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Oceanography of the Black Sea: a review of some recent results

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Abstract

A new synthesis of the Black Sea oceanography is presented, primarily based on studies carried out in the southern Black Sea, as well as on some recent work covering the entire basin, obtained in a new era of increasing cooperation between the riparian countries. A review of the physical environment is given. Seasonal and interannual climatic variability of the system are discussed in relation to its hydrology. Water mass variability and formation are studied, with emphasis on the inflow of Mediterranean waters, pycnocline variability, shelf and internal mixing, and double diffusive convection. The general circulation of the basin, and the roles of stratification, topography and coastline variations in determining the behaviour of the rapid, unstable boundary currents and upwelling along the coast are discussed, based on hydrographic data and satellite observations. Impacts of the physical processes on the ecosystem are discussed. © 1997 Elsevier Science B.V.

Keywords: mixing; convection; circulation; currents; climatic variability; ecosystems

1. Introduction

With a maximum depth of ~ 2200 m, a surface area of 4.2×10^5 km^2 and a volume of 5.3×10^5 km^3, the Black Sea is a unique marine environment, representing the largest land-locked basin in the world (Fig. 1). Its waters are in a state of almost complete isolation from the world ocean, as a result of the restricted exchange with the Mediterranean Sea through the Turkish Straits System (the Bosphorus, Dardanelles Straits and the Sea of Marmara). As a result, the basin is almost completely anoxic, containing oxygen in the upper 150 m depth (13% of the sea volume) and hydrogen sulphide in the deep waters. A permanent halocline separates the oxic and anoxic waters.

In recent decades, the increasing anthropogenic inputs, and most significantly, mineralized nutrients from continental Europe, have driven a trend for eutrophication (Bologa, 1986; Chirea and Gomoiu, 1986; Mee, 1992), leading to alterations in the ecosystem, bottom hypoxia in the northwestern shelf region, changes in marine populations, invasion by opportunistic species (Tolmazin, 1985a; Zaitsev, 1993), and changes in the nutrient structure (Tuğrul et al., 1992; Saydam et al., 1993). It is most likely that the recent collapse of the basin's fisheries (Kıdeyş, 1994) is closely linked with the above processes, as well as with increased fishing.

Specific mechanisms determine the health of the marine environment in the Black Sea. The physical processes of circulation and mixing largely determine the redistribution and biochemical cycling of elements leading to biological productivity culminating in living resources. New insights into the basic

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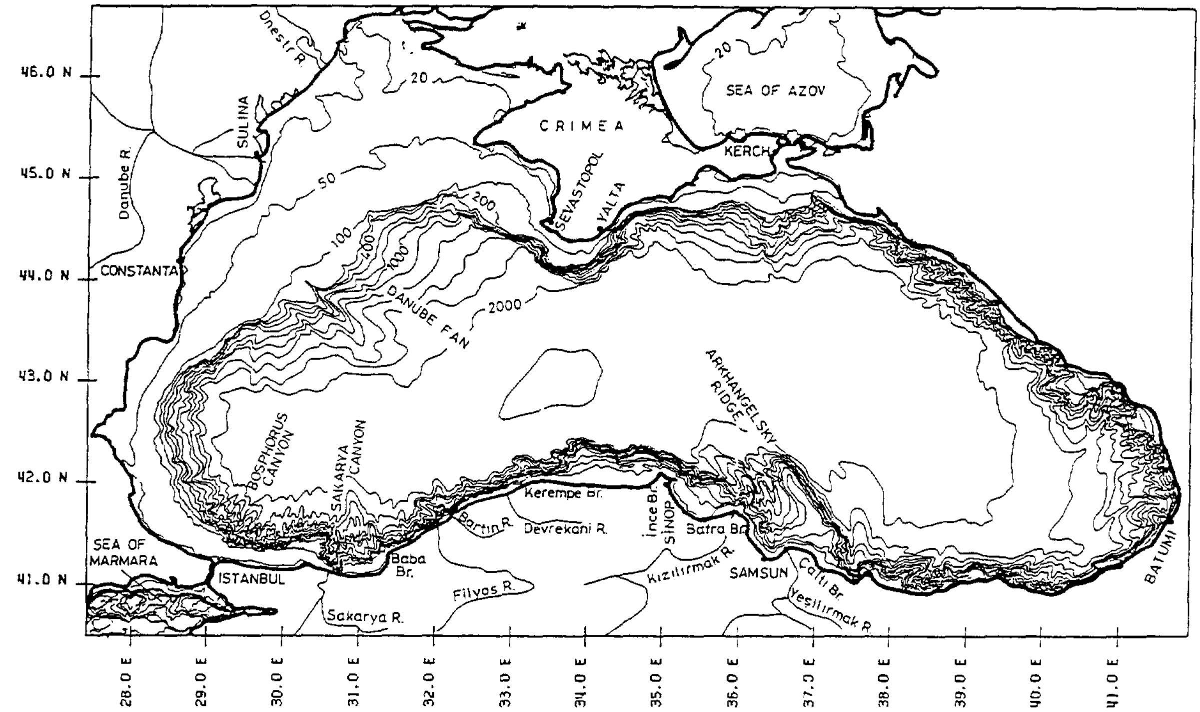

Fig. 1. Layout and bathymetry of the Black Sea basin. Depth contours are labelled in m.

physical and chemical functioning of the system have been gained through research activities in the last decade (e.g. Murray, 1991; Aubrey et al., 1992a).

The basin's oceanography is strongly influenced by freshwater inputs from rivers, active atmospheric forcing, thermohaline driving factors, fluxes through straits and sharp changes in topography. The investigation of the active Black Sea circulation, with rapidly changing jets and eddies, is crucial to determine its role in the transport of basic properties, the realization of primary production, and the growth, migration and entrainment of pelagic marine organisms. The study of mixing processes is essential in determining the stability of the existing stratification, the sources and redistribution mechanisms of nutrients, the factors contributing to new production and eutrophication processes. other countries.

2. Observations and methodology

A historical data base of hydrographic measurements exists in the Black Sea from the beginning of the century till the 1980s, compiled through the efforts of the former USSR (e.g. Mamayev, 1993) and other countries. The recent years have evidenced systematic surveys with much increased coverage, and improved resolution and quality of data: some surveys were carried out by R/V *Bılım* along the Turkish coast during 1987–1989. Then, the first of the recent cooperative surveys were carried out in 1988–1989, with Turkish–USSR cooperation on board the R/V *Kolesnikov* and R/V *Dmitriy Mendeleev*, and with USA–Turkish cooperation during the visit of the USA R/V *Knorr* in 1988 (Murray, 1991) with R/V *Bılım* guiding the R/V *Knorr* tracer surveys near the Bosphorus (Özsoy et al., 1993a). After 1990, coordinated multi-institutional surveys were carried out, first within the context of the NATO TU–Fisheries program (Bingel et al., 1994), continued later within the CoMSBlack international program, and currently within the NATO TU–Black Sea program, resulting in intercalibrated and pooled data sets (Aubrey et al., 1992a,b; Oğuz et al., 1993a,c; Konovalov et al., 1994; Ivanov et al., 1994). During the recent cooperative studies, oceanographic stations were located with a nominal spacing of ~ 20 km, and covered the either the western part, or the entire basin in most cases after 1990. Examples of station coverage during two cases are shown in Fig. 2.

The hydrographic data available to us at the time of writing of this review covered the period of 1987–1993. The cooperative studies of the Black Sea have continued since then, and are continuing at present. Therefore, we have made reference to more recent other literature in updating the review.

Current velocity profile measurements were obtained using an ADCP system with a vessel-mounted 150 kHz transducer on board the R/V *Bılım* (Güngör,

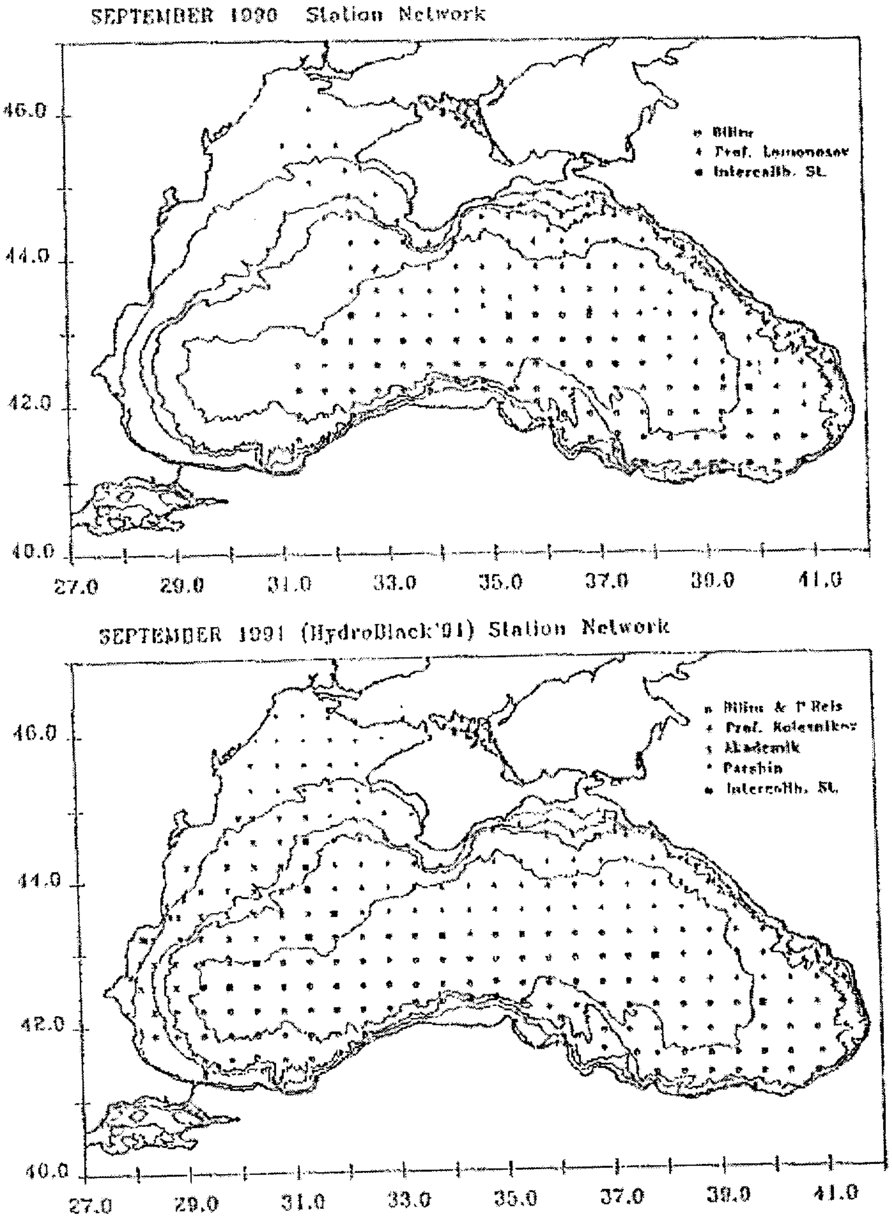

Fig. 2. Examples of the station networks during recent coordinated surveys: (a) September 1990, (b) September 1991.

1994; Sur et al., 1996; Oğuz et al., 1996a,b), starting in April 1993 (Fig. 2b). A bin size of 2 m or greater was used in the data collection, sampling up to 128 depth bins. Ensemble averaging was carried out at half-hour intervals at oceanographic stations. Under cruising conditions, the data were ensemble-averaged with 10 min intervals. Reliable measurements were obtained only for depths smaller than 200–250 m.

For most of the satellite data presented here, image processing, including standard procedures for atmospheric corrections, extraction of clouds, and Mercator projection, was done on the Seapak and Mapix interactive systems at the IMS-METU. After 1994, the high-resolution (HRPT) satellite data were received directly at the Institute. The visible and thermal infrared imagery from CZCS and NOAA AVHRR satellites, complementing the in-situ data, have been successfully used in studying the circulation and phytoplankton production patterns of the Black Sea (Oğuz et al., 1992; Sur et al., 1994, 1996; Barale, 1994; Barale and Murray, 1995).

3. A review of regional characteristics

3.1. Bathymetry

The flat abyssal plain (depth > 2000 m) of the Black Sea (Fig. 1) occupies more than 60% of the total area. The maximum depth is about 2300 m, and the average depth of the basin was calculated to be 1240 m (Ross et al., 1974). The abyssal plain is separated from the margins by steep continental slopes, excluding the gentler slopes near the Danube and Kerch fans. Continental shelves (depth < 200 m) constitute about 25% of the total area. The wide northwestern continental shelf (mean depth ~ 50 m) occupies the region between the Crimean Peninsula and the west coast, and extends along the western and southwestern coasts of the Black Sea, with a depth of ~ 100 m at the shelf break. This continuous region of flat topography decreases in width towards the south and reaches an abrupt termination at Sakarya Canyon, where the depth suddenly increases from 100 m to about 1500 m. The continental shelf in the remaining part of the Black Sea rarely exceeds a width of 20 km and occurs as narrow stretches along the coasts of Anatolia, Caucasus and Kerch, often separated by canyons or steep slopes adjoining the land. In addition to many canyons along the continental slope, prominent deep features, such as near the Arhangelsky ridge (depth > 400 m), present further complications of the peripheral topography, especially along the Anatolian and Caucasian coasts.

3.2. The atmospheric setting

The Black Sea region is affected by seasonal changes of atmospheric pressure patterns over the adjoining lands of Europe and Asia, and frequented by eastward-travelling depressions especially during the October–March period. Two main tracks of winter storms are particularly noted: (1) from the Mediterranean, moving in a northeastward direction over the Marmara Sea; (2) from Bulgaria and Romania, moving in eastward and southeastward directions. About 30 cyclones per year arrive from the central Mediterranean region (Reiter, 1975). It is also quite common that a cyclone moving along the Mediterranean coast of Turkey produces a secondary lee trough along the Black Sea coast (Brody and Nestor, 1980).

Major topographic features influence the atmospheric flows and the passage of cyclones in the Black Sea region. In the west, the Carpathian Mountains, Transylvanian Alps and the Balkan Mountains block air flows, leaving the low-lying area of Marmara as the major gap allowing passage of cyclones. The topography of the North Anatolian Mountains along the southern boundary and the Caucasus Mountains in the east act as barriers or wave-guides influencing the speed and paths of cyclones passing through the region (Brody and Nestor, 1980). The flat land in the north does not restrict air flows, so that cold outbreaks can reach the region from the north, especially when there is a persistent high-pressure system located near the Balkans.

Wind conditions over the Black Sea are variable in winter. The dominant wind direction is north-northeast in the western part, whereas southerlies dominate the eastern part of the basin. Gales from the northwest are common in winter.

The summer months are warmer, with more uniform distribution of air temperature over the Black Sea. Air temperature decreases sharply in late October and November, and reaches a minimum in January and February. In winter, the air temperature has a strong north–south gradient. The daily average temperature can decrease to about 8°C in the southern Black Sea, while negative temperatures are common in the northern parts, particularly in the region between the Danube basin and Crimea.

4. Hydrology and the water budget

Because the Black Sea is by large a land-locked basin, its overall mass budget and hydrochemical structure critically depends on elements of the hydrological balance. The characteristics of its near-surface waters are mainly controlled by the freshwater inflow, amplified as a result of the restricted exchange across the shallow Bosphorus Strait. On the other hand, the ventilation of the deeper layers and the structure of the halocline are closely linked with the inflow of Mediterranean water through the Bosphorus.

4.1. Surface fluxes

The Black Sea has a positive water balance, in which the inputs from freshwater sources exceed losses by evaporation. Although there is a large variation in the estimates reported, current estimates, based on a review of literature can be given as $\sim 300\ km^3/yr$ for precipitation, $\sim 350\ km^3/yr$ for runoff waters, $\sim 350\ km^3/yr$ for evaporation from the sea surface (Ünlüata et al., 1990). The net flux through the Bosphorus accounts for the remaining component of the water budget.

While the above figures represent estimated annual averages, there are uncertainties in the surface fluxes, mainly resulting from climatological variations in the water and heat budgets, and sampling problems. The significance of the interannual temporal variations in the Danube and Bosphorus fluxes are explored in the following sections.

4.2. Freshwater influxes

The net freshwater inflow into the Black Sea has a large seasonal and interannual variability. Although we do not have reliable information on the atmospheric components, the river runoff data (Özturgut, 1966; Serpoianu, 1973; Tolmazin, 1985a; Bondar, 1989; Bondar et al., 1991) indicate such variability. The Danube, Dnepr and Dnestr are the major rivers discharging into the northwestern shelf in the region between Crimea and Romania. The Danube River alone is the greatest contributor, accounting for about 50% of the total river runoff. The total discharge of the Dnestr and Dnepr rivers is about three times smaller than that of the Danube, and the total discharge of the remaining rivers account for a fraction ($< 1/5$) of the total river runoff. The annual mean discharge of the Danube, monitored for more than a century shows large natural variations (Fig. 3). The seasonal changes in the Danube water flux are about $\pm 30\%$ 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 (Sur et al., 1994). More significantly, a cursory examination shows that the Danube influx appears well correlated with sea-level changes on interannual time-scales (Fig. 3), as a result of the controls exerted by the Bosphorus. This is also true when considering the total water budgets, and the atmospheric pressure effects (Özsoy et al., 1996).

Low-salinity measurements near the Anatolian coast suggest freshwater from the northwestern shelf reaching the southwestern coast in modified form. Continuous measurements indicate great interannual variability in the timing and the minimum salinity value of the waters reaching the Bosphorus (Acara, 1958; Artüz and Uğuz, 1976). There are records of ice floes reaching the Bosphorus from the north (Acara, 1958) during extreme cold events, though this is not a common occurrence at present. The travel time between the Danube and the Bosphorus is estimated to be 1–2 months, but additional factors of mixing and dispersion determine the arrival of Danube waters at the Anatolian coast, which occurs some time between spring and late summer. The mean surface salinity in the southwestern Black Sea (computed from 1985–1992 R/V *Bilim* data in the upper 10 m within the region of 28–32°E and 41–42°N) indicates (Fig. 4) decreases of salinity to 16–17‰ (from a mean salinity of 18‰) in the March–August period, subject to significant differences from one year to another (Sur et al., 1994).

