

The Black Sea biogeochemistry and circulation dynamics

Temel Oğuz

oguz@ims.metu.edu.tr
Institute of Marine Sciences, Middle East Technical University, PO Box 28, Erdemli, Icel, Turkey

Abstract- Some observational and modeling efforts have been performed for the Black Sea within the framework of several international programs within the last several years. These efforts were devoted ultimately to exploring, quantifying, and predicting circulation, ecosystem and biogeochemical variability from the overall basin scale to coastal/shelf domains, and over time scales extending from weeks to seasons. Here, we present an overview of our recent progress achieved on (i) the circulation characteristics inferred from the altimeter data, (ii) a unified dynamical description of the pelagic food web and vertical biogeochemical structure via coupling of its major processes and interactions between the oxic, suboxic and anoxic layers, and (iii) identifying impacts of the circulation dynamics on biogeochemical transports.

Keywords- Black Sea, biogeochemistry, circulation dynamics, modeling

Introduction

Constructing a mathematical framework for studying interdecadal transformations of the Black Sea ecosystem and biogeochemistry is a challenge. It requires to deal with a complex set of interactions between key autotrophic, heterotrophic and carnivore species and/or groups at different periods of the temporally-changing ecosystem. Our modeling initiative started at the mid-1990s by a one-dimensional, vertically-resolved (with a ~3 m grid spacing), five compartment biological model coupled with the upper ocean physics and the Mellor-Yamada order 2.5 turbulence mixing parameterization (Oğuz et al., 1996). This model has then been elaborated on by introducing sophistications, as well as carrying out extensive sensitivity, calibration and validation studies for the food web (Oğuz et al., 1999; 2001a), the nitrogen and redox cycles (Oğuz et al., 2001b), and the water column oxygen dynamics (Oğuz et al., 2000).

Results and Discussion

The main features of the biogeochemical model, which provides a unified description of the pelagic food web, nitrogen cycle and oxidation-reduction reactions, are summarized in Fig. 1. The food web structure comprises two groups of phytoplankton (diatoms and phytoflagellates), two classes of herbivorous-omnivorous zooplankton (microzooplankton and mesozooplankton), nonphotosynthetic free living bacterioplankton and medusae *Aurelia aurita* and ctenophore *Mnemiopsis leidyi*, as well as the opportunistic omnivorous dinoflagellate *Noctiluca scintillans*. These microbial and herbivorous-carnivorous

food web structures are coupled through particulate and dissolved organic material fluxes to transformations among organic and inorganic (nitrate, nitrite and ammonium) forms of dissolved nitrogen. They are further linked with a model of oxygen and redox dynamics based on a set of oxygen, nitrogen and sulfur reactions coupled with the manganese cycle, as suggested by Murray et al. (1995). Hydrogen sulfide, elemental sulfur, dissolved oxygen, dissolved and particular manganese constitute the main elements of the redox model (Oğuz et al., 2001b). When dissolved oxygen is available, it oxidizes particulate organic material and hydrogen sulfide, ammonium, and dissolved manganese transported upwards from deeper levels. In oxygen depleted waters, dissolved oxidized manganese reacts with nitrate to produce settling particulate oxidized manganese and nitrogen gas. Hydrogen sulfide and ammonium are then oxidized by particulate oxidized manganese to locally form elemental sulfur, nitrogen gas and dissolved manganese. Elemental sulfur is reduced back to hydrogen sulfide by bacteria; nitrogen gas escapes to the atmosphere, and dissolved manganese is re-oxidized by nitrate.

A set of model simulations demonstrated how the simultaneous controls imposed by bottom-up forcing associated with anthropogenic-based nutrient enrichment and top-down grazing pressure introduced by gelatinous predators on mesozooplankton could lead to the changes in functioning of the Black Sea ecosystem during its transformation from a healthy state in the 1960s to a eutrophic state in the 1980s (Oğuz et al., 2001a). Much smaller and almost uniform plankton distributions characterized the unperturbed ecosystem for most of the year. The increased anthropogenic nutrient load (bottom-up control) together with population explosions in medusa *Aurelia* during the 1970s (top-down control) were shown to lead to practically uninterrupted phytoplankton blooms and a major reduction in microzooplankton and omnivorous mesozooplankton biomass. The major bloom event of the year took place during late winter to early spring as a consequence of nutrient accumulation in the surface waters at the end of the winter mixing season. This was followed by two successive and longer events during spring-early summer, and autumn. The early spring bloom was followed first by a mesozooplankton bloom of comparable intensity, which reduced the phytoplankton stock to a relatively low level, and then by an *Aurelia* bloom that similarly grazed down the mesozooplankton. The phytoplankton recovered and produced a weaker late spring bloom, which triggered a steady increase in *Noctiluca* biomass during the mid-summer. As the *Aurelia* population decreased in August, first mesozooplankton and then phytoplankton, *Noctiluca* and *Aurelia* gave rise to successive blooms during September-November period.

