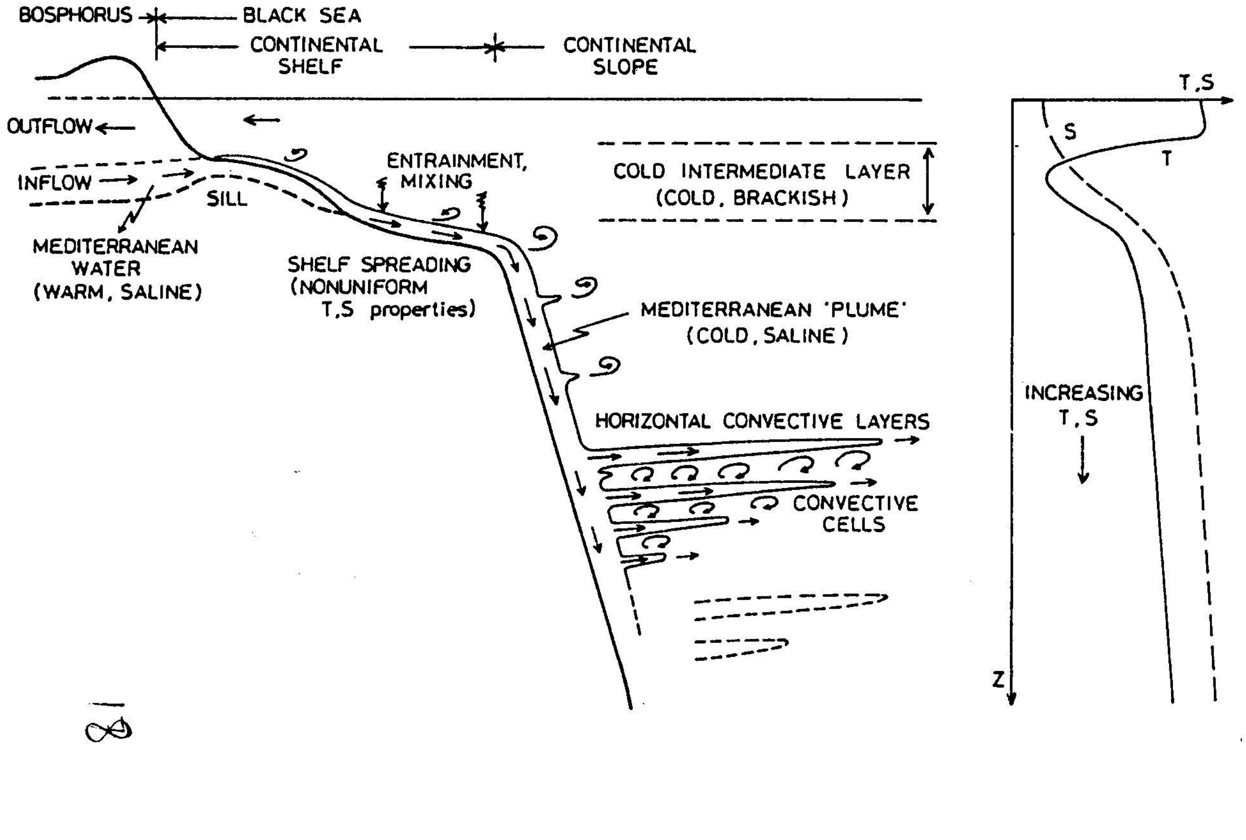


Pressure (dbar)
0
500
1000
1500
2000
Density Ratio , R_ρ
-0.8
-0.4
0
0.4
0.8
STABLE
DIFFUSIVE REGIME



