Chapter 33. PYHSICAL AND BIOGEOCHEMICAL CHARACTERISTICS OF THE BLACK SEA (28,S)

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Contents

1. Introduction

The Black Sea, located approximately between latitudes of 41° to 46°N and longitudes of 28° to 41.5°E, is an elongated and nearly-enclosed basin connected with the Bosphorus Strait to the Mediterranean Sea. It has experienced one of the worst environmental degradations of the world oceans during the last three decades. The environmental crisis and subsequent dramatic changes in the ecosystem and its resources were a direct consequence of anthropogenic pollution due to an enormous increase in nutrients and pollutant load from rivers discharging into the northwestern region of the sea, uncontrolled industrial and municipal wastewater inputs around the periphery, dumping of wastes (including radioactive substances and solid wastes) into open parts of the sea, and accidental and operational releases of oil. Introduction of a jellyfish-like animal (*Mnemiopsis leidyii*), and overfishing have added further complications to the problem. At the beginning of the 1960s, total inorganic nitrogen, phosphate and silicate input from the Danube was 140 kt yr^{-1}, 12 kt yr^{-1}, and 790 kt yr^{-1} , respectively (Almazov, 1961). Three decades later, the Sulina branch of the Danube (one of its three main branches) alone discharged 800 kt yr^{-1} of total inorganic nitrogen, 32 kt yr^{-1} phosphate, and 1500 kt

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yr^{-1} silicate into the Black Sea (Cociasu et al., 1996). The total sediment load into the basin from the rivers around the periphery is about 145 million ton yr^{-1}, 65% of which enters into the northwestern shelf region (Hay, 1994). The Turkish rivers together contribute only 20% of the total sediment load (Hay, 1994). As a result, a major part of the Black Sea, particularly its northwestern shelf region, has become critically eutrophic and hypoxic (Zaitsev and Mamaev, 1997; Lancelot et al., 2002a). The exploitation of resources has been unsustainable during the last few decades as a result of dramatic reduction in fish stocks and falling recruitment.

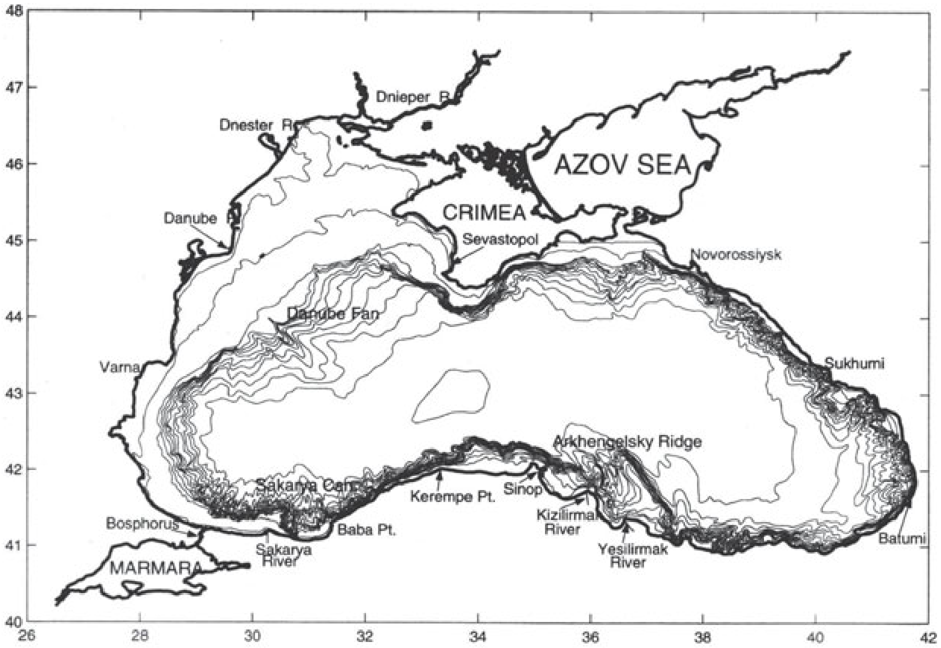

Figure 33.1 The Black Sea: geographic setting, main rivers and bathmetric features (from Besiktepe et al., 2001).

