Chapter 31. THE BLACK SEA
COASTAL SEGMENT (28,S)

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Contents

1. Introduction
2. Hydrology
3. Coastal Sea Mixing Processes
4. Circulation Characteristics
5. Physical Controls on the Marine Ecosystem
References

1. Introduction

The Black Sea is practically an enclosed sea. The restricted exchange imposed by the Turkish Straits is responsible for anoxia in 87% of its volume, making it the largest such body in the world. In recent decades, anthropogenic inputs have led to devastating alterations in the ecosystem (Mee, 1992; Zaitsev, 1993) as a result of eutrophication.

The surface area of the basin is 4.2×10^5 km^2 and the volume is 5.3×10^5 km^3. The geometry of the basin is simple (Fig. 31.1), yet the wide continental shelf regions (depth <100 m, constituting 25% of the total area) and the flat abyssal plain (maximum depth 2200 m) represent two vastly different environments interacting via transport processes. Steep continental slopes encircle the abyss, except near the Danube and Kerch Fans. The northwest shelf becomes narrower toward the south and terminates abruptly at Sakarya Canyon along the Anatolian coast in the south. The remaining small stretches of shelf separated by many canyons and slopes adjacent to the coast define a rugged submarine topography, especially along the Anatolian and Caucasian coasts.

The basin's oceanography and state of health are strongly influenced by freshwater inputs from major rivers (the Danube, Dniepr, Dniestr and Kuban Rivers in

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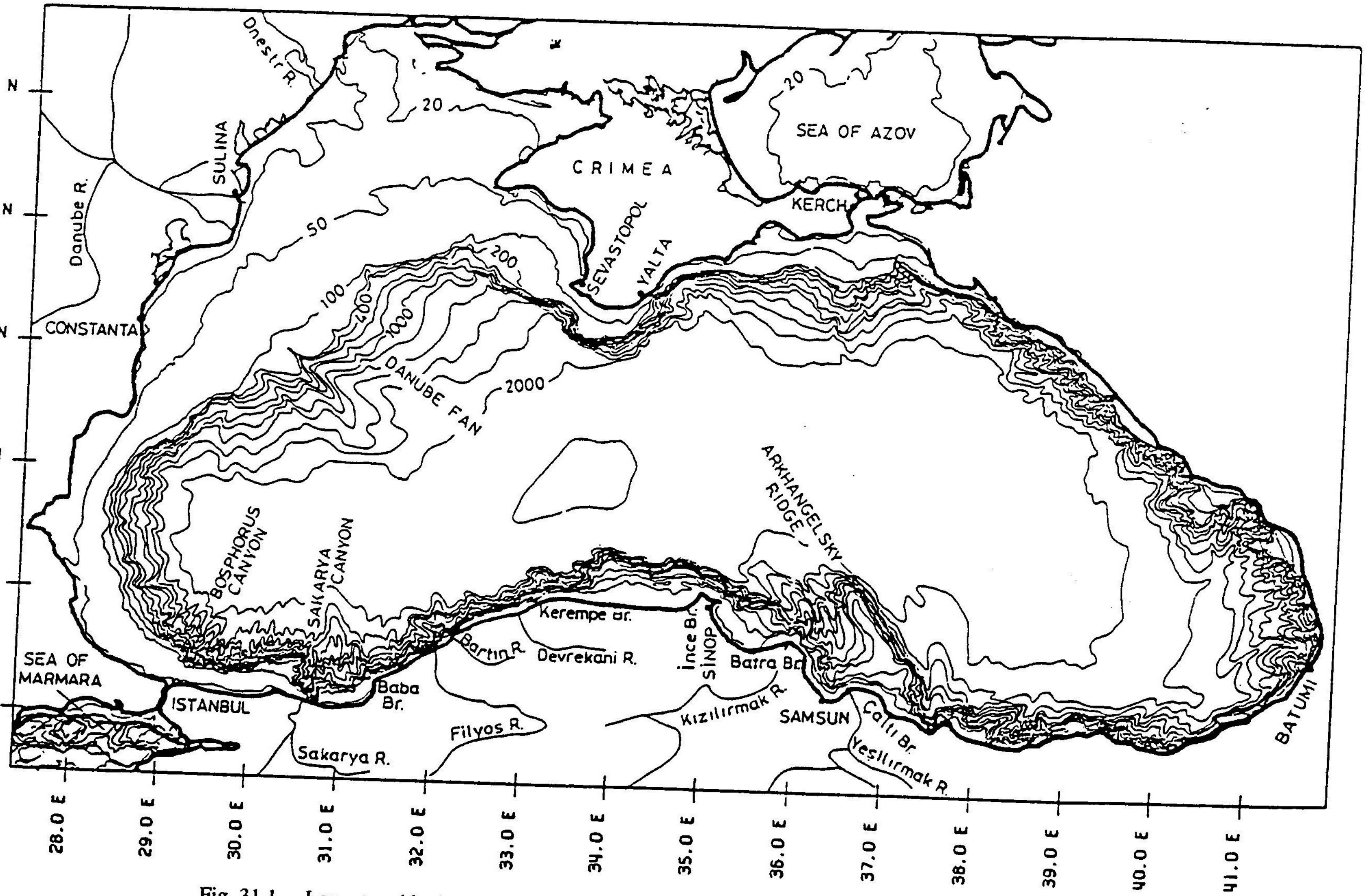


Fig. 31.1. Layout and bathymetry of the Black Sea Basin. Depth contours are labeled in meters.

the north and Kizihrmak in the south). Inflows from rivers and the Bosphorus Strait, surface fluxes and strong topography are all important factors maintaining the circulation and ecological state of the Black Sea. The important roles of turbulent eddies and jets, mixing processes and a peculiar stratification also need attention from this perspective.

The increased influxes of highly mineralized nutrients originating from major rivers draining large areas of the continent has been driving the processes of eutrophication in the Black Sea (Bologa, 1986, Chirea and Gomoiu, 1986; Mee, 1992), which had catastrophic consequences, starting with the bottom hypoxia and the changing species composition in the northwestern shelf region (Tolmazin, 1985a; Zaitsev, 1993), and with effects progressing south along the western shelf in time (Musayeva, 1985; Bologa, 1986). The adverse changes are not confined to the shelf regions alone: in the last few decades, the nutrient distribution has changed drastically in the entire basin (Tuğrul et al., 1992, Saydam et al., 1993), and there is evidence that opportunistic species are occupying gaps in the food web (Zaitsev, 1993). It is most likely that the recent collapse of the basin's fisheries (Kideyş, 1994) is closely linked with the foregoing processes, as well as increased fishing.

The region is atmospherically very active and complex, because of confinement by land topography. About 30 storms per year approach from the Mediterranean or the Balkans (Reiter, 1975), including secondary centers of the Mediterranean cyclones (Brody and Nestor, 1980). In winter, northerly winds are associated with cold outbreaks in the west, while southerlies occur in the east. As the air temperature decreases sharply in late autumn, it becomes much colder in the north (especially near Odessa), by about 8–10°C compared to the south, and contrasting with the uniform distribution in summer.

Plenty of measurements were made, mainly by the USSR scientists, since the beginning of the century; the hydrographic data have been quality checked and made available to the community recently (e.g., Mamayev, 1993). The recent years have seen systematic surveys with much increased coverage, and improved resolution and quality of data. A number of recent surveys were carried out by R. V. *Bilim* along the Turkish coast in 1987–1989. Then a series of cooperative surveys were carried out in 1988–1989, with Turkish–USSR cooperation on board the USSR ships R.V. *Kolesnikov* and R.V. *Dmitriy Mendeleev*, and with U.S.–Turkish cooperation during the visit of the U.S. ship R.V. *Knorr* in 1988 (Murray, 1991) with R.V. *Bilim* guiding the R.V. *Knorr* tracer surveys near the Bosphorus (Özsoy et al., 1993). After 1990, coordinated multi-institutional surveys were carried out, utilizing multiple ships from riparian countries, first within the context of the NATO TU–FISHERIES program (Bingel et al., 1994), continued later within the CoMSBlack international program (Aubrey et al., 1992a; Ünlüata et al., 1993), 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; Ivanov et al., 1994; Konovalov et al., 1994). Recently, current velocity profile measurements were obtained using an ADCP system with a vessel-mounted 150-kHz transducer on board the R.V. Bilim (Güngör, 1994; Oğuz et al., 1998). Additional surveys, including a turbulence and microstructure investigation of the Bosphorus flows and the Mediterranean effluent by R.V. Bilim in 1994 (Gregg, 1995) and visits of the NATO ship R.V. Alliance in 1995 and 1996, investigating the physical oceanography of the same region, are expected to yield additional scientific results in the near future. Visible and thermal infrared imagery from CZCS and NOAA AVHRR satellites, complementing the in situ data, have been used successfully in studying the hydrodynamic flow and phytoplankton production patterns of the Black Sea current systems (Oğuz et al., 1992; Sur et al., 1994, 1996; Barale, 1994; Barale and Murray, 1995).

2. Hydrology

2.1. *Water Budget*

Because the Black Sea is practically a landlocked basin, its overall mass budget and hydrochemical structure depend critically on the elements of its hydrological balance, with precipitation (ca. 300 $km^3\ yr^{-1}$) and runoff (ca. 350 $km^3\ yr^{-1}$) exceeding evaporative losses (ca. 350 $km^3\ yr^{-1}$); the excess is balanced by a net outflux of water (ca. 300 $km^3\ yr^{-1}$) across the Bosphorus (Ünlüata et al., 1990).

