

# Simulation of eddy-driven phytoplankton production in the Black Sea

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**Abstract.** A three dimensional, three-layer biological model is used to assess impact of eddy-dominated horizontal circulation on the spatial and temporal variations of plankton biomass in the Black Sea. Simulations are shown to exhibit patchy distributions of phytoplankton biomass as inferred from satellite images, and their intensities agree reasonably well with observations. Overall performance of the three layer model points to its potential capability as a practical alternative tool to more complex and computationally expensive multi-level models, without sacrificing much from the basics of the ecosystem dynamics.

## Introduction

One of the major findings of oceanographic research in the Black Sea during the 1990's was the recognition of intense mesoscale activity in the upper layer circulation, and its impact on the biogeochemical fields. The boundary flow system, named the Rim Current, exhibits a narrow and pronounced frontal structure between the less saline/less dense coastal waters and saltier/colder interior waters. This system is accompanied by intense mesoscale activity such as filaments, squirts and mushroom eddies [Oguz *et al.*, 1992, 1994; Sur *et al.*, 1994; Gregoire *et al.*, 1998; Oguz and Besiktepe, 1999]. Their impact on the Black Sea pelagic ecosystem and nutrient cycling are clearly evident by available satellite imagery [Sur *et al.*, 1996; Nezhin, 1999]. By way of example, we display in Fig. 1 the SeaWIFS chlorophyll distribution for early March 1999 where mesoscale features control patchiness and intensity of chlorophyll distribution in the range of 1-3 mg m<sup>-3</sup> in the basin. An exception is a band of higher chlorophyll concentrations (about 5-to-10 mg m<sup>-3</sup>) along the northwestern coast formed as a consequence of anthropogenic-based eutrophication of this region. It is, however, isolated from the rest of the basin by a permanent fresh water derived inner shelf density front.

A three dimensional, three layer biological model is developed to interpret these observations on a more quantitative ground, and to elaborate our present understanding of the role of mesoscale dominated circulation on the Black Sea pelagic ecosystem. The present paper describes an idealized process-oriented study demonstrating how a typical eddy-dominated circulation system can lead to a temporally

and spatially highly-structured early-spring phytoplankton bloom formation event in the Black Sea.

## Model Description

The vertical biogeochemical structure of the upper layer water column is represented by three interactive layers. The first layer characterizes the seasonally varying *mixed layer*,  $H_1(t)$ , regulated by air-sea interactions. Its thickness is computed by

$$\frac{\partial H_1}{\partial t} + \mathbf{v}_1 \cdot \nabla H_1 = w_e - w_h, \quad (1)$$

where  $w_e$  is the entrainment/detrainment velocity ( $w_e > 0$  for entrainment), and  $w_h$  is the vertical velocity representing contributions of the basinwide geostrophic circulation and Ekman pumping ( $w_h > 0$  when directed upwards) at the base of the mixed layer. The second layer,  $H_2(t)$ , represents the water column below the seasonal thermocline up to the base of the euphotic zone. The euphotic zone depth,  $H_e(t)$ , is determined by the position of the 1% level of the photosynthetically available radiation at the surface for given values of the extinction coefficients of pure water and living and nonliving substances. The third layer,  $H_3(t)$ , signifies the entire aphotic zone up to the anoxic interface. It is the difference between the total upper layer water column depth,  $H_T$  (=120 m), and the euphotic zone depth,  $H_e$ . This layer acts as the principal nitrate pool where the sinking particulate material is constantly remineralized and converted to inorganic nitrogen. The subsurface nitrate is then made available for plankton production when entrained, upwelled and/or diffused into the euphotic zone.

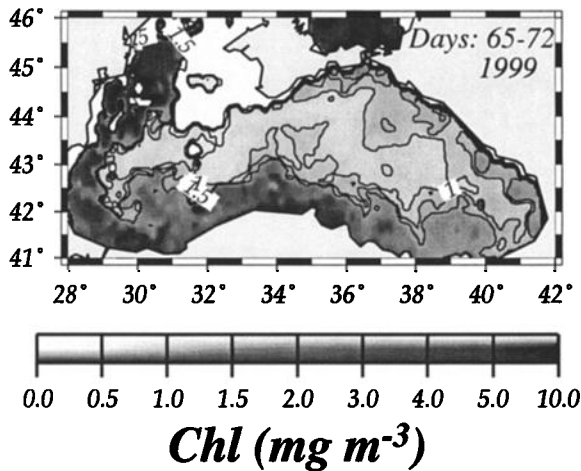
The plankton dynamics is modeled as in Oguz *et al.*, [1999] using two groups of phytoplankton (diatoms and flagellates) and two types of zooplankton (microzoo- and mesozoo-), labile pelagic detritus, nitrate, and ammonium. Particulate organic detritus is assumed to be converted directly to ammonium without explicitly considering the microbial loop mediating the remineralization process. The structure of the biological model is shown in Fig. 2.