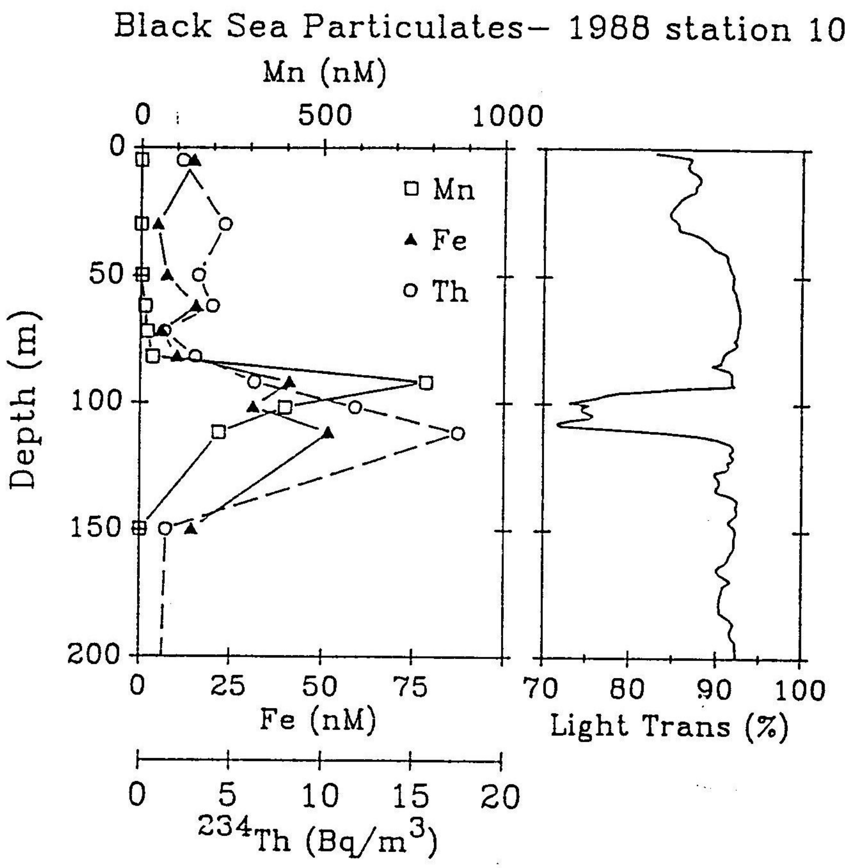
Pressure (dbar)
0
500
1000
1500
2000
Turner Angle , Tu (degrees)
-180
-90
0
90
180
OVERTURNING
DIFFUSIVE
STABLE
FINGERS
OVERTURNING

17



BOSPHORUS
BLACK SEA
CONTINENTAL SHELF
CONTINENTAL SLOPE
OUTFLOW
INFLOW
SILL
MEDITERRANEAN WATER (WARM, SALINE)
ENTRAINMENT, MIXING
COLD INTERMEDIATE LAYER (COLD, BRACKISH)
SHELF SPREADING (NONUNIFORM T,S properties)
MEDITERRANEAN 'PLUME' (COLD, SALINE)
HORIZONTAL CONVECTIVE LAYERS
CONVECTIVE CELLS
T,S
S
T
INCREASING T,S
Z

18



19

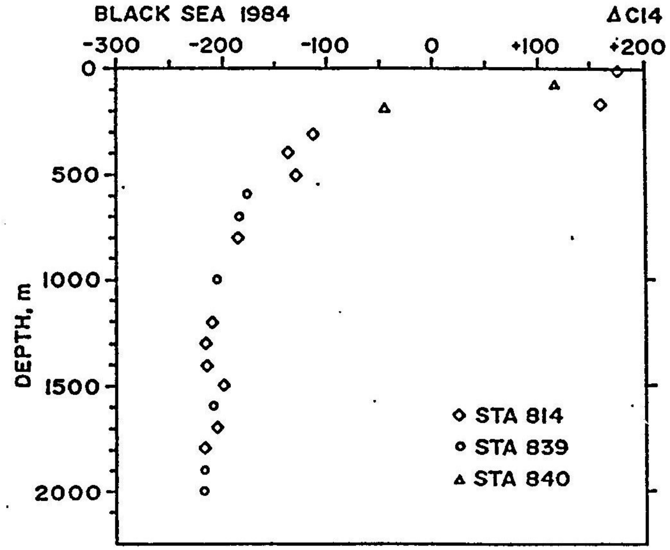


Fig. 2. C14 in the Black Sea. Vityaz - 84.