The Danube, Dnepr and Dnestr Rivers in the northwest are the most important sources of fresh water, with the Danube contributing about half, the Dnestr and Dnepr a third and the remaining rivers accounting for less than a fifth of the total river runoff.

Freshwater inflow into the Black Sea displays large seasonal and interannual natural variability (Serpoianu, 1973; Bondar et al., 1991). Annual mean Danube discharge varies by a factor of about 2 (Sur et al., 1994), while monthly average discharge data indicate a long-term overall factor of about 7 between the seasonal maximum and minimum fluxes. A significant correlation exists between Danube influx and sea level at seasonal and interannual time scales, suggesting efficient climatic control by the Bosphorus (Bondar, 1989; Sur et al., 1994; Özsoy et al., 1995, 1996). The northwest shelf waters identified with riverine signatures reach the southwest within one to two months after the peak outflows, with significant interannual variations within the March–August period (Sur et al., 1994).

2.2. *Controls at the Bosphorus Strait*

Mass balance estimates of the two-layer exchange flows through the Bosphorus, based on long-term salinity measurements (Ünlüata et al., 1990) yield an average upper-layer outflow of about 600 $km^3\ yr^{-1}$ and a lower-layer inflow of about 300 $km^3\ yr^{-1}$. The ADCP-based instantaneous fluxes greatly differ from these estimates, as they follow closely the transient meteorological and hydrological forcing in adjacent basins (Özsoy et al., 1994, 1995, 1996). The Bosphorus operates in the full range of weak to strong barotropic forcing in either direction, resulting in transient fluxes, subject to significant variations even within any single day. Temporary blocking of the lower layer occurs during peak freshwater influxes in spring and summer, while upper-layer blocking occurs under southwesterly winds in winter (Latif et al., 1991; Özsoy et al., 1995).

The Bosphorus is the foremost example of a strait with *maximal exchange* (Ünlüata et al., 1990; Oğuz et al., 1990; Özsoy et al., 1995, 1996). The nonlinear, asymmetrical dynamics driven by a net freshwater flux (Farmer and Armi, 1986), and barometric pressure difference (Özsoy et al., 1996) under these conditions results in a complex response of the strait flows on time scales of several days to a few years (Latif et al., 1991; Özsoy et al., 1994, 1996).

2.3. *Water Masses and Stratification*

The Black Sea has a peculiar stratification, with colder, fresher surface waters overlying warmer, more saline deep waters. In summer, a seasonal thermocline forms at the base of the shallow (ca. 10–30 m) mixed layer. The region between the seasonal thermocline and the permanent pycnocline is occupied by the Cold Intermediate Water (CIW), a perennial water mass convectively replenished in winter. The CIW is characterized by temperatures cooler than 8.0°C (minimum ca. 6–7°C at the core). Because of the greater role of salinity in determining density, the permanent pycnocline approximately coincides with the main halocline.

The Black Sea possesses an oxycline and a chemocline again roughly coinciding with the pycnocline, perhaps as a result of similar controls on the vertical exchange of scalar properties. Yet there are subtle processes in the chemistry, resulting in a suboxic layer, particulate layers, and so on, in close relation with redox reactions and boundary processes (Shaffer, 1986; Murray 1991; Murray et al., 1989, 1993). Stratified midwater biology is indicated by mesoplankton accumulations in the suboxic layer (Vinogradov et al., 1990), and various other organisms arranging themselves in vertical succession. Questions with regard to the stability of these structures, such as posed by the recent controversies on shoaling of the oxic–anoxic interface (Fashchuk and Ayzatullin, 1986; Bryantsev et al., 1988; Murray et al., 1989), can only be answered through a better understanding of the physical and biochemical controls on the pycnocline region. Stability with respect to the vertical position and structure of the chemocline within decadal time scales is confirmed by such studies (Tuğrul et al., 1992; Saydam et al., 1993; Buesseler et al., 1994), yet these studies have also shown significant changes in the nutrient concentration profiles since the 1960s, as well as seasonal and interannual changes in temperature and salinity structure of the pycnocline seasonal and interannual changes in temperature and salinity structure of the pycnocline (Murray et al., 1991; Ivanov et al., 1997a,b).

The variability in properties decreases rapidly below the halocline, except near the boundaries, where local instabilities are able to produce fine structures (Özsoy and Beşiktepe, 1995); the waters below 500 m are essentially stagnant.

Below a depth of 1700 m, potential temperature and salinity are absolutely uniform, as a result of bottom convection in a bottom mixed layer (Özsoy et al., 1991, 1993; Murray et al., 1991; Özsoy and Beşiktepe, 1995), driven by geothermal heat fluxes in an environment of stable salinity stratification (Huppert and Linden, 1980). A close examination of the properties of this Bottom Water based on multiyear 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 [slightly different from values reported by Murray et al. (1991) in relation to possible salinity drift between measurement periods], with an estimated variation of less than 0.001 unit in both potential temperature and salinity across the basin.

3. Coastal Sea Mixing Processes

3.1. *Cold Intermediate Water Formation*

The CIW is of great significance for the transport and renewal of the upper Black Sea waters, yet its origin in time and space remains largely unresolved. Intuitively, the CIW is a product of winter convection tied intimately with atmospheric fluxes, upper ocean flow patterns and topography. Yet winter data are too scarce to conclude specific details of the formation processes.

Local convection hypotheses were popular during the early part of the century. Later observations of the CIW core, displaying temperatures much smaller than the minimum surface values reported in the larger part of the Black Sea and with rather uniform distribution across the basin, suggested advective contributions to CIW (Kolesnikov, 1953; Filippov, 1965, 1968), possibly originating from the shallow northwest shelf and near Kerch Strait (Filippov, 1965; Blatov et al., 1984; Tolmazin, 1985a). The local convection hypothesis was revived later (Isaeva et al., 1987; Ovchinnikov and Popov, 1987; Kaminskey et al., 1989), amended by a scheme of isopycnal advection from the cyclonic center toward the periphery.

Near-freezing temperatures of 2–4°C, coinciding with reduced freshwater inflow in winter, could briefly form dense water on the northwestern shelf (Tolmazin, 1985a), which would then cascade down to contribute to CIW. Satellite images (Fig. 31.2; see the color plate) consistently show cold water all along the shallower part of the western shelf (Ünlüata and LaViolette, 1990; Sur et al., 1994, 1996), suggesting shallow convection similar to that in the Adriatic Sea (Malanotte-Rizzoli, 1991). Recent studies indicate that the CIW, once formed, is stored in the anticyclones 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 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. 31.2) appears to be important in forming a new water mass contributing to CIW. The cold winter temperatures and the low salinities increase the importance of a nonlinear equation of state for seawater in this environment. Cursory examination of the increase in the density of water that would be formed by mixing of the two water types across the front may suggest cabelling effects (e.g., Fofonoff, 1995) implied to be of significance in other frontal regions of the ocean, yet there is no positive evidence for this process at present.

The cold-water formation by convection processes on a shallow continental shelf is known to be significantly more efficient in the case of long and shelf regions, since the total cooling in this case is intensified by rotational effects (Whitehead, 1993). The western Black Sea shelf satisfies Whitehead's criterion for the additional effects of rotation, since its length (ca. 600 km) is equal to or greater than the critical length scale, estimated to be $L_c \simeq 200$–600 km, for 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 calculate a temperature difference of greater than 8°C across the shelf-break front, compared with a value of about 5°C observed in Fig. 31.2.

The adjustment of the shelf-break front leads to cross-shelf circulation and jet flows along the shelf break (Symonds and Gardiner-Garden, 1994), which then creates exchanges between the shelf and the deep ocean during its relaxation. Strong baroclinic eddies and filaments similar to Fig. 31.2 were observed to develop across the front in laboratory experiments (Whitehead, 1993). Further, the cold water formed and trapped on the shelf would be expected to cascade down the canyons, cutting across the continental slope (Sugimoto and Whitehead, 1983; Bignami et al., 1990);

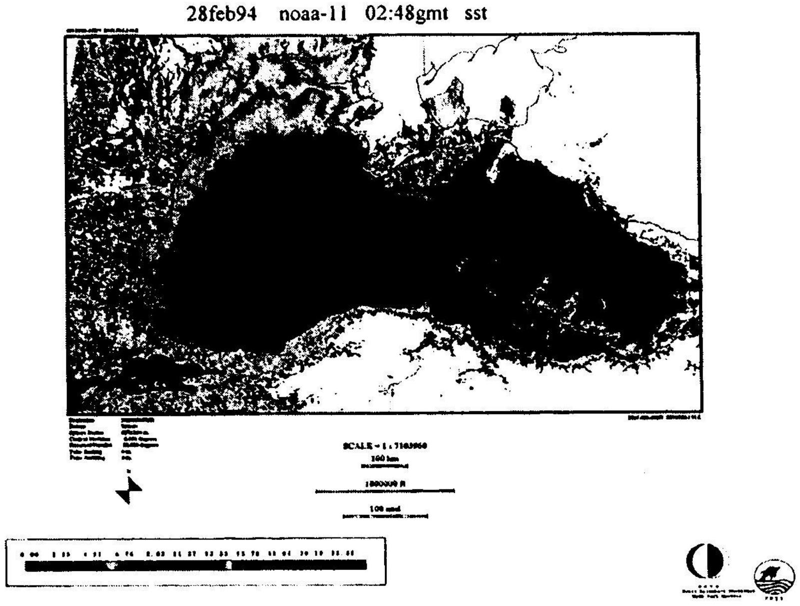


Fig. 31.2. See color insert. Sea-surface temperature (SST) derived from NOAA-11 advanced very high resolution radiometer (AVHRR) satellite image on February 28, 1994. The SST in the western shelf ranges between 3 and 7°C, with the coldest temperatures in the far north. The cold water on the shelf follows closely the bottom contours (Fig. 31.1). The warm water (ca. 10°C) off the Caucasian coast is rapidly developing large meanders (compare with Fig. 31.10). (After Sur et al., 1996.)

the termination of the cold shelf water in the southwestern Black Sea region near the Bosphorus and Sakarya Canyons (Figs. 31.1 and 31.2) could suggest canyon processes, despite the lack of direct wintertime evidence on these possibilities.