The last decade has introduced a new era in Black Sea oceanography because of collaborative research and management programs developed by the riparian states, and supported by various international organizations. They were aimed to address environmental and socio-economic issues facing the region, and to explore oceanographic characteristics of this relatively unknown, and in many respects, challenging sea. The present paper provides an overview of recent advances achieved within the framework of these efforts. Sections 2 and 3 outline the physical characteristics including the topography, water budget, and stratification, as well as major features of the upper layer horizontal circulation, respectively. This is followed in section 4 by description of the vertical biogeochemical characteristics of the upper layer water column up to the anoxic interface. This section also covers a brief overview of biogeochemical exchanges with the atmosphere. In Section 5, paleoceanographic characteristics are presented with special emphasis on connection of the Black Sea to the Aegean Sea, and sediment geochemical characteristics. Section 6 deals with major changes that took place in Black Sea ecosystem characteristics since 1970s. An overview of interdisciplinary modeling efforts is then provided in section 7. Conclusions are provided in section 8.

3. Circulation characteristics

The upper layer waters of the Black Sea are characterized by a predominantly cyclonic, strongly time-dependent and spatially-structured basinwide circulation. Many details of the circulation system have been explored using recent hydrographic data (Oguz et al., 1993, 1994, 1998; Oguz and Besiktepe, 1999; Gawarkiewicz et al., 1999; Krivosheya et al., 2000), AVHRR data (Oguz et al., 1992; Sur et al., 1994, 1996; Sur and Ilyin, 1997; Ginsburg et al., 2000, 2002a; Afanasyev et al., 2002; Zatsepin et al., 2003), altimeter data (Korotaev et al., 2001 and 2003; Sokolova et al., 2001), and CZCS and SeaWIFS data (Ozsoy and Unluata, 1997; Oguz et al., 2002a; Ginsburg et al., 2002b). These analyses reveal a complex, eddy-dominated circulation with different types of structural organizations within the interior cyclonic cell, the Rim Current flowing along the abruptly varying continental slope and margin topography around the basin, and a series of anticyclonic eddies in the onshore side of the Rim Current. The interior circulation comprises several sub-basin scale gyres, each of them involving a series of cyclonic eddies. They evolve continuously by interactions among each other, as well as with meanders, and filaments of the Rim Current. The Rim Current structure is accompanied by coastal-trapped waves with an embedded train of eddies and meanders propogating cyclonically around the basin (Sur et al., 1994; Sur et al; 1996; Oguz and Besiktepe, 1999; Krivosheya et al., 2000; Ginsburg et al., 2002a,b). Over the annual time scale, westward propogating Rossby waves further contribute complexity to the basinwide circulation system (Stanev and Rachev, 1999). According to the Acoustic Doppler Current Profiler measurements (Oguz and Besiktepe, 1999), the Rim Current jet has a speed of 50–100 cm/s within the upper layer, and about 10–20 cm/s within the 150–300 m depth range. The mesoscale features evolving along the periphery of the basin as part of the Rim Current dynamic structure apparently link coastal biogeochemical processes to those beyond the continental margin, and thus provide a mechanism for two-way transports between nearshore and offshore regions. Taking the relatively narrow width of the basin into account, such mesoscale processes can easily give rise to meridional transports from one coast to another.

Apart from complex eddy-dominated features, larger scale characteristics of the upper layer circulation system possess a distinct seasonal cycle, as suggested by objectively analyzed, optimally interpolated and dynamically assimilated sea level anomaly data provided by the Topex-Poseidon and ERS-1/2 altimeters period from 1 January 1993 to 31 December 1998 (Korotaev et al., 2003). As shown by the model-derived circulation patterns (Fig. 33.4) for the middle of February, July and October, the interior cyclonic cell in winter months involves a two-gyre system surrounded by a rather strong and narrow peripheral jet without any appreciable lateral variations (Fig. 33.4a). This system transforms into a multi-centered composite cyclonic cell surrounded by a broader and weaker Rim Current zone in summer (Fig. 33.4b). The interior basin flow field further weakens and finally disintegrates into smaller scale cyclonic features in autumn (Fig. 33.4c). A composite peripheral current system is hardly noticeable in this season (Afanasyev et al., 2002). The turbulent flow field is, however, rapidly converted into a more intense and organized structure after November-December.

