Reconnaissance of the main Black Sea’s ecohydrodynamics by means of a 3D interdisciplinary model

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Abstract

A 3D interdisciplinary model has been used to test the sensitivity of the Black Sea’s ecosystem to physical processes. The hydrodynamical model of the general circulation has been built up, using the GHER primitive equation model. A model with 15 km horizontal resolution and 25 vertical levels is used to compute the typical seasonal cycle. The model is forced by climatological monthly mean fields of temperature, salinity and wind stress at the air–sea interface; the river discharges of the Danube, Dnestr and Dnepr are taken into account. An ecosystem model at basin scale is then defined by a nitrogen cycle considering several phytoplankton and zooplankton sizes and including the microbial loop. The ecosystem model is embedded on-line into the 3D hydrodynamical model with a superimposed cycle for the light intensity. This model must be regarded rather as a first tool for testing the coupling of hydrodynamic and ecosystem submodels, while acquiring some preparatory assessment of the effect of physical processes on the ecodynamics. The results display a highly three-dimensional aspect with important horizontal and vertical variations, obviously imparted to the system by the physical processes (horizontal and vertical advection, vertical mixing and diffusion, upwelling . . .) associated with light limitation at depth and sinking of dead organisms. In this paper, the results are described emphasizing the effects of the hydrodynamic constraints on the space–time distribution of the primary and secondary production.

Keywords: Black Sea; mathematical models; ecohydrodynamics

1. Introduction

One of the objectives of the EROS-2000 Black Sea Program is the study of the effects of the Danube on the eutrophication of the Black Sea’s North Western continental shelf. This requires an interdisciplinary approach, combining hydrodynamical, bio-geochemical and ecological investigations and the development of coupled models.

A fine resolution interdisciplinary model of the shelf is in preparation. As a first step —with the view in particular of clarifying the open-sea boundary conditions for the shelf model— a basin scale study of the general circulation and the associated synoptic structures, their seasonal variability and their effect on the primary and secondary production’s space–time patterns was made with the GHER 3D ecohydrodynamic model.

The three-dimensional PE turbulent closure ecohydrodynamic mathematical model developed at the
GeoHydrodynamics and Environment Research Laboratory (GHER) of the University of Liège has been described in various earlier publications (e.g. Nihoul and Djenidi, 1987; Nihoul and Beckers, 1989; Nihoul et al., 1989, 1994; Nihoul and Djenidi, 1991, Adam, 1991; Beckers, 1991). In its general formulation, it consists in two sectorial submodels:

(1) The hydrodynamic model, the state variables of which are the three components of the velocity vector, the pressure, temperature, buoyancy (or salinity), the turbulent kinetic energy and the turbulent dissipation rate (or the mixing length);

(2) The plankton ecosystem model, represented by three classes of autotrophic plankton, diatoms, autrophic dinoflagellates and nanoflagellates, three groups of heterotrophic organisms, bacteria, microzooplankton (heterotroph dinoflagellates and ciliates) and meso zooplankton (copepods) four nutrients, nitrate, ammonium, silicate and phosphate, particulate and dissolved organic matter and particulate silicate.

The objective of this work is not to develop a complex ecosystem model of the Black Sea considering a large number of species and involving a lot of sophisticated processes with a large number of parameters having to be calibrated, we only want to test the sensitivity of the Black Sea’s ecosystem to the physical processes by using a 3D interdisciplinary model. In this paper, the main findings of the hydrodynamic model are summarized stressing those aspects of the current and hydrological fields that affect the ecosystem. The ecosystem model is described and exemplary results are given in illustration.

2. Hydrodynamic results

It is widely accepted in the Black Sea oceanography that the sea surface elevation has a maximum in the coastal zone and decreases with increasing distance from the coast (Filippov, 1968; Gamsakhurdia and Sarkisyan, 1976; Stanev, 1988; Oğuz et al., 1994). This general pattern explains the cyclonic currents at the sea surface encompassing the whole basin, as a result of the adjustment between the velocity and mass fields. The mean position of the surface currents coincides approximately with the position of the continental slope, but important deviations are observed due to eddy variability, direct impact of extreme atmospheric forcing or interannual variability. This cyclonic type of circulation dominates the vector plots, Fig. 1, but shows pronounced seasonal dependency, which is important for the transport of plankton and other biological components. One begins by analysing the seasonal variability, simulated by the model, using Fig. 1, which show the daily averaged sea surface temperature (SST). Each figure corresponds to one specific state of the sea during its seasonal evolution. Fig. 1a (15 February) corresponds to winter, that is to the state when the cooling, and the resulting formation of the cold waters is strongest; Fig. 1b (1 June) corresponds to the end of spring, when the sea is strongly affected by the river discharges; Fig. 1c (1 September) corresponds to the time immediately after the strongest summer heating and just before the thermohaline fields start to change, due to the cooling in fall.

Currents reach maximal values along the Caucasian coast in fall. Qualitative time-changes of the circulation (reversals) are very pronounced between the main gyre and the coast, and in particular in the western basin. The circulation in the central and eastern parts of the sea remains relatively stable during the year, and the patterns do not show reversals of the circulation. The variability in these areas is illustrated, for instance, by the large meander, at the Caucasus coast, Fig. 1a,b, which disappears in

Fig. 1. Horizontal temperature distribution (in °C) at 5 m with currents superimposed: (a) in February (15), when the cooling and the resulting formation of the cold waters is strongest; (b) in June (1), at the end of spring, when the sea is strongly affected by the river discharges; (c) in September (1), corresponding to the time after the strong summer heating and just before the thermohaline fields start to change due to the cooling in fall. In these 3 figures, the circulation is of cyclonic type with pronounced seasonal dependency. Qualitative time-changes of the circulation (reversals) are very pronounced between the main gyre and the coast, and in particular in the western basin. The circulation in the central and eastern parts of the sea remains relatively stable during the year while on the shelf, the circulation exhibits the largest changes over the year. The simulated sea surface temperatures show pronounced seasonal variability and in winter important horizontal gradients can be observed.
The circulation on the shelf exhibits the largest changes over the year. The current follows the coast in winter, starting from the southern coast of the Crimea Peninsula, and reaching the Bulgarian coast to the south west. An anticyclonic eddy is formed on the shelf, off the Danube delta, in late spring. This area widens to the east in summer.

The large loop of the western branch of the main gyre, formed in late spring could have an important impact on the ecological processes in this area. After the current reaches the northern Bulgarian coast, it abruptly turns towards the Danube inflow area. After reaching the coast there it turns again to the south. Such meandering type of behaviour is typical for non-linear currents, which could be regarded as extensions of the river plumes into the open sea (Chao and Boicourt, 1986). The analysis of the dynamics of river plumes (see fig. 2 by Oey and Mellor, 1993) proves that the inertia tends to balance the Coriolis acceleration, which results in the formation of intrusion of the open sea water towards the plume.