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

3.2. Mediterranean Outflow

Shelf Mixing of the Mediterranean Effluent

The incursion of warm, saline waters from the Mediterranean has a significant effect on the stratification and coastal circulation of the Black Sea. Topography plays a crucial role in the exit region of the Bosphorus. The warm, saline, Mediterranean water initially preserves much of its identity while it flows over a sill and continues to be contained within a bottom channel oriented northwest. Upon exit to the flat midshelf region, it spreads into a thin sheet and mixes rapidly with overlying waters; finally, it turns east and cascades off the shelf following a delta structure of shallow bottom grooves. This detailed description of the topographical effects by Latif et al. (1991) superseded the earlier and often conflicting accounts provided by Tolmazin (1985b) and Yüce (1990). Further investigations of the Mediterranean outflow have been continued in 1994 (Gregg, 1995) and in 1996, resulting in a historic data set promising to yield further details.

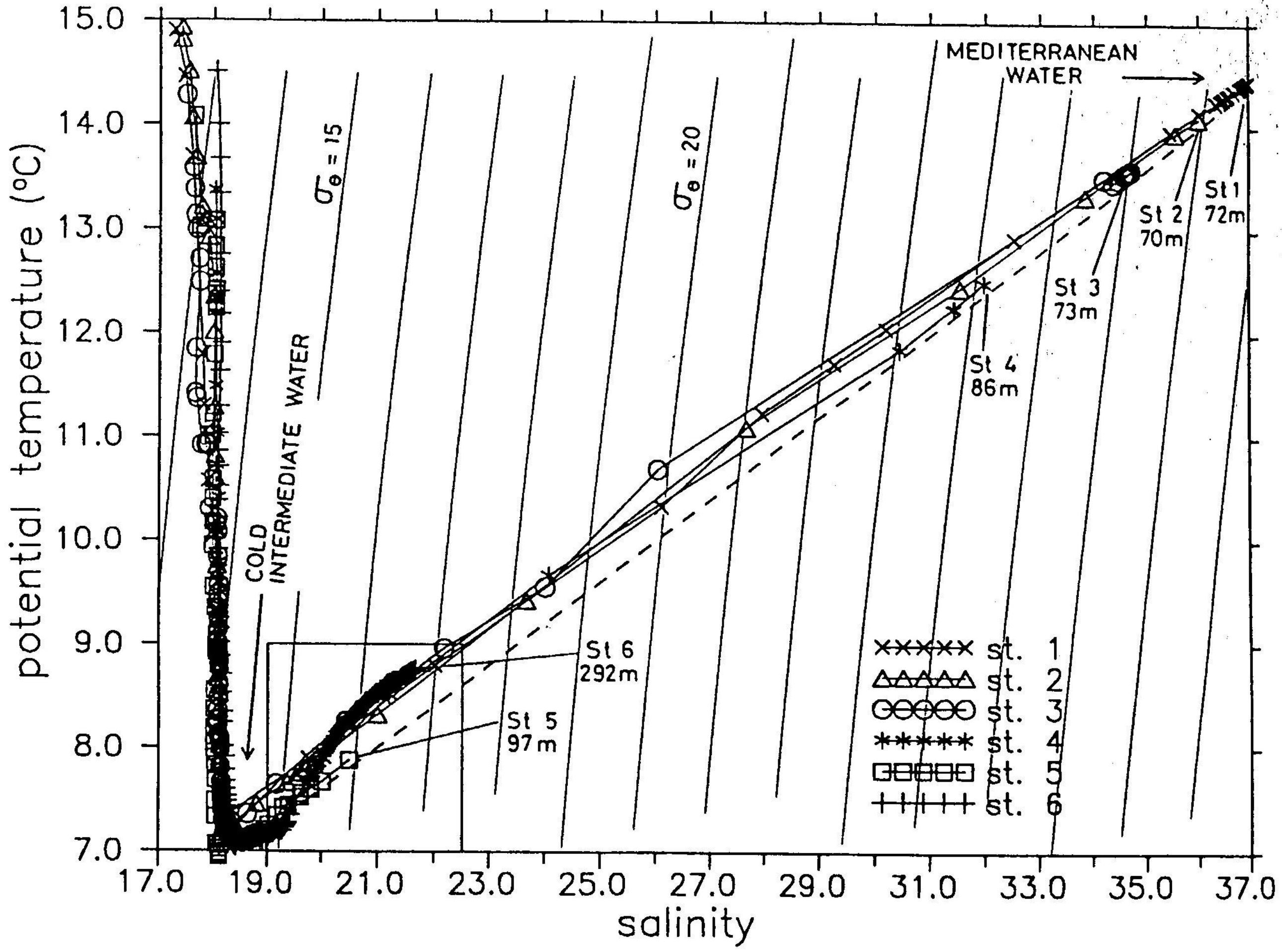


Fig. 31.3. Evolution of temperature–salinity across the shelf. Stations 1–5 extend from the Bosphorus to the shelf break. Station 6 is a deeper station immediately offshore. The dashed line models the changes in the Mediterranean effluent at the bottom. At the shelf break (station 5), the modified bottom waters are colder than waters at comparable depths of the continental slope (station 6). (After Özsoy et al., 1993.)

The warm saline (dense) Mediterranean Water (MW) flowing along the shelf bottom at depths of 50–100 m comes into direct contact with the overlying CIW, and by entrainment and mixing, the temperature and salinity at the core of Mediterranean Water rapidly decreases from respective values of 14.5°C and 37 at the northern end of the Bosphorus to about 8°C and 23 at the shelf break (Özsoy et al., 1993). On a potential temperature versus salinity (θ–S) diagram, the change in the properties of the bottom water follows direct, linear mixing between the two major water masses on the shelf (dashed line in Fig. 31.3). The dense bottom water emerges at the shelf edge with colder, yet more saline properties compared to ambient waters of the continental slope, imparting to the shelf-modified Mediterranean Water a signature totally different from the initially warm, saline characteristics. From there on, the cascading dense water is differentiated from the ambient waters with a cold anomaly (Özsoy et al., 1993).

The flux of water entrained into the bottom flow along the shelf is estimated to be about three to six times the flux issuing from the Bosphorus (Özsoy et al., 1993), consistent with some earlier overall estimates (e.g., Ünlüata et al., 1990; Buesseler et al., 1991; Murray et al., 1991; Swart, 1991), often extending beyond the shelf region.

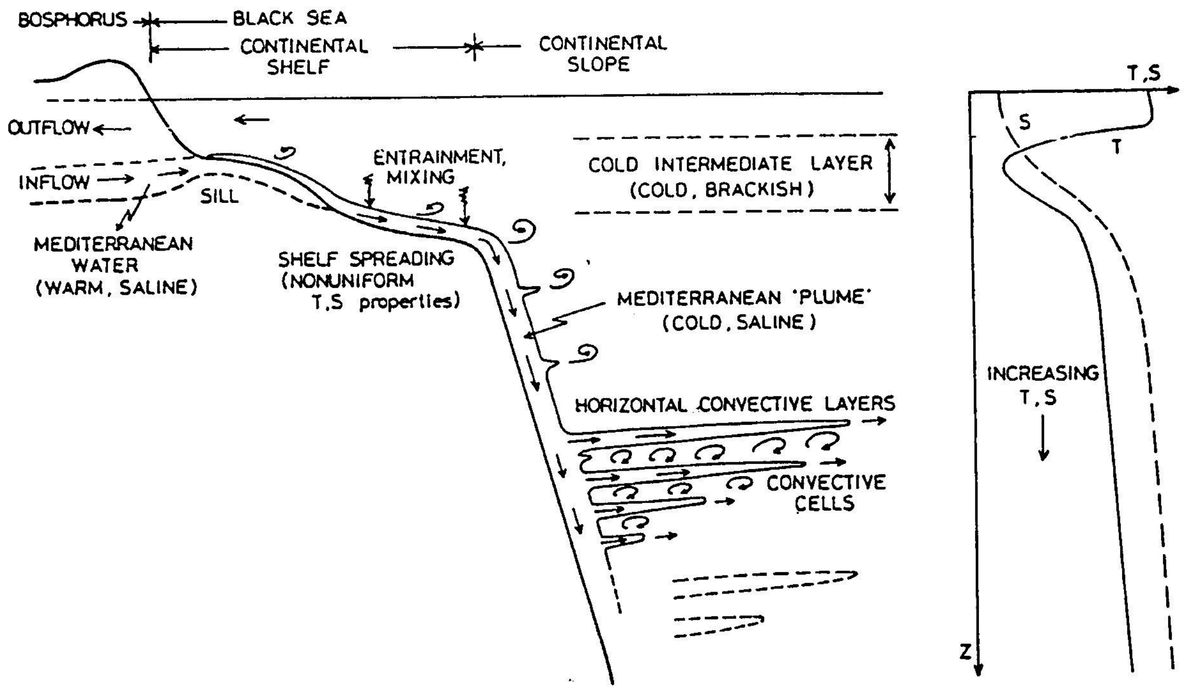


Fig. 31.4. Schematization of the boundary mixing driven by the Mediterranean outflow. Linear, direct mixing occurs on the shelf region and on part of the slope. At intermediate depths, double-diffusive instabilities in the temperature and salinity contrasts drive the intrusions. (After Özsoy et al., 1993.)