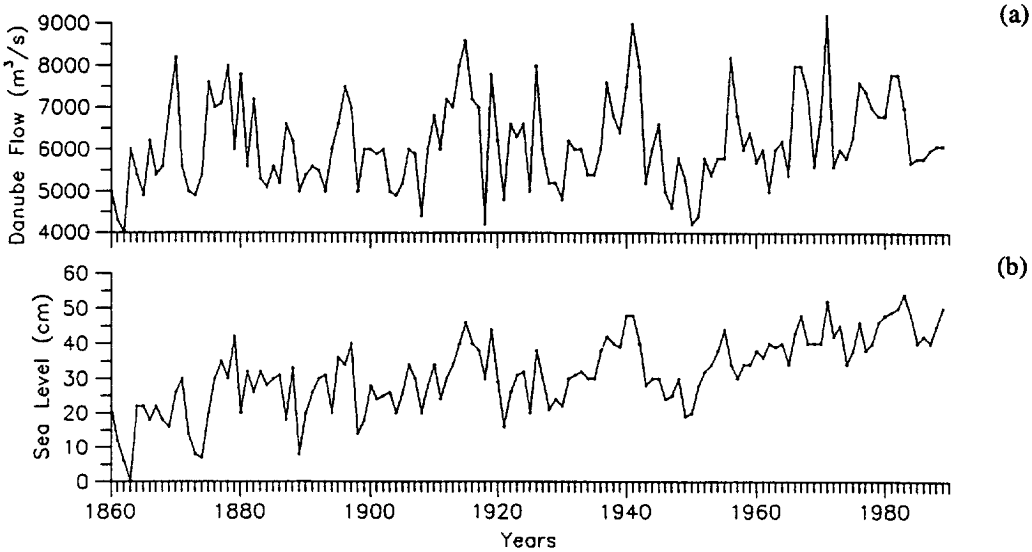

Fig. 3. Long-term measurements of annual average (a) Danube discharge, (b) sea-level at Sulina on the Romanian coast (after Bondar, 1989).

4.3. Exchange through the Bosphorus

The two-layer flows through the Bosphorus (the exchange flows to and from the Black Sea) have been estimated in various literature sources, based on the mass budgets, e.g. the Knudsen relations expressing the salt budget. A critical review and improved estimates are given by Ünlüata et al. (1990). Based

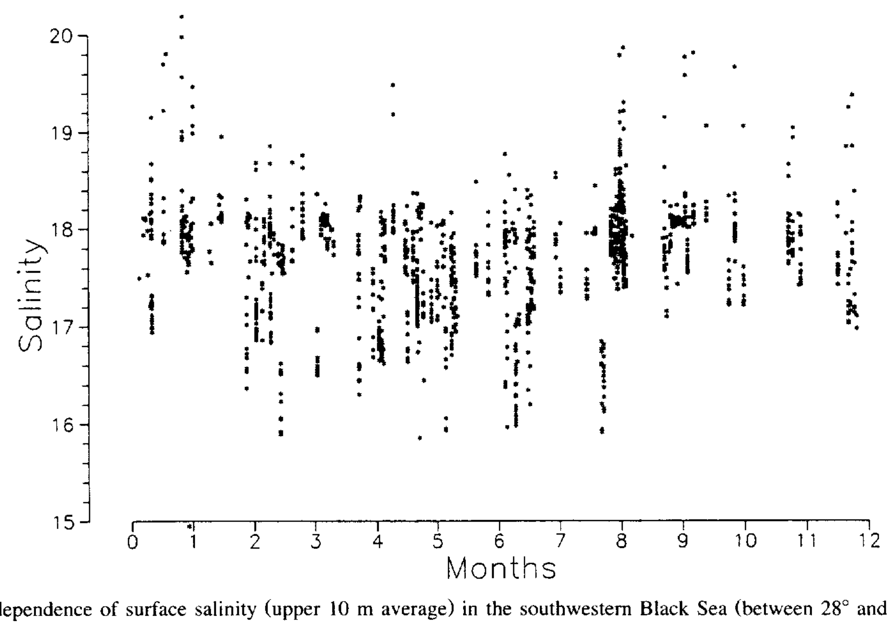

Fig. 4. Seasonal dependence of surface salinity (upper 10 m average) in the southwestern Black Sea (between 28° and 32°E, and 41° and 42°N). Each data point corresponds to a hydrographic station occupied in the area, including the many in the Bosphorus during 1986–1992.

on long-term averages of salinity at the strait entrances and using the steady-state mass and salt balances (Özsoy et al., 1986, 1988; Latif et al., 1990), the average fluxes at the Black Sea end of the Bosphorus (Fig. 5) have been computed to be ~ 600 km^3/yr (~ 20,000 m^3/s, outflowing from the Black Sea) and ~ 300 km^3/yr (~ 10,000 m^3/s, flowing into the Black Sea), respectively. The steady-state salt budget of the Black Sea requires that the ratio $Q_1/Q_2 = S_2/S_1 = 35.5/17.9 \approx 2$, where Q_1, S_1 and Q_2, S_2 are the upper (1) and lower (2) layer volume fluxes and salinities defined at the Black Sea entrance of the Bosphorus.

Although the average fluxes must satisfy the mass budgets, the exchange flows at any instant of time greatly differ from these estimates, as a result of the time-dependent meteorological and hydrological forcing originating from the adjacent basins. The transience of the Bosphorus transports on various time scales has been quantified by repeated measurements (Özsoy et al., 1986, 1988, 1994, 1995, 1996; Latif et al., 1990, 1991, 1992; Oğuz et al., 1990; Ünlüata et al., 1990).

The Bosphorus operates in the full range of weak to strong barotropic forcing in either direction. Blocking of the flows in either layer occurs during extraordinary events, lasting for a few days each time (Fig. 6). The lower layer blocking typically occurs during the spring and summer months, when the net freshwater influx into the Black Sea increases. The upper layer blocking events (identified locally as Orkoz), occur in the autumn and winter months, when the surface flow reverses (Özsoy et al., 1986, 1988, 1994, 1996; Latif et al., 1990, 1991). Current-meter measurements and flux computations based on acoustic Doppler current profiler (ADCP) measurements at Bosphorus cross-sections have yielded more accurate information, showing large transient changes in the Bosphorus fluxes in short periods, even within a single day (Özsoy et al., 1994).

With two supercritical transitions at a contraction and a sill, the Bosphorus is the foremost example of a strait with maximal exchange (Özsoy et al., 1986, 1996; Ünlüata et al., 1990), verified by numerical computations (Oğuz et al., 1990). Two important characteristics determine the exchange in the specific case of the Bosphorus: (1) suitable reservoir conditions in the adjacent basins and two hydraulic control sections lead to maximal exchange; and (2) the flow system is asymmetrical and sensitive to geometry when the sill is located nearer to the smaller density basin (Farmer and Armi, 1986; Armi and Farmer, 1987).

The controlled flow system of the Bosphorus has a complex response to forcing on time scales from several days to a few years. Exchange flows, including storage resulting from sea-level changes in the Black Sea, blocking of flows, and seasonal, time-dependent elements of forcing has been considered by

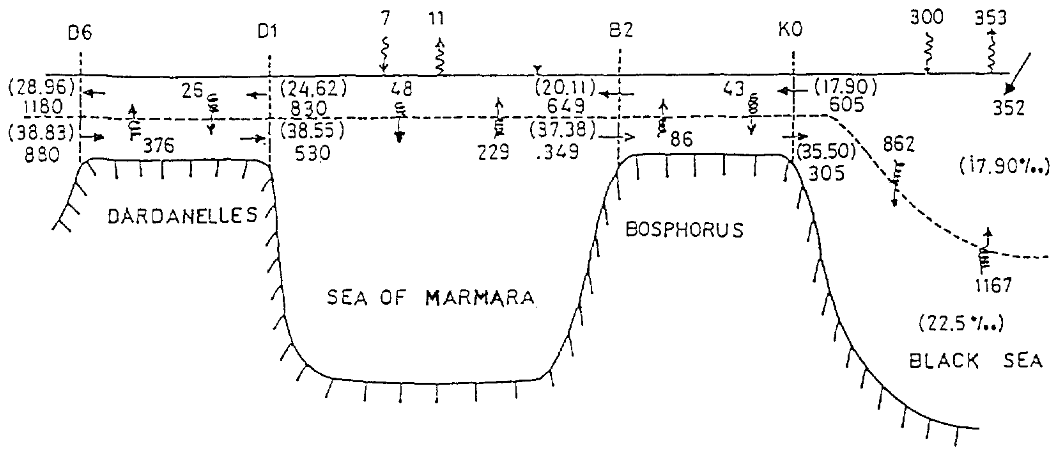

Fig. 5. Mean annual volume fluxes in the Turkish Straits System, after Ünlüata et al. (1990), and Latif et al. (1991). The fluxes are given in units of km^3/yr (1 $km^3/yr = 31.7\ m^3/s$). Numbers in parentheses are average salinity values used in the computations.

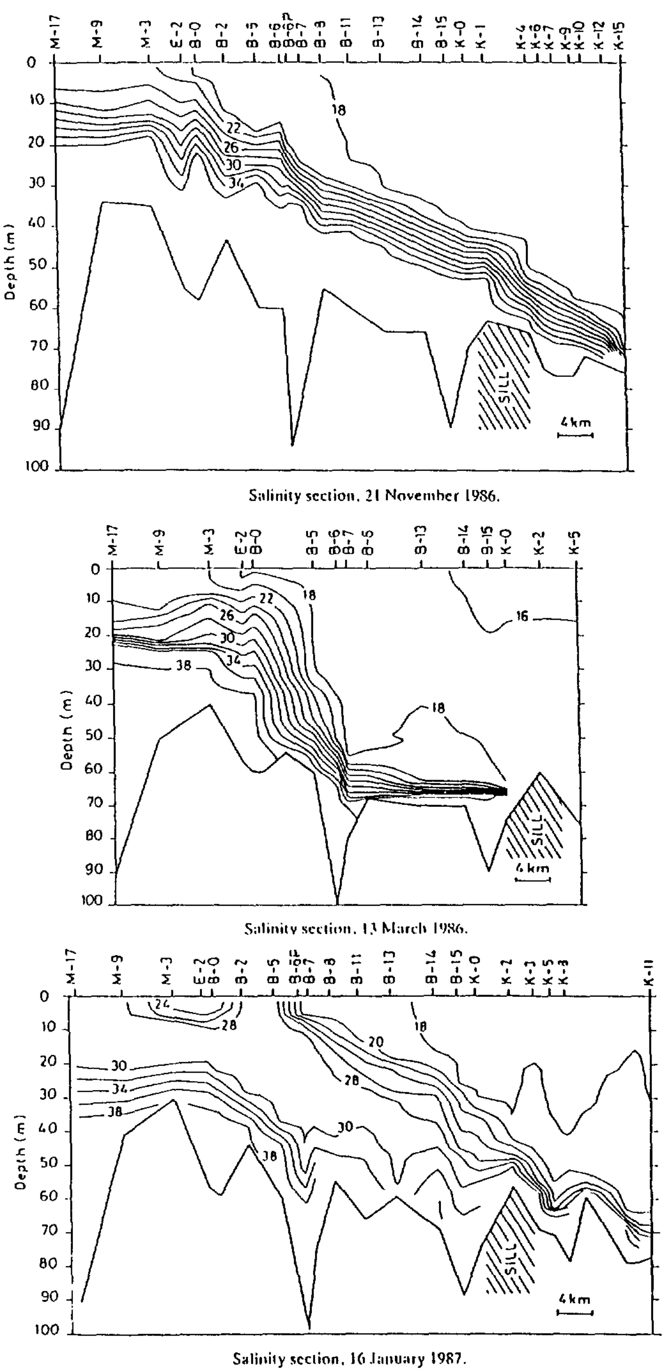

Fig. 6. The salinity distribution in the Bosphorus: (a) 'normal' two-layer exchange, (b) lower layer flow blocked at the northern sill, (c) upper layer blocked, with resulting three-layers. Hydraulic controls apply at the northern sill (st. K-2), and at the southern Bosphorus contraction (st. B-7).

Özsoy (1990) and Özsoy et al. (1996). The results suggest long-term changes in sea-level and currents, resulting from the interannual forcing of the Bosphorus by water budgets and atmospheric pressure differences. The exchange flows and sea-level in the Black Sea were shown to be correlated with the barometric pressure and net water fluxes (Özsoy et al., 1996) on time scales of a few days to several years. The results exemplified the difference between calculated steady fluxes and the observed temporal variability, depending on the flow regimes of the Bosphorus.

5. Water masses and vertical stratification

A peculiar vertical stratification is maintained in the Black Sea, with colder, fresher surface waters overlying warmer, more saline deep waters. The low salinity at the surface results from freshwater influence, while the higher salinity in deep waters is an imprint of the Mediterranean influence. The density in the subsurface waters is largely determined by salinity in the equation of state (except within the thin surface mixed layer of depth < 10–30 m, where temperature effects predominate in summer). As a result of the limiting effects of the salinity stratification on convection, the halocline and the pycnocline coincide at a typical depth interval of 100–200 m, which further coincides with the lower boundary for the Cold Intermediate Water (CIW), characterised by the 8°C limiting isotherm. The oxycline and the chemocline also occur in the same depth intervals as the halocline, because similar mechanisms determine the vertical exchange of these scalar properties. The

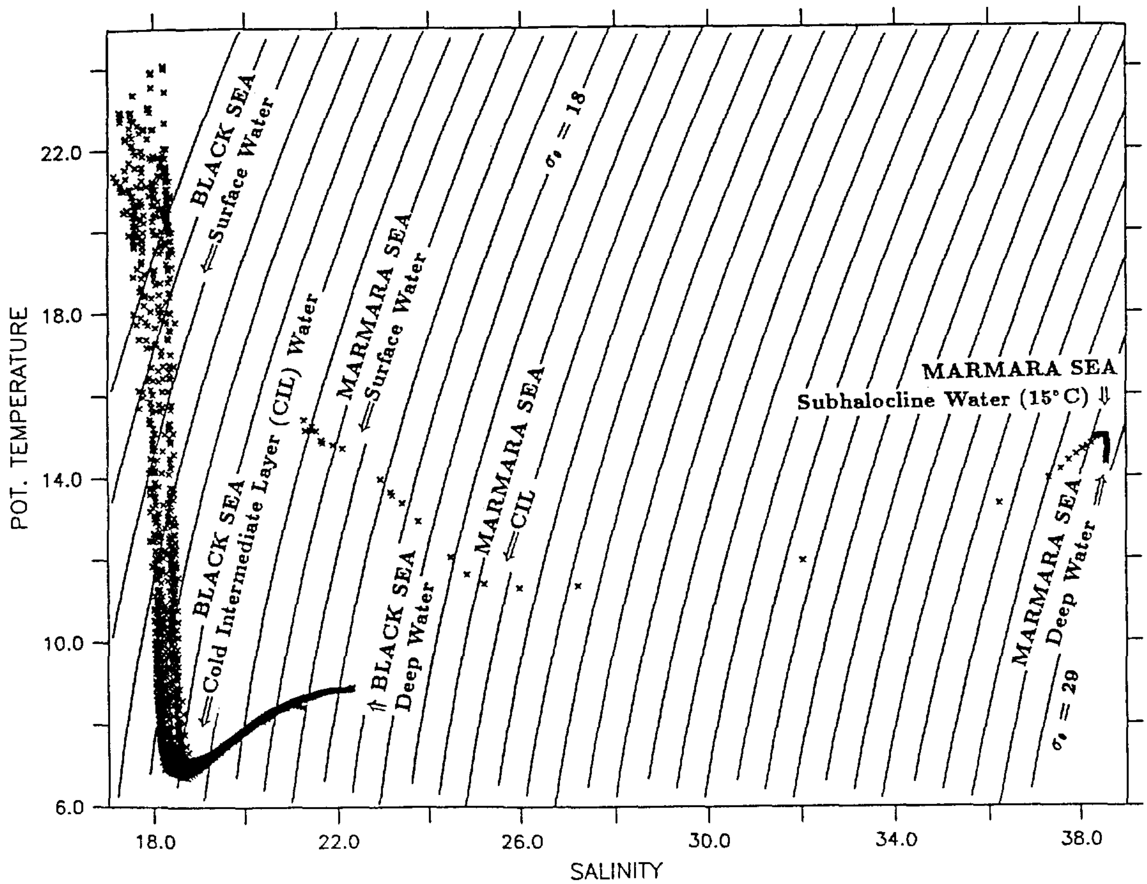

Fig. 7. Potential temperature versus salinity for Black Sea, with one station from Marmara Sea superimposed. The data are from the R/V *Knorr* Leg 4 Cruise in 1988 (after Özsoy et al., 1991).

chemical stratification has finer details (Shaffer, 1986; Murray et al., 1989, 1993; Murray, 1991) such as the suboxic zone (a transition layer between the oxic and anoxic domains), and particulate layers, etc., governed by redox reactions. Perhaps not so surprisingly from the point of a stratified biochemical regime, a zone of maximum mesoplankton concentration also coincides with the suboxic zone (Vinogradov et al., 1990).

Despite early claims on possible shoaling of the anoxic interface (Fashchuk and Ayzatullin, 1986; Bryantsev et al., 1988; Murray et al., 1989), the vertical position and structure of the chemocline appear reasonably stable within the last few decades, especially when compared with respect to the existing density stratification (Tuğrul et al., 1992; Saydam et al., 1993; Buesseler et al., 1994). However, seasonal and interannual temperature and salinity variations exist in the upper ocean and pycnocline regions (Murray et al., 1991; Ivanov et al., 1997a,b).