Table 1

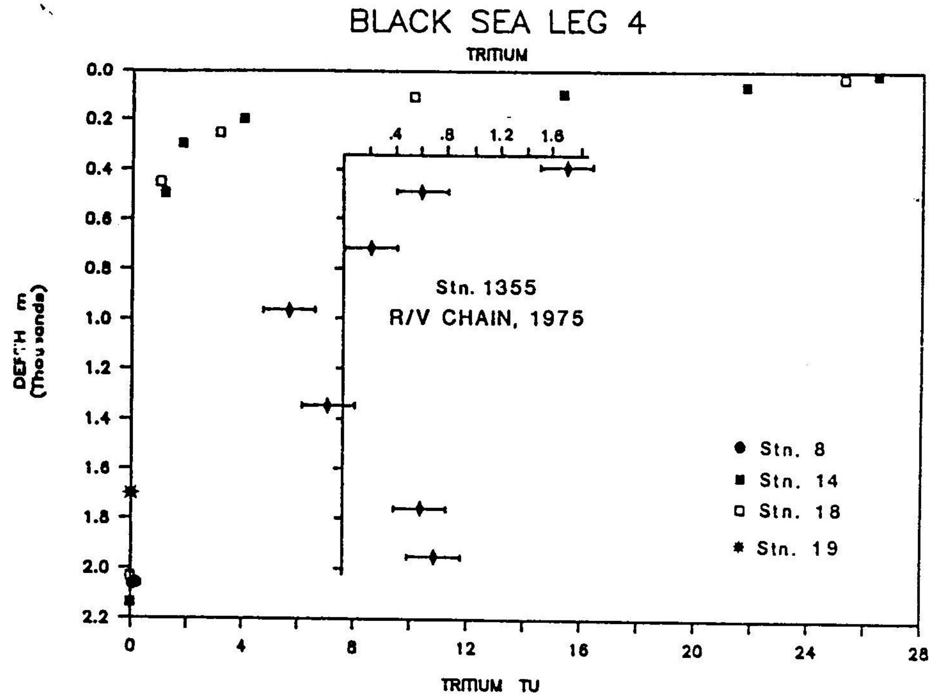
BLACK SEA 1984

C13, C14 AND RENEWAL TIME SCALE

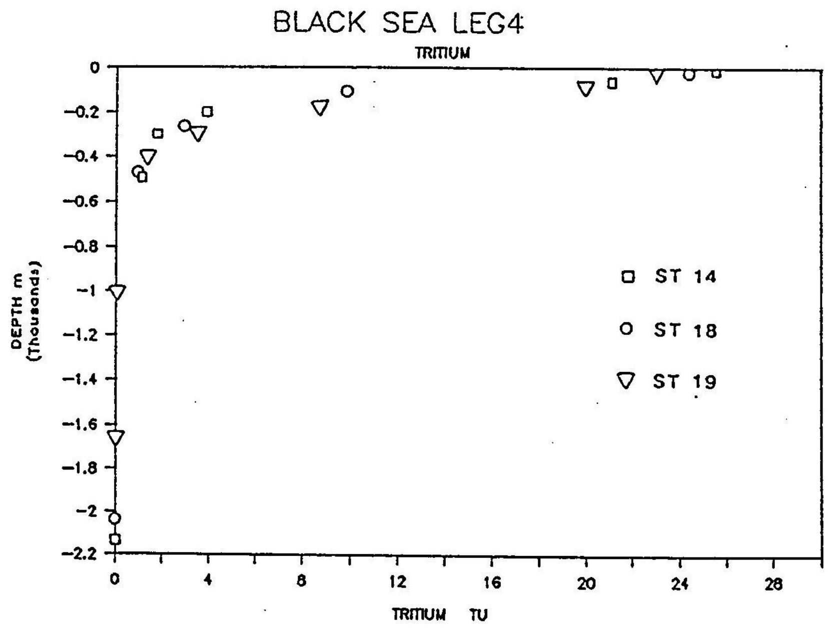
Stn	Depth m	TCO2* µM/kg	dC13** 0/00	ΔC14 0/00	Ratio 0/0	Renewal years	TCO2*** µM/kg
814	1	2985	-1.7	167.0	122.4		2990
840	80	(3100)	-2.7	104.4	115.6		3120
814	160	3214	-3.4	151.0	120.3		3215
840	200	(3228)	-3.7	- 52.2	99.0	84	3260
814	300	3262	-4.6	-125.2	91.2	798	3340
814	400	3388	-7.2	-144.6	88.7	1053	3445
814	500	3502	-7.0	-133.4	89.9	929	3540
839	600	3502	-6.9	-181.7	84.9	1470	3620
839	700	3855	-5.8	-187.4	84.5	1516	3710
814	800	3853	-7.9	-199.4	82.9	1705	3775
839	1000	3980	-9.5	-207.4	81.8	1839	3885
814	1200	3936	-7.4	-215.6	81.3	1901	3965