A model of the dense bottom water flow (Simeonov et al., 1997), including the spreading phase on the shelf and the plume phase along the continental slopes has so far yielded promising results. Yet, additional fine details of the physical processes must be taken into account to fully resolve the contrast of concentrated veins of dense water on the shelf bottom with the overall diffuse character of changes in water-mass characteristics in a much larger region.

The boundary processes at the basin periphery driven by the Bosphorus outflow are recognised to be of significance (following sections) in controlling the eddy circulation and the evolution of the Black Sea pycnocline; it is therefore important to study these effects for a better understanding of the climatic changes and variability of the Black Sea.

Double-Diffusive Intrusions near the Continental Slope

The cascade of cold, dense water from the shelf results in a series of intrusions along the continental slope (Fig. 31.4), corresponding to a convection pattern driven by salinity–temperature contrasts of the sinking water versus the interior, aided by the double-diffusive instabilities of the ambient stratification (Özsoy et al., 1993; Özsoy and Beşiktepe, 1995). Similar features have been detected earlier in the same region (Oğuz et al., 1991; Oğuz and Rozman, 1991; Özsoy et al., 1991). Large discrepancies occur between the modern observations and the historical ones (e.g., Bogdanova, 1961; Tolmazin, 1985b), possibly deriving from the improved accuracy of the modern measurements.

In the θ–S space (Fig. 31.5), the cold water which is initially attached to the continental slope (dashed lines) separates into discrete layers identified for several hundreds of kilometers east of the source. The breakdown into layers is a consequence

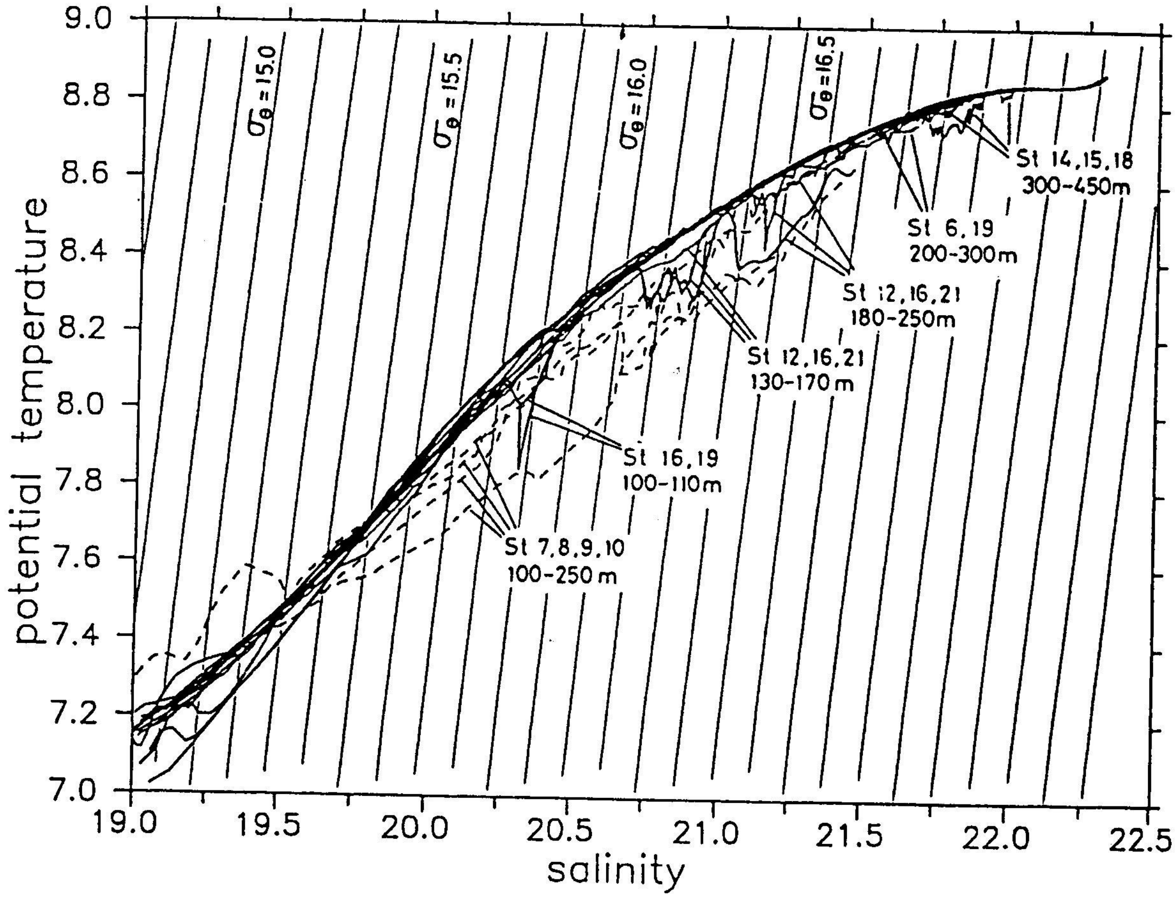


Fig. 31.5. Potential temperature–salinity relationship in the southwestern Black Sea. Dashed lines are within the cascading water adjacent to the continental slope, while discrete layers of intrusions are identified immediately offshore. (After Özsoy et al., 1993.)

of a double-diffusive instability in the stratified environment (Turner, 1973, 1978; Huppert and Turner, 1980), verified by reviewing the vertical and horizontal distributions of the density ratio (or Turner angle). Short-term variability and intermittency are basic features of these intrusions, which are separated by a series of alternating diffusive–fingering interfaces (Özsoy et al., 1993; Özsoy and Beşiktepe, 1995).

More direct evidence of shelf processes near the Bosphorus is provided by measurements of suspended matter, nutrients and Chernobyl radiotracers (Buesseler et al., 1991; Kempe et al., 1991; Codispoti et al., 1991; Özsoy et al., 1993), consistently traced back to common sources near the southwest margin. Intermittency and filamentation are common, resulting from the interactions of currents with prominent topography such as near Sakarya Canyon (Özsoy et al., 1993; Sur et al., 1994).

Effects of Ventilation

Mixing along the Anatolian margin of Black Sea has long been recognized as a possible source of ventilation (Grasshoff, 1975). There is ample evidence for vigorous mixing along this coast, resulting from mesoscale dynamical instabilities (Sur et al., 1994) and the Mediterranean outflow (Özsoy et al., 1993). In the latter case, the cascade of shelf water constitutes a time- and depth-dependent random source (e.g., Rooth, 1986; Stigebrandt, 1987), capable of driving a vertical recirculation.

The various ventilation processes in the Black Sea are schematized in Fig. 31.6.