A thin (~ 30 m) mixed layer of low salinity (~ 18‰) responds strongly to seasonal heating and cooling at the surface. The Cold Intermediate Layer (CIL), characterized by the CIW, with minimum core temperatures of ~ 6°C, occurs between the permanent halocline and the seasonal thermocline. Because the CIW is capped by a warm surface layer in summer, it appears in the form of a subsurface temperature minimum. In winter, cooling and the ensuing convection establish an isothermal layer reaching depths of 70–80 m or deeper, with minimum temperatures of 6–7°C in most areas of the Black Sea, e.g. along the Turkish coast of the western Black Sea. There are regions where this mini-

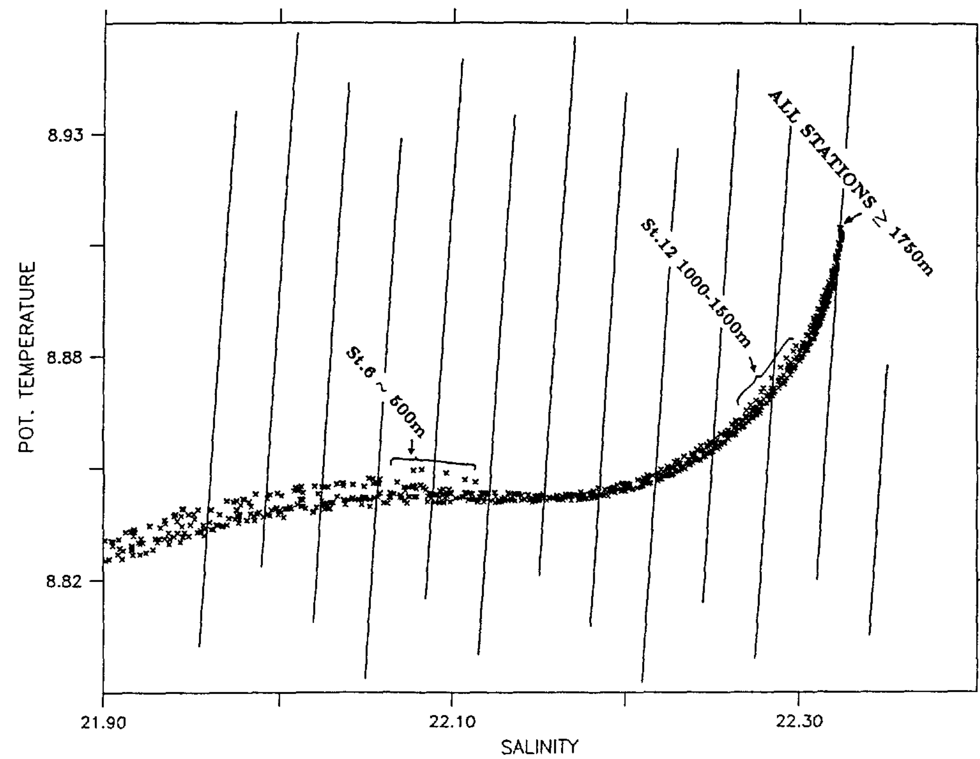

Fig. 8. Deep water potential temperature versus salinity (after Özsoy et al., 1991). All data below a depth of 1750 m collapse to a single point because of bottom convection.

mum temperature drops to extremely cold values: near the northernmost reaches of the NWS region, the water temperature decreases to a minimum of about 2°C in winter (Tolmazin, 1985a).

The variability of temperature and salinity in the waters below the halocline are much smaller. In fact, seasonal and interannual variability extends to depths of ~ 500 m, below the halocline, where intrusions of Mediterranean water entering from the Bosphorus drives the interior circulation and mixing (Özsoy et al., 1993a). The temperature and salinity characteristics of the Black Sea, observed during the 1988 R/V *Knorr* Leg 4 cruise, are depicted in Fig. 7, showing the above features (Özsoy et al., 1991). Data from a station in the neighbouring Marmara Sea has been superposed to show its relationship with the deep waters of the Black Sea.

The deep waters of the Black Sea below 500 m depth are essentially stagnant (Özsoy et al., 1991, 1993a), showing not much sign of change in properties, except near the boundaries, where local instabilities are able to produce fine structures (Özsoy and Beşiktepe, 1995). Below a depth of 1700 m, a bottom convection layer of thickness ~ 400 m is driven by geothermal heating from the sea floor (Özsoy et al., 1991, 1993a; Murray et al., 1991; Özsoy and Beşiktepe, 1995). The deep-water temperature/salinity diagrams (Fig. 8) show little sign of variability, and in the case of the Bottom Water below the 1700 m depth, collapses to a single point in temperature–salinity space (uniform potential temperature of 8.90°C and salinity of 22.32‰, (Murray et al., 1991). Closer examination of the properties of this layer based on multi-year intercalibrated data sets (Aubrey et al., 1992b; Oğuz et al., 1993c; Ivanov et al., 1994; Ivanov and Shkvorets, 1995) shows that it has a potential temperature of 8.893°C and salinity of 22.333‰, with a variation of less than 0.001 units in both potential temperature and salinity across the basin.

Horizontal variability of the salinity and temperature stratification is mainly associated with the motion fields. Because diapycnal mixing is limited, and decays rapidly with depth, the horizontal density variations at the pycnocline are mainly associated with the geostrophic currents, with the depth and structure of the pycnocline changes occurring between the cyclonic central part and the anticyclonic regions near the basin boundary, as well as within the eddy fields (Oğuz et al., 1993a; Saydam et al., 1993; Bingel et al., 1994).

6. Mixing and convection processes

6.1. Cold Intermediate Water (CIW) formation and spreading

Despite its great importance in affecting the physical and biochemical structure of the basin, the exact mechanism and sources of the Cold Intermediate Water (CIW) formation are not exactly clear. Evidently the process of CIW formation is one that is closely related with the intensity and localization of convection events corresponding to specific meteorological and hydrodynamical conditions, under conditions of local circulation, frontal dynamics and interaction with shelf topography.

Conflicting hypotheses have been advanced to date: early Soviet oceanographers in the 1930s attributed CIW formation to local mixed layer deepening by winter convection. Later observations revealed some contradictions: often the CIW core occurred deeper than the maximum depth reached by the mixed layer. Furthermore, the CIW core properties were relatively uniform in the interior region, and did not correlate well with the surface gradients of meteorological fields. These observations soon brought up the question of advective contributions to CIW. Based on observations of extremely cold water in the north, it was proposed that CIW is formed in the northwestern shelf (NWS) region of the Black Sea and in the proximity of the Kerch Strait (Filippov, 1965; Tolmazin, 1985a). On the other hand, in a revival of earlier hypotheses, supported by a set of new CTD measurements, Ovchinnikov and Popov (1987) proposed the centres of cyclonic gyres to be CIW formation regions. Their scheme of local convection, mainly confined to the open waters, and presumably feeding the peripheral CIW by isopycnal advection, has, since then, been supported in a number of other studies (Isaeva et al., 1987; Kaminskey et al., 1989; Oğuz et al., 1991). In reality, the CIW formation seems to be a result of more complex convective processes not adequately described by these simple models (Ivanov et al., 1997a).

The shallow (depth < 100 m) NWS region, sub-

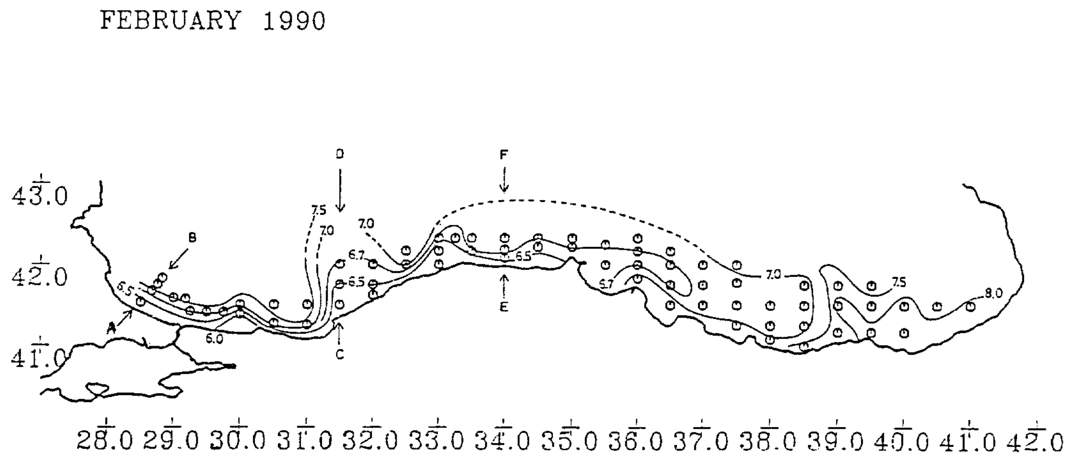

Fig. 9. Surface temperature distribution during the February 1990 cruise of the R/V *Bilim*.

ject to a large influx of riverine waters and cold and dry northerly winds, constitutes the coldest part of the Black Sea throughout the year. The cooling season coincides with the period of decreased riverine fluxes, promoting an increase in the shelf salinity. The resulting cold shelf water in winter is therefore denser than the remaining part of the Black Sea surface waters (Tolmazin, 1985a).

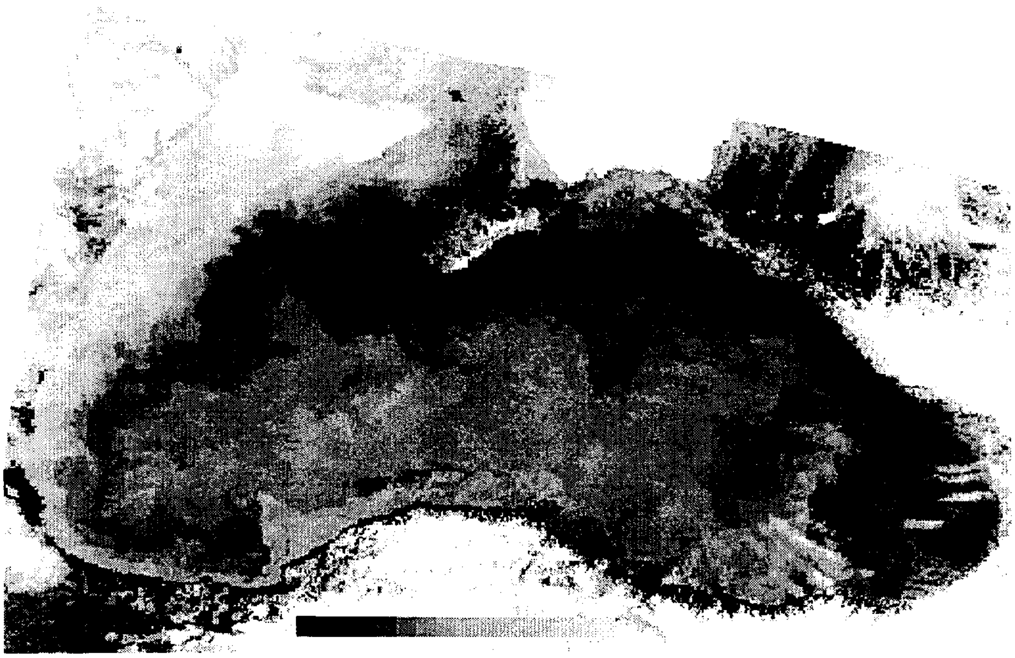

Fig. 10. Advanced very high-resolution radiometer (AVHRR) satellite image on February 27, 1990. The satellite images represent atmospherically uncorrected (NOAA-10) channel 4 where darker tones represent warmer water, and the lighter tones represent colder water. After Sur et al. (1996).

Because winter data are limited, it is usually difficult to show uniform properties on the shelf. Tolmazin (1985a) describes vertically uniform temperatures of 2–5°C in the NWS region (colder near the northern end) in March, 1962. Observations in April, 1993 (Bingel et al., 1994) showed residual cold water of 4–5°C trapped in the shallower part of the NWS, partly advected to the south along the shelf.

The available satellite and hydrographic observations suggest the entire western shelf to be a formation and advection region of cold water. Based on measurements near the southern coast, Sur et al. (1994) detected the southern extension of a coastal band of cold water in February 1990 (Fig. 9) with uniform temperature and salinity values of ~ 6.5°C and < 18‰ in the southeastern Black Sea. The same feature was evident in an infra-red (AVHRR) satellite image (Fig. 10), showing a vein of cold water along the entire western continental shelf (depth < 100 m), contrasting sharply with the warmer waters in the offshore region. The band of cold water was apparently a stable feature formed along the inner western shelf, as it was observed to cover almost the same area in satellite images earlier in January 1990, during the same winter (Ünlüata and LaViolette, 1990). A similar feature, with cold water covering the entire western shelf region, is observed in Fig. 11, in February 1994. In about 10 days between the first image on February 17 (Fig. 11a), and the second one in February 28, 1994 (Fig. 11b), significant changes occur in the sea surface temperature. In the first image, near-freezing temperatures of about 1–2°C occur very near the coast in the NWS region,

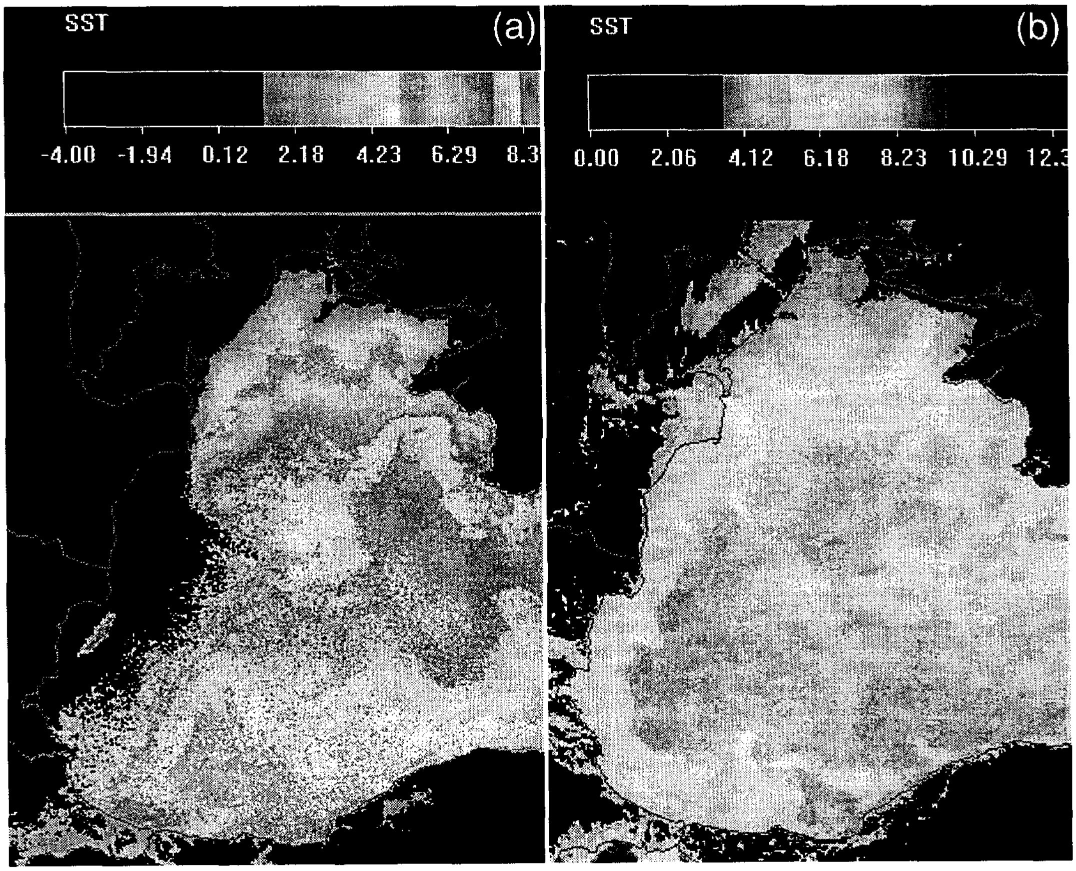

Fig. 11. SST derived from advanced very high-resolution radiometer (AVHRR) satellite images on (a) February 17, and (b) February 28, 1994.