814	1300	(4000)	-8.1	-218.3	80.9	1952	4000
814	1400	3995	-7.0	-224.0	80.5	2002	4030
814	1500	3989	-13.8	-205.2	81.3	1901	4060
839	1600	4008	-7.1	-213.2	81.6	1864	4085
814	1700	(4115)	-13.0	-212.4	80.7	1977	4110
814	1800	4119	-7.3	-224.5	80.4	2015	4125
839	1900	(4160)	-8.3	-223.8	80.3	2028	4145
839	2000	(4180)	-7.3	-224.5	80.4	2015	4160

* Values in parentheses are interpolated.
** If we assume that the organic material produced by photosynthesis (marine plant tissue) has a δ C13 which is about 20o/oo lower than that of the dissolved inorganic carbon then the data fit the equation

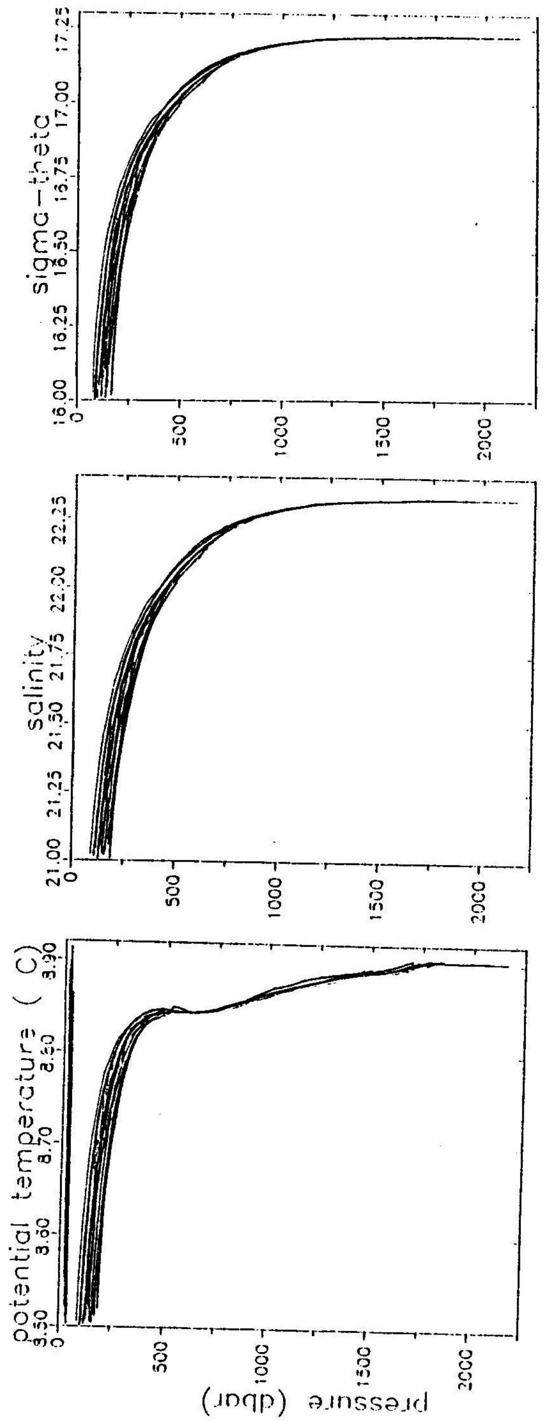
$$\delta C13 \cdot TCO_2 = -23\ (TCO_2 - 3100) - 3 \cdot 3100$$