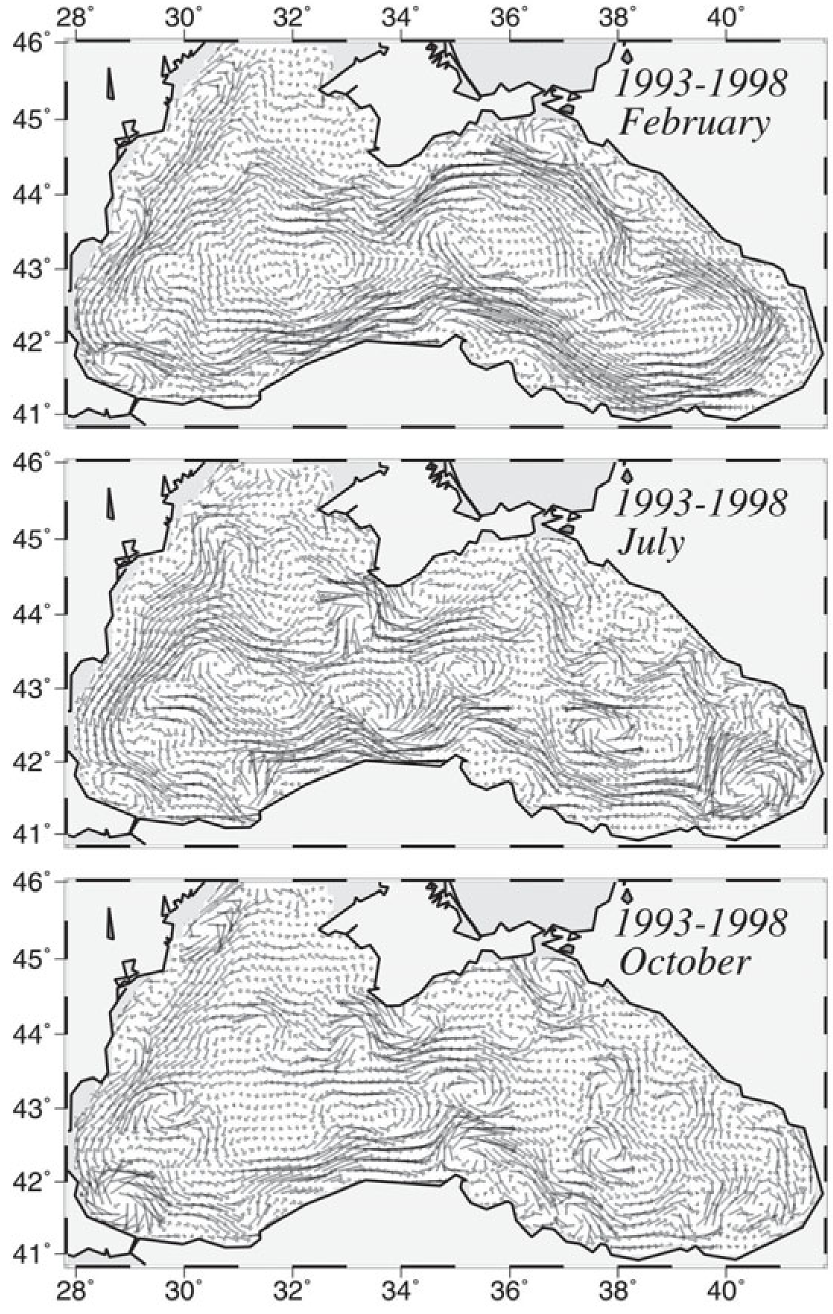

Figure 33.4 The upper layer circulation maps for (a) mid-February, (b) mid-July, (c) mid-October, constructed by the six year (1993–1998) averaging of the daily circulation fields computed by assimilating the Topex-Poseidon and ERS-I,II altimeter data into a 1.5 layer reduced gravity model described by Korotaev et al. (2003).

The most notable quasi-persistent and/or recurrent features of the circulation system, as schematically presented in Fig. 33.5, include (i) the meandering Rim Current system cyclonically encircling the basin, (ii) two cyclonic sub-basin scale gyres comprising four or more gyres within the interior, (iii) the Bosphorus, Sakarya, Sinop, Kizilirmak, Batumi, Sukhumi, Caucasus, Kerch, Crimea, Sevastopol, Danube, Constantsa, and Kaliakra anticyclonic eddies on the coastal side of the Rim Current zone, (iv) bifurcation of the Rim Current near the southern tip of the

Crimea; one brach flowing southwestward along the topographic slope zone, and the other branch deflecting first northwestward into the shelf and then contributing to the southerly inner shelf current system, (v) convergence of these two branches of the original Rim Current system near the southwestern coast, (vi) presence of a large anticyclonic eddy within the northern part of the northwestern shelf.