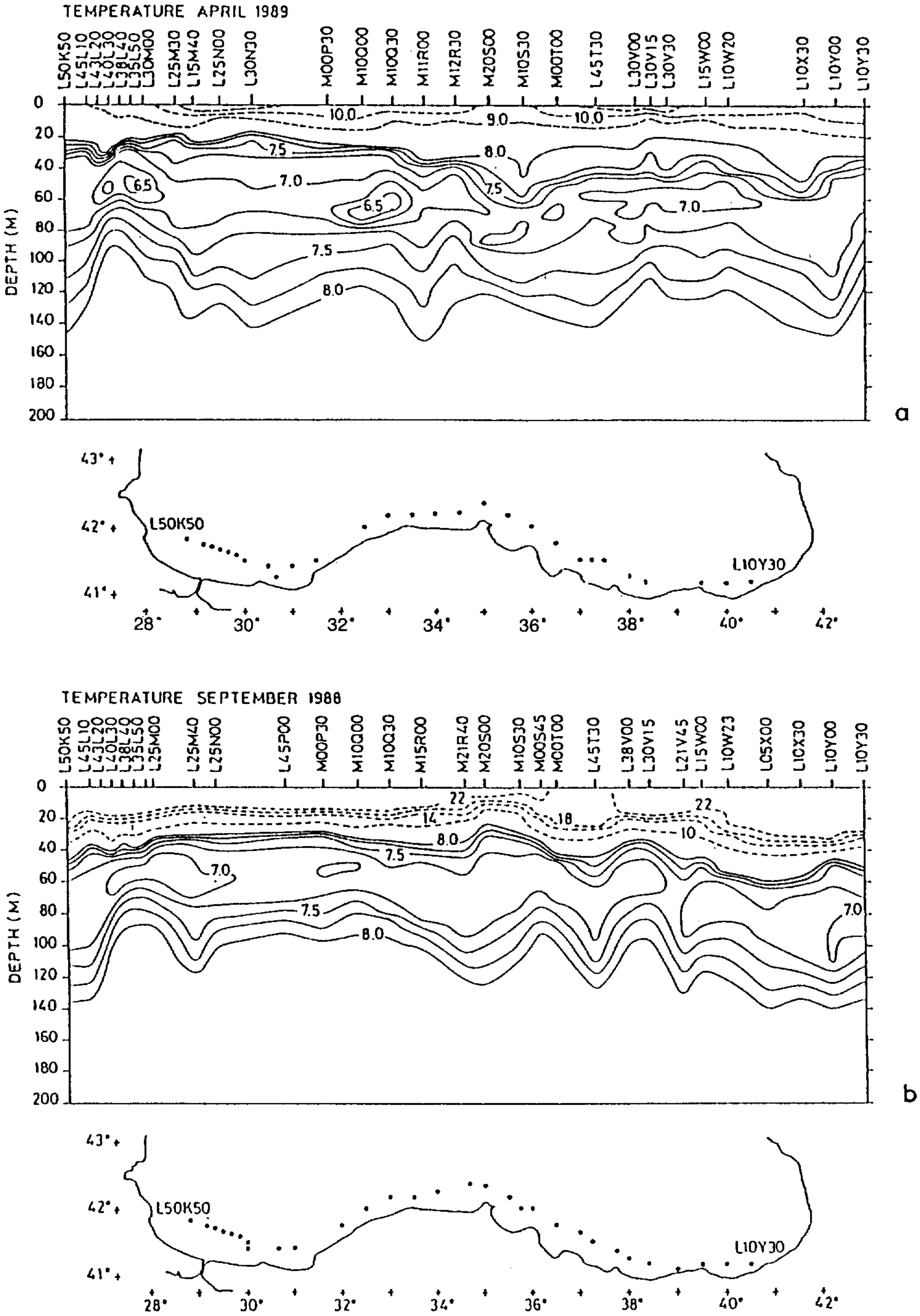

Fig. 12. Vertical sections of temperature along the shelf break of the Turkish coast in (a) September 1988, (b) April 1989 surveys of the R/V *Bilim*. After Oğuz et al. (1991).

replaced by slightly warmer temperatures later. In the second image (Fig. 11b) the cold water extends further south along the western shelf. In this case, the temperature gradient of the shelf break front is decreasing towards the south, as a result of the numerous mesoscale eddies participating in the horizontal mixing. Based on these observations, it is conceivable that a cold, dense water mass is created in the shallow shelf region by riverine waters and convection processes by cooling analogous to the water mass formation on the Adriatic Sea continental shelf (Malanotte-Rizzoli, 1991).

Yet, the winter observations are too scarce to establish a direct link between the observed cold shelf water and the CIW. Cascading of the shelf formed cold water along the continental slope could potentially contribute to the CIW core, if one were able to show the density of the cold shelf water to be comparable with the target water mass. Although it is clear that the cold water in the northernmost area could reach densities nearly as high as the CIW core, the same cannot be claimed for the rest of the western shelf. On the other hand, the shelf or peripheral water is effectively isolated from the interior CIW by a front coincident with the continental slope region (Ivanov et al., 1994), though, frontal or shelf break processes would contribute a limited transport of cold water into the CIW core.

Changes in CIW properties, in relation to water mass formation, are shown in the two consecutive temperature sections of Fig. 12. Between September 1988 and April 1989, the thickness of the Cold Intermediate Layer increased, and the minimum (core) temperature decreased, by an annual contribution to the water mass. As compared to the uniform distribution in autumn 1988, the decrease of the temperatures from west to east in spring 1989 suggests advection away from sources in the west (Oğuz et al., 1991). The cold spots are the intersections with the CIW core transported along the meandering boundary current. Eddy dispersion, and mixing generated by topographic irregularities such as Sakarya Canyon are potential factors contributing to the eastward increase of temperature in the CIW core (Özsoy et al., 1993a).

Recent studies indicate that the CIW, once formed, is stored in the anticyclonic circulations along the periphery. After the extreme cold winter of 1991–1992, water mass characteristics indicated massive formation of CIW during that winter, both as a result of local convection and by advection and mixing of cold shelf water. The greatest change in stored heat occurred on the periphery, along the 'rim current' (Ivanov et al., 1997a), showing that the formation process most intensively takes place in the neighbouring regions. The CIW was massively formed after the extreme cold winter of 1991–1992, as a result of local convection and by advection and mixing of cold shelf water along the continental slope periphery (Ivanov et al., 1997a), which continued to affect the pycnocline for a number of years after the event (Ivanov et al., 1997b). In the case of the Black Sea, the frontal mixing of cold, low-salinity shelf water with warmer, more saline offshore water in winter (Fig. 11) appears to be important in forming a new water mass contributing to CIW.

The particular geometry of the western shelf appears important. Convection and the resultant water mass production on a shallow continental shelf is known to be significantly more efficient in the case of 'long' shelf regions, based on the intensification of cooling by rotational effects (Whitehead, 1993). It can be stated that the western Black Sea shelf satisfies Whitehead's criterion for rotational effects, since its length ($\sim$ 600 km) is equal to or greater than the critical length scale $L_c \approx 200-600$ km, corresponding to typical values of shelf width (50–100 km), mean depth (100 m), and mean winter heat flux ($H = 200$ W m^{-2}). Again, with these values, one would expect a temperature difference of > 8°C across the shelf break front, compared with the $\sim$ 5°C difference observed in Fig. 11.

Frontal baroclinic eddies and filaments, similar to Fig. 11, are evident in laboratory experiments on shelf convection (Whitehead, 1993). When water is cooled on a wide shelf, a shelf break density front with a corresponding jet is created (Symonds and Gardiner-Garden, 1994), with possible ensuing instabilities that could generate the observed structure. Similar structures have been observed along other freshwater driven coastal currents, e.g. the Norwegian Coastal Current (Johannessen et al., 1989). The cold water trapped on the shelf does not immediately mix with the interior waters, but is expected eventually to either sink along the continental slope or cascade down the numerous canyons (not adequately resolved in Fig. 1), cutting across the continental slope (Sugimoto and Whitehead, 1983; Bignami et al., 1990). The sudden and dramatic termination of the cold shelf water in the southwestern Black Sea region near the Bosphorus and Sakarya canyons (Figs. 1 and 11) suggests possible canyon processes in this region (Sur et al., 1994, 1996).

Although a coherent picture of the mechanisms leading to CIW formation does not emerge from the above discussion, it is evident that mesoscale frontal and topographic processes, downwelling anticyclonic eddies, as well as convection near continental slopes are important elements. Recent modelling experiments addressing the formation of CIW to some extent suggest that all of the above processes should indeed be important (e.g. Oğuz and Malanotte-Rizzoli, 1996; Staneva and Stanev, 1997).

6.2. Climatic variability

Because the Black Sea is an enclosed basin, it responds sensitively to interannual and longer-term

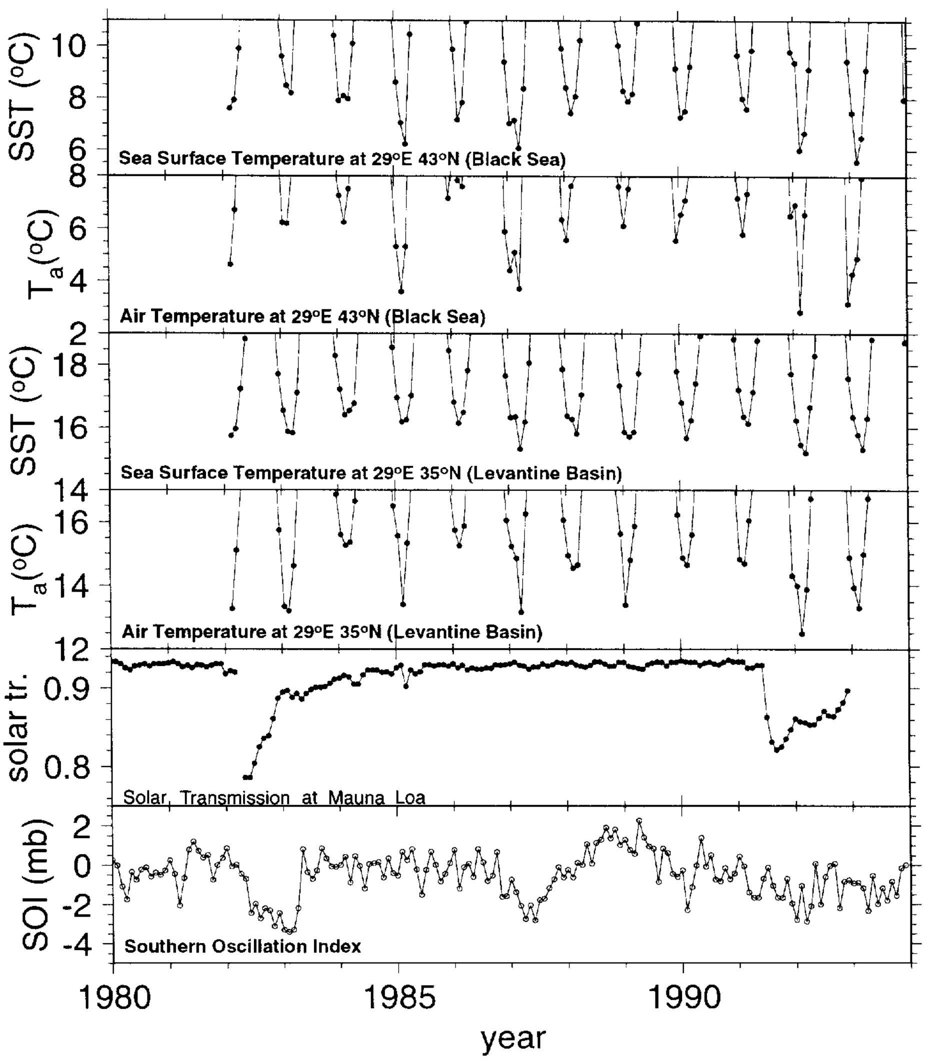

Fig. 13. Time series of surface temperature (SST) and air temperature (T_a) in 2-degree squares centred at 29°E, 43°N in the Black Sea (uppermost panels) and at 29°E, 35°N in the Levantine basin of the eastern Mediterranean Sea (middle panels, solar transmission at Mauna Loa, and the Southern Oscillation Index (lower panels).

climatic variability in atmospheric fluxes, which are well recorded in the structure of its stable pycnocline.

Long-term data (more than 40 years in duration) suggest strong climatic changes in the features of the upper ocean influenced by convection (an archive of historical and recent data constructed at the IMS-METU; H.İ. Sur, pers. commun.), with synchronism suggested with the adjacent seas. For example, an extreme event of cooling evidently took place in

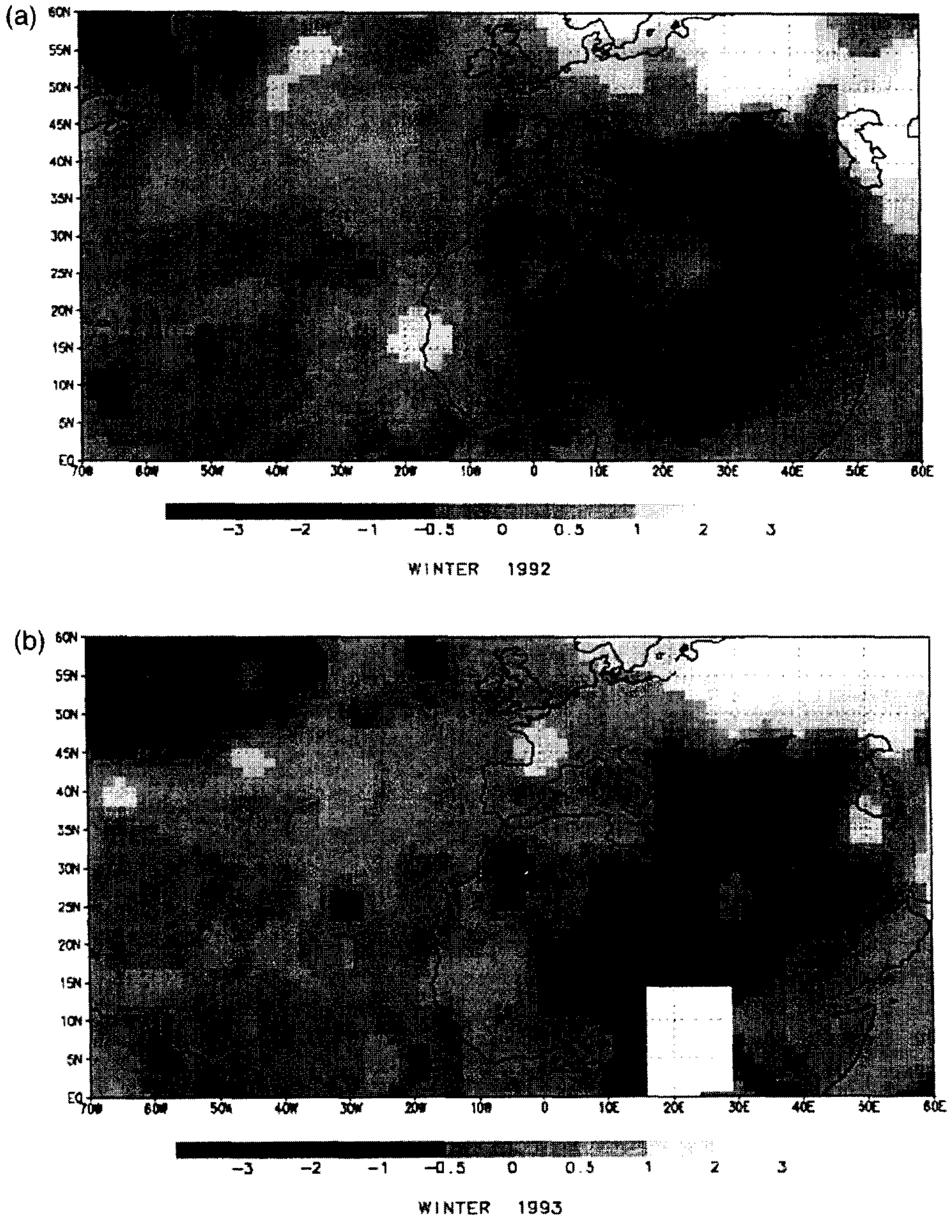

Fig. 14. Temperature anomalies for the winter seasons of (a) 1992 and (b) 1993, showing extreme cooling in the eastern Mediterranean–Black Sea–North African regions during both years. Merged ocean and atmospheric climatological temperature data sets are used (after Baker et al., 1995).

1987, when similar effects were noted in the surrounding seas, e.g. dense water intrusion into the Marmara Sea from the Aegean (Beşiktepe et al., 1993; Beşiktepe et al., 1994), and deep water formation in the Rhodes Gyre region (Gertman et al., 1990). It is tempting to note that an extraordinary productivity event was detected in the Black Sea, occurring some time between May 1986 and July 1988, based on radioactive dating of fresh bottom sediments present in the 'fluff layers' adjacent to the bottom (Moore and O'Neill, 1991). CIW formation with extreme properties was repeated in 1992 (Ivanov et al., 1997b), when deep water formation simultaneously recurred in the Rhodes Gyre region (Sur et al., 1992; Özsoy et al., 1993b). The strong cooling event in 1992 changed the main pycnocline structure in the Black Sea, with effects lasting for a number of years after the event (Ivanov et al., 1997b).

The changes in air temperature (T_a) and sea surface temperature (SST) during the recent years in 2-degree squares in the Black Sea, centred at 29°E 43°N and in the Levantine Basin of the eastern Mediterranean Sea, centred at 29°E 35°N, are shown in Fig. 13, based on the COADS data set (Woodruff et al., 1993). The extreme cold values of the surface air temperature, corresponding to severe winters, occurred simultaneously in both areas in 1982, 1985, 1987 1992 and 1993, with corresponding minimum values reflected in the SST. As indicators of global effects, the solar transmission time series measured at Mauna Loa (Dutton, 1994), and the Southern Oscillation Index (SOI), i.e. the mean sea-level pressure difference between Darwin and Tahiti (Reports to the Nation, 1994).

In the case of winter 1991–1992, the cooling event appears to be linked with the persistent atmospheric anomaly pattern that occurred in the eastern Mediterranean/Black Sea region (Özsoy and Latif, 1996) following the eruption of Mount Pinatubo in June 1991. The Pinatubo eruption was an event of global significance with effects (Fiocco et al., 1996) on decreased solar energy input (Dutton, 1994), especially in the Northern Hemisphere, and anomalous atmospheric conditions in the following years (Halpert et al., 1993; Boden et al., 1994). The surface atmospheric and sea temperature anomalies in Fig. 14, derived from climatological data sets (Baker et al., 1995), show similar patterns of cold anomalies in the 'Middle East' region in the winters of both 1992 and 1993. In Turkey, the winter of 1992 was the coldest in the last 60 years (Türkeş et al., 1995), and in Israel, it was the coldest in the last 46 years (Genin et al., 1995).

The other case of a decrease in the atmospheric solar transmission is the eruption of the El Chichon in 1982, which precedes an El Niño (SOI) anomaly. The winter of 1982, as well as the 1985 and 1989 (Levantine) cooling events in Fig. 13 remain unexplained by both factors, and could be local anomalies.

It is clear that, at least during the recent observation periods, there has been good correspondence between eastern Mediterranean and Black Sea cooling events. Some of the cold years in Fig. 13 correspond well with ENSO events signified by the negative values of the Southern Oscillation (El Niño) Index (e.g. 1982–1983 (?), 1986–1987, 1991–1992 (?), evident in Fig. 13, and as cited in Meyers and O'Brien (1995), and other anomalous cold years (e.g. 1992–1993) appear connected with the Pinatubo volcanic eruption, although positive physical linkages cannot be proved at present.