Increases of the biomass of the ctenophore *Mnemiopsis leidyi* led to even more pronounced and longer-lasting phytoplankton blooms due to stronger top-down control introduced into the ecosystem. The resulting plankton distribution possesses three successive bloom events during winter, spring and summer. An intense winter phytoplankton bloom emerged as a new feature of the annual phytoplankton structure after *Mnemiopsis* colonization. It is, in fact, a modified version of the late winter event of the pre-*Mnemiopsis* era, shifted as a consequence

of the particular form of grazing pressure exerted by *Mnemiopsis*, which almost completely depleted the microzooplankton, and *Noctiluca* stocks toward the end of autumn season. The lack of grazing pressure on the phytoplankton community then promoted earlier growth starting by the beginning of January. Winter blooms with that intensity were not reported until 1990s, but were persistently observed in both satellite and in situ data during the 1990s (Yilmaz et al., 1998; Oğuz et al., 2002). The other two blooms may also be interpreted as the modified forms of late spring to early summer and autumn events.

Almost continuous particulate organic matter production associated with the year-long biological activity supports an efficient nitrogen cycling within approximately the upper 75 m of the water column, where dissolved oxygen generated photosynthetically and by air-sea interactions is depleted due to consumption during aerobic particulate matter decomposition (Oğuz et al., 2000). The layer below could not be ventilated even for the conditions of exceptionally high winter cooling due to the presence of a strong density stratification. Even with a highly simplified representation of the redox processes, the model provided a quasi-steady state suboxic-anoxic interface zone structure similar to observations, and was able to give quantitative evidence for the presence of an oxygen depleted and non-sulfidic suboxic zone. This model pointed out the crucial role of the downward supply of nitrate from the overlying nitracline zone and the upward transport of dissolved manganese from the anoxic pool below for maintenance of the suboxic layer. The model findings support available data suggesting that the suboxic-anoxic interface has always been a stable feature, but the upper boundary of the suboxic layer may have moved to a shallower position after the 1970s (Kononov and Murray, 2001). The model is also used to test the assumption of isopycnal homogeneity of the SOL properties and their independence from the circulation features, as asserted previously (Tugrul et al., 1992). It is found that the SOL properties do not possess isopycnal uniformity throughout the basin, and vary depending on the intensity of vertical diffusive and advective oxygen fluxes across the oxycline (Oğuz, 2002). Anticyclones, with downwelling and downward diffusion (i.e., with stronger net downward supply of oxygen), attain a thinner suboxic layer at a deeper part of the water column relative to cyclones. The position of the upper boundary of the SOL changes from $\sigma_t \sim 15.6 \text{ kg m}^{-3}$ in cyclonic to 15.9 kg m^{-3} in anticyclonic regions, whereas its position in the peripheral Rim Current transition zone occurs at intermediate density values. Re-analysis of the existing data provides firm evidence for such differences.