The local temporal variations of all variables are expressed by advective-diffusive equations of the general form

$$\frac{\partial F_i}{\partial t} + \mathbf{v}_1 \cdot \nabla F_i = A_h \nabla^2 F_i + \frac{Q_i}{H_i} + \mathfrak{R}_i \quad (i = 1, 2, 3) \quad (2)$$

where  $F_i$  represents concentration or biomass of any biological variable in layer  $i$ ,  $\mathbf{v}_1$  is the horizontal velocity field,  $H_i$  is the layer thickness. The horizontal diffusion coefficient is denoted by  $A_h$ ,  $t$  is time,  $\nabla$  is the horizontal gradient operator with the  $x$  and  $y$  coordinates positive in the east and north directions, respectively,  $\partial$  represents the partial derivative. The entrainment velocity  $w_e$  is computed by a Kraus and Turner type mixed layer model. The entrainment formulation and the forms of interfacial transports,  $Q_i$ , are

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**Figure 1.** The 8-day composite SeaWiFS chlorophyll distribution (in  $\text{mg m}^{-3}$ ) in the Black Sea for the period 6-13 March 1999. Contours are plotted at intervals of 0.25 from 0.25 to 1.5  $\text{mg m}^{-3}$ . The unshaded (white) area in the northwestern part of the sea has no data.

similar to those given by *McCreary et al.* [1996]. A detailed description of the biological source/sink terms,  $\mathfrak{R}_i$ , is given by *Oguz et al.* [1999].

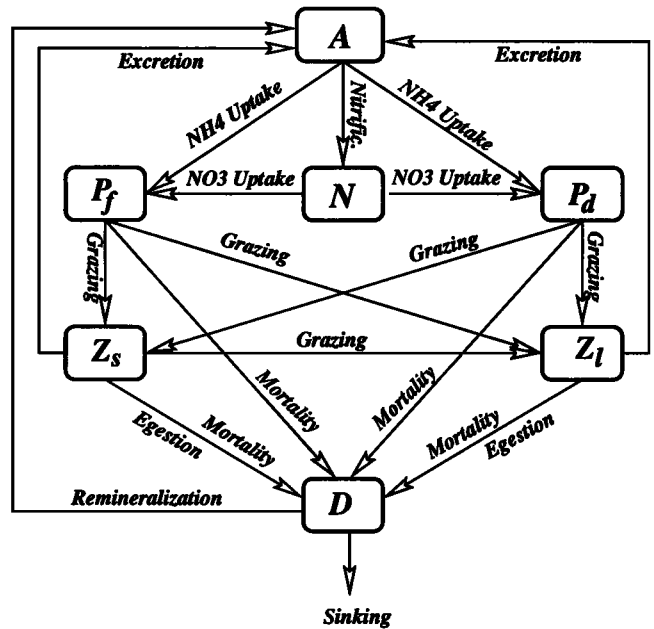
A rectangular Arakawa C grid with the individual box dimensions of 19.5 and 18.5 km in the longitudinal and latitudinal directions, respectively, is used to approximate the Black Sea geometry. The model is initialized by a typical vertical nitrate structure and small finite values for all other state variables. The flow field in the layers is specified by the optimally-derived geostrophic currents from the basin-wide HydroBlack'91 survey [*Oguz et al.*, 1994]. It shows major features of primarily cyclonic, complex eddy-dominated circulation such as the meandering Rim Current, a series of anticyclonic mesoscale eddies around the periphery of the basin, and an interconnecting series of eddies and gyres with different size, shape and rotation within the interior of the sea (Fig. 3). The model does not incorporate the river runoff and related nutrient input into the northwestern Black Sea. It, therefore, does not simulate the corresponding high chlorophyll concentrations of the western coastal zone shown in Fig. 1, and explores only the role of subsurface nutrient supply on the biological production.

The vertical velocity,  $w_h$ , is taken to be proportional to relative vorticity of the horizontal flow multiplied with the mixed layer thickness [*Pedlosky*, 1987; p. 209]. The proportionality constant is chosen to make the values of  $w_h$  comparable with those of  $w_e$ . Its values were further adjusted to integrate to zero over the basin. For its typical values of around 50 m/yr, the model results are found to be not sensitive to the details of this parameterization.

The model is integrated for four years, in which all the biological fields reach an equilibrium state. It is independent from the initial state and develops solely in response to the internal trophodynamic conditions.