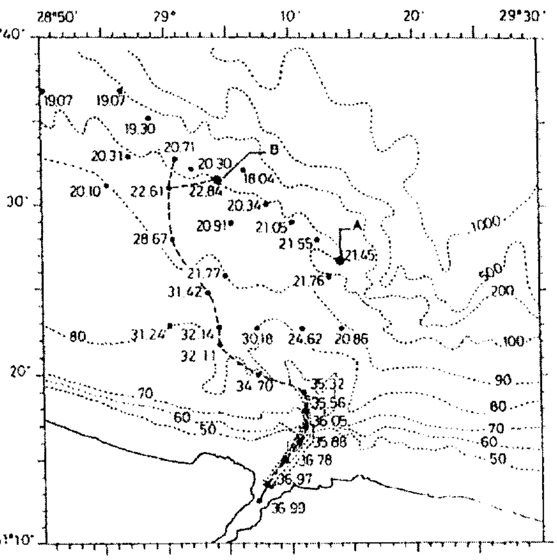

Fig. 15. The bathymetry and the distribution of bottom salinity on the southwest Black Sea shelf region adjoining the Bosphorus during *Bilim* 2 cruise (after Latif et al., 1991). The sill controlling the flow of dense Mediterranean water has a depth of 60 m, located north of the Bosphorus exit and inside a bottom channel leading from the exit to the shelf region.

Although the short- and long-term atmospheric variability in the eastern Mediterranean Black Sea regions is well known, hypotheses on teleconnections with global atmospheric events, via coupling with the Indian Monsoon system have recently been put forward (Ward, 1995). Polonsky et al. (1997)

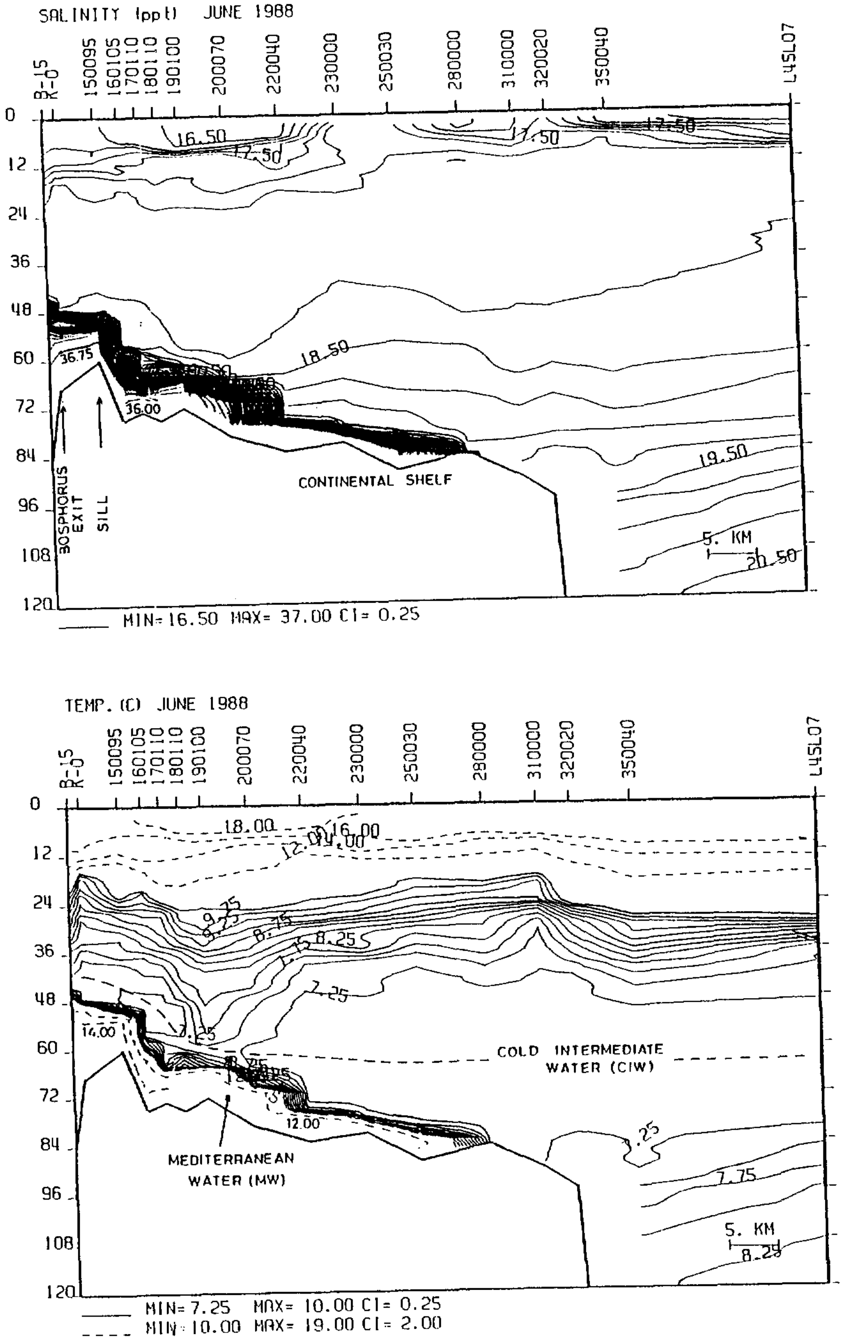

Fig. 16. (a) Salinity and (b) temperature cross-sections across a transect extending from the Bosphorus towards deep water, and following the bottom channel carrying the Mediterranean inflow, denoted by the dashed line in Fig. 16. After Özsoy et al. (1993a).

have shown good correlation between North Atlantic SST variability and the Black Sea hydrology, as an indicator of the global ocean–atmosphere coupling.

6.3. The Mediterranean water influx and effects on the Black Sea interior

6.3.1. Shelf mixing and entrainment of the Mediterranean effluent

The cross-shelf spreading of the Mediterranean inflow in the Black Sea has been described earlier by Tolmazin (1985b) and Yüce (1990), and a full account, based on carefully designed experiments has been given by Latif et al. (1991). Further investigations of the Mediterranean outflow have been continued in 1994 (Gregg, 1995), and in 1996 during the visit of the NATO ship R/V *Alliance*, resulting in a historic data set promising to yield further details.

Topography plays an important role in the exit region. The warm, saline Mediterranean water entering the Black Sea through the lower layer of the Bosphorus initially overflows a sill located some 3–4 km northeast of the Bosphorus exit, then follows a steep bottom channel towards the northwest, to reach the flat mid-shelf region where it spreads to form a thin sheet of anomalous bottom water (Latif et al., 1991). The trajectory of the Mediterranean Water on the shelf is revealed by the maximum

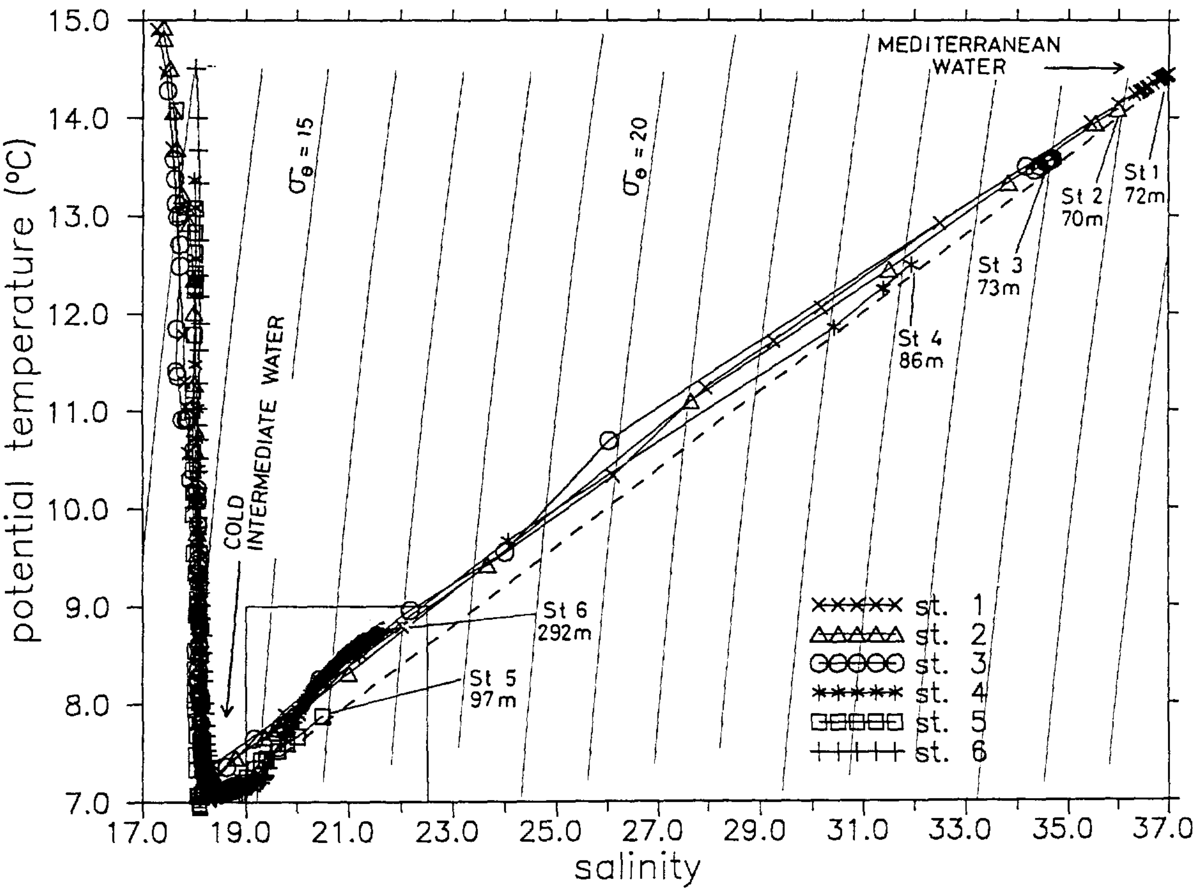

Fig. 17. Evolution of temperature – salinity across the shelf. Stations 1–5 extend from the Bosphorus to the shelf break. Station 6 is a deeper station immediately offshore. The dashed line models the changes in the 'Mediterranean effluent' at the bottom. At the shelf break (station 5), the modified bottom waters are colder than the waters at comparable depths of the continental slope (station 6). After Özsoy et al. (1993a).

bottom salinities displayed in Fig. 15. The Mediterranean Water is in the form of a thin vein of negatively buoyant flow along the same trajectory (Fig. 16). Where the flow is confined in the channel it has a thickness of about 10 m; when it reaches the flat region its thickness decreases to ~2–3 m, becoming more difficult to detect, except within delta-like structures cutting across the bottom (observed on echosounder records).

The layer of water with minimum temperature at depths of 50–75 m in Fig. 16a is the Cold Intermediate Water (CIW). By mixing with the overlying CIW, the temperature at the core of Mediterranean Water rapidly decreases from 14.5°C at the northern end of the Bosphorus to about 8°C at the shelf break. Similarly, the salinity in the core declines from about 37‰ at the Bosphorus exit to a maximum of 22.8‰ along the shelf break at the head of a canyon feature at around 41°35′N and 29°E (Özsoy et al., 1993a).

We note that, due to the depth range of the sill and the adjoining shelf region, the warm saline (dense) Mediterranean Water discharged from the Bosphorus comes into direct contact with the CIW, and entrains it. Fig. 17 shows the changing temperature–salinity characteristics at selected stations (along the same section as Fig. 16), where CTD data were obtained within a few metres of the bottom, to detect the Mediterranean inflow. Direct mixing of the Mediterranean Water with the CIW results in a linear evolution of the bottom water modelled by the dashed line. When the dense bottom water reaches the shelf edge (Station 5), it has become colder, yet more saline than the environment on the continental slope (Station 6), where both temperature and salinity increase with depth. The initially warm and salty Mediterranean Water is thus transformed into water differentiated from the ambient waters with a cold anomaly. Finally, when this water sinks along the continental slope to form intermediate depth intrusions, it continues to carry this signature of the Cold Intermediate Water impressed upon it on the shelf (Özsoy et al., 1993a). Based on salinity changes across the shelf, the ratio of the entrainment flow (Q_I) to the Bosphorus outflow (Q_B) is estimated to

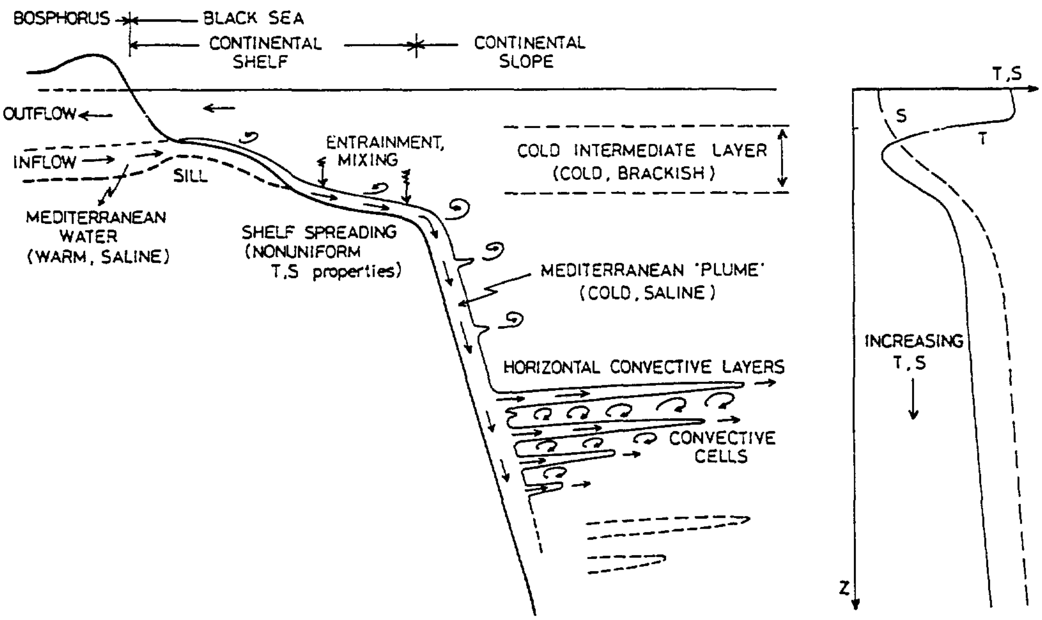

Fig. 18. Schematization of the boundary mixing processes driven by the Mediterranean effluent issuing from the Bosphorus. Linear, direct mixing occurs on the shelf region and on part of the slope. At intermediate depths, double diffusive instabilities are generated due to the temperature and salinity contrasts of the intrusions and the potential instability of the interior. After Özsoy et al. (1993a).

be $Q_I/Q_B \approx 3 - -6$ (Özsoy et al., 1993a). 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., 1990; Swart, 1991; Koczy and Östlund (1966, quoted by Buesseler et al. (1991).

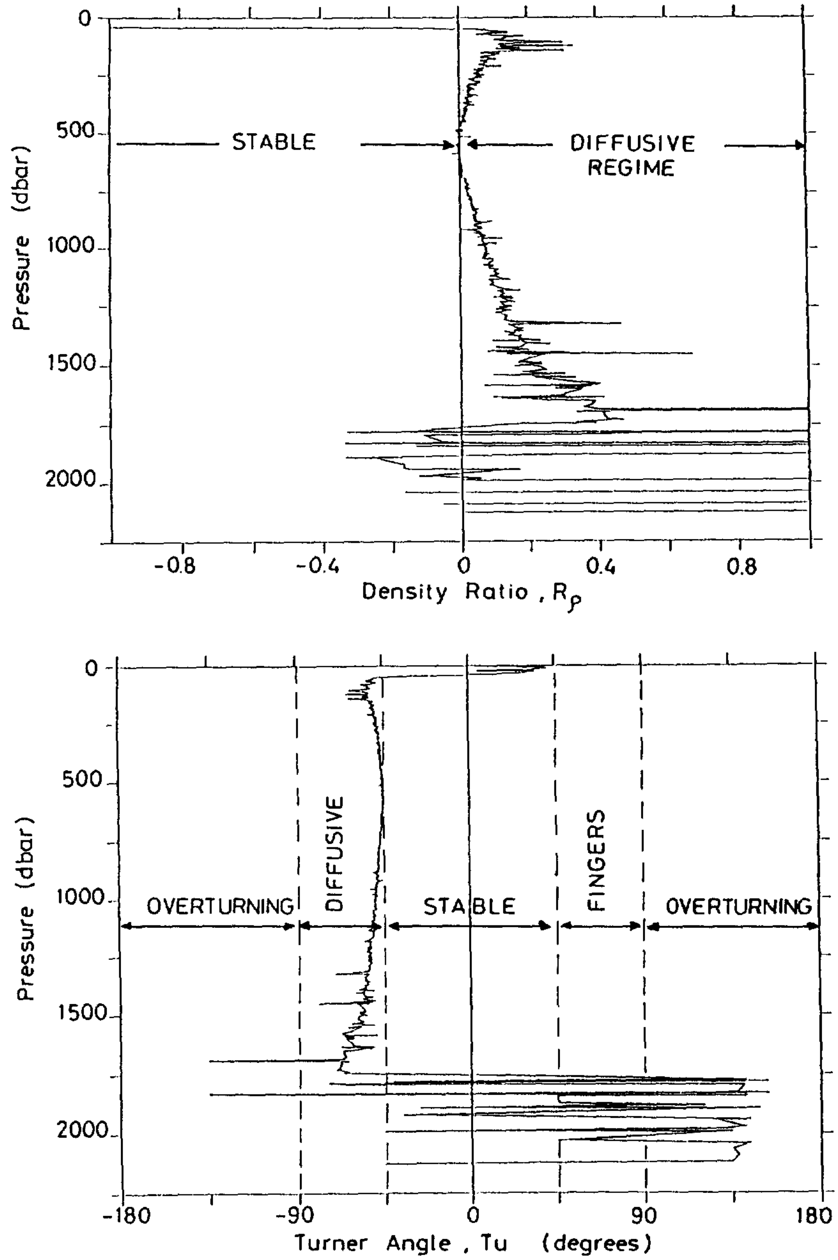

Fig. 19. The average stratification parameters computed from an ensemble of Black Sea deep water profiles: (a) the density ratio $R_\rho = (\alpha dT/dz)/(\beta dS/dz)$, and (b) the Turner angle $\mathrm{Tu} = \tan^{-1}(R_\rho + 1)/(R_\rho - 1)$, where α and β are coefficients of expansion for temperature and salinity. The ranges for stable, statically unstable, and double diffusively unstable regimes are indicated. After Özsoy et al. (1993a).