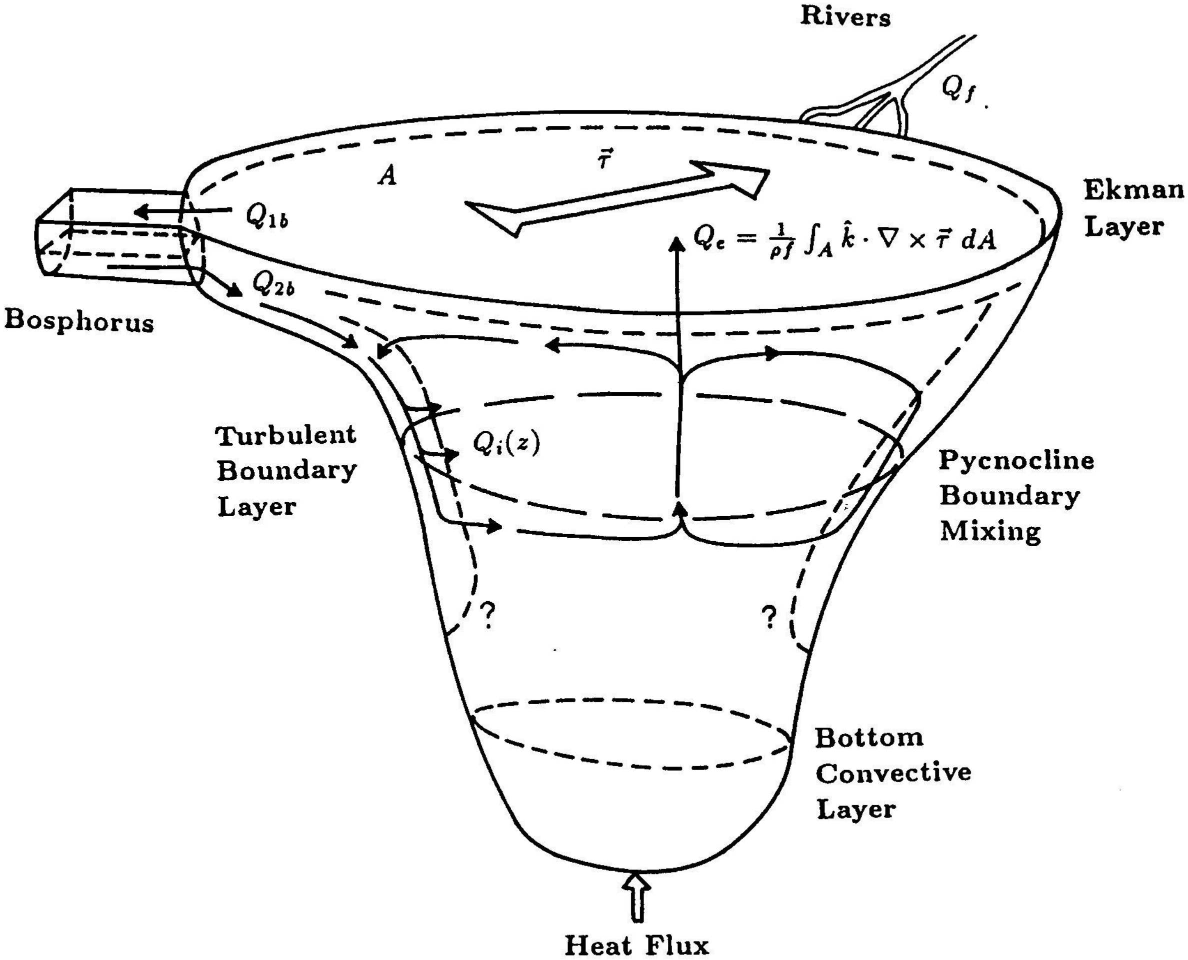


Fig. 31.6. Schematization of boundary layer–driven ventilation in the Black Sea. (After Özsoy et al., 1993.)

Ekman pumping in a closed-geometry, buoyancy-driven lateral boundary layers with double-diffusive features and exchanges through the Bosphorus constitutes the balance of mass fluxes. With the rapid decrease of turbulent mixing below the halocline, the boundary mixing component driven mainly by the Mediterranean outflow, could dominate the vertical renewal of upper Black Sea waters. Efficient ventilation across the halocline is indicated (Buesseler et al., 1991) by this mechanism. Another important consequence is the horizontal transport of shelf material into the interior at intermediate depths covering the anoxic zone (e.g., Spencer et al., 1972; Brewer and Spencer, 1974; İzdar et al., 1986; Hay, 1987; Honjo et al., 1987; Buesseler et al., 1991; Kempe et al., 1991). Based on the detection of intrusions and the temperature structure, the ultimate penetration depth of Bosphorus intrusions is estimated to be about 500 m at present (Özsoy et al., 1993, 1995), consistent with ^{14}C (Östlund, 1974; Östlund and Dyrssen, 1986) and tritium measurements (Top et al., 1991).

Efficient intermediate depth mixing, resulting in a vertical recirculation in the Black Sea (Fig. 31.7), is akin to the mechanism of boundary mixing in the deep ocean (Garrett, 1979, 1990; Ivey and Corcos, 1982; Phillips et al., 1986; Salmun et al., 1991; Woods, 1991), advanced to explain relatively large effective vertical diffusivities in the abyssal ocean, where molecular diffusivity fails to account for the observed level of mixing. Although these concepts could be applicable to the Black

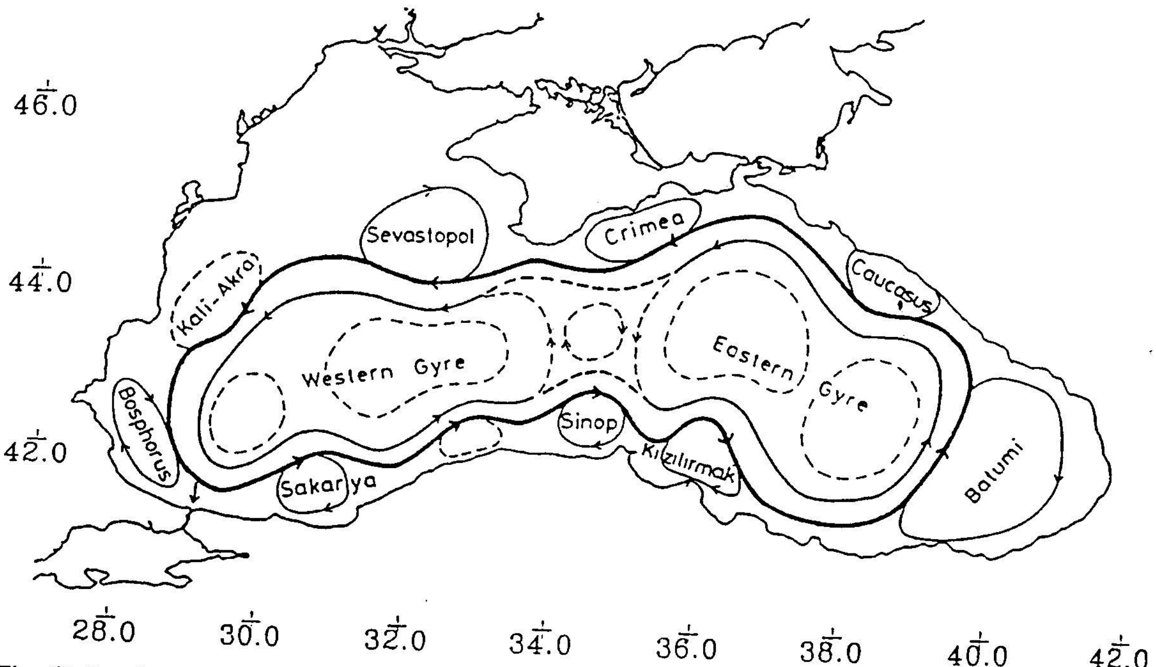


Fig. 31.7. Schematization of upper-layer general circulation based on a synthesis of recent studies. (After Oğuz et al., 1993a.)

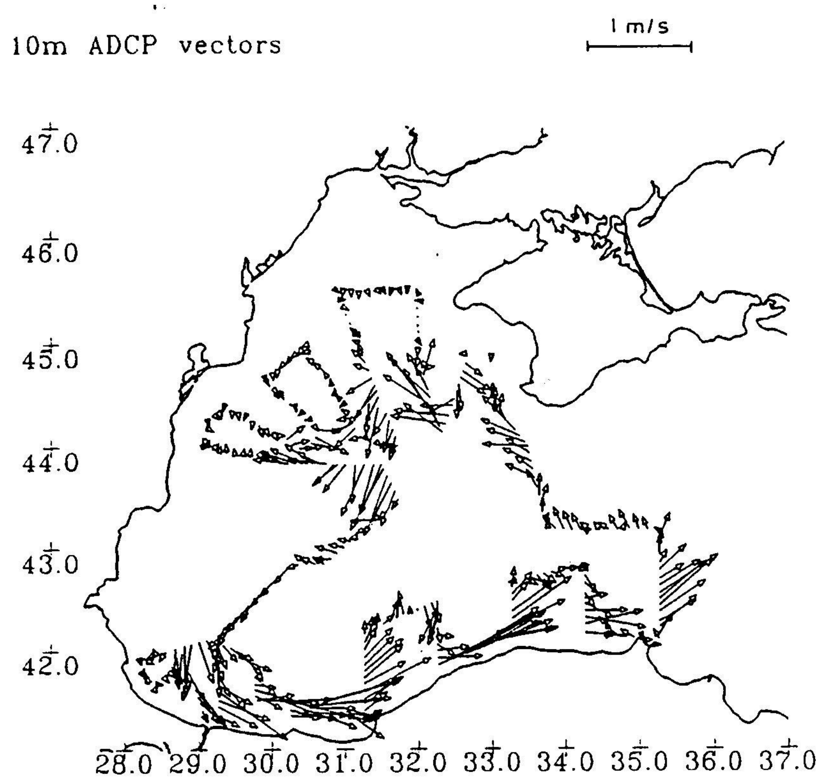
Sea ventilation at the pycnocline and deeper levels, further factors, including the double-diffusive instability of the ambient waters (Turner, 1978; Özsoy et al., 1993), need to be accounted for.

4. Circulation Characteristics

4.1. *Basin General Circulation*

A coherent, basin-scale, cyclonic boundary current (the *Rim Current*; Oğuz et al., 1992, 1993a, 1998) is the main feature of the Black Sea general circulation (Figs. 31.8 and 31.9; see the color plate), occasionally encompassing partial cells within the cyclonic central part, a number of anticyclonic eddies along the periphery, and a quasi-permanent anticyclonic circulation in the eastern corner. A somewhat simpler version of this general circulation was first described by Knipovich (1932) and Neumann (1942), with some structural variability added later by Filippov (1968), Boguslavskiy et al. (1976), Blatov et al. (1984), Eremeev et al. (1992) and Trukchev and Demin (1992).

Despite the modern level of description based on detailed observations, the physical factors driving the circulation have yet to be established with some confidence. In this respect, modeling studies are expected to yield improved understanding. Classically, a positive curl of wind stress (e.g., Rachev et al., 1991) has been recognized as the main reason for the cyclonic circulation (e.g., Neumann, 1942; Moskalenko, 1976). Earlier diagnostic models used coarse climatological data (Dzhioev and Sarkisyan, 1976; Gamsakhurdiya and Sarkisyan, 1976; Moskalenko, 1976), and the modern efforts in modeling for many years concentrated attention on wind stress forcing alone (Stanev et al., 1988; Demyshev, 1992; Eremeev et al., 1992; Trukhchev and Demin, 1992; Klimok and Makeshov, 1993). Recently, the effects of forcing



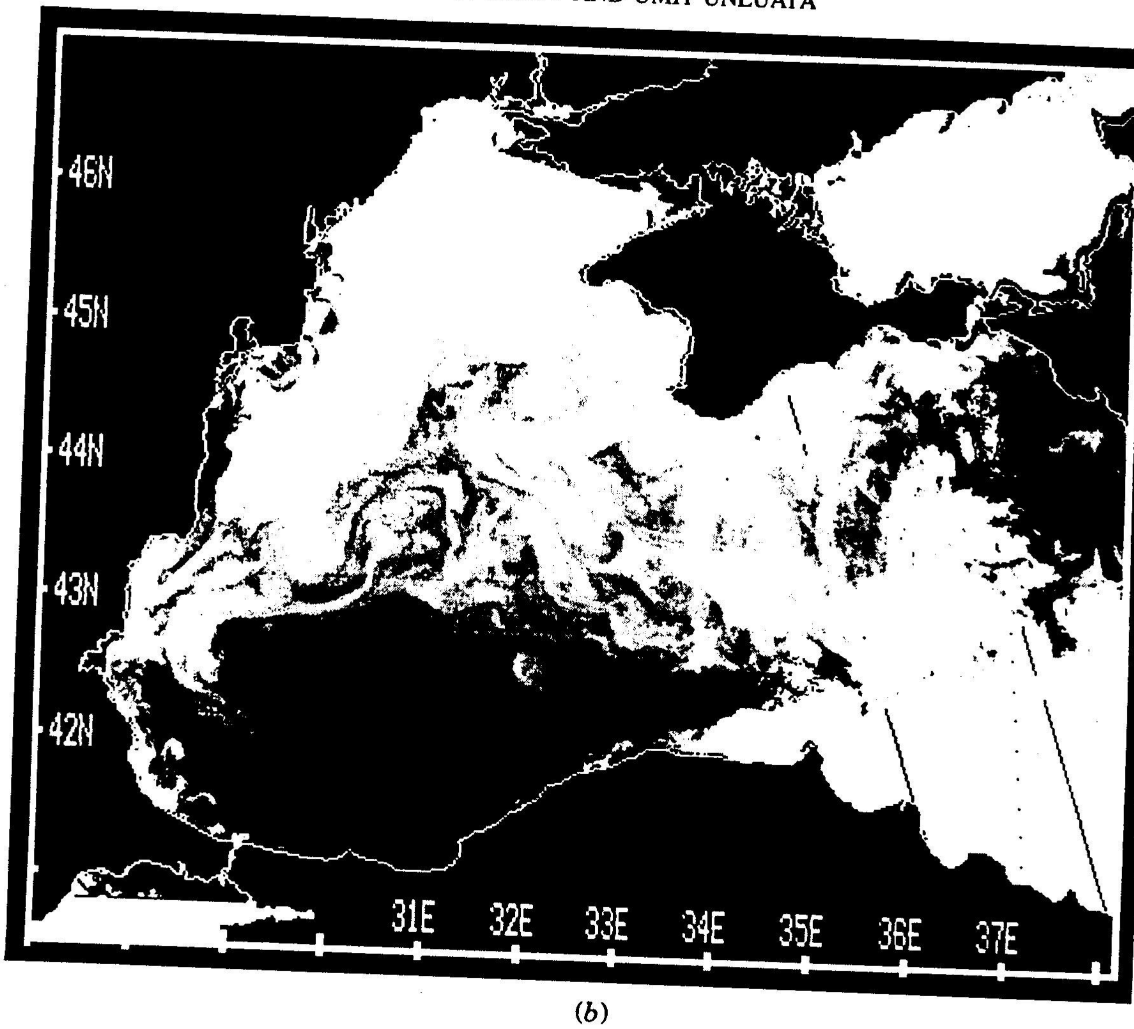
(*a*)

Fig. 31.8. (*a*) ADCP current measurements at 10 m depth, April 1993; (*b*) infrared AVHRR image, April 19, 1993; (*c*) surface dynamic topography (cm), referenced to 500 m and computed from multivariate analyses of ADCP and CTD data. (After Güngör, 1994; Sur et al., 1996.)

by buoyancy fluxes, including the atmospheric components (surface fluxes) and the river–strait components, were found to be equally important (Stanev, 1990; Bulgakov et al., 1993; Korotaev, 1997) in driving the horizontal as well as the vertical components of the circulation. A model with high resolution, turbulence closure and active thermodynamics (Oğuz et al., 1995) showed the topography, wind, surface and lateral buoyancy fluxes to be first-order contributors in driving the 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 that better resolved some features and confirmed the roles of lateral buoyancy sources and topography (e.g., Stanev, 1990) in driving mesoscale activity along the periphery of the basin.

4.2. *Coastal Mesoscale Variability*

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, amply demonstrating various mesoscale eddies, meanders and filaments riding on, or being shed from the rim current (Blatov et al., 1984; Latun, 1990; Golubev and Tuzhilkin, 1990, Stanev, 1990; Ünlüata and LaViolette 1990; Ünlüata et al., 1990; Oğuz et al., 1992, 1993a–c; Özsoy et al., 1993; Sur et al., 1994, 1996). These meandering currents and filaments have a leading influence on the exchange of materials between the coastal and open-sea regions and are therefore very impor-



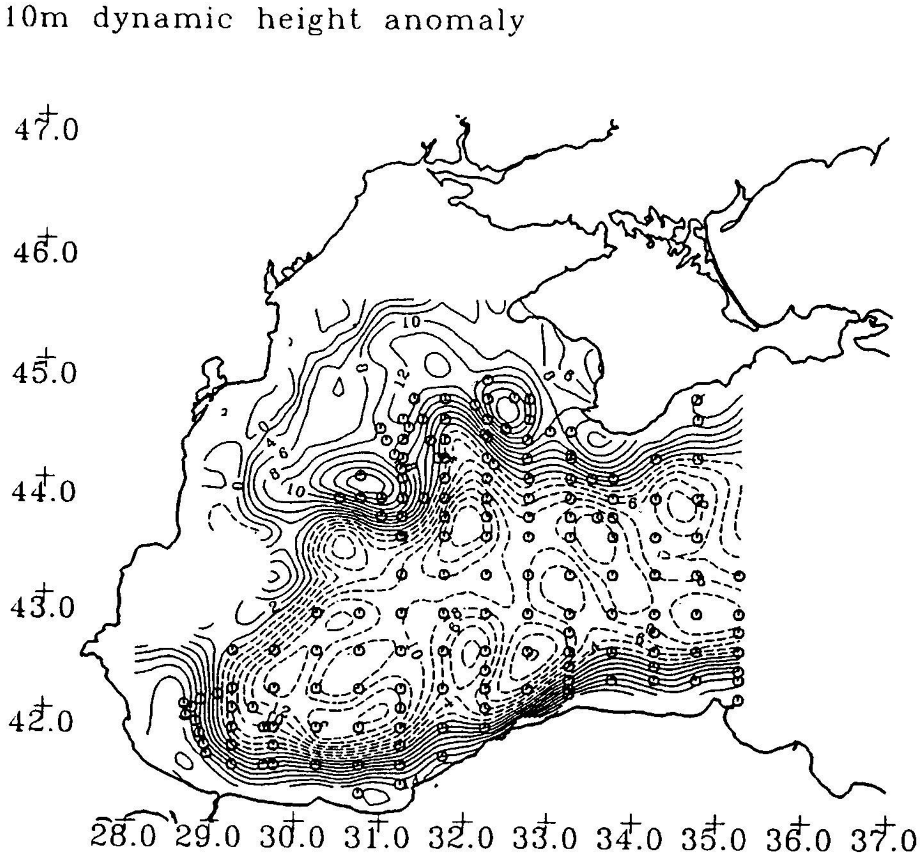
(*b*)

Fig. 31.8. (*Continued*)

tant in determining the cycling of materials and the state of health of the Black Sea.

ADCP measurements confirm the existence of an intense boundary current attached to the continental slope, with speeds of up to 1 m s^{-1} in the southwestern Black Sea (Fig. 31.8*a*). Corresponding infrared data (Sur et al., 1996) (Fig. 31.8*b*), and multi-variate analysis of dynamic height derived from CTD and ADCP data (Özsoy and Güngör, 1993; Güngör, 1994) (Fig. 31.8*c*) illustrate the structure of the rim current.

In addition to the various mesoscale features extending into the interior from the rim current, a semipermanent feature frequently detected in the north is the Sevastopol eddy, located on the lee side of the Crimean Peninsula (Fig. 31.8). Along the southwest coast, unstable features in a wide range of scales are generated. The abrupt termination of the shelf at Sakarya Canyon, and changes in bottom slope and coastline orientation along the western Anatolian coast, are influential in triggering transient mesoscale activity along the same coast (Sur et al., 1994, 1996). These unstable features, initially attached to the continental slope, tend to grow in amplitude and develop into a separated turbulent jet (Fig. 31.9) about one month after their initiation in early summer. Dipole eddies have been detected at headlands near river mouths (Sur et al., 1994, 1996). Large meanders of the stream are common



(c)

Fig. 31.8. (*Continued*)

along the Caucasian coast (Oğuz et al., 1993; Sur et al., 1994, 1996). These rapidly developing large meander motions appear to be dynamically linked with the Batumi anticyclone, a large, semipermanent feature trapped upstream, in the southeastern corner of the Black Sea. As shown in Fig. 31.2, obtained about one month later than the large coherent eddy formations of Fig. 31.10, the meanders grow initially from large eddies along the same coast, reaching great distances offshore.

Persistent upwelling (Fig. 31.11) is observed along the southwest coast at Capes Kerempe and İnce (Sur et al., 1994) every summer, when the winds are not particularly strong to induce upwelling. 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, similar to other cases of transient upwelling observed in similar frontal regions (e.g., Millot, 1991; Beckers and Nihoul, 1992).

Along the Anatolian coast, waters advected from the northwest shelf by the cyclonic circulation often display interesting density current features. In the winter of 1990, the satellite and in situ data showed cold water originating from the north and advected along the entire western shelf. The vein of cold, low-salinity 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 (Fig. 31.12) as it interacted with the sharp headland and topographic transition at Cape Baba (Sur et al., 1994, 1996).

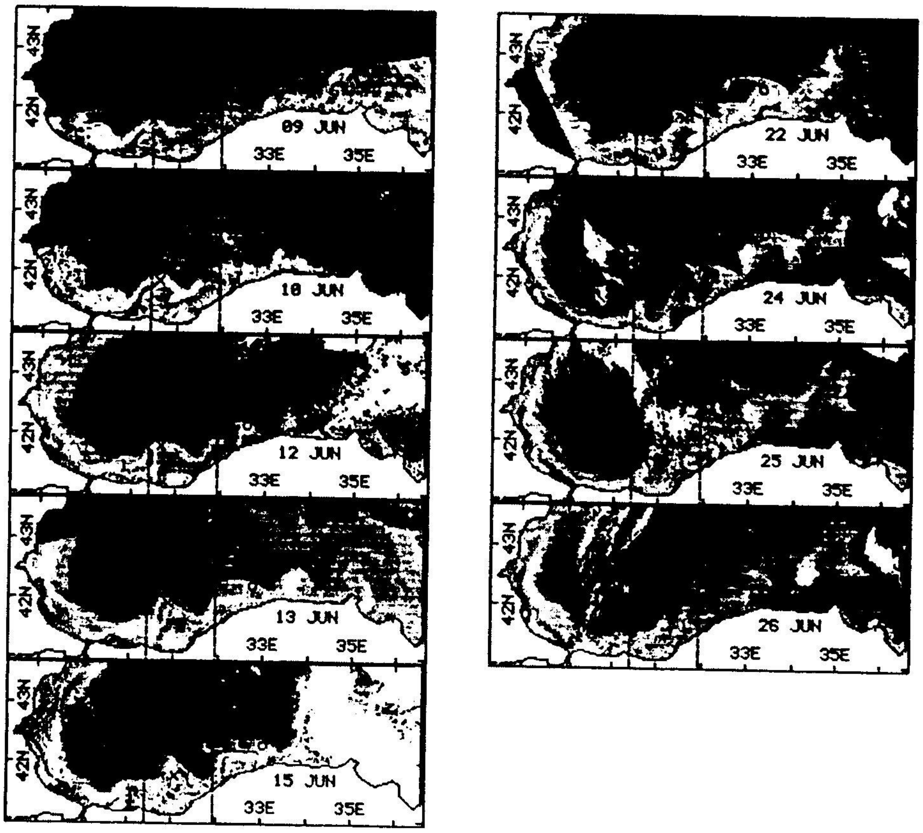


Fig. 31.9. See color insert. Sequence of CZCS channel 3 (550 nm) images, showing the development of turbulent motions and the associated spread of primary productivity in the western Black Sea during the period June 9–26, 1980. Vertical lines mark the same positions, while the cross and circle symbols trace the eastward motion of meander crests, with a speed of about 10–15 km day^{-1}. (After Sur et al., 1994, 1996.)

5. Physical Controls on the Marine Ecosystem

The recent environmental problems and losses in the Black Sea, related to processes of eutrophication (Mee, 1992) and accumulation of major contaminants (IOC, 1993), deserve urgent attention, as a special, high-ranking case of adverse changes threatening the semienclosed seas of the globe. The general circulation of the Black Sea, as well as the mesoscale features, have a large impact on the distribution of nutrients and oxygen. Indeed, the eutrophication had its origins in the shallow northwestern shelf, where riverine influxes of nutrients have multiplied within the last decades (Mee, 1992), and hypoxia on the bottom has developed across the shallow, wide shelf region (Zaitsev, 1993). Later, with increasing levels of nutrients input into the Black Sea, the effects of eutrophication have spread first along the western shelf and then into the deep interior region by transport processes and have altered the existing biochemical cycles.

During its operational time in the 1980s, the coastal sea color scanner (CZCS) satellite data (e.g., Fig. 31.9) has shown massive plankton blooms developing pro-

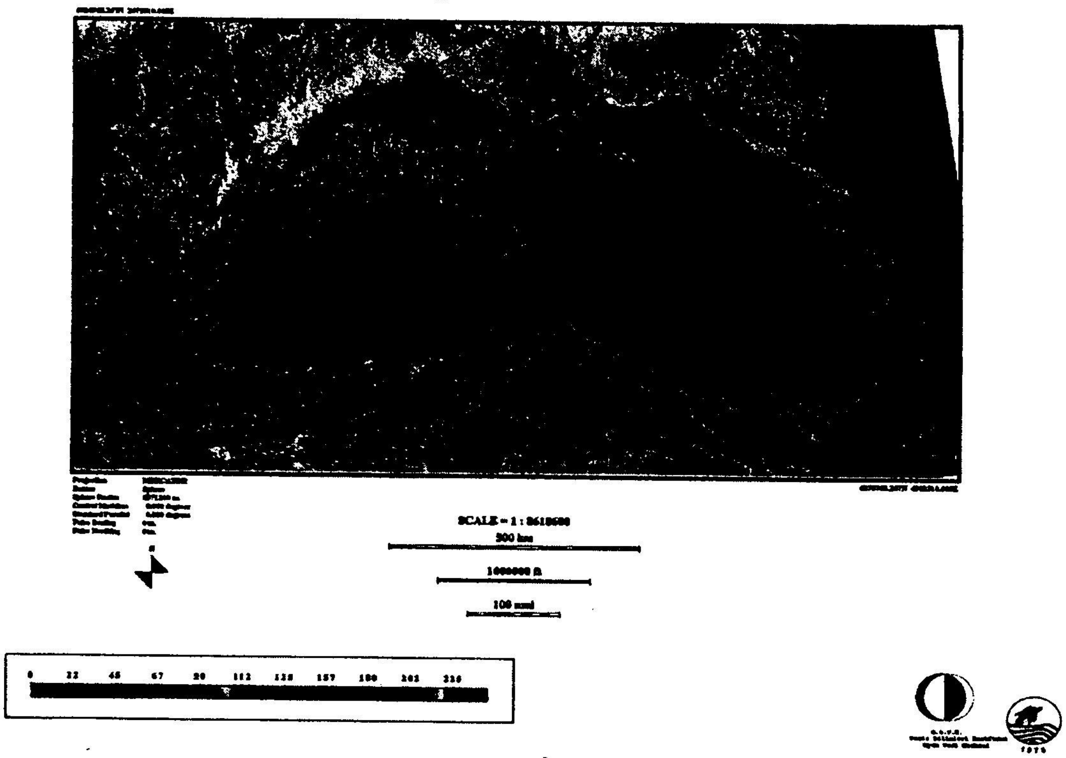


Fig. 31.10. See color insert. NOAA-10 AVHRR channel 4 satellite image on February 9, 1994, showing a warm-core eddy that is part of a developing large meander near the Caucasian coast. Compare with Fig. 31.2, for later development. (After Sur et al., 1996.)

gressively along the western shelf (Barale, 1994; Sur et al., 1994, 1996; Barale and Murray, 1995).

The spectral content of satellite images shows further details: In summer, populations rich in chlorophyll *a* are persistent near the freshwater sources in the northwestern shelf. To the south, along the shelf, this first population in early summer gives way to the coccolithophore species *Emiliania huxleyi* (Holligan et al., 1983), consistently verified by coastal and sediment trap measurements (Bologa, 1986; Benli, 1987; Hay and Honjo, 1989; Hay et al., 1990, 1991). In fact, the first bloom of *Emiliania 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), only to come to a sudden end in late summer, when dinoflagellate blooms take over.

The around-basin transport by the cyclonic boundary current and the cross-shelf transport by frontal and jet instabilities have important implications on the pattern of primary production, because recent results emphasize the contribution of riverine sources to new production (Murray et al., 1993; Çokacar, 1996), despite common assumptions regarding the deep water as the main reserve of nutrients supplied to the photic zone (e.g., Fonselius, 1974; Sorokin, 1983). 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 satellite-derived pigment patterns show transport and dispersal of materials originating from the northwest shelf (e.g., Fig. 31.9).