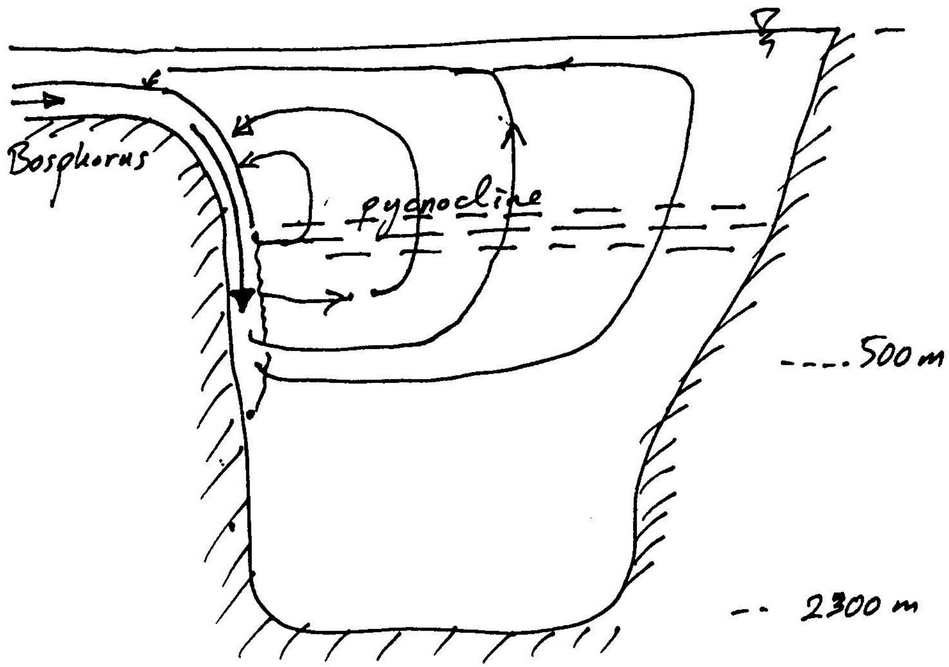
g. 4. Composite tritium profile from Stas 8, 14 and 18. Inset shows the 1975 measurements of Top and Clarke (1983) on an expanded scale.