### Simulation of Euphotic Zone Phytoplankton Structure

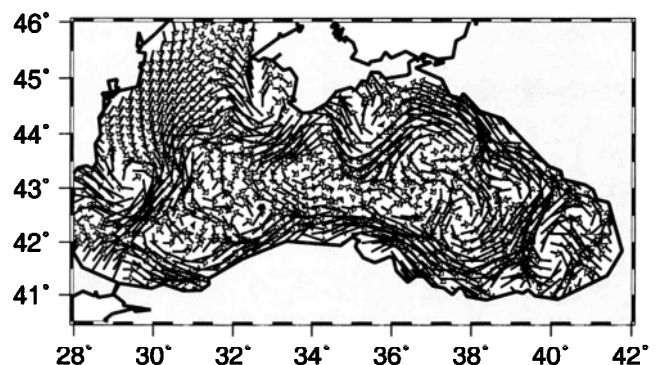
The horizontal distributions of the euphotic zone nitrogen content in February and March prior to the early spring



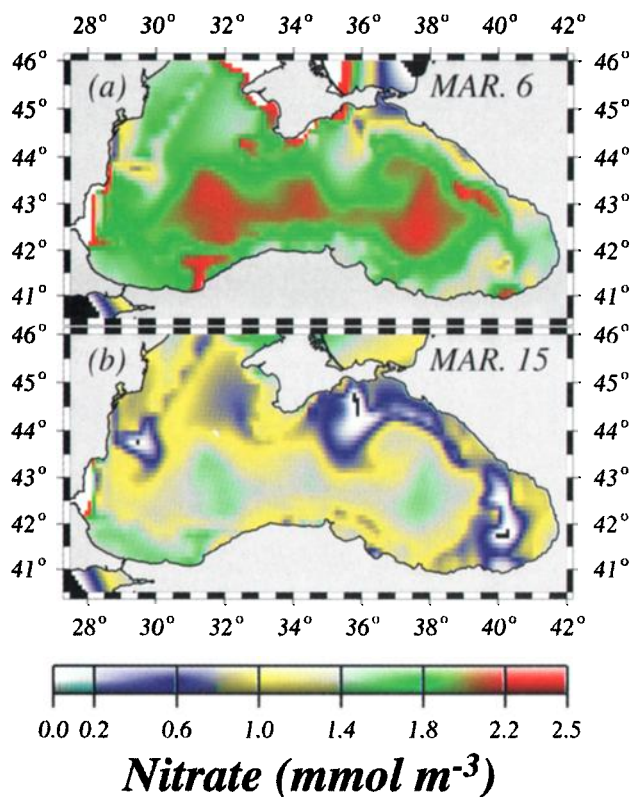
**Figure 2.** Diagrammatic representation of the major biological processes and interactions between diatom  $P_d$ , flagellate  $P_f$ , microzooplankton  $Z_s$ , mesozooplankton  $Z_l$ , detritus  $D$ , ammonium  $A$ , and nitrate  $N$  compartments of the pelagic ecosystem model.

bloom show nitrate concentrations in excess of 2.0  $\text{mmol N m}^{-3}$  almost everywhere within the central part of the basin since this region is able to transfer more nitrate directly from the third layer due to the combined effects of the entrainment and upwelling. A typical difference between the nitrate concentrations across the Rim Current zone is around 0.5-1.0  $\text{mmol M m}^{-3}$  during early March, shortly before its intense utilization in the phytoplankton growth (Fig. 4a). Thereafter, the euphotic zone nitrogen content depletes gradually as the bloom event progresses during the second part of March (Fig. 4b).

The euphotic zone phytoplankton biomass distributions given in Fig. 5a-d display the early spring bloom evolution within the basin. According to Fig. 5a, initiation and spreading of the bloom originates from the coastal zone of the eastern basin where relatively shallower mixed layer



**Figure 3.** The circulation field used to represent the horizontal advective processes in the biological model. It is based on the geostrophic computations from the September 1991 survey, and redrawn from *Oguz et al.* [1994] after interpolated into the model grid.



**Figure 4.** The basinwide distributions of the euphotic zone nitrate concentration (in  $\text{mmol N m}^{-3}$ ) shortly before and after the initiation of the early spring bloom event at days (a) 6 March, (b) 15 March of the perpetual year.