The basic mechanism which controls the flow structure in the surface layer of the northwestwern shelf is spreading of the Danube outflow. Wind stress and Rim Current structure along the offshore side of the shelf are additional modifiers of this system. The freshwater discharge influences not only the circulation and mixing properties, but also the ecosystem of the entire shelf region along the western coast. The Danube plume generally forms an anticyclonic bulge confined within the upper 25 m layer. The leading edge of this plume protrudes southward (i.e downstream) as a thin baroclinic boundary current along the western coastline. The coastal jet is separated from the interior waters by a well defined front with salinity differences of more than 3.0 over an approximately 50 km zone along the coast. It is often unstable, exhibits meanders and spawns filaments, which extend across the wide topographic slope zone. The shelf and interior waters undergo cross-shelf exchanges as reported consistently in hydrographic surveys, satellite imagery, and altimeter data. An anticyclonic circulation system accompanying with small-scale structures over the northwestern shelf, shown in Fig. 33.5, have also been reproduced by modeling studies (e.g. Oguz et al., 1995; Staneva et al., 2001; Beckers, et al., 2002).

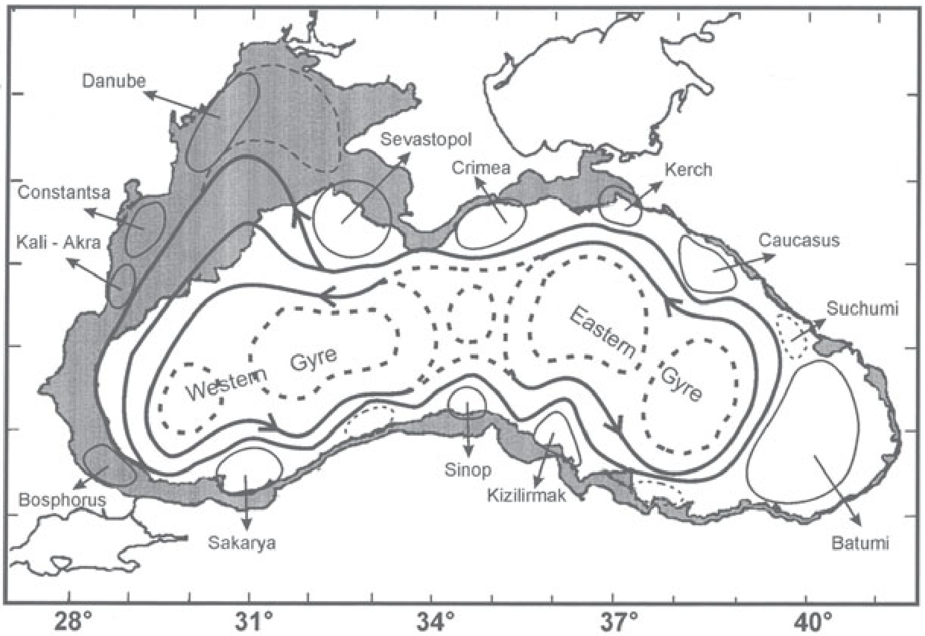

Figure 33.5 The schematic diagram showing major quasi-permanent/recurrent features of the upper layer circulation identified by synthesis of hydrographic studies and analysis of the Topex-Poseidon and ERS-I,II altimeter data.

coccolithophorids *E. Huxleyi* in the Black Sea during June and July every year, as suggested by the SeaWIFS mean normalized water-leaving radiance data (Cokacar et al., 2004). Low-level meridional atmospheric transport carried nss-sulfate aerosols over Anatolia into the marine atmosphere of the Eastern Mediterranean Sea roughly from the end of May to the end of September. The lateral aerosol supply from the Black Sea was found to terminate after September as the direction of low level air motions was shifted preferentially to northwesterlies during the autumn and winter months.

There is growing evidence that aeolian transported materials, particularly enriched in elements of ecological concern, such as iron, nitrogen, phosphorus, trigger phytoplankton production in the oceans (Duce et al., 1991). The Black Sea is under the particular influence of long-range aeolian transport from the Sahara, Middle East, Eastern Europe and Russian mainland in the northeast. A number of case studies confirmed transport from North Africa towards the Black Sea, particularly during spring and autumn months (Kubilay et al., 2000). On the basis of measurements performed during July 1992, dust deposition provided a total nitrogen supply of 44 kt yr^{-1}, which roughly corresponded to 13% of the total inorganic nitrogen input by the Danube outflow (Kubilay et al., 1995), and thus aerosol transport is important intermittently if not on the annual time scale.

5. Paleoceanographic characteristics

During the last glacial maximum before 12,000 BP, the Black Sea, the Sea of Marmara and Aegean Sea were about 120 m below their present levels, and were therefore decoupled from each other by shallow sills of the Bosphorus and Dardanelles. Freshwater conditions used to prevail both the Black Sea and Marmara Sea whereas the Aegean Sea reflected marine conditions. With the rise of sea level after the end of glaciation, the global sea level reached the 80 m sill depth of the Dardanelles around 12, 000 BP, and salty Mediterranean water started filling the Sea of Marmara, leading to the formation of a sapropel between 10,600 and 6400 BP (Cagatay, et al., 2000). The date upon which saline Mediterranean water first entered the Black Sea during the Holocene is more uncertain and indeed a contraversial issue. The traditional view (Ross and Degens, 1974; Stanley and Blanpied, 1999), later elaborated by Aksu et al. (1999, 2002), suggested that the Black Sea during the period from 12,000 to 9,500 BP still remained as a freshwater lake, receiving a large freshwater inflow from the receding European ice sheet through the rivers around the periphery of the basin. These factors resulted in a substantial rise of the Black Sea level from its pre-flooding depth of -120m; by ~11,000–10,000 BP, the Black Sea has risen to the Bosphorus sill depth of -40m and subsequently began to spill large volume of waters first into the Marmara Sea across the Bosphorus, and later into the Aegeran Sea across the Dardanelles Strait. Evidence for this view includes the presence of a sapropel in the Sea of Marmara (Cagatay et al., 2000), studies of shelf sediments in the Black Sea (Gorur et al., 2001), westerly-oriented bedforms in the Sea of Marmara (Aksu et al., 1999), and the analysis of planktonic and benthic foraminifera (Yanko et al., 1999; Kaminski et al., 2002). Following incursions of saline Mediterranean water into the Marmara Sea after the rise of the Aegean Sea level above the Dardanelles sill depth during the period from 12,000 to 9,500 BP, the rising sea level enabled Mediterranean inflow into the

Black Sea across the Bosphorus Strait starting by 9000 BP. The saline wedge had possibly penetrated well into the strait 500–1000 yr later, and led to a gradual salination of the Black Sea, and development of a two-layer stratification and formation of anoxic conditions by perhaps 8000 BP.

On the basis of sedimentary data from the northwestern and northern shelves of the Black Sea, Ryan et al. (1997) offered an alternative and contrasting view for the timing and development of marine connection between the Black Sea and the Sea of Marmara following the last deglaciation. According to this so-called "flood hypothesis" the Mediterranean-Black Sea post-glacial connection occured as a result of refilling of the Mediterranean basin and then flooding catastrophically into the Black Sea in less than 2 years at a flow rate of more than 50 km^3 day^{-1} during 7150±100 yr BP. This hypothesis has largely been based on the rapid first appearance of euryhaline (Mediterranean) mollusks on the Black Sea shelves at ~7,5000 BP. They further speculated that this flooding event was actually the reason for the migration of early Neolithic peoples from the region as mentioned in the biblical story of Noah's flood (Ryan and Pitman, 1999). Ballard et al. (2000) identified the location of ancient beach at 155 m water depth below the present day sea surface in the south-central Black Sea, and infered the marine flooding of the Black Sea between 7.46 and 6.82 ka by means of radiocarbon dating of mollusk shells. Ryan et al. (2003) later refined the hypothesis by considering large amounts of additional data. Aksu et al. (2002) believe that the euryhaline colonization of mollusks was not a consequence of catastrophic flooding but rather the outcome of a slow establishment of two-way flow in the Bosphorus and a time lag during which the fresher waters of the deep Black Sea were replaced by more saline inflow, eventually allowing marine organisms to colonize the Black Sea shelves. They suggested that mollusks arrived at the region about 7500 years ago when the level of salty Mediterranean water rose to the 100 m depths where mollusks thrive.

The Black Sea sediments deposited during the last 30,000 yr consist of three different environmental conditions of the Late-Quaternary history of the basin (Cagatay, 1999). At the bottom, *Unit 3* deposition during ~30,000–7,000 BP is a laminated clay with a low (~15%) carbonate content, and signifies the fresh water environmental conditions prior to inflow of the Mediterranean water through the Bosphorus. It also includes dark laminae that are formed by high concentrations of unstable iron monosulfides. *Unit 2* is ~ 40 cm thick sapropel deposition consisting of mainly gelatinous organic matter with some coccolith remains, clays, inorganically precipitated aragonite, iron monosulfides and pyrite. Sapropels are occasionally interrupted by turbidite layers of terrigenous origin. Sapropel unit was deposited during a period of high plankton productivity after the flooding of the lacustrine Black Sea basin by the Mediterranean waters via the Bosphorus Strait at around 7000 BP and terminated around 2000–1600 BP. Prior to termination of Unit 2 deposition, there is a period of time with intermittent coccolith invasions whose characteristics reveal some regional variability within the basin. *Unit 1* is ~30 cm thick coccolith mud, consisting of alternations of light- and dark-colored microlaminae. The light-colored laminae are composed mainly by calcareous coccolith remains deposited within the last 2000 yr after the invasion of the Black Sea coccolithophore *Emiliania huxleyi.* The dark laminae consist of clays and organic matter. The clay minerals include predominantly chlorite, smectite and illite with high chlorite/illite and smectite/illite ratios Three peak periods of coccolith deposition implied by maximum carbonate concentrations occurred around 450, 1050, and 1500 BP. They match closely with the transitions from high to low sea level changes that took place in the history of the Black Sea.

6. Changes in the ecosystem characteristics since the 1970s

The last three decades of the Black Sea have been characterized by profound changes in its pelagic ecosystem. These changes were first noted in the biomass, taxonomic structure and succession of the phytoplankton community, particularly in the northwestern shelf. The natural phytoplankton annual cycle with spring and autumn maxima in biomass has been replaced by a pattern characteristic of eutrophied waters identified by several exceptional maxima- the summer one being the most pronounced. In addition to an increase in the frequency of blooms and the number of blooming species, individual blooms have become more monospecific. Diatoms, which were the most abundant group of the annual phytoplankton community structure prior to the 1970s, were replaced by more predominant blooms of dinoflagellates and coccolithophores (Moncheva and Krastev, 1997; Mikaelyan, 1997; Uysal et al., 1998). This phenomenon may have been caused by changes in the silicon to nitrogen ratio due to eutrophication as well as a reduction in the dissolved silicate load of the River Danube (Moncheva and Krastev, 1997) as a result of dam construction in the early 1970s (Humborg et al., 1997) and/or increased eutrophication within the Danube itself (Garnier et al., 2002). Average phytoplankton biomass in the northwestern shelf area increased from 1 g m^{-2} in the 1960s to 19 g m^{-2} in the 1970s and 30 g m^{-2} in the 1980s (Zaitsev and Mamaev, 1997). A similar trend with lower intensity was also reported for other parts of the basin (cf. Fig. 33.8a, and Mikaelyan, 1997; Kovalev et al. 1998). The transparency (as revealed from Secchi Disk measurements shown in Fig. 33.8b) of even open waters was decreased during the 1970s and 1980s. At first the ecosystem responded favorably to increased primary production by producing higher mesozooplankton and fish stocks during the second half of the 1970s and early 1980s (cf. Fig. 33.8c,e, and Porumb, 1989). By the mid-1980s, a five-fold decrease in total mesozooplankton biomass was observed due to their consumption by opportunistic species such as *Noctiluca scintillans, Aurelia aurita, Pleurobrachia rhodopis* and *Mnemiopsis leidyi.* The total abundance of these new organisms reached 99% of the total zooplankton wet weight (Shushkina et al., 1998; Kovalev et al, 1998; Shiganova, 1998; Kideys and Romanova, 2001). As quantified by the Flow Network Analysis (Gucu, 2002), overfishing that took place during the early phase of the eutrophication (i.e. early 1980s) may have triggered destabilization of the ecosystem and the population explosion of gelatinous species.

Increase in the population of gelatinous carnivores apparently led to increases in particulate and dissolved organic matter content in the upper layer water column. This resulted in enhanced bacterial production and more active organic matter decomposition (Lancelot et al., 2002a), which then resulted in increased oxygen deficiency within the upper nitracline-oxycline zone of the water column and more denitrification and associated nitrate consumption within the suboxic zone. Two implications of such modifications in the biogeochemical structure were broadening of the suboxic zone from its position at σ_t~15.9 kg m^{-3} in the 1960s to σ_t~15.6 kg m^{-3} during the 1980s, and a change in the gradient of the subsurface nitrate struc-