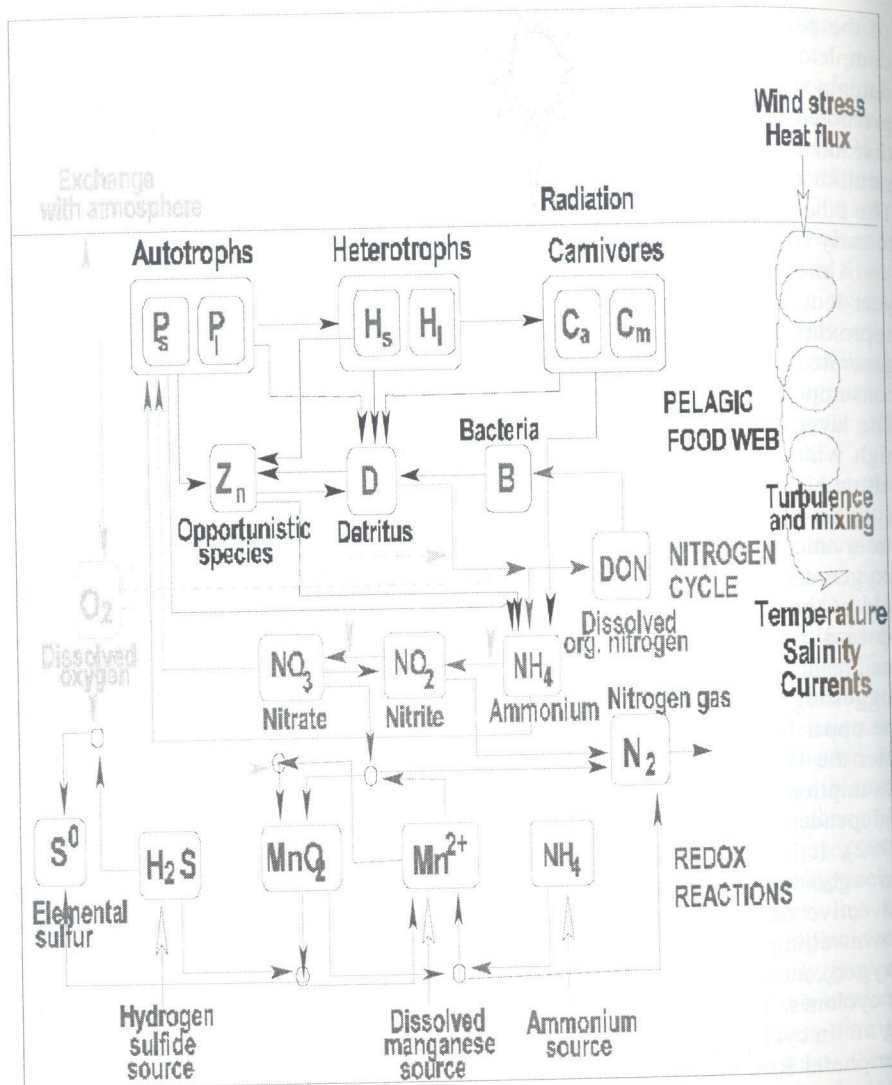


Fig. 1. Schematic representation of the major processes and interactions between biogeochemical model compartments. P_s , P_l denote large and small phytoplankton groups, H_s is microzooplankton, H_l is mesozooplankton, C_a is jellyfish *Aurelia aurita*, C_m is ctenophore *Mnemiopsis leidyi*, Z_n is opportunistic dinoflagellate *Noctiluca scintillans*, MnO_2 is particulate manganese. Meaning of the other variables are as shown in the Fig.. The biogeochemical model is coupled to the physical model through vertical diffusivity and temperature.

Our conception of the Black Sea circulation has had significant progress during the last decade through realization of several basinwide, multi-ship field campaigns, complemented by different types of satellite data. Common to all data sets is the bi-modal character of the circulation during the year. The winter circulation is persistently dominated by a two cyclonic gyre system in the western and eastern basins, encircled by a weakly meandering, an organized and strong Rim Current jet (Fig. 2a). During the spring and summer seasons, this system transforms into one composite basinwide cyclonic cell comprising multi-centered cyclonic eddies, surrounded by a weaker but broader and more variable Rim Current zone (Fig. 2b). During the autumn, the upper layer circulation attains its most disorganised form identified by a series of cyclonic eddies within the interior cell and accompanying pronounced lateral variabilities and larger coastal anticyclonic eddies around the periphery. A composite cyclonic peripheral Rim Current circulation is hardly identified during this period. On the other hand, the northwestern shelf exhibits a highly variable and dynamic circulation structure throughout the year. It is formed by a combination of the Danube outflow, wind stress forcing and the Rim Current structure of the basinwide circulation system along its offshore side. The southward direction of the coastal current emerges as the predominant path of the fresh water-induced flow regime within the inner shelf along the west coast. It may be deflected occasionally northward towards the upstream, and forms an anticyclonic circulation cell confined within the northern part of the shelf. The southward coastal flow largely diminishes under such cases. Moreover, the outer flank of shelf flow system has often an unstable structure; it exhibits meanders, spawns filaments toward the wide topographic slope zone, and is also modulated by onshelf intrusions by the Rim Current meanders. The four years time series of the SeaWiFS chlorophyll data from September 1997 to the end of December 2000 provide examples for various forms of the northwestern shelf circulation and its mesoscale and sub-mesoscale structures (Oğuz et al., 2002).