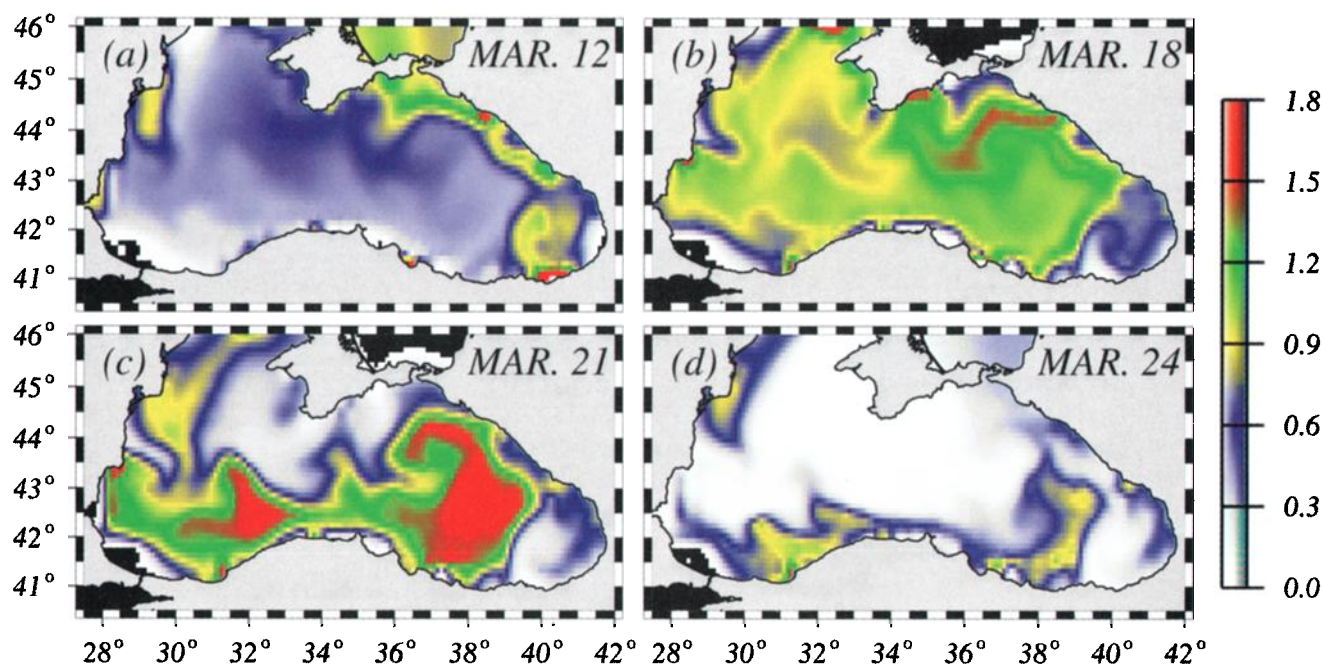
thicknesses lead to somewhat higher values of the average light limitation function. The average phytoplankton biomass of about  $0.9 \text{ mmol N m}^{-3}$  is almost twice of the values observed in the rest of the sea. Within a week, the phytoplankton biomass increases to  $0.7 \text{ mmol N m}^{-3}$  inside the basin and  $1.4 \text{ mmol N m}^{-3}$  ( $\sim 3.0 \text{ mg Chl m}^{-3}$ ) along the same coast (Fig. 5b). Later on, while the nitrate depletion causes degradation of the bloom in this coastal region, shallower mixed layer depth and higher nitrate content now favors the biomass increase within the interior (Fig. 5c). This is a “new production-based” bloom developed by consuming the nitrate entrained from the subsurface pool during January and February. While the growth is light limited during this early bloom period, as the time progresses towards mid-March, the phytoplankton growth may locally depend on either light or nutrient limitation.

Towards the end of March, the bloom weakens gradually starting from the northern sector of the basin to the southern coastal zone (Fig. 5d), and terminates eventually throughout the basin. Termination of the bloom occurs as a result of depletion of the nitrate stocks and/or increasing role of the grazing pressure imposed by the growing zooplankton community.

Following the mixed layer-intensified phytoplankton growth in March, organic material recycled within the euphotic zone together with the additional contribution of nitrate diffused upwards from the third layer lead to a series of regenerated-based productions during the following spring and summer months in the first and second layers.

## Conclusions

This work demonstrates that the biological model with a three layer vertical configuration of the trophodynamic structure and nutrient cycling can adequately simulate ma-



**Figure 5.** The basinwide distributions of the euphotic zone total phytoplankton biomass (i.e. the sum of diatoms and flagellates in the first two layers, in  $\text{mmol N m}^{-3}$ ) showing the initiation, spreading and termination of the early spring bloom event at days (a) 12 March, (b) 18 March, (c) 21 March, (d) 24 March of the perpetual year.

for observed features of the Black Sea pelagic ecosystem. It further indicates how the eddy-dominated circulation system introduces horizontal variability in the light and nutrient limitation functions as well as in the mixed layer thickness, and therefore controls patchiness of phytoplankton biomass. The phytoplankton blooms tend to initiate from the interior of the basin and then spread towards the periphery.

The simulations described here were not intended to reproduce a specific, observed ecosystem structure. They were rather aimed to explore the first order response of a highly simplified ecosystem to an idealized, eddy-dominated circulation system. Even for such a simple physical-biological system, the simulated spring bloom structure was consistent with the observations in terms of both its timing and spatial pattern (Oguz et al., 1999; Nezlin, 1999). Its details are, however, likely to be affected by interannual variabilities of the system as suggested by the SeaWiFS data.

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