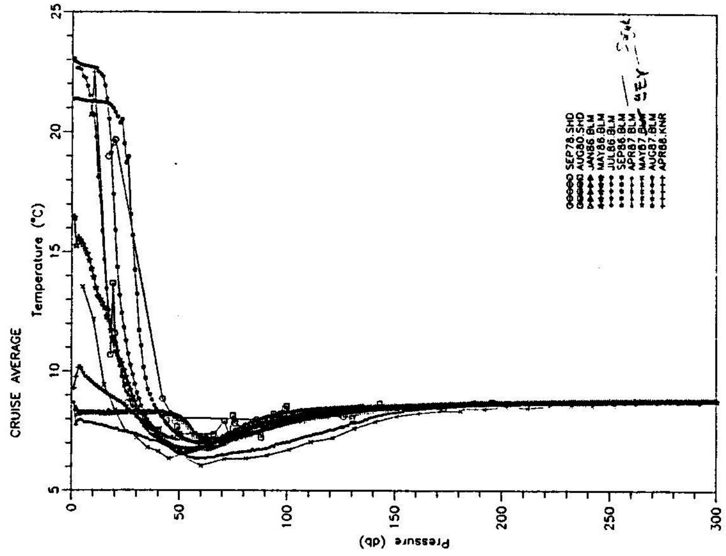


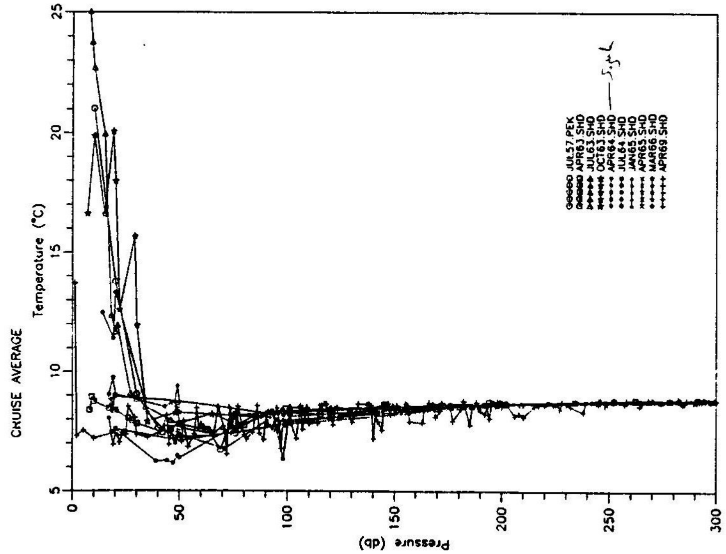
21

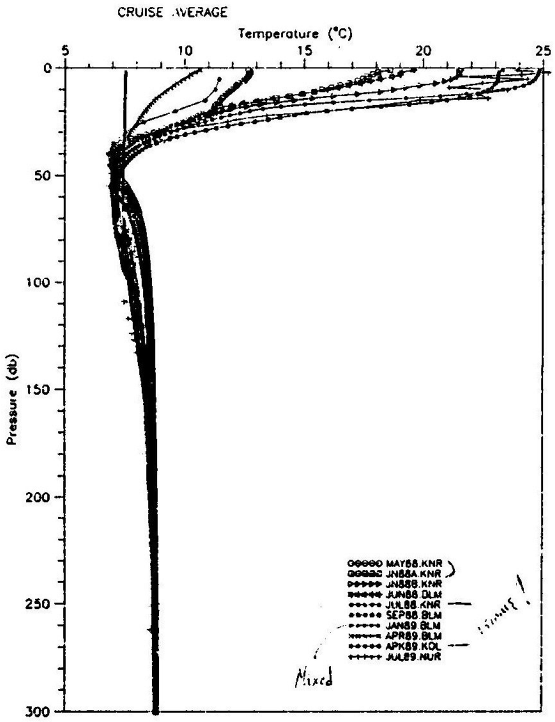


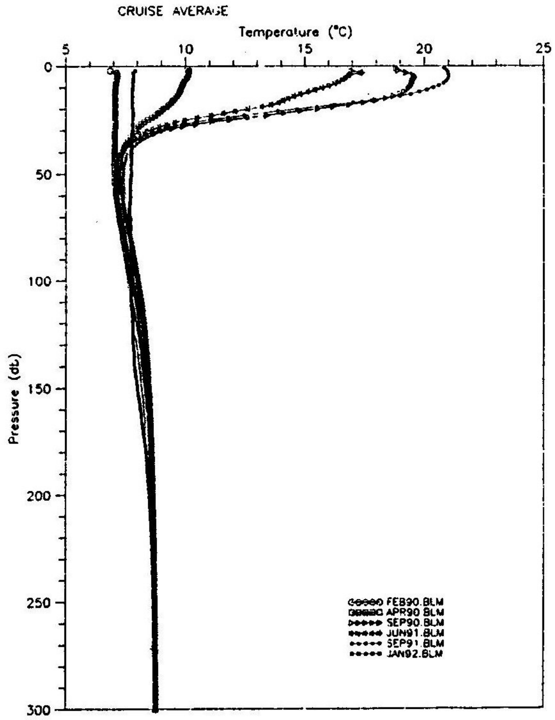
22


Bosphorus
pycnocline
500 m
2300 m


CRUISE AVERAGE
Temperature (°C)
Pressure (db)
SEP78.SHD
AUG80.SHD
JAN86.BLM
MAY86.BLM
JUL86.BLM
SEP86.BLM
APR87.BLM
MAY87.BLM
AUG87.BLM
APR88.KNR


