Dynamics of Phytoplankton Blooms in the Baltic Sea – Numerical Simulations

L. Dzierzbicka-Głowacka, and M. Janecki

Abstract—Dynamic of phytoplankton blooms in the Baltic Sea has been analyzed applying the numerical ecosystem model 3D-CEMBS. The model consists of the hydrodynamic model (POP, version 2.1) and the ice model (CICE, version 4.0), which are imposed by the atmospheric data model (DATM7). The 3D-CEMBS model has an ecosystem module, activated in 2012 in the operational mode. The ecosystem model consists of 11 main variables: biomass of small-size phytoplankton and large-size phytoplankton – diatoms and cyanobacteria, zooplankton biomass, dissolved and molecular detritus, dissolved oxygen concentration, as well as concentrations of nutrients, including: nitrates, ammonia, phosphates and silicates. The 3D-CEMBS model is an effective tool for solving problems related to phytoplankton blooms dynamic in the Baltic Sea.

Keywords—Ecosystem model, phytoplankton, Baltic Sea.

I. INTRODUCTION

THE Baltic Sea is one of the largest reservoirs of brackish waters in the world. When compared with deep-sea water regions, the Baltic with low-salinity waters is extremely poor in flora and fauna. At present, water salinity over most of the Baltic region ranges from 5 to 8 PSU, hence the environment is too „freshened" for typical marine fauna and too „saline" for freshwater organisms. The range of 5–8 PSU is often defined as a „minimum-species zone" in the literature. In almost all world seas with observable impact of fresh waters (estuaries, bays), the least number of species occurs within this range of salinity. This means that the Baltic is a unique, saltwater (brackish) sea sentenced to low species diversity [1]. The development of phytoplankton is mainly affected by the sunlight cycle. At a certain day length (characteristic of individual species and algae groups), the amount of light in spring is sufficient for effective photosynthesis. Quickly dividing algal cells use biogenic substances, the resources that become richer after the winter season. Spring sunlight heats the surface water layer, and the freshwater from the melting ice forms a sea surface layer, which results in the density stratification. The dividing algal cells sink slowly in the water column (sedimentation). They do not fall on the bottom, however instead they are retained within the density-jump layer. This pattern of algal blooms continues till biogenic substances in the upper water layer are depleted. The Baltic Sea is not situated within the polar zone of the sunlight cycle, and the light for photosynthesis is available throughout the year, thus phytoplankton blooms occur in the sea once again,

i.e. in the late summer and early autumn, and are being supported by regenerated biogenic substances after the first spring algal blooms.

Producers, i.e. plants-phytoplankton are the first link in the food chain of the seas and oceans. The major part of the producer's organisms occurs within the upper layer of the water column (within the closest proximity of the light). Phytoplankton consists of thousands of species, supplying 99% of food resources for marine animals. The phytoplankton development is determined not only by the amount of sunlight, but also by the inflow of inorganic nutrients, mainly nitrates and phosphates. Therefore, the largest production of algae occurs in the vicinity of continents, especially within the zones where the nutrient-rich deep waters are moved towards the ocean surface (upwelling zones).

This study presents numerical simulations of seasonal changes in the phytoplankton biomass in the Baltic Sea. In addition, the difference in the phytoplankton biomass distribution for two selected sites of Gdańsk Bay is presented.

In the presented paper, the three-dimensional ecosystem model 3D-CEMBS (http://deep.iopan.gda.pl/CEMBaltic/new_lay/index.php) has been used for numerical simulations to determine seasonal changes in the phytoplankton biomass for the Baltic Sea. Furthermore, the difference in the phytoplankton biomass distribution in the Southern Baltic was presented, divided into the coastal zone − P2 (the Gdańsk Bay) and the open sea − P1 (the Gdańsk Deep) (Fig. 1).
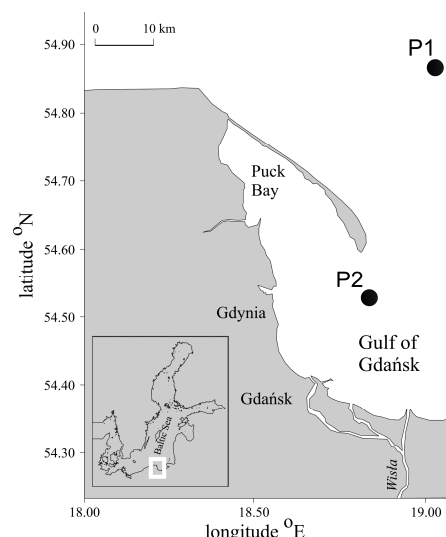

Fig. 1 Simulation stations

II. BIOLOGICAL MODEL

The ecosystem model consists of 11 main variables: biomass of small-size phytoplankton and large-size

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phytoplankton – diatoms and cyanobacteria, zooplankton biomass, dissolved deposit and molecular detritus, dissolved oxygen concentration, as well as concentrations of nutrients, including: nitrates, ammonia, phosphates and silicates (Fig. 2).
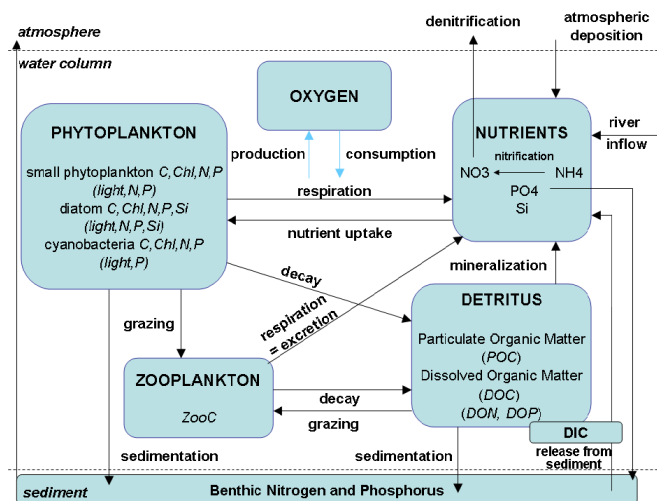

Fig. 2 Structure of the ecosystem model

The class of small phytoplankton comprises nano and pico phytoplankton, and can be limited by nitrates, phosphates and available light. The class of larger phytoplankton is represented by diatoms and can be limited by the aforementioned factors, as well as by silicates. Phosphates and light availability determine cyanobacteria growth rate. The biological module is described by a set of equations in the form of a turbulent diffusion equation with an advection component [2]. This equation describes the rate of changes in the concentration of the studied variables in time and space, taking into account the function of the source and losses:

$$\frac{\partial S}{\partial t} + (V + w_s) \cdot \nabla S = \frac{\partial}{\partial z}\left(K_z \frac{\partial S}{\partial z}\right) + \sum_{i-1}^{2} \frac{\partial}{\partial x_i}\left(K_{x_i} \frac{\partial S}{\partial x_i}\right) + F_S$$

where:
S – each model variable,
V – velocity vector,
W_s – sinking velocity of phytoplankton or pelagic detritus,
K_z, K_x – vertical and horizontal turbulent diffusion coefficients,
F_S – biogeochemical source-sink term

The function F_S is determined based on the knowledge of biogeochemical processes occurring in the marine environment and their mutual relations. The aforementioned processes were selected from the relevant literature. Components of the flow velocity vector, temperature and salinity distributions were defined from the hydrodynamic module − ocean-ice POPCICE [3]-[5].

III. PHYTOPLANKTON

Net growth rate of algae is determined in natural conditions, where usually external losses occur. It is calculated based on the difference between the production rate and the rate of losses. The rate of losses is affected by several processes that proceed with different rates depending on physical conditions, as well as characteristic features of the population structure and behavioral and metabolic animal processes. The biomass of phytoplankton is determined mainly by primary production, which defines the amount of assimilated carbon during photosynthesis. Processes determining the internal and external losses are associated with respiration of phytoplankton, consumption by zooplankton, its mortality and sedimentation.

Equation defining the net growth rate of phytoplankton can be presented in the following way:

$$\frac{\partial Phyt}{\partial t} = primary production$$

$$-respiration - grazing - mortality - sinking$$

More detailed equations of phytoplankton biomass changes are presented in Appendix A.

IV. RESULTS

Fig. 3 and Fig. 4 present spring phytoplankton blooms obtained from the model. It shows that simulated algal blooms in the area of Skagerrak and Kattegat start earlier than in the Baltic Proper. Spring algal blooms in the Baltic Proper start first in the coastal zone and in the southern part of the sea area, and then spread in the northern direction.
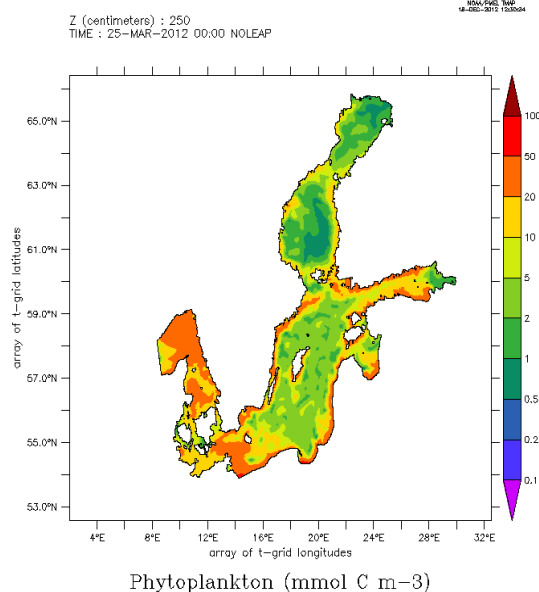

Fig. 3 Phytoplankton concentration for 25th May 2012

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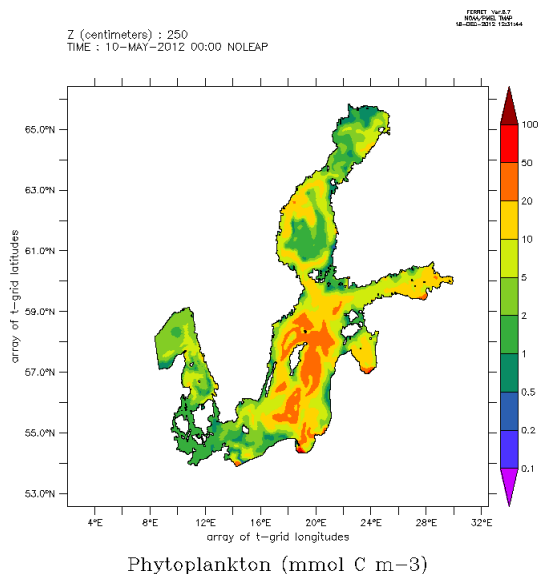International Journal of Environmental and Ecological Engineering
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Fig. 4 Phytoplankton concentration for 10th May 2012

In late spring/early summer, algal blooms begin in the Gulf of Finland and the Bothnia Sea, and then in the Gulf of Bothnia (Fig. 5). Whereas in the summer, cyanobacteria blooms appears, mostly in the coastal zone.