A reduced gravity model of the dense water outflow on the shelf (Simeonov et al., 1997), including the spreading and plume phases along the continental shelf and slope regions has been used to study the water mixing properties and distribution.

6.3.2. Double diffusive intrusions

Intrusions of anomalous waters in the vicinity of the Bosphorus have often been noted in the past. Bogdanova (1961) and Boguslavskiy et al. (1982) have claimed to have observed warm lenses of Mediterranean water within the interior of the basin. Recently, measurements with more accurate instruments have also shown fine structures in the region with cold water anomalies (Oğuz et al., 1991; Oğuz and Rozman, 1991; Özsoy et al., 1991, 1993a). The characteristics of the anomalous waters observed in the vicinity of the Bosphorus by Bogdanova (1961) and cited in Tolmazin (1985b) do not match the description based on these recent measurements. The large positive temperature anomaly and the magnitude of salinity anomalies reported by Bogdanova (1961) are not consistent with the present-day observations, and could be artificially created by the older instrumentation they used.

The cascading of the shelf-modified cold dense water along the shelf slope apparently results in a series of intrusions in the vicinity of the Bosphorus. The unstable intrusions are driven by salinity–temperature contrasts of the sinking modified shelf waters, and aided by the double diffusive instabilities of the interior (ambient) stratification (Turner, 1978). As a result, a unique convection pattern is generated adjacent to the southwestern margins of the Black Sea. The boundary mixing processes resulting from the Bosphorus inflow, its shelf mixing and the double diffusive convection, in the form of laterally penetrating intrusions along the continental slope are schematized in Fig. 18 (Özsoy et al., 1993a).

The 'Christmas-tree' pattern of double diffusive convection schematised in Fig. 18 is in many ways similar to the pattern triggered by two-dimensional effects (e.g. lateral boundaries) and by buoyancy sources in stratified environments with two diffusing properties, characterized by a series of alternating diffusive/fingering interfaces (Turner, 1973, 1978;

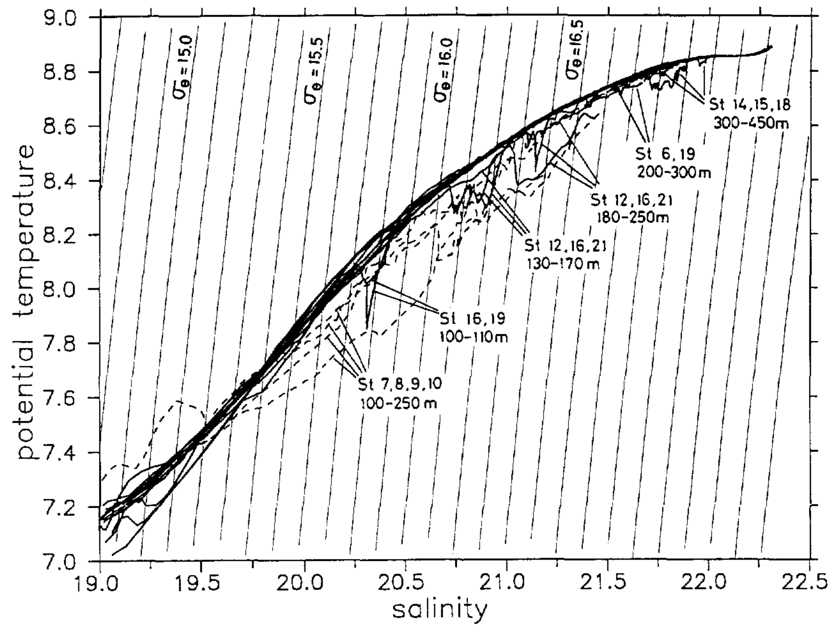

Fig. 20. The potential temperature–salinity relationship for stations near the southwestern shelf of the Black Sea. Dashed lines represent stations closest to the continental slope, i.e. within the boundary layer. The intrusive features at other stations offshore of the shelf region occur in the form of discrete layers spreading into the interior. After Özsoy et al. (1993a).

Huppert and Turner, 1980; Tanny and Tsinober, 1988; Jeevaraj and Imberger, 1991). Examination of the stratification parameters (the density ratio and Turner angle, Fig. 19) indicate a potentially unstable double diffusive regime (diffusive range) in the entire water column of the Black Sea below the CIW core (depth ≥ 50–100 m), capable of supporting various types of instabilities. Short-term variability and intermittency are basic features of the intrusions (Özsoy et al., 1993a).

Additional factors influencing the intermittency and filamentation appear to be the interaction of the sinking flow with many canyon features and local currents in the region. The interaction of the currents with the abrupt topography of Sakarya Canyon is shown to have singular effects on the cross-shelf transports in the immediate vicinity (Özsoy et al., 1993a; Sur et al., 1994).

In the temperature versus salinity diagrams (Fig. 20), the intrusions are identified first as a cold sheet of water on the continental slope (dashed lines), then as discrete layers of anomalous characteristics in the entire neighbourhood of the Bosphorus, extending hundreds of km east of the source.

Transport is motivated by the horizontal spreading of 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 Chernobyll radiotracers and shelf-derived particulates (Buesseler et al., 1991; Özsoy et al., 1993a). The perfect coincidence of seawater, particulate and nutrient anomalies (Codispoti et al., 1991; Özsoy et al., 1993a), such as shown in Fig. 21, indicate a common source of the materials that can be traced back to the southwest margin of the Black Sea. Much diluted imprints are also found further along the Anatolian coast (Kempe et al., 1991).

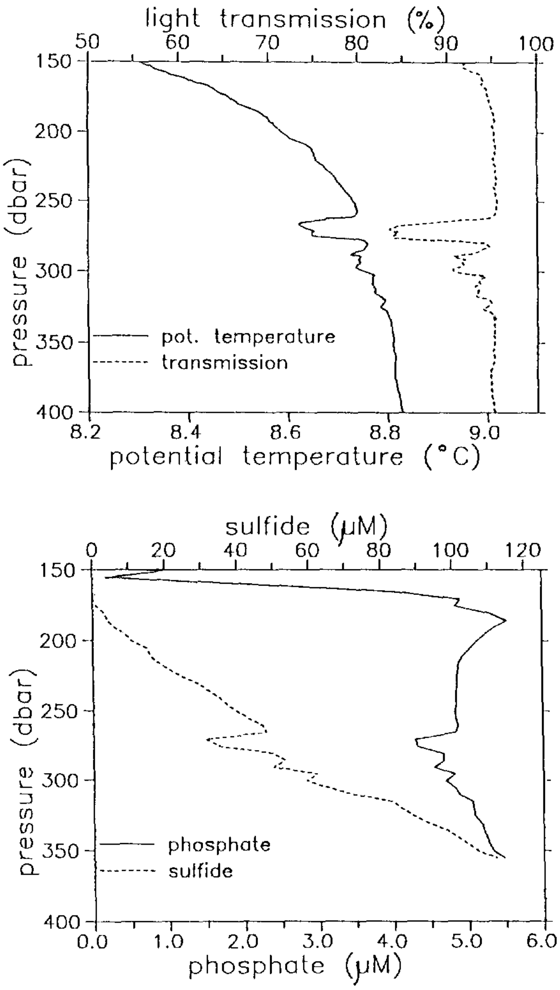

Fig. 21. Potential temperature, light transmission, sulphide and phosphate profiles in the southwestern Black Sea. The intrusions advect the water properties modified on the shelf and the continental slope, into the interior. Because the intrusions are below the pycnocline (or the oxycline), they contribute to the mixing across the halocline. After Özsoy et al. (1993a).

6.3.3. Mixing and ventilation in the Black Sea interior

An important result of the boundary mixing processes is the transport patterns 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. Spencer et al., 1972; Brewer and Spencer, 1974; İzdar et al., 1987; Hay, 1987; Honjo et al., 1987; Kempe et al., 1991). Buesseler et al. (1991) found injections of particulate Iron, Manganese and radioisotopes below the anoxic interface and a rapid deepening of fallout after the Chernobyll disaster, implying efficient ventilation across the halocline. Based on a time series of measurements, Buesseler and Livingston (1997) show a rapid decrease in the cross-pycnocline gradient of Chernobyll tracers since the initial fallout.

Based on the observation of a zone of vanishing vertical gradients in the potential temperature profiles, Özsoy et al. (1993a) estimated the maximum penetration depth of Bosphorus intrusions to be ~ 500 m, and suggested that the double diffusive fluxes would likewise vanish at this depth. This limit on the depth of efficient vertical mixing is consistent with the 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; Östlund and Dyrssen, 1986). The Tritium from atmospheric sources has only penetrated to about the same depth (Top et al., 1991).

Interestingly, Grasshoff (1975) attributed the ventilation of the upper water column to mixing along the Anatolian coastal margin. Özsoy et al. (1993a) showed the importance of the Mediterranean intrusions and interaction of boundary currents with Sakarya Canyon topography, in generating mixing in the southwestern Black Sea. Sur et al. (1994) found topographic and frontal instabilities of the boundary current leading to additional mixing along this coast.

The mixing in the southwestern shelf and slope regions are significant in terms of the interior circulation. The Black Sea interior stratification appears strongly coupled to the boundary transports. The intermittent terminations of the density currents along the continental slope (Fig. 18) suggest a time and depth dependent source function of water introduced into the halocline region, generating a recirculation in the upper part of the interior, schematized in Fig. 22. The termination of boundary currents in a wide area of the continental slope is consistent with the random termination ventilation model of Rooth (1986), and with a similar model of Stigebrandt (1987) who used it to explain the monotonously increasing temperature and salinity structure of the Baltic Sea halocline. The halocline region is also very wide in the Black Sea, possibly as a result of the renewals driven by the unique boundary transports.

The transport between the bottom convective layer and the overlying waters occurs through a diffusive

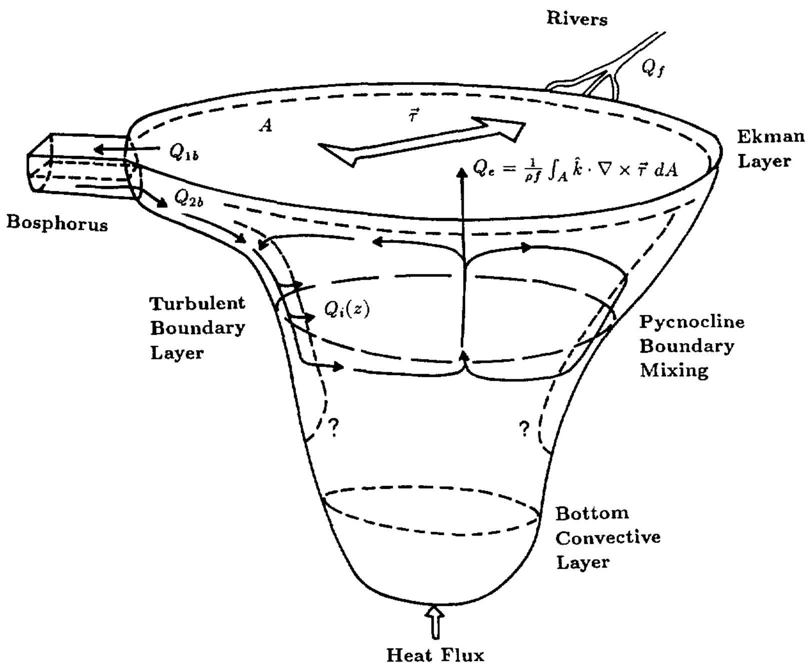

Fig. 22. Schematization of the recirculation driven by boundary mixing processes in the Black Sea. Mechanisms capable of driving a recirculation between boundary layers and the interior are emphasized. After Özsoy et al. (1993a).

interface. Double diffusion is most likely to be the main vertical transport mode for heat and salt in the deep waters extending from the lower part of the pycnocline to the bottom convective layer (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 (Özsoy and Beşiktepe, 1995).

The need to explain relatively large effective vertical diffusivities (much larger than molecular diffusivity) observed in the deep waters of the world ocean has motivated the development of boundary mixing theories (Garrett, 1979, 1990; Ivey and Corcos, 1982; Phillips et al., 1986; Woods, 1991; Salmun et al., 1991), attempting to explain the mixing by secondary and tertiary circulations set up near the pycnocline by turbulent boundary layers. Although the boundary mixing concepts should be applicable for Black Sea ventilation, important additions are required in the basic ingredients of the theory. For example, the efficient interior mixing created by double-diffusive intrusions is one of the unique characteristics of Black Sea, typically resulting from lateral fluxes into stratified environments (Turner, 1973; Huppert and Turner, 1980), and resulting in even more efficient mixing in the case when ambient waters are double-diffusively unstable (Turner, 1978), such as in the Black Sea.

Stanev and Staneva (1996) have used a general circulation model coupled with plume parameterization of mixing to resolve water mass transformations in the upper pycnocline and to study the fate of tracers, showing better agreement with observed stratification and ventilation, compared with the case not utilizing this parameterization. We believe that further improvements can be made in modelling of Black Sea ventilation if the full details of the cascading flow and the double diffusive convection could be adequately represented in the models.

6.4. The bottom convection layer

Deep CTD casts in the Black Sea indicate constant temperature and salinity in a 300–400 m thick layer above the bottom (Fig. 23). The water properties in this layer are homogenised both vertically and horizontally by convective motions (Fig. 8). Geothermal heat fluxes, acting against the stable

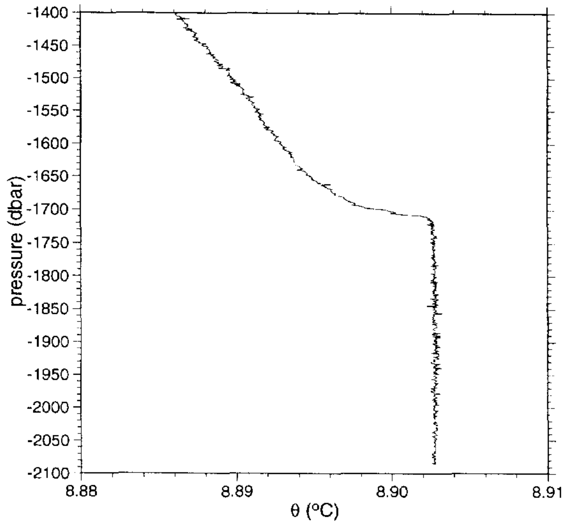

Fig. 23. A typical potential temperature profile within the bottom convective layer of the Black Sea. After Özsoy et al. (1991).

salinity gradient of salinity in the otherwise tranquil deep waters, drive the convective motions at the bottom of the Black Sea. The geothermal heat flux at the bottom, comparable in magnitude with the neighbouring seas (Zolotarev et al., 1979; Haenel, 1979), supports the bottom convective motions in the Black Sea.

Various examples of similar cases in lakes and oceans, where bottom heating is applied to water with a stable salinity stratification, are well known (Turner, 1969; Fernando, 1989). The convection corresponding to this case has been extensively investigated in laboratory experiments (e.g. Turner, 1968; Huppert and Linden, 1979; Fernando, 1987). The Black Sea case is rather special, because the layer thickness ($\sim$ 400–500 m) is the largest ever observed in the world ocean, and it seems that the available theory is far from fully explaining the time evolution of the convective layer, unless an asymptotic regime is considered. Because the layer thickness initially would have to increase as $\sim t^{1/2}$, the observed structure cannot be scaled with some of the laboratory experiments, except with the special experiments considered by Fernando (1987, 1989) and Fernando and Ching (1991), covering the long time limit of the relevant regime. It has been shown that the features of the Black Sea convective layer agreed with this limit of the 'low stability' regime, where the interfacial entrainment becomes vanishingly small upon reaching a state in which the growth of the layer occurs at a much smaller rate (Özsoy et al., 1991; Murray et al., 1991; Özsoy and Beşiktepe, 1995).

The characteristic time scale of overturning in the convective layer is found to be on the order of 6 days, implying a homogenisation period of about 40 years for a basin of the size of the Black Sea (Özsoy and Beşiktepe, 1995). Based on these interpretations, the age of the bottom convective layer is inferred to be on the same order as the average age of deep waters of the Black Sea (on the order of a few thousands of years).

The bottom convective layer holds the memory of the evolution of Black Sea waters, and could lead to a better understanding of deep mixing, if tracer experiments could be done to evaluate mixing with overlying waters. The presence of a bottom convective layer also poses important scientific questions with regard to the redistribution of sediments settling on the bottom. For example, a layer of loose sediments called the 'fluff layer' exists immediately above the bottom (Moore and O'Neill, 1991; Lyons, 1991), and the sluggish, turbulent motions in the convective layer could play a role in its structure. Similarly, bottom sediment laminae (varves) display exceptional continuity across the basin, despite the inhomogeneous geographical distribution of sinking particles from terrigenous and biogenic surface sources (Hay and Honjo, 1989; Hay et al., 1991; Sur et al., 1994). Bottom convection could obviously play a significant role in homogenizing sediments by resuspension, transport and settling, and later in their diagenesis, analogous to the part it plays in homogenising the water properties. These are aspects worthy of further examination.