CRUISE AVERAGE
Temperature (°C)
Pressure (db)
JUL57.PEK
APR63.SHD
JUL63.SHD
OCT63.SHD
APR64.SHD
JUL64.SHD
JAN65.SHD
APR65.SHD
MAR66.SHD
APR69.SHD





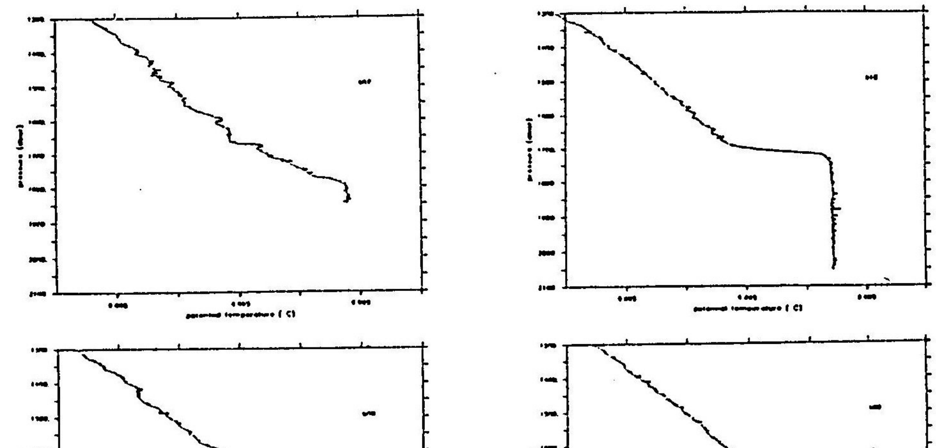
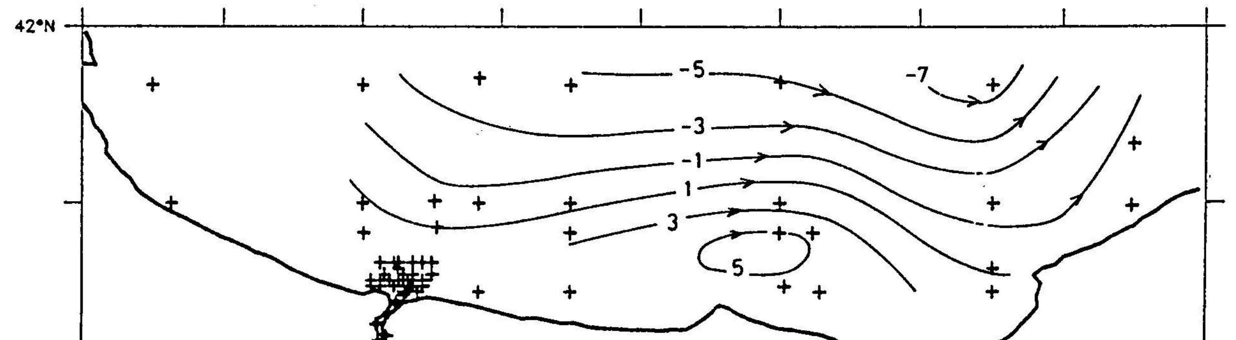


Figure 12. Potential temperature θ (°C) versus pressure (decibar) at the deeper parts (1300-2100 dbar) of (a) station 7, (b) station 18, (c) station 9, (d) station 8.


42°N
41°N
28°E
29°E
30°E
31°E
32°E
-7
-5
-3
-1
1
3
5