Physical features such as summer upwelling (Sur et al., 1994) have great impact on

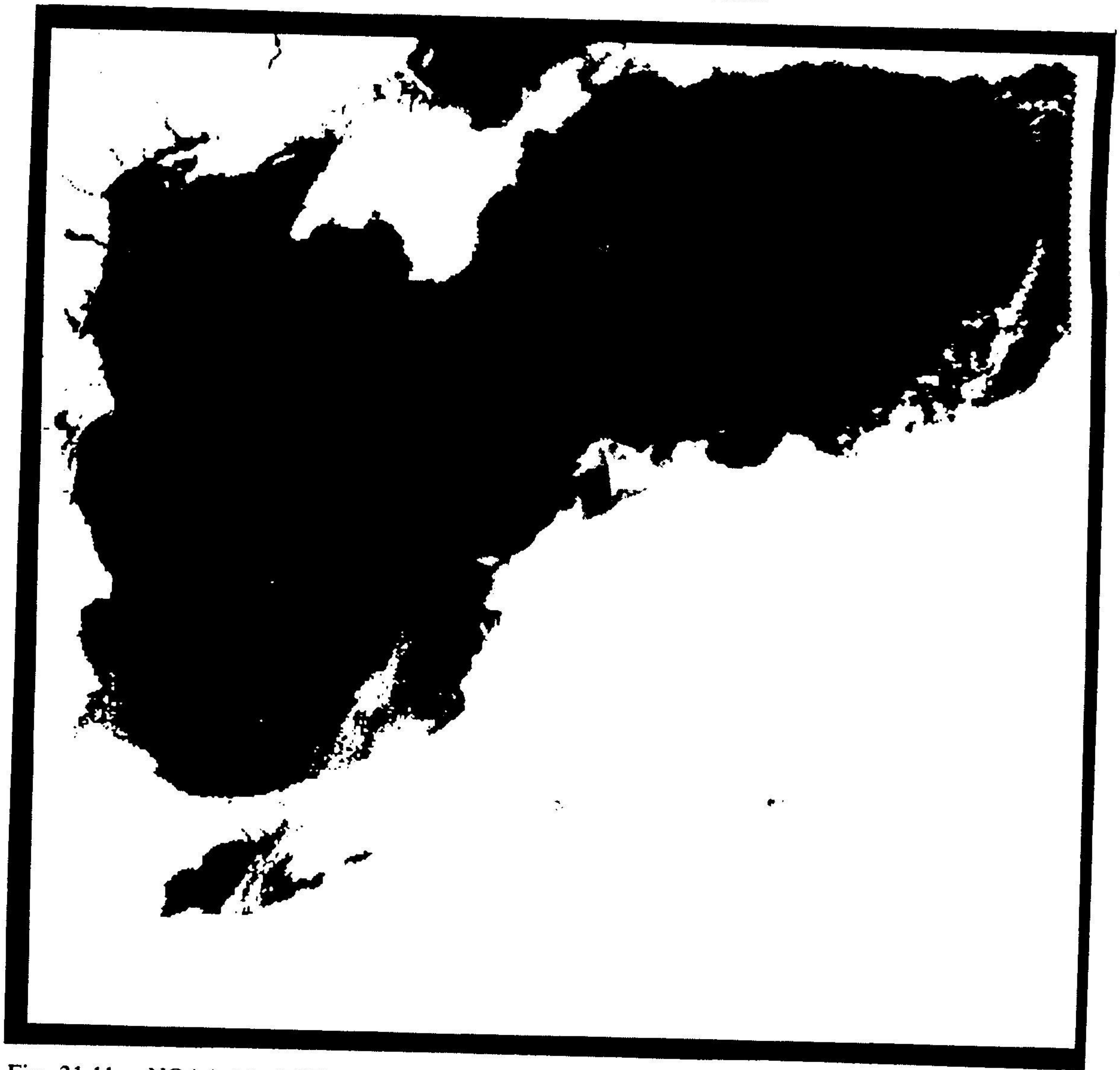


Fig. 31.11. NOAA-10 AVHRR infrared image on September 3, 1992. Lighter shades correspond to colder temperatures. (Data supplied by Paul Gerdeers of the Royal Netherlands Meteorological Institute.)

local variability of this pattern. For example, during upwelling in 1992 (Fig. 31.11), 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 upwelling patches along the Anatolian coast, while phytoplankton did not show any particular pattern related to upwelling (Bayrakdar et al., in preparation). Interestingly, a similar situation was evident in July 1957 (Einarsson and Gürtürk, 1960; Niermann et al., 1993), but was overlooked earlier.

The winter encroachment of cold shelf water from the western shelf to the southwestern coast (e.g., Fig. 31.2) appeared well correlated with specific diatom blooms propagating along this coast (Sur et al., 1994; Uysal and Sur, 1995). The large meander motion along the Caucasian coast (Figs. 31.2 and 31.11), 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).

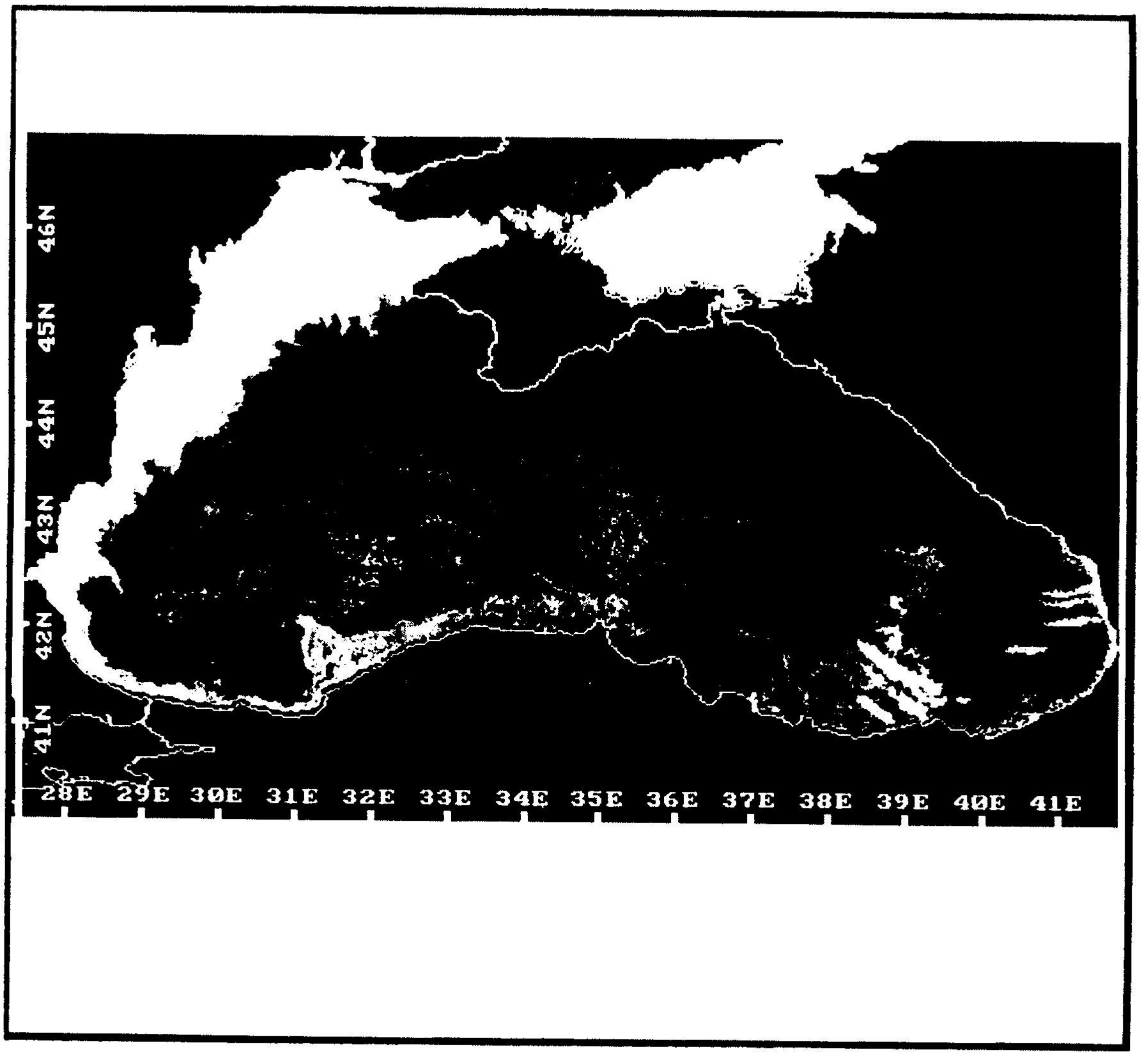


Fig. 31.12. NOAA-10 AVHRR infrared image (channel 4) on February 27, 1990. Light shades correspond to cold temperatures. The cold water is advected along the entire western shelf and undergoes a sudden expansion at Cape Baba.

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 machinery of the ecosystem. Recent coordinated efforts attempt to understand the basic elements of nutrient cycling and productivity by basinwide 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; Çokacar, 1996; Oğuz et al., 1996), and further rapid development is expected.

Acknowledgments

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 CoMSBlack (Cooperative Marine Science Program for the Black Sea) set the environment for collaborative work on the periphery of the Black Sea as reported here. 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 U.S. National Science Foundation. Other measurement programs in the Turkish Straits System, such as the projects supported by the City of İstanbul, 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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