The simulated SST, Fig. 1a–c show pronounced seasonal variability. The winter minimum of about 3.5°C is reached on the largest part of the northwestern shelf. Water, cooler than 7°C can be found between the isobath 100 m and the coast, which correlates well with the pattern derived from the satellite data (Sur et al., 1995). Temperature maximum in February of about 9.5°C is simulated in the easternmost Black Sea.

When one analyses the SST in the warm part of the year, one has to take into account the fact that the sea surface is much warmer than the intermediate layer. The core of the CIL is about 50 m below the sea surface, and it is 10–15°C colder than the surface waters. Thus, this cold water is a very good ‘tracer’, which could dye surface waters with low temperatures, and show the existing upwelling, Fig. 1b. However, these strong gradients are not crucial dynamically, since the circulation in the Black Sea is dominated by salinity gradients.

In winter, the mixed layer depth varies from 40 m to 70 m. For instance, in the region of intrusion of the Danube’s fresh water and in the central part of the eastern main cyclonic gyre, the pycnocline moves to the sea surface reducing the mixed layer depth to about 20 m. Less strong upwellings can also be observed in the eastern part of the sea and in the central part of the western main cyclonic gyre. In the region of the Danube’s delta, the intrusion of the fresh waters reduces the mixed layer depth to 40 m.

Fig. 2. 3D representation of the density field in winter (σ_θ values). A permanent upwelling of deep waters can be observed in the central part of the eastern main cyclonic gyre, the upper margin of the main pycnocline moves to the sea surface reducing the mixed layer depth to about 20 m. Less strong upwellings can also be observed in the eastern part of the sea and in the central part of the western main cyclonic gyre. In the region of the Danube’s delta, the intrusion of the fresh waters reduces the mixed layer depth to 40 m.
about 40 m while along the western coast (south of the Romanian coast) and on the shelf (east of the Danube’s waters) the water cooling and the extreme convective mixing penetrate to 60–70 m (Fig. 2). In summer, the mixed layer is limited by the thermocline at 10 m.

3. Ecosystem model

3.1. Introduction

The ecosystem model consists of a set of equations. These equations are all of the same general form expressing that the rate of change of any state variable is the result of advection, local production–destruction, diffusion by horizontal subgrid scale motions and vertical turbulence.

If $y$ denotes any of the state variables, the space–time evolution equation for $y$ can be written:

$$\frac{\partial y}{\partial t} + \nabla \cdot (u y) + \frac{\partial (w y)}{\partial z} + \frac{\partial (w^s y)}{\partial z} = Q^y + \frac{\partial}{\partial z}\left(\bar{v} \frac{\partial y}{\partial z}\right) + \mathcal{D}$$

where $u$ is the horizontal velocity, $w$ is the vertical velocity, $\mathcal{D}$ is the horizontal sub-grid diffusion, $\bar{v}$ is the vertical sub-grid (turbulent) diffusivity, $w^s$ is the sedimentation velocity (which differs from zero only for diatoms, particulate organic matter and particulate silicate) and $Q^y$ is the rate of production destruction of $y$ by interactions with the other state variables (matter exchanges).

The results of the hydrodynamic model are used as the inputs of the ecosystem model. Feed-backs from the ecosystem to the physics are assumed to be a second order effect in our problem.

In a first study, a very simple ecosystem model was used to acquire some preparatory assessment of the effects of physical processes on the ecodynamics. The state variables of this model were defined according to the recommendations of the GLOBEC Numerical Modelling group (Globec, 1995) as those which are necessary and sufficient to assess the effects of the physical processes on the primary and secondary productions space–time pattern. This simple model was defined by a nitrogen cycle which was described by NO$_3^-$, NH$_4^+$, phytoplankton, zooplankton and dissolved organic matter. Bacterioplankton was eliminated, assuming quasi-equilibrium prey–predator relationships within the microbial loop (Walsh et al., 1989; Nihoul et al., 1994). No independent state variable was introduced to account for the particulate organic matter and particles were included in sedimenting fractions of both the phytoplankton (dead cells) and the zooplankton (dead animals, faecal pellets) biomasses (with appropriate sedimentation velocities determined by inspection of the data base). This model is described in Grégoire et al. (1997).

3.2. The ecosystem model description

The reduction in the Danube’s water discharge due to river management has led to an increase in the nitrogen and phosphorus delivery to the north west Black Sea by factors of 3 and 10 respectively, as a consequence of industrial development and intensive agriculture. In the same time, silica decreased significantly (about 4 times) due to the reduced solid flow altogether result in a modified N:P:Si balance of inorganic nutrients. These chemical changes have increased the frequency and the intensity of blooms. Indeed, in the past (before the last decade), the peaks in primary productivity of the Black Sea were known to occur twice a year with a major early spring bloom of mainly diatoms, followed by a secondary autumn bloom of mainly coccolithophorids (Sur et al., 1994). For several years, winter blooms of arctic and subarctic forms of diatoms have been observed, the small phytoflagellates flourish abundantly during the late spring or early autumn and summer blooms of dinoflagellates and coccoliths have increased (Sorokin, 1983).

The model is defined by a nitrogen cycle which is described by 13 state variables (Fig. 3). Primary producers are described as three different functional groups according to their size and their physiological properties: nanoflagellates, autotroph dinoflagellates and diatoms. The secondary producers are described by ciliates, copepods and bacteria, carnivorous species are not taken into account in this model. Four nutrients are considered: ammonium, nitrate, phosphate and silicate. Ammonium, phosphate and nitrate are taken up by the three autotrophic organisms while silicate is only taken up by diatoms. Primary
Fig. 3. Schematic representation of the ecosystem model. The model is defined by a nitrogen cycle which is described by 13 state variables. The food-web is composed of two branches: the linear food-chain and the microbial food-chain. Copepods feed on the three phytoplankton species and on the microzooplankton, with a large size prey preference, initiating the linear food-chain. Ciliates are grazing on bacteria and nanoflagellates linking the microbial and the linear food-chain. The N:P ratio of the phytoplankton, the zooplankton and of bacteria, as the diatoms N:Si ratio, are assumed constant.

Producers are grazed by the secondary trophic level or converted into particulate organic matter by cell lysis. The particulate organic matter is hydrolysed into dissolved organic matter and particulate silicate is remineralised into silicate. Particulate organic matter and silicate, as diatoms are submitted to sedimentation. The N:P ratio of phytoplankton, zooplankton and bacteria, as the diatoms N:Si ratio, are assumed constant. So, the ratio of phytoplankton inorganic nitrate uptake to phosphate uptake (and to silicate uptake for diatoms) is taken constant in order to ensure that the phytoplankton N:P ratio (and N:Si ratio for diatoms) remains constant and the N:P ratio of the zooplankton’s excretion is computed at each time step so as to keep constant the zooplankton N:P ratio.
Bacteria require carbon, nitrogen and phosphorus in a stoichiometric balance set by the physiological state of the cell population (Herbert, 1976); the elemental chemical composition (C:N:P ratio) of the bacterial biomass is relatively invariant at about 45:9:1. In a balanced growth situation, the ammonium uptake will depend on the C:N ratio of the dissolved organic matter and bacterial growth efficiency for nitrogen and carbon (Goldman et al., 1987). Following Fasham et al. (1990), the ratio of bacterial ammonium uptake to dissolved organic matter uptake should be constant in order to ensure that bacterial biomass of the required C:N ratio is produced from dissolved organic matter with a given C:N ratio. The bacterial inorganic phosphate uptake is computed so as to keep constant the bacterial N:P ratio. The nitrification process is parameterized as a direct conversion of ammonium to nitrate without the intermediate level of nitrite transformation. The nitrification rate is computed as a function of density (Ward and Kilpatrick, 1991). At deeper levels (i.e. within the anoxic layer), no nitrification takes place, but nitrate is denitrified.

### 3.2.1. Mathematical formulation of the interaction rates

The mathematical formulation of the production–destruction term (Q) (see Eq. (1)) is

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>Symbols and units for the processes described in the ecosystem model</td>
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<table>
<thead>
<tr>
<th>Symbols</th>
<th>Processes</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>specific growth rate of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \mu_x )</td>
<td>ammonium consumption rate for the growth of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \mu_n )</td>
<td>nitrate consumption rate for the growth of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta_i )</td>
<td>mortality rate of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( r_{\text{PN}} )</td>
<td>P:N ratio</td>
<td>( \mu \text{atg P/\mu atg N} )</td>
</tr>
<tr>
<td>( r_{\text{SiN}} )</td>
<td>Si:N ratio of ( \varphi_1 )</td>
<td>( \mu \text{atg Si/\mu atg N} )</td>
</tr>
<tr>
<td>( r_{\text{PN}} )</td>
<td>P:N ratio</td>
<td></td>
</tr>
<tr>
<td>( r_{\text{SiN}} )</td>
<td>Si:N ratio</td>
<td></td>
</tr>
<tr>
<td>( \delta^a_{1,0} )</td>
<td>assimilation rate of ( z_1 )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^a_{2,1} )</td>
<td>assimilation rate of ( z_2 )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^i_{1,0} )</td>
<td>ingestion rate of prey ( x ) by ( z_1 ) with ( x = \varphi_1, \beta )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^i_{2,1} )</td>
<td>ingestion rate of prey ( x ) by ( z_2 ) with ( x = \varphi_1, \varphi_2, \varphi_3, \varphi_{31} )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^e_{0} )</td>
<td>excretion rate of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( m_s )</td>
<td>mortality rate of ( y )</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( a_y )</td>
<td>assimilation efficiency of ( y )</td>
<td></td>
</tr>
<tr>
<td>( b_y )</td>
<td>biomass of prey potentially capturable by ( y )</td>
<td>( \mu \text{atg N/l} )</td>
</tr>
<tr>
<td>( r_{\text{PNy}} )</td>
<td>P:N ratio of ( y ) excretion</td>
<td>( \mu \text{atg P/\mu atg N} )</td>
</tr>
<tr>
<td>( r_{\text{SiNy}} )</td>
<td>Si:N ratio of ( y ) excretion</td>
<td></td>
</tr>
<tr>
<td>( \delta^e_{a1} )</td>
<td>specific growth rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^e_{s1} )</td>
<td>excretion rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^s_{1} )</td>
<td>mortality rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^a_{1} )</td>
<td>ammonium uptake rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^d_{1} )</td>
<td>dissolved organic matter uptake rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^p_{1} )</td>
<td>phosphate uptake rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( r_{\text{PNp}} )</td>
<td>P:N ratio</td>
<td>( \mu \text{atg P/\mu atg N} )</td>
</tr>
<tr>
<td>( r_{\text{SiNp}} )</td>
<td>Si:N ratio</td>
<td></td>
</tr>
<tr>
<td>( \delta^h_{1} )</td>
<td>hydrolysis rate of particulate organic matter</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^n_{1} )</td>
<td>nitrification rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^d_{1} )</td>
<td>denitrification rate</td>
<td>day(^{-1} )</td>
</tr>
<tr>
<td>( \delta^s_{1} )</td>
<td>silicate remineralisation rate</td>
<td>day(^{-1} )</td>
</tr>
</tbody>
</table>
given below. The significance of symbols and units are listed in Table 1.

\[
Q^{v_1} = (\mu_{v_1}(\xi, i, n_1, n_2, n_3) - \delta_{v_1}^{m_1}) \varphi_1
- \delta_{v_1}^{m_1}(b_{v_1}, \varphi_1) z_2 - \delta_{v_1}^{m_1}(b_{v_1}, \varphi_1) z_1 \tag{2}
\]

\[
Q^{v_2} = (\mu_{v_2}(\xi, i, n_1, n_2, n_3) - \delta_{v_2}^{m_2}) \varphi_2
- \delta_{v_2}^{m_2}(b_{v_2}, \varphi_2) z_2 \tag{3}
\]

\[
Q^{v_3} = (\mu_{v_3}(\xi, i, n_1, n_2, n_3, n_4) - \delta_{v_3}^{m_3}) \varphi_3
- \delta_{v_3}^{m_3}(b_{v_3}, \varphi_3) z_2 \tag{4}
\]

\[
Q^{v_4} = (\mu_{v_4}(\xi, i, n_1, n_2, n_3, n_4) - \delta_{v_4}^{m_4}) \varphi_4
- \delta_{v_4}^{m_4}(b_{v_4}, \varphi_4) z_2 \tag{5}
\]

\[
Q^{v_5} = (a_{v_5} \delta_{v_5}^{m_5}(b_{v_5}) - \delta_{v_5}^{m_5}(T) - m_{v_5})
\times z_1 \delta_{v_5}^{m_5}(b_{v_5}, z_1) z_2
\]

\[
= (\delta_{v_5}^{m_5}(b_{v_5}, z_1) - \delta_{v_5}^{m_5}(T) - \delta_{v_5}^{m_5}(b_{v_5})) z_1
- \delta_{v_5}^{m_5}(b_{v_5}, z_1) z_2 \tag{6}
\]

\[
Q^{v_6} = (\delta_{v_6}^{m_6}(\omega_2, n_1) - \delta_{v_6}^{m_6}(T) - \delta_{v_6}^{m_6})
\times \beta - \delta_{v_6}^{m_6}(b_{v_6}, \beta) z_1 \tag{7}
\]

\[
Q^{v_7} = \delta_{v_7}^{m_7}(T) \beta + \delta_{v_7}^{m_7}(T) z_1 + \delta_{v_7}^{m_7}(T) z_2 - \delta_{v_7}^{m_7} n_1
\]

\[
- \mu_{v_7}(\xi, i, n_1, n_2, n_3) \varphi_1
- \mu_{v_7}(\xi, i, n_1, n_2, n_3) \varphi_2
- \mu_{v_7}(\xi, i, n_1, n_2, n_3) \varphi_3
- \delta_{v_7}^{m_7} n_1 \tag{8}
\]

\[
Q^{v_8} = \delta_{v_8}^{m_8}(n_1) - \mu_{v_8}(\xi, i, n_1, n_2, n_3) \varphi_1
\]

\[
- \mu_{v_8}(\xi, i, n_1, n_2, n_3) \varphi_2
- \mu_{v_8}(\xi, i, n_1, n_2, n_3) \varphi_3 - \delta_{v_8}^{m_8} n_2 \tag{9}
\]

with \( \mu_{v_i}(\xi, i, n_1, n_2, n_3) \) given above, and \( n_3 \) has to be taken into account only for \( \varphi_3 \). \( \ldots \)

\[
Q^{v_9} = r_{p_e,v_9}(\delta_{v_9}^{m_9}(T) z_2 + r_{p_e,v_9}(T) z_1)
\]

\[
+ r_{p_e,v_9}(T) \beta - (\mu_{v_9}(\xi, i, n_1, n_2, n_3, n_4)
\times \varphi_1 + \mu_{v_9}(\xi, i, n_1, n_2, n_3, n_4) \varphi_2
+ \mu_{v_9}(\xi, i, n_1, n_2, n_3, n_4) \varphi_3) r_{p_e,v_9}
- r_{p_e,v_9}(T) \beta \tag{11}
\]

\[
Q^{v_{10}} = - r_{v_{10}}^m \mu_{v_{10}}(\xi, i, n_1, n_2, n_3, n_4) \varphi_3 + \delta_{v_{10}}^{m_1} \omega_{v_{10}} \tag{12}
\]

\[
Q^{v_{11}} = \delta_{v_{11}}^{m_1} \varphi_1 + \delta_{v_{11}}^{m_1} \varphi_2 + \delta_{v_{11}}^{m_1} \varphi_3 + \delta_{v_{11}}^{m_1} (\varphi_1, \varphi_2, \varphi_3,
\varphi_4, \varphi_5, \varphi_6, \varphi_7,
\varphi_8, \varphi_9, \varphi_{10}, \varphi_{11}) z_2 + \delta_{v_{11}}^{m_1} (b_{v_{11}}, z_1) + \delta_{v_{11}}^{m_1} \beta - \delta_{v_{11}}^{m_1} \omega_1 \tag{13}
\]

\[
Q^{v_{12}} = \delta_{v_{12}}^{m_1} \omega_1 - \delta_{v_{12}}^{m_1} (\omega_2, n_1) \beta \tag{14}
\]

\[
Q^{v_{13}} = r_{v_{13}} \delta_{v_{13}}^{m_1} \varphi_3 - \delta_{v_{13}}^{m_1} \omega_{v_{13}} \tag{15}
\]

3.2.2. Mathematical representation of the processes

The mathematical formulation of the phytoplankton growth rate \( \mu(\xi, i, n_1, n_2, n_3) \) is the same for each species, but with different parameters. Diatoms can also be limited by silicate availability.

\[
\mu(\xi, i, n_1, n_2, n_3, n_4) = \mathcal{P}(i) \mathcal{L}(\xi)
\times \left( \frac{n_1}{n_1 + c_{n_1}} + \frac{n_2}{n_2 + c_{n_2}} \right)
\times \exp(-\lambda \nu_1) \left( \frac{n_3}{n_3 + c_{n_3}} \right)
\times \left( \frac{n_4}{n_4 + c_{n_4}} \right) \tag{16}
\]

where \( \mathcal{L}(\xi) \) and \( \mathcal{P}(i) \) are respectively the temperature limitation function and the photosynthetic rate and \( n_4 \) has to be taken into account only for \( \varphi_3 \).

It appears from early work (e.g. Ryther, 1956) that there may exist a broad division between taxonomic groups with respect to their \( \mathcal{P} \) versus \( i \) curve. Basic parameters describing a \( \mathcal{P} \) vs. \( i \) curve, being generally understood by ecologists and physiologists are the maximum rate of photosynthesis (\( \mathcal{P}_{\text{max}}^B \)) and the initial slope of the \( \mathcal{P} \) vs. \( i \) curve (\( \alpha \)). \( \mathcal{P}_{\text{max}}^B \) varies widely depending on changes in environmental conditions and the physiological state of algae (Parsons et al., 1990). In this model, \( \mathcal{P}_{\text{max}}^B \) is assumed to be solely dependent on the temperature.
following the equation proposed by Eppley (1986), 

\( \alpha \), is a function of the light reaction and is not usually affected by other factors, some measurements have shown a remarkable similarity in the photosynthetic behaviour of organisms within each taxonomic group, but a rather striking difference between those of different groups. For instance, following Côté and Platt (1983), small species have a greater photosynthetic efficiency than large species.

Under high light intensities, photosynthesis is inhibited by photoinhibition. However, the mechanism of photoinhibition has not been fully understood yet; empirical approximation is therefore the only way to formulate a \( \mathcal{P} \) vs. \( i \) curve with photoinhibition. The

<table>
<thead>
<tr>
<th>Processes</th>
<th>Symbols</th>
<th>Formula</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pho\textit{Photosynthesis}tosynthesis</td>
<td>( \mathcal{P}(i) )</td>
<td>( \mathcal{P}(i) = \beta_i(1 - \exp(-\alpha_i i))\exp(-\beta_i i) )</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>where ( i ) = (\text{PAR}(z))/( \beta )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mathcal{P}<em>\text{max} = \beta</em>\text{max}(\frac{\text{PAR}(z)}{\beta_\text{max}})^{1/2} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \log \mathcal{P}_\text{max} = 0.0275T - 0.07 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>where ( PAR(z) ) is the photosynthetically active radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu E m^{-2} s^{-1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature limitation function ( \mathcal{Z}(\xi) )</td>
<td>( \mathcal{Z}(\xi) = \delta(\xi)(1 + \beta_\xi \xi)/(1 + 2 \beta_\xi \xi + \xi^2) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>where ( \xi = (T - T_{\text{crop}})/(T_{\text{crop}} - T_{\text{inf}}) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \delta(\xi) = \text{heaviside} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zooplankton growth and excretion</td>
<td>( \delta_{j,i}^{z_1} )</td>
<td>( \delta_{j,i}^{z_1} = \delta_{j,i}^{z_1} = \frac{1}{b_j(\phi, \beta)} \exp(\theta(x)) )</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( \phi ) = ( \frac{x}{x + c_j} \theta(x) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>where ( x = b_j(\phi, \beta) - b_0 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_j(\phi, \beta) = e_{z_1,i} \phi_{z_1} + e_{z_1,i} \beta )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \theta(x) = \text{heaviside} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu \text{atg N/1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assimilation rate of ( z_1 ) ( \delta_{j,i}^{z_1} )</td>
<td>( \delta_{j,i}^{z_1} = \delta_{j,i}^{z_1} = \frac{1}{b_j(\phi, \beta)} \exp(\theta(x)) )</td>
<td>day(^{-1})</td>
<td></td>
</tr>
<tr>
<td>( \phi ) = ( \frac{x}{x + c_j} \theta(x) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>where ( x = b_j(\phi, \beta) - b_0 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_j(\phi, \beta) = e_{z_1,i} \phi_{z_1} + e_{z_1,i} \beta )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \theta(x) = \text{heaviside} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu \text{atg N/1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingestion rate of prey x by ( z_1 ) ( \delta_{z_1,i}^{x} )</td>
<td>( \delta_{z_1,i}^{x} = \frac{\delta_{j,i}^{z_1}}{b_j(\phi, \beta)} \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
</tr>
<tr>
<td>where ( x = \theta_0, \beta )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu \text{atg N/1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingestion rate of prey x by ( z_2 ) ( \delta_{z_2,i}^{x} )</td>
<td>( \delta_{z_2,i}^{x} = \frac{\delta_{j,i}^{z_2}}{b_j(\phi, \beta)\theta(x)} \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
</tr>
<tr>
<td>where ( x = \theta_0, \beta )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu \text{atg N/1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_2 ) mortality rate ( m_{z_2} ) ( m_{z_2} )</td>
<td>( m_{z_2} = \mu_{z_2} \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
</tr>
<tr>
<td>( \mu_{z_2} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu_{z_2} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excretion rate ( \delta_{y}^{z_1} ) ( \delta_{y}^{z_1} = \exp(\theta(x)) \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>where ( y = z_1, z_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu \text{atg N/1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacterial growth and excretion ( \beta_{j,i} ) ( \beta_{j,i} = \beta_{j,i} \theta(x) \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{j,i} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{j,i} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bacterial growth rate ( \beta_{j,i} ) ( \beta_{j,i} = \beta_{j,i} \theta(x) \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{j,i} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{j,i} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bacterial excretion rate ( \beta_{j,i} ) ( \beta_{j,i} = \frac{\beta_{j,i}}{\theta(x)} \theta(x) )</td>
<td>day(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{j,i} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
formulation described by Platt and Gallegos (1980) has been chosen to represent the photosynthesis.

It is well known that all biological processes have a temperature dependence. Generally, process rates double for each 10°C increase in temperature. The hydrodynamic results show the existence in the winter of important sea surface temperature gradients (Fig. 1a). For instance, on most of the northwestern shelf, a winter minimum of 3.5°C is reached while in the eastern part, the temperature is about 9°C (Stanev and Beckers, 1997). We can expect that these important gradients affect the species composition. In this preliminary study, only the phytoplankton’s growth and the zooplankton’s excretion rate depend on the temperature following the model of Andersen and Nival (1988). This model introduces a lethal temperature for each phytoplankton species. The possibility of development of arctic species is taken into account by assuming a lower lethal temperature of 0°C for diatoms.

The mathematical representation of the processes is given in Table 2. The calibration and the sensitivity study of the model has not been straightforward in the 3D ecosystem model due to the large number

Table 3

Parameters used for the phytoplankton growth

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>$\varphi_1$</th>
<th>$\varphi_2$</th>
<th>$\varphi_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_T$ shape factor for the thermo-inhibition curve</td>
<td>°C</td>
<td>-0.6</td>
<td>-0.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>$T_{\text{min}}$ lower lethal temperature</td>
<td>°C</td>
<td>7</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>$T_{\text{opt}}$ optimal temperature</td>
<td>°C</td>
<td>14</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>$c_{\text{NH}}$ half-saturation constant for ammonium</td>
<td>$\mu\text{atg N/l}$</td>
<td>0.5</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>$c_{\text{NO}}$ half-saturation constant for nitrate</td>
<td>$\mu\text{atg N/l}$</td>
<td>0.75</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$c_{\text{PO}}$ half-saturation constant for phosphate</td>
<td>$\mu\text{atg P/l}$</td>
<td>0.07</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$c_{\text{Si}}$ half-saturation constant for silicate</td>
<td>$\mu\text{atg Si/l}$</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda$ constant of inhibition of nitrate uptake by the presence of ammonium</td>
<td>$(\mu\text{atg N/l})^{-1}$</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$\alpha$ Photosynthetic efficiency</td>
<td>$(\mu\text{Em}^{-2}\text{s}^{-1}\text{day}^{-1})^{-1}$</td>
<td>0.01</td>
<td>0.007</td>
<td>0.009</td>
</tr>
<tr>
<td>$\beta$ Index of photo-inhibition</td>
<td>$(\mu\text{Em}^{-2}\text{s}^{-1}\text{day}^{-1})^{-1}$</td>
<td>0.01</td>
<td>0.007</td>
<td>0.009</td>
</tr>
<tr>
<td>$\delta_{\text{m}}$ mortality rate</td>
<td>day$^{-1}$</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>$r_{\text{P:N}}$ P:N ratio</td>
<td>$\mu\text{atg P/\mu\text{atg N}}$</td>
<td>1:16</td>
<td>1:16</td>
<td>1:16</td>
</tr>
<tr>
<td>$r_{\text{Si:N}}$ Si:N ratio</td>
<td>$\mu\text{atg Si}/\mu\text{atg N}$</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_{\text{m}}$ sedimentation velocity</td>
<td>m day$^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4

Parameters used for the zooplankton growth

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>$z_1$</th>
<th>$z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{\text{max}}$ maximum ingestion rate</td>
<td>day$^{-1}$</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$c_{\text{g}}$ half-saturation constant for ingestion</td>
<td>$\mu\text{atg N/l}$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$k_l$ Ivlev’s coefficient</td>
<td>$(\mu\text{atg N/l})^{-1}$</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>$b_0$ threshold concentration</td>
<td>$\mu\text{atg N/l}$</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>$a_s$ assimilation efficiency</td>
<td></td>
<td>0.8</td>
<td>0.65</td>
</tr>
<tr>
<td>$\langle k_{E/0} \rangle_0$ excretion rate at 0°C</td>
<td>day$^{-1}$</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>$b_l$ shape factor for the excretion curve</td>
<td></td>
<td>1.05</td>
<td>1.077</td>
</tr>
<tr>
<td>$m_{\text{m}}$ mortality rate of $z_1$</td>
<td>day$^{-1}$</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$\delta_{\text{m}}$ maximum mortality rate of $z_2$</td>
<td>day$^{-1}$</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$\delta_{\text{m}}$ minimum mortality rate of $z_2$</td>
<td>day$^{-1}$</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$x_{\text{m}}$ threshold of the mortality curve of $z_2$</td>
<td>$\mu\text{atg N/l}$</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$r_{\text{P:N ratio of excretion}}$</td>
<td>$\mu\text{atg P/\mu\text{atg N}}$</td>
<td>1:8</td>
<td>1:12</td>
</tr>
<tr>
<td>Parameters</td>
<td>Units:</td>
<td>$\varphi_1$</td>
<td>$\varphi_2$</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$c_{\text{g},x}$ capture efficiency of prey $x$ by $z_1$</td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>$c_{\text{g},x}$ capture efficiency of prey $x$ by $z_2$</td>
<td></td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>
of simulation experiments needed. A box version of the ecosystem model has been used so as to give an idea of the most sensitive parameters of the model. This 0D model considers the same state variables except phosphate, silicate and particulate silicate. It seems that the most sensitive parameters are the half-saturation constant for phytoplankton uptake, the photosynthetic efficiency and the maximum zooplankton ingestion rate. This box version has been integrated during several years and the system seems to move on a two years periodical cycle as in Antarctic (Desaive, 1997). Once the most sensitive parameters of the box version are known, the calibration of the 3D model can be made by adjusting them. The other parameters are found in the literature (Andersen and Rassoulzadegan, 1991; Oguz et al., 1997).

However, in a 3D interdisciplinary model, the physical processes act as a permanent constraint on the biological interactions reducing the strong sensitivity of the solution on the parameters values. Indeed, the advection term maintains, at all scales, a permanent hydrodynamic stress on the state variables and allows, in the absence of any significant feedback, the structures of the velocity fields to be impressed on the ecosystems. Nihoul et al. (1994) show after examination of the orders of magnitude of the different terms involved in the evolution equation of each ecosystem state variable (Eq. (1)), that in the regions of upwellings, the interaction and sinking rates are at least one order of magnitude smaller than the rates of advection and diffusion, thus the spatial distribution of nutrients and biological populations adapt themselves rapidly to the hydrodynamic current and diffusion patterns, almost as passive constituents, and later evolve with the flow field while ecological interactions and sinking take place.

The values of the parameters are given in Tables 3–5.

### 3.3. Initial and boundary conditions

The model ran for six months, from the beginning of January until the end of June, this takes a computation time of about 4 days on a power parallel system.

The initial nutrients vertical profiles are computed as a function of the density so as to exclude variability resulting from dynamical effects. Indeed, chemical concentrations plotted against density, rather than depth, may be expected to give individually similar density profiles, independent of seasons and location (Tugrul et al., 1992; Saydam et al., 1993).

For instance, the initial nitrate concentrations increase from the depths corresponding to \( \sigma_t \approx 14.0 \) and reach a maximum of 8–9 \( \mu \text{M} \) at the depths of \( \sigma_t \approx 15.4 \) (i.e. the upper boundary of the oxic/anoxic interface defined as the dissolved oxygen concentrations \( \leq 20 \mu \text{M} \) and \( \text{H}_2\text{S} \) concentrations less than 5 \( \mu \text{M} \)), then the nitrate concentrations diminished sharply to trace levels (\( \leq 0.10 \text{ mmol/m}^3 \)) near the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\delta z)_{\text{max}})</td>
<td>maximum growth rate</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(v_{\text{max}})</td>
<td>half-saturation constant for uptake</td>
<td>(\mu \text{atg N/l})</td>
</tr>
<tr>
<td>((\delta z)_{0})</td>
<td>excretion rate at 0°C</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(b_{v})</td>
<td>shape factor for the excretion curve</td>
<td></td>
</tr>
<tr>
<td>(r_{\text{P:N}})</td>
<td>P:N ratio</td>
<td>(\mu \text{atg P}/\mu \text{atg N})</td>
</tr>
<tr>
<td>(r_{\text{P:N}\text{ex}})</td>
<td>P:N ratio of excretion</td>
<td>(\mu \text{atg P}/\mu \text{atg N})</td>
</tr>
<tr>
<td>(\eta)</td>
<td>((\text{NH}_4^+))/(DOM) uptake</td>
<td></td>
</tr>
<tr>
<td>(\delta_{w})</td>
<td>hydrolysis rate</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(\delta_{w})</td>
<td>silicate remineralisation rate</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>(w_{\text{s}})</td>
<td>sedimentation velocity</td>
<td>m day(^{-1})</td>
</tr>
</tbody>
</table>
The initial ammonium concentrations increase with the density, from 0.2 μatg N/l at the sea surface to 80 μatg N/l in the anoxic layer (Sorokin, 1983). The initial silicate concentrations increase with the density following the profile given in Tugrul et al. (1992).

The Danube’s nutrients discharge is also taken into account for the computation of the initial nutrients concentrations. The position of the Danube’s waters at the beginning of the simulation, in January, has been determined by releasing, in the hydrodynamical model, a passive tracer at the Danube’s mouth, then the hydrodynamical model has been performed during several years until a steady state solution has been reached. Once the position of the Danube’s waters has been known, the Danube’s nutrients supply can be computed with the nutrients data given by Cociasu et al. (1997) at the Danube’s mouth. Fig. 4 shows the initial nitrate field at 20 m.

For the other ecosystem state variables, initial constant values are imposed. A zero flux is imposed at the sea surface considered as a rigid boundary, while the bottom is supposed to permit only sinking fluxes towards sediments. Three open sea boundaries are considered: the Danube, the Dnepr and the

![Fig. 4. Horizontal distribution of the initial nitrate field at 20 m (in μatg N/l). A strong front takes form, reaching the southern Romanian coast. It does not show gradients south of this latitude which are comparable to the ones on the shelf. The Danube’s waters follow the coast with some intrusions of the rich nitrate water towards the open sea, especially along the Turkish coast. In the central part of the eastern main cyclonic gyre, where a permanent upwelling occurs, a patch of high nitrate concentration can be observed.](image-url)
Bosphorus strait. Since the Dnepr mouth and the Dnestr mouth are very close to one another, the river discharge is allocated in the location of the river mouth of the biggest river, i.e., the Dnepr.

A zero gradient condition is imposed for each ecosystem state variable at each boundary, except when we dispose of data. So, at the Bosphorus strait, for ammonium, phosphate, nitrate, dissolved and particulate organic matter, a Dirichlet condition is imposed (the values are found in Polat and Tugrul, 1995). At the Danube’s mouth, the nutrients flux are imposed (the values are found in Cociasu et al., 1997).

4. Results

The simulation is performed by solving the ecosystem model conjointly with the physical model, avoiding the problems of undersampling in the physical model and for computer disk space availability when an off-line solution is reached. The simulation cannot be performed during several years to see if a steady state solution can be reached because all the redox processes occurring in the transitional layer and having an important influence on the nutrients profiles have not been taken into account in this model.

The Black Sea’s autumn bloom is followed by a progressive intensification of the mixing, which leads to the light limitation of winter phytoplankton and also to the replenishment of the surface layer in nutrient.

The intrusion of the Danube’s fresh water towards the open sea results in a strong vertical stratification of the water column. The upper margin of the main pycnocline moves to a depth of about 40 m and thus prevents the penetration of the convective mixing to depths (the model results show a great production of turbulent kinetic energy from the sea surface up to 40 m). This shallow mixed layer and the Danube’s nutrients discharge create optimal conditions for the phytoplankton growth. The results show the existence of a diatom bloom at the end of January in this Danube water area (Fig. 5). This bloom occurs under the very low temperatures induced by the strong convective cooling occurring in this area in winter (Fig. 1a). As has been said before, in this model, the possibility of development of arctic species which are able to grow under very low temperatures and

![Image](image_url)

**Fig. 5.** Sea surface diatoms distribution at the end of January (in μatg N/l). The bloom is particularly important in the region of the Danube’s delta where the intrusion of fresh water reduces the mixed layer depth and where a great amount of nutrients is brought by the Danube’s discharge. On the rest of the shelf, east of the Danube water where the convective overturning penetrates to 70 m, bringing to the sea surface rich nutrient waters, a weaker bloom can be observed. South of the Romanian coast, along the western coast where the mixed layer extends to about 60 m, a weak bloom feeding on the nutrients brought by the Danube water can be observed.
light intensities has been taken into account in the choice of the parameters values included in the formulation of the diatoms growth (a lower lethal temperature of 0°C has been chosen and the photosynthetic rate has been calibrated with data relative to shade-type species). Currents in the shelf area tend to pinch this diatoms bloom close to the western coast. In spring, this fresh water front amplifies due to the increased river runoff and anticyclonic currents on the shelf tend to retain large amount of fresh water close to the coast.

On the rest of the shelf, east of the Danube water, the water column is not stratified, the water cooling and the extreme convective mixing, resulting in the formation of a cold intermediate layer, penetrate to 70 m (a great production of turbulent kinetic energy can be observed from the sea surface until 70 m) leading to the light limitation of phytoplankton. A weak bloom can be observed in this area (Fig. 5). A permanent upwelling of deep nutrient-rich waters to a depth of about 30 m can be observed in the central part of the eastern main cyclonic gyre (Fig. 2). In this area, the upper margin of the main pycnocline moves to the sea surface, reducing the mixed layer depth to about 30 m. These conditions are favourable to the development of phytoplankton and a diatoms bloom, extending from about 20 m until 30 m, can be observed (Fig. 6). This bloom vanishes as nutrients are progressively exhausted and as the grazing pressure increases. Along the western coast, south of the Romanian coast where the convective mixing penetrates to a depth of about 60 m, a bloom of diatoms, limited by the light availability and feeding on nutrients Danube’s discharge, can be observed (Figs. 5 and 6).

In winter, nitrogen is the most limiting nutrient of the diatoms growth, especially in the central part of the sea (0.08 for nitrogen at the sea surface in the central part of the sea against 0.5 for phosphate). Obviously, these values are strongly sensitive to the values chosen for the half-saturation constants for phytoplankton uptake.

Fig. 7 shows, at the end of February, the sea surface diatoms concentrations with the currents patterns superimposed emphasizing the effect of the general circulation on the space–time distribution of the primary production. The bloom is advected by the current along the western and the Turkish coasts. At some places, along the Turkish coast (west of Cape Kerempe at longitude 32.5) and near Samsun at...

Fig. 6. Distribution of diatoms (in μg N/L) in a perpendicular section (at constant latitude: 43.3°N) through the eastern main cyclonic gyre at the end of January. In the region of the eastern main cyclonic gyre, where a permanent upwelling occurs, a weak bloom extending from about 18 m up to 35 m can be observed. This bloom vanishes as nutrients are progressively exhausted and as the grazing pressure increases. Along the western coast, where the convective mixing penetrates up to 60 m, a bloom occurs from the sea surface until 60 m.
Fig. 7. Sea surface diatoms distribution (in μg N/l) with the currents patterns superimposed at the end of February. This picture emphasizes the effect of the hydrodynamical constraints on the space–time distribution of the primary production. The bloom is advected by the general circulation along the western and the Turkish coasts with some intrusions, occurring especially along the Turkish coast, of the diatoms rich waters towards the open sea waters. In the region of the Danube water, the bloom decreases due to the increasing pressure of copepods.

longitude 36.5), we can observe the intrusion of the diatoms population, advected by the current, towards the open sea.

In the region of the Danube water, on the shelf, the bloom decreases due to the increasing grazing pressure of copepods. At 40 m a patch of phyto-

Fig. 8. Sea surface diatoms distribution (in μg N/l) with the currents patterns superimposed at the end of March. The bloom occurs in the Dnepr delta area where the intrusion of fresh waters towards the shelf creates a shallow mixed layer about 30 m. In the region of the Danube’s delta, the important grazing pressure prevents the phytoplankton development.
plankton depletion can be observed due to the self-shading effect.

In March, the bloom occurs in the Dnepr delta area (Fig. 8) where the intrusion of fresh waters towards the shelf creates a shallow mixed layer (about 30 m) (the hydrodynamical results show that the Danube’s rich nutrients water first moves to the north, where it merges with the water originating from the Dnepr river). Then, this bloom is advected towards the south by the general circulation.

In the region of the Danube’s delta, the important grazing pressure prevents the phytoplankton development. In the frontal area, where the Danube’s plume and open sea waters (for instance, upwelled waters coming from the western main cyclonic gyre) meet, frontal instabilities increase the mixed layer depth, allowing the phytoplankton development at depth.

Along the Turkish coast, diatoms are still entrained from the coast towards the open sea by the eastern and western main cyclonic gyres. This winter outburst exhausts rapidly the available nutrients, so that the spring–summer production depends essentially on the in-situ regeneration of nutrients.

In April, the diatoms bloom decreases and vanishes, the dead diatoms increase the particulate organic matter biomass. This biomass leaves by sedimentation the sea surface and is regenerated at depth (20–40 m) by bacteria. At these depths, a bloom of ciliates, feeding on bacteria, can be observed. Zooplankton and bacterial excretion of inorganic nutrients (phosphate and ammonium) allow the development of the regenerated production.

In May, the results show the existence of a nanoflagellates bloom feeding on regenerated nutrients (Figs. 9 and 10). This bloom occurs at the sea surface above the thermocline where the grazing pressure of ciliates consuming bacteria is not too strong.

At the end of June, a dinoflagellates bloom occurs in the region of the Danube water where consumed nutrients are constantly replaced by the discharged river waters. This bloom is completely included in the mixed layer limited by the thermocline at about 10 m. It is well known that dinoflagellates display a...

Fig. 9. Horizontal diatoms distribution (in μg N/l) at 40 m with the currents patterns superimposed at the end of June. At the end of spring, the diatoms growth is limited by the thermo-inhibition and photo-inhibition processes; however, their growth does not seem to be limited by silicate availability. A weak diatoms bloom can be observed below the thermocline where the temperatures and the light intensities are not too high.
Fig. 10. Sea surface nanoflagellates distribution (in μg N/l) with the currents patterns superimposed in May. A nanoflagellates bloom feeding on regenerated nutrients occurs at the sea surface above the thermocline where the grazing pressure of ciliates is not too strong.

diel migration in which they absorb nutrients from 15 to 20 m during the night and swim to the surface during the day where light is available for photosynthesis and growth. In this model, this behaviour has not be considered. The results show that for each species, at the end of spring, phosphate becomes the most limiting nutrient of the phytoplankton growth on the shelf, while in the central part of the sea nitrogen remains the most limiting nutrient. In this model, the diatoms growth does not seem to be limited by the silicate availability but at the beginning of summer their growth is limited by the

Fig. 11. Sea surface phytoplankton concentrations: mean values in spring (in μg N/l). The competition between phytoplankton growth (feeding on river plume nutrients) and grazing is very likely responsible for the spatial structures of the phytoplankton concentration. The bloom is particularly important in the region of the Danube water, on the shelf, and follows the coast with some intrusions towards the open sea.
Fig. 12. CZCS estimate of the sea surface chlorophyll field: mean values in spring 80 (in mg m$^{-3}$).
 thermo-inhibition and the photo-inhibition processes. At the end of June, a weak diatoms bloom can be observed below the thermocline where the temperatures and the light intensities are not too high (Fig. 9). Following Sorokin (1983), in summer subtropical and even tropical forms of diatoms flourish, such as Chaetoceros diversus, C. peruvianus, Coscinodiscus janischii. Such diatoms species are able to grow under high temperatures and high light intensities.

The competition between phytoplankton growth (feeding on river water nutrients) and grazing is very likely responsible for the spatial structures of the mean spring phytoplankton concentration shown in Fig. 11. The simplicity of the model and the lack of sufficient data available at the time of this preliminary simulation did not allow a thorough validation of the model. However, it is illuminating to compare the model’s results with CZCS images of surface chlorophyll —Fig. 12 shows for instance the surface chlorophyll field for the spring 1980. Obviously, since 1980, the extending and amplifying eutrophication process has led to an important increase in the nutrient content. Besides, we do not have the phytoplankton N:Chl-$a$ ratio depending on the phytoplankton species and showing space-time variations. Thus, a qualitative comparison rather than a quantitative one can be made and shows a good agreement. The bloom is particularly important on the shelf in the region of the Danube’s delta and follows the whole western coast and the Turkish coast with some intrusions towards the open sea waters.

5. Conclusions

In this paper, we showed how a hydrodynamical model was implemented and extended to include an ecosystem model. The representation of the general circulation in the Black Sea by the hydrodynamical model is probably accurate enough for the simulation of a phytoplankton bloom at basin scale. In particular, the cyclonic circulation and interior upwellings induced by the wind fields are taken into account as well as the cold intermediate water formation and frontal systems on the north western shelf.

The results of this model display a highly three-dimensional aspect showing the horizontal and vertical structuring of both the phyto- and the zooplankton fields by the hydrodynamic constraints (horizontal and vertical advection, vertical mixing and diffusion, upwelling…) associated with light limitation at depth and sinking of dead organisms.

The results show that the bloom can be perceived as the succession of 3 blooms. The strongest bloom, made of diatoms, occurs in winter in the Danube plume area. Following this winter bloom, the model predicts a weaker and shorter bloom, made of nanoflagellates, in May; the formation of this bloom is caused by the ammonium generated as a by-product at the winter bloom. Finally, at the end of June, a bloom of dinoflagellates, feeding on the Danube’s nutrients discharge and on the regenerated nutrients, can be observed.

Nitrogen, and phosphate at the end of spring, limit the phytoplankton growth whereas silicate does not seem to be limiting.

Obviously, a lot of problems remain in this model:

1. The ecosystem model is defined by a nitrogen cycle and the C:N:P ratio of phytoplankton, zooplankton and bacteria is assumed constant. However, a thorough representation of some processes such as bacterial growth or inorganic nitrogen uptake by phytoplankton needs to simulate the carbon cycle.

2. The possibility of the development of opportunistic species is not tackled by the model. Introduction of large volumes of anthropogenic nutrient and contaminant loads from the Danube has been coupled with the massive growth of opportunistic species such as Noctiluca, Aurelia, the invader ctenophore Mnemiopsis leidii… These factors together with the over-exploitation of fish resources have affected all components of the ecosystem (Mee, 1992). These problems of pollution are dramatic on the northwestern shelf, receiving runoffs from the Danube, the Dnestr and the Dnep while, in the central Black Sea, they are relatively less severe because of its isolation from coastal and shelf waters by the Rim Current frontal zone (Oğuz et al., 1997).

3. The calibration, initialisation and validation of the ecosystem model are not optimal due to the lack of data available for the Black Sea.

4. The model does not take into account all the oxidation-reduction processes occurring in the transitional layer between the oxic and anoxic waters, resulting in changes in the speciation of many ele-
ments. This transitional layer is subject to considerable spatial variability. So, the upper margin varies from 70 to 125 m within the basin in accordance with the general circulation; it is shallower in the cyclonic regions and deeper in the anticyclonic regions (Saydam et al., 1993). In the central parts of the eastern and western main cyclonic gyres, the redox reactions may influence the nutrients profiles of the surface waters.

5. On the shelf, the influence of sediments on the nitrogen cycle has been neglected.

So, a more sophisticated ecosystem model has to be developed. Obviously, computational and intellectual limitations, the difficulty of interpreting too large sets of data, the increasing uncertainty on the values of parameters as their number increases faster than the number of state variables and the difficulty of to collect enough data to operate and initiate large models, set a limit to the size of the set of state variables (Nihoul, 1996).

According to the recommendations of the GLOBEC Numerical Modelling Group (Globec, 1995), our future objective is to develop a model involving all the state variables necessary to describe the basic dynamics of the ecosystem, reproducing the observed energy transfers within reasonable bounds (the so-called, optimal set). On the northwestern Black Sea, where the ecohydrodynamics are particularly complex, a nested high resolution interdisciplinary model will be implemented to simulate the eutrophication processes. The fine resolution model needs boundary conditions that can be computed by an interdisciplinary model covering the whole basin. The nesting method requires the coupling between a high resolution model and a coarse resolution model using different resolutions in space and time and also in the state space. This sets the problem of downsizing a complex ecosystem model to a simplified model by aggregation of the state variables.

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References