The eddy resolving three-dimensional, physical-ecosystem model studies elucidate how the patchiness of phytoplankton blooms are linked with the mesoscale character of the circulation system. The physical model involves a two and half layer reduced gravity circulation model endowed with active thermodynamics and bulk mixed layer dynamics. It is coupled with a four layer biological model involving a food web structure similar to the one shown in Fig. 1 except for the bacterial dynamics. Three of these four layers represent the euphotic zone resolved by the mixed layer at the surface and two intermediate layers below. The fourth layer corresponds to the aphotic part of the water column up to the anoxic interface. As demonstrated by Oğuz et al. (2001c), representation of the upper layer water column in the form of four layers can simulate reasonably well the annual phytoplankton biomass structure, consistent with its computationally more demanding multi-level counterpart. The model, tuned for predicting the 1990s ecosystem conditions, is able to successfully reproduce major bloom events of the year inferred from the SeaWiFS chlorophyll data as well as available composite in situ measurements performed during the last decade. In particular, the

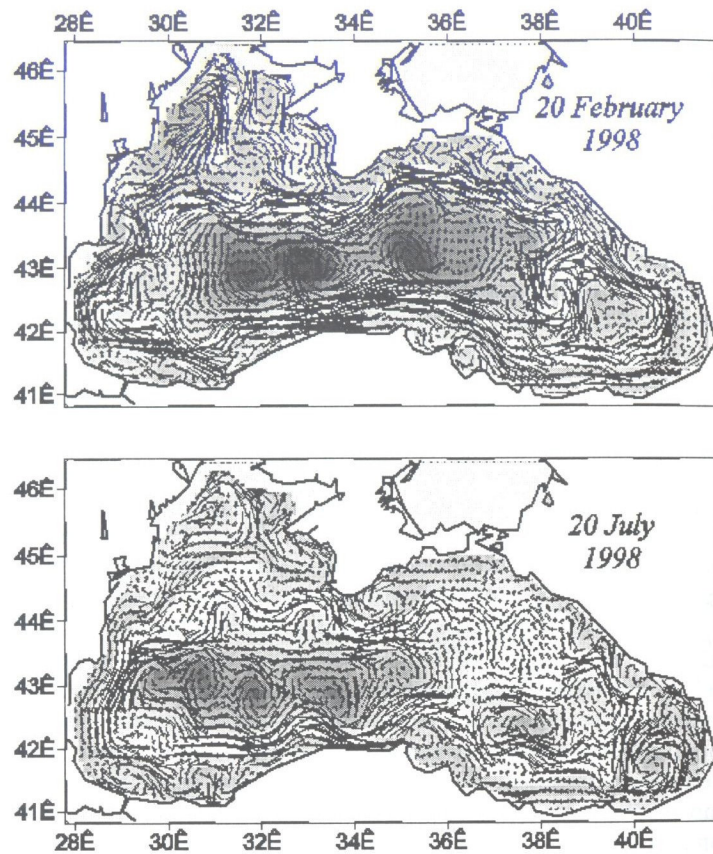


Fig. 2. The upper layer circulation pattern for (a) February 1998, and (b) June 1998 shown as an example for the winter horizontal flow structure. They are derived by assimilation of the Topex-Poseidon and ERS II altimeter data into a 1.5 layer reduced-gravity model. The background colors show the corresponding sea level anomaly pattern given by the altimeter data.

model provides the extended, almost two month-long, autumn and winter phytoplankton blooms, separated from each other by a short period of transition in January. The presence of complex top-down controls operating simultaneously by jellyfish *Aurelia* and ctenophore *Mnemiopsis* on heterotrophs and autotrophs is responsible for the presence of such extended autumn-winter bloom events. Eddy-induced lateral transports, asymmetries on the mixed layer depth and its layer-averaged light intensities, together with a complex and highly variable nutrient supply into the euphotic zone controlled by the combination of wind-driven coastal upwelling, eddy-pumping, entrainment due to mixed-layer deepening, and vertical diffusion are shown to manifest complex patterns of phytoplankton blooms of both new and regenerated production (Fig. 3) similar to those observed in SeaWiFS images.