7. Circulation characteristics

7.1. The basin's general circulation

A basin-scale, coherent, cyclonic boundary current (referred to as the 'Main Black Sea Current' in former-Soviet literature, and as the 'Rim Current' in Oğuz et al., 1992, 1993a) is the main feature of the Black Sea general circulation (Fig. 24). This basic circulation occasionally encompasses partial (double or triple) cells occupying the cyclonic central part, a number of anticyclonic eddies along the periphery, and a quasi-permanent anticyclonic circulation (the Batumi eddy) in the easternmost corner of the basin. The cyclonic general circulation with two cells was first described by Knipovich (1932) and Neumann (1942), with further aspects of variability added later to the description of the circulation by Filippov (1968), Boguslavskiy et al. (1976), Blatov et al. (1984), Eremeev et al. (1992), Trukhchev and Demin (1992). A common deficiency of these climatologi-

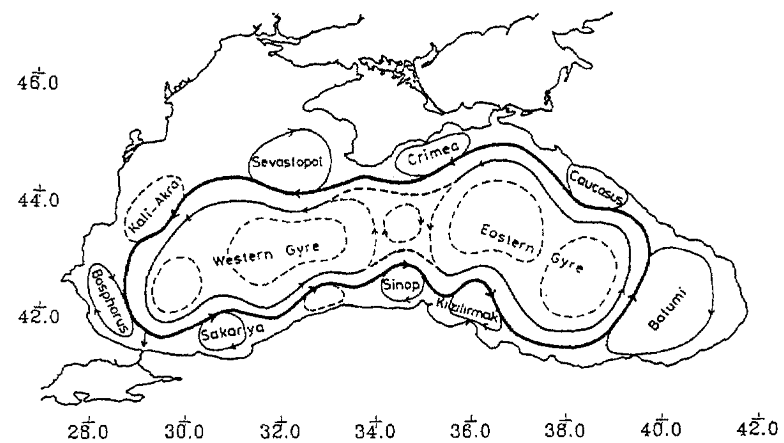

Fig. 24. Schematization of the main features of the upper layer general circulation based on a synthesis of past and recent studies. Solid (dashed) lines indicate quasi-permanent (recurrent) features of the general circulation. After Oğuz et al. (1993a).

cally based earlier studies is their non-synoptic nature with coarse sampling resolution, restricting the description of currents to relatively larger-scale features.

The present state of knowledge on the circulation is based on the results of a number of recent, nearly synoptic oceanographic surveys covering the entire basin. Analyses of satellite data both during these surveys and for other periods, have greatly enhanced this detailed description. The first series of studies, with detailed coverage, were the R/V *Bilim* surveys along the Anatolian coast in 1987–1989 (Oğuz et al., 1991), and the first set of coordinated measurements of a former USSR and Turkish experiment in September 1990 (Oğuz et al., 1993a), yielding current patterns which were considerably more complex than any of the previous descriptions. Several anticyclonic eddies were observed west of the Bosphorus, east of Sinop, and on both sides of the Crimean Peninsula, shoreward of the Rim Current. The most prominent feature was the quasi-permanent Batumi anticyclonic gyre in the southeastern corner of the basin. The double gyres of the eastern and western basin, as depicted in the early literature could not be confirmed; instead, a number of centres existed in the central region enclosed by the Rim Current. A large excursion into the interior region was made by the Rim Current near the Caucasian coast east of Crimea. Similar results were found in coordinated surveys of September 1991 (Aubrey et al., 1992b; Oğuz et al., 1993b), July 1992 (Oğuz et al., 1993c) and in later coordinated cruises which are being continued at present. The Rim Current typically has a width of about 50 km, and had meanders with length scales of ~ 100–200 km. The synthetic upper ocean circulation in Fig. 24 reveals a series of semi-permanent anticyclonic eddies on the periphery between the rim current and the undulations of the coast. These meandering currents consist of standing structures as well as transient, propagating features.

Despite the modern level of description based on detailed observations, it is not clearly established what physical factors drive the basic, cyclonic Black Sea circulation. Modelling studies, addressing basic aspects, but with uncompromising realism in terms of driving forces, fluxes and topography, are needed to answer some of these questions. Classically, the cyclonic wind pattern (positive curl of wind stress) has been recognized as the main forcing for the cyclonic surface circulation (e.g. Neumann, 1942; Moskalenko, 1976; Dzhioev and Sarkisyan, 1976; Stanev et al., 1988; Rachev et al., 1991; Eremeev et al., 1992; Demyshev, 1992; Trukhchev and Demin, 1992; Klimok and Makeshov, 1993). On the other hand, the results of numerical studies by Marchuk et al. (1975) and Stanev (1990) indicate a seasonal thermohaline circulation driven by nonuniform surface fluxes, complementary to the wind driven circulation, and generating surface currents of comparable magnitude.

Relatively little is known on the role of freshwater runoff from major rivers in establishing a density driven component of the circulation. The northwestern shelf and the Bosphorus vicinity are the two major areas where lateral sources and convection modify the Black Sea circulation (Stanev, 1990). Freshwater inflow and winter convection in the first area and intrusions of the dense Mediterranean inflow in the second area act as vorticity source functions resulting in increases of eddy kinetic energy at the expense of the mean circulation (Stanev, 1990). Similarly, Bulgakov and Korotaev (1987) and Korotaev (1997) showed that forcing by lateral buoyancy fluxes from rivers and the strait inflows could generate a cyclonic surface circulation confined to the coastal region, overlying a reverse, compensating flow at depth. In addition, surface atmospheric fluxes were also found to be important (Stanev, 1990) in driving the circulation.

Observations show that the location of the rim current and its corresponding density front generally coincide well with the continental slope region, and it is therefore natural to expect the slope currents to be controlled by topography. On the other hand, the pycnocline depth, typically at depths of 100–150 m in the peripheral region also coincides with the depth of the shelf break, especially along the wide western shelf. The impact of the joint effect of baroclinicity and bottom relief (the 'jebar' effect) would therefore expected to be very important in the Black Sea circulation, as originally suggested by Gamsakhurdiya and Sarkisyan (1976). Stanev (1990) argues that this effect in the Black Sea could be suppressed, as a result of the inhibiting effects of the strong stratification on the vertical circulation. Despite these contrasting interpretations, the insufficient resolution of the present numerical models, and different parameterizations of physical processes make impossible to give a more definite estimate on the role of the 'jebar' effect in the Black Sea.

A model with high resolution, turbulence closure, and active thermodynamics (Oğuz et al., 1995) showed the topography, wind stress, and surface and lateral buoyancy fluxes to be first-order contributors in driving the Black Sea general circulation. With seasonal forcing (Oğuz and Malanotte-Rizzoli, 1996), the basic conclusions about the relative roles of forcing mechanisms remained the same, with the addition of a seasonal cycle which better resolved some features, and confirmed the roles of lateral buoyancy sources and topography in supporting the mesoscale activity along the periphery of the basin.

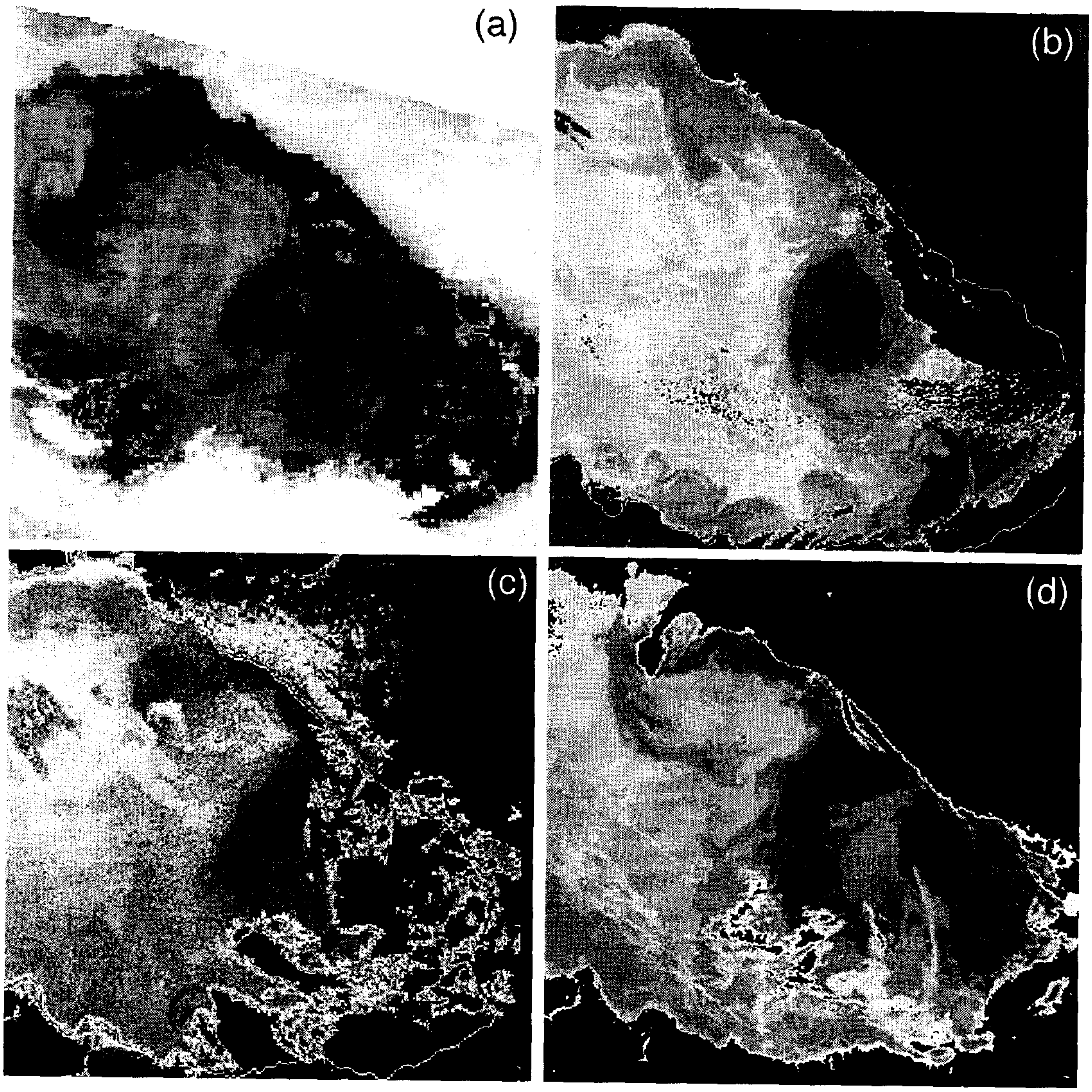

Fig. 25. Advanced very high-resolution radiometer (AVHRR) satellite images of the eastern Black Sea on (a) September 15, 1991 (b) February 9, 1994, (c) February 17, 1994, (d) February 28, 1994. (a–c) show meander development and propagation towards the northwest in a short period. Darker tones represent warmer water.

7.2. Sub-basin and mesoscale circulation features

The increased resolution obtained from recent oceanographic surveys and the availability of satellite data have added significant detail to the description of the Black Sea circulation, demonstrating various mesoscale eddies, meanders and filaments riding on, or being shed from the 'rim' current (Blatov et al., 1984; Latun, 1990; Stanev, 1990; Golubev and Tuzhilkin, 1990; Ünlüata and LaViolette, 1990; Ünlüata et al., 1990; Oğuz et al., 1991, 1992, 1993a,b,c; Özsoy et al., 1993a; Sur et al., 1994, 1996). These meandering currents and filaments have a leading influence on the exchange of materials between the coastal and the open sea regions, and are therefore very important in the cycling of materials in the upper ocean and in determining the general state of health of the Black Sea.

Of the various eddies along the periphery of the Black Sea, the Batumi anticyclonic circulation is the most prominent closed circulation in the eastern corner of the Black Sea, the only region where the cyclonic boundary current ceases to follow the basin slope boundary. Large meanders of the stream are common along the Caucasian coast (Oğuz et al., 1993a; Sur et al., 1994, 1996). An example of the Caucasian large meander flow is shown in Fig. 25a during September 1991. These rapidly developing large meander motions appear to be dynamically linked with the Batumi anticyclone. The satellite images of Fig. 25 show the rapid development, during a period of 20 days in February 1994, of these large meanders, initially from a coherent eddy along the same coast.

A semi-permanent feature frequently detected in the north is the Sevastopol eddy, located on the lee side of the Crimean Peninsula (Sur et al., 1996).

ADCP measurements confirm the existence of an intense boundary current attached to the continental slope, with speeds of up to 1 m/s in the southwestern Black Sea (Fig. 26a). Corresponding satellite infrared data (Sur et al., 1996; Fig. 26b), and multivariate analysis of dynamic height derived from the CTD and ADCP data (Özsoy and Güngör, 1993; Güngör, 1994; Fig. 26c) illustrate the meandering and small mesoscale structure of the rim current.

Dipole (mushroom) eddies tend occur along the periphery (Sur et al., 1994, 1996), such as the one made visible by a characteristic pattern of spirals and streamers transporting particulates at the Kızılırmak river mouth (Fig. 27). Coherent dipole structures are often observed along unstable boundary currents, such as the Black Sea rim current system, typically excited by density or wind impulses (e.g. Griffiths and Linden, 1981; Fedorov and Ginsburg, 1989). They have been reproduced in laboratory studies (Fedorov et al., 1989; van Heijst and Flor, 1989; Voropayev, 1989) and numerical studies (Mied et al., 1991) in rotating and stratified fluids.

Along the southwestern coast, unstable features are generated with a wide range of space and time scales. The abrupt termination of the shelf at Sakarya Canyon, and changes in bottom slope and coastline orientation along the western Anatolian coast (Capes Baba, Kerempe, Ince) are important in triggering transient mesoscale activity along the same coast (Sur et al., 1994, 1996). Examples of these unstable features are shown in a sequence of images displayed in Fig. 28. The speed of propagation of the wave pattern of the rim current instabilities in this case is about 10–15 km/day. Note that the motion is initially attached to the continental slope, and tends to grow in amplitude, shedding a multitude of filaments and small mesoscale turbulent features, while developing into a separated turbulent jet, about one month after its initiation in early summer.

Advection from the northwestern shelf towards the Anatolian coast often has typical features of a density driven current. For example, in winter 1990, satellite and in-situ data revealed the motion of a vein of cold, low-salinity water advected along the entire western shelf. The cold water adhered to the narrow shelf bathymetry along the Anatolian coast, and after bypassing the wide Sakarya Canyon region, underwent an explosive increase in width (Figs. 9 and 10) as it interacted with the sharp headland and topographic transition at Cape Baba (Sur et al., 1994, 1996).

7.3. Coastal upwelling along the Anatolian coast

One of the most striking aspects of the circulation along the Anatolian coast is the observation of persistent upwelling events, near Capes Kerempe and Ince (Sur et al., 1994, 1996) recurring almost every summer, at a time when the typical wind pattern is

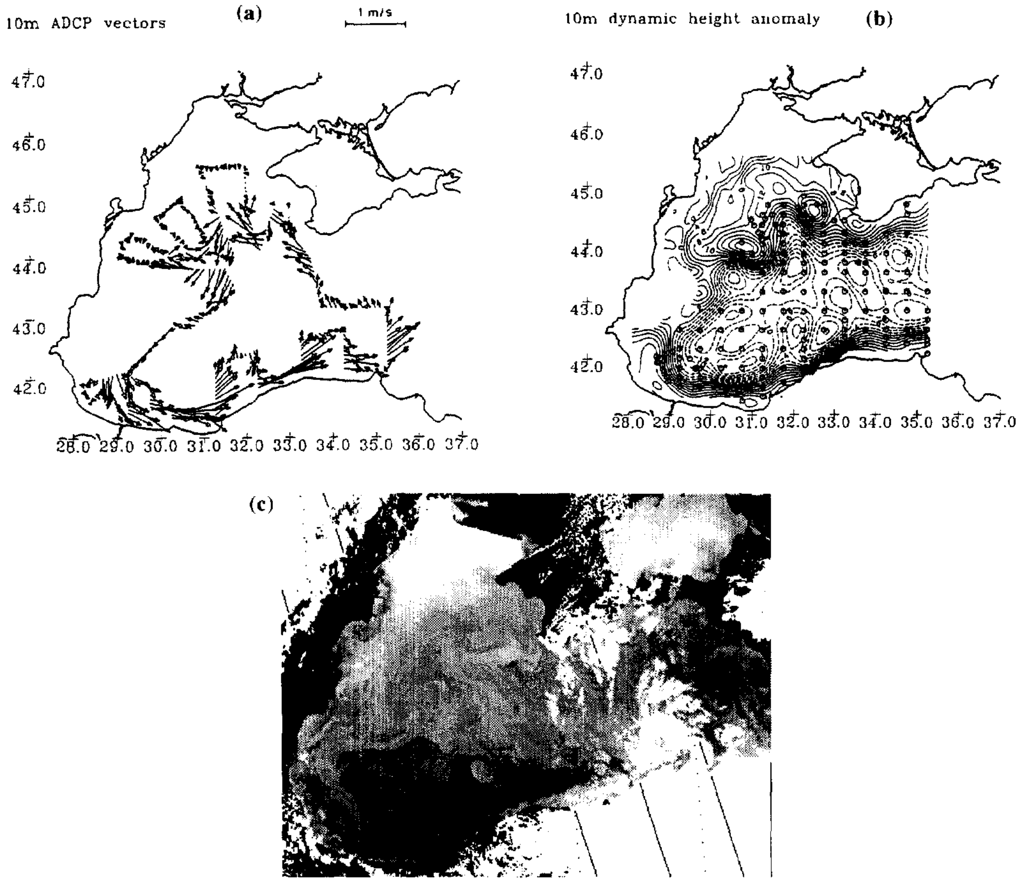

Fig. 26. (a) ADCP-derived horizontal current velocity at 20 m depth, (b) dynamic topography (cm) at 10 m depth, obtained from multi-variate analysis of CTD- and ADCP-based measurements, and (c) corresponding AVHRR IR image, April 1993.

Fig. 27. Coastal zone colour scanner (CZCS atmospherically corrected channel 3, 550 nm) satellite image on October 13, 1980, showing a dipole eddy near the mouth of the Kızılırmak river and other instabilities along the Rim Current system. Lighter shades are colder. After Sur et al. (1994).

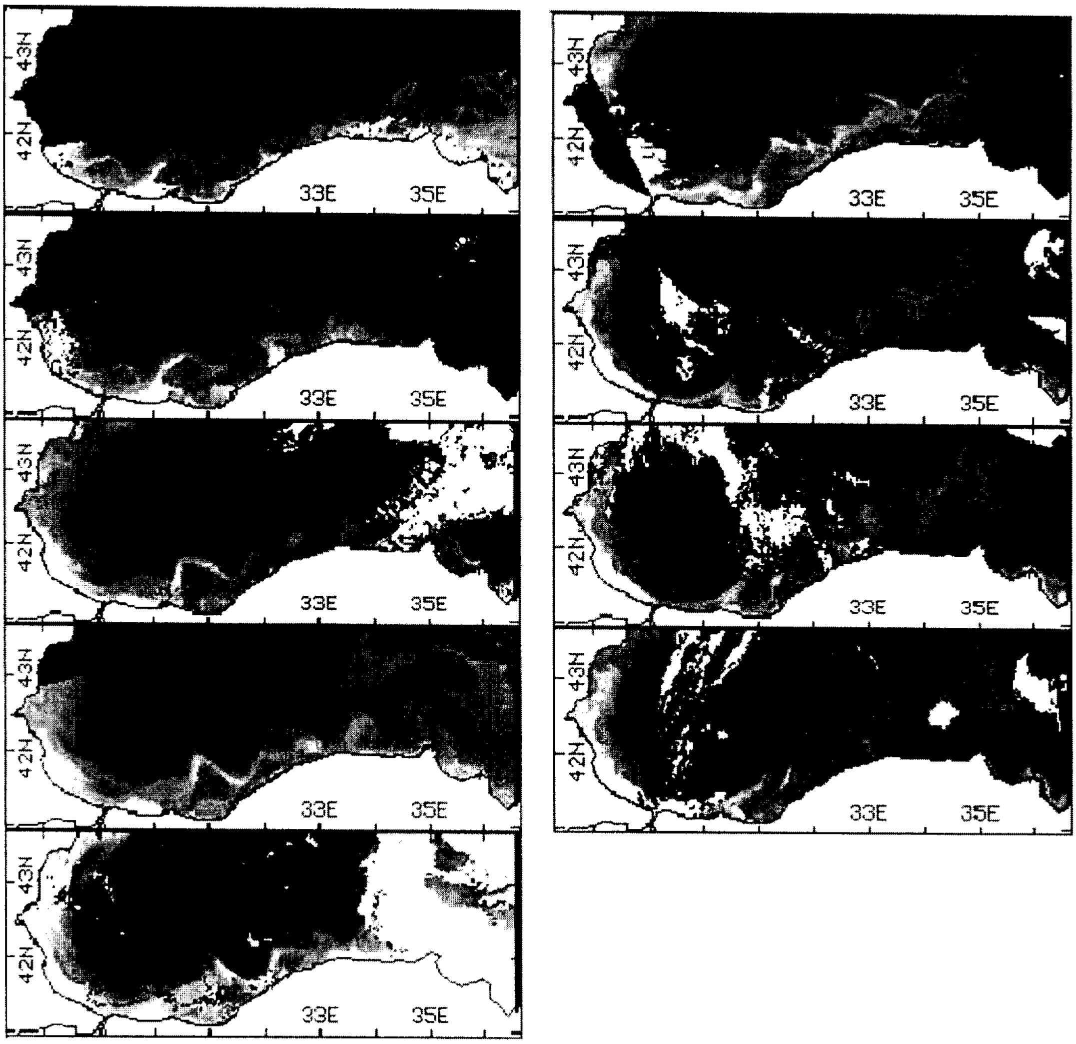

Fig. 28. A sequence of CZCS channel 3 (550 nm) images showing the development of turbulent motions and the associated spread of primary productivity in the west and southwestern Black Sea during the period of 9–26 June 1980. The light areas represent reflections from phytoplankton, mainly consisting of coccolithophores. After Sur et al. (1994).

not suitable to induce upwelling. Often the reason for the upwelling in the southwest region is the interactions of the flow with the Anatolian coast; e.g. its initial attachment, followed by a separation from the coast (near Cape Kerempe). In the lee of the separation point, a region of upwelling occurs near the coast. The surfacing of CIW from below a thin, warm mixed layer in areas of mesoscale local divergence, seems to be the only mechanism by which patches of cold water are created along the Anatolian coast.

The analysis of July 1992 hydrographic data and satellite images (Fig. 29a,b) showed persistent upwelling with surface temperatures as low as 12°C along the Anatolian coast. The data indicated penetration of the surface mixed layer by the upwelled Cold Intermediate Water. A sequence of satellite images (Sur et al., 1994; Fig. 29c) confirmed upwelling patterns in both regions during the entire month of August and in the beginning of September 1992.

It is interesting that a similar situation was actu-

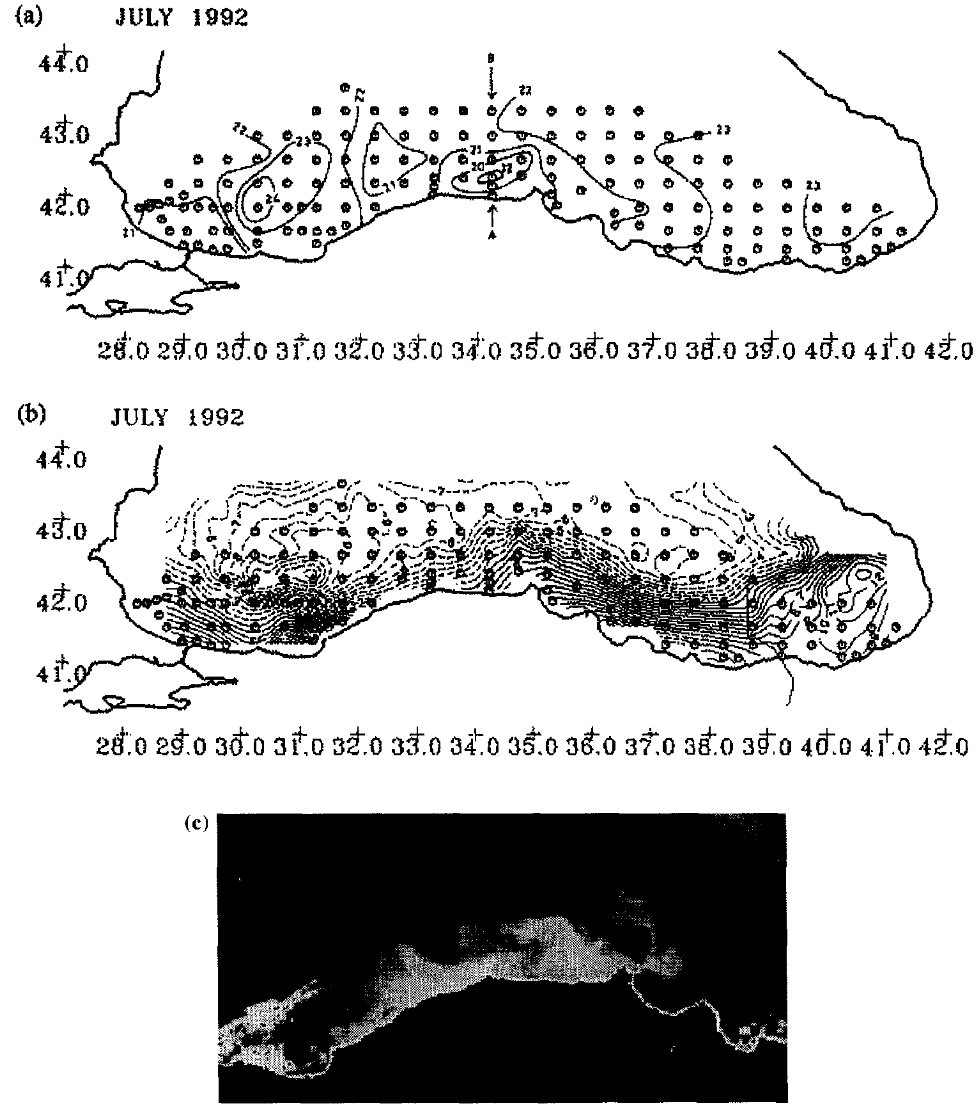

Fig. 29. (a) Surface temperature (°C), and (b) dynamic height anomaly during July 1992, (c) AVHRR (NOAA-11) infrared image on September 3, 1992, lighter shades corresponding to colder temperatures. After Sur et al. (1994).

ally evident in a survey in July 1957 (Einarsson and Gürtürk, 1960; Niermann et al., 1993), but could only be interpreted in a correct way in the light of recent satellite observations and in-situ data (Sur et al., 1994). In this case, the upwelling region extended from Cape Baba to Cape Ince, with a cold spot of minimum temperature 11.6°C (at 10 m depth) in the same location as the 1992 upwelling.

A review of satellite data, indicates persistent upwelling in summer, along the Turkish coast between Cape Baba and Cape Ince. Transient flows interacting with the coastline geometry and continental slope bathymetry appear capable of creating divergences leading to the penetration of the relatively thin surface layer by the underlying CIW (Sur et al., 1994, 1996). Similar events of transient upwelling have been observed elsewhere along fronts and unstable current systems (e.g. Millot, 1991; Beckers and Nihoul, 1992).

8. Physical controls on the marine ecosystem

The general circulation and mesoscale activity have a large impact on the distribution of nutrients and oxygen in the Black Sea. It is now evident that the eutrophication process (Bologa, 1986; Chirea and Gomoiu, 1986; Mee, 1992) starting with bottom hypoxia and changing species composition in the NWS (Tolmazin, 1985a; Zaitsev, 1993), have multiplied within the last few decades, and hypoxia on the bottom has developed across the shallow, wide northwestern shelf region (Tolmazin, 1985a; Zaitsev, 1993). Later, with increasing levels of nutrients input into the Black Sea, the effects of eutrophication have spread first along the western shelf (Musayeva, 1985; Bologa, 1986) and later into the deep interior region by transport processes, drastically changing the nutrient (Tuğrul et al., 1992; Saydam et al., 1993), and possibly leading to changes in the ecosystem of the entire basin.

Satellite data from the Coastal Sea Colour Scanner (CZCS), such as displayed in Fig. 28, typically show massive plankton blooms developing progressively along the western shelf (Sur et al., 1994, 1996; Barale, 1994; Barale and Murray, 1995). The numerous meanders, eddies and filaments shown in Figs. 11 and 25–28 serve as the main mixing agents between the coastal and interior regions, and thus carry coastal materials into the entire basin.

The around-basin transport by the cyclonic rim current and the cross-shelf transport by frontal and jet instabilities determine the pattern of primary production in most parts of the Black Sea, in view of recent results emphasizing the relative contribution of riverine sources to new production (Murray et al., 1993; Çokacar, 1996), despite the more common assumptions regarding the deep water as the main reserve of nutrients supplied to the photic zone (e.g. Fonselius, 1974; Sorokin, 1983). In comparison, the role of atmospheric sources of nutrients appears to be marginal (total atmospheric $NO_3 + NO_2$ input estimated to be 13% of the Danube input; Kubilay et al., 1995).

The spectral content of the satellite images provide additional details. In summer, populations rich in chlorophyll-a are persistent near the freshwater sources in the northwestern shelf. To the south, along the shelf, and with increasing distance from the river mouths, this first population gives way to the coccolithophore species *Emiliania huxleyi* (Holligan et al., 1983) in early summer, consistently verified by coastal and sediment trap measurements in the Black Sea (Bologa, 1986; Benli, 1987; Hay and Honjo, 1989; Hay et al., 1990, 1991). In fact, the first bloom of *E. huxleyi* develops on the periphery of the first population, i.e. along the shelf break front, and later increases in abundance when it spreads along the shelf (Sur et al., 1994, 1996), only to come to a sudden end in late summer, when dinoflagellate blooms take over.

Physical features, such as summer upwelling (Sur et al., 1994) have great impact on local variability of this pattern. For example, during the 1992 upwelling (Fig. 29), the anchovy eggs and larvae (Niermann et al., 1993) and the invader *Mnemiopsis leidyi* (Mutlu et al., 1994) decreased in abundance, and the cold water copepod species *Pseudocalanus elongatusa* increased (Ergün, 1994) considerably within the upwelling patches along the Anatolian coast, while phytoplankton did not show any particular pattern related to upwelling (Bayrakdar et al., 1996). Interestingly, a similar situation was evident in July 1957 (Einarsson and Gürtürk, 1960; Niermann et al., 1993), but was overlooked earlier.

Similarly, the winter encroachment of cold shelf water from the western shelf to the southwestern coast (e.g. Figs. 9 and 10) appeared well correlated with specific wintertime diatom blooms propagating along this coast (Sur et al., 1994, 1996). The diatom *Chaetoceros* sp. was dominant with increasing numbers within the vein of cold water upstream and the separated flow downstream of Cape Baba, and decreased gradually towards the east. The plankton diversity decreased abruptly within the band of cold water (Uysal, 1993; Uysal and Sur, 1995).

The large meander motion along the Caucasian coast (Fig. 25), ensuing from an instability of the southeastern gyre, could have consequences with regard to the migrations of anchovy stocks which are found to be abundant in this feature during certain periods of the year (Panov and Chashchin, 1990).

As a result of the rapid deterioration in the health of the Black Sea, there is a pressing need to understand the basic parameters and the machinery of the ecosystem. Recent coordinated efforts attempt to understand the basic elements of nutrient cycling and productivity by basin-wide surveys oriented for this purpose, and by using a hierarchy of ecosystem models at different levels of complexity, eventually leading to a better understanding via coupled hydrodynamical/chemical/biological models. First efforts in this direction have been made (e.g. Lebedeva and Shuskina, 1994; Oğuz et al., 1996a; Çokacar, 1996), and further rapid development is expected.

9. A summary and recommendations for further research

The synthesis of recent results, based on an improved data collection strategy, provide finer details of the ocean processes in the Black Sea and suggest possible physical mechanisms of transport/mixing and pathways of nutrient supply, which need to be fully understood before the surmounting environmental and ecological problems can correctly be addressed.

The advection of materials along the periphery of the basin by the rim current, its coastal interactions and instabilities, and the ensuing cross-shelf transports by turbulent features are important for the redistribution of materials within the basin, and set the time and space scales of a succession of plankton blooms and their transformation into higher trophic levels, playing important roles in basin-scale eutrophication. It appears that upwelling along the Anatolian coast occurs frequently in summer, with an impact on the distribution of fish eggs and larvae. Similarly, winter convection on the western continental shelf and its advection seems to play important roles in winter-time productivity. It is also recognized that these circulation features are important for the migration spawning behaviour of the mainly pelagic fish stocks of the Black Sea, although they are now under increasing threats. Yet, the integrated effects of these processes on productivity is poorly understood. For example, we do not have quantitative knowledge of the fluxes of nutrients from the different sources, i.e. the atmosphere, the rivers, and the deep ocean, and their recycling. It is not clear how this leads to the abundance of plankton or translated into the higher trophic levels. Similarly, the expected links between frontal processes and the population dynamics of migrating fish stocks are not clearly understood.

An important domain of research with impact on the health of the sea is the transport processes, and interactions with neighbouring seas. Ventilation in the Black Sea interior is governed by surface fluxes as well as boundary mixing processes. The unique nature of the Black Sea with a double diffusive regime in almost the entire water column, and a geothermally driven bottom convection layer, determines the mean residence time of particles versus depth. Reliable quantitative estimates of the lateral and vertical fluxes are needed. Even the modern dating techniques prove to be of limited use in establishing quantitative and reproducible estimates of the mean age distribution of Black Sea waters. Adequate parameterizations of vertical mixing, taking into account double diffusive convection and secondary circulations, to reproduce realistic stratification in general circulation models are not well developed. This is also true for the upper part of the ocean, where an adequate understanding of CIW formation does not exist, despite its strong influence on upper ocean variability and the vertical distributions of biological components.

Interannual and climatic variability appears to be strong in the region, and especially important in the Black Sea, which is subject to rapid ecosystem changes and deterioration in health. It is therefore necessary to obtain long time series of detailed observations on every aspect of the environment.

Only a better understanding of the system and a massive effort by collaborating European and Asian states to control their harmful effluxes can save Pontos Euxeinos (i.e. the hospitable sea, as it was called by the early civilizations and trade colonies who inhabited its coasts since the dawn of human civilisation).

Acknowledgements

The present review incorporates results from a number of independent studies. Most of the data presented were collected during the two NATO Science for Stability projects, TU-FISHERIES and TU-BLACK SEA carried out by the IMS-METU, joining efforts with National Monitoring projects covering the Turkish Black Sea coast and supported by the Turkish Scientific and Technical Research Council (TÜBİTAK). The coordinated interdisciplinary scientific program of CoMSBlack (Cooperative Marine Science Program for the Black Sea) set the environment for collaborative work on the periphery of the Black Sea. Some of the results were obtained by combined analyses of the early data with those derived from measurements on board the R/V *Knorr*, during its visit in 1988, supported by the National Science Foundation, USA. Other measurement programs in the Turkish Straits System, such as the projects supported by the City of Istanbul, Water and Sewerage Administration (İSKİ), and the Marmara Sea National Monitoring project supported by TÜBİTAK helped to establish the conditions at the Straits and transition from adjacent seas.

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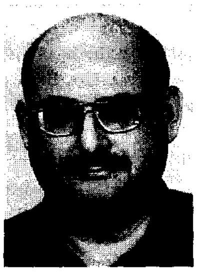

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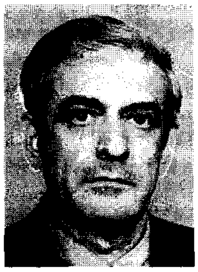

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