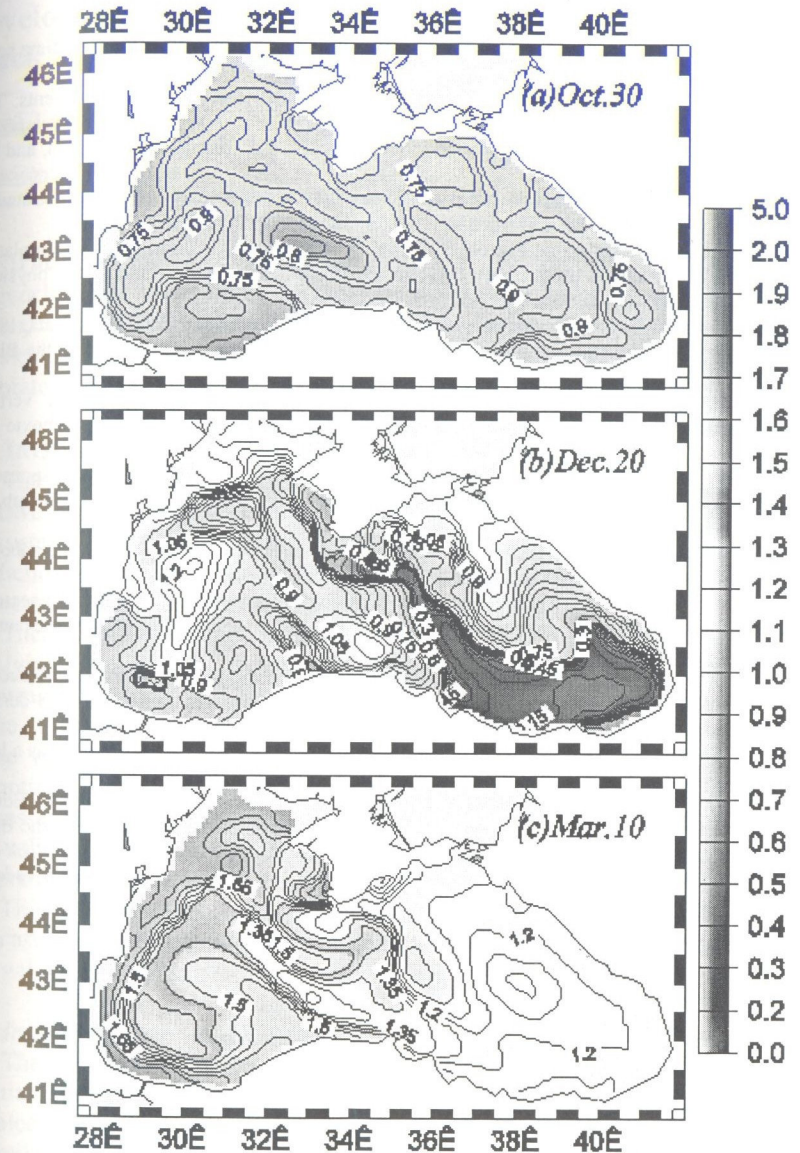


Fig. 3. Snapshots of model simulated phytoplankton biomass distributions (in mmol N m^{-3}) at three instants of the year corresponding to (a) October 30, (b) December 20, (c) March 10. They represent, respectively, the autumn subsurface, the early winter and the late winter-early spring mixed layer phytoplankton bloom events for the 1990s ecosystem conditions. They suggest an almost continuous spatially-structured biological activity during autumn-winter months as also inferred by the SeaWiFS data. Contours are drawn at an interval of $0.05 \text{ mmol N m}^{-3}$.

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Development of the Black Sea

Şükrü T. Beşiktepe

sukru@ims.metu.edu.tr
Institute of Marine Sciences,

Abstract- Black Sea biogeochemical variability in the context of the NATO SSG project. The physical and biochemical models are calibrated and validated.

Introduction

The primary objective of the ODBMS Black Sea project is to predict ecosystem variabilities, prediction of future states (nowcasting) and, the prediction of future states.

There are three stages involved in exploratory studies. Determining features and phase, leading to confirmation phase involves the confirmation of synoptical dynamical processes governing the system and validation of the model in the predictive phase.

This 3-phase strategy is a forecast system. In the forecast and validation studies.

Interdisciplinary

The Harvard Ocean Observing System simulations of physical and coupled dynamical processes and assimilation schemes. HOPS is a flexible, powerful forecasting and data analysis system. In 1996, Robinson, 1996, including real-time skill of forecast skill (Robinson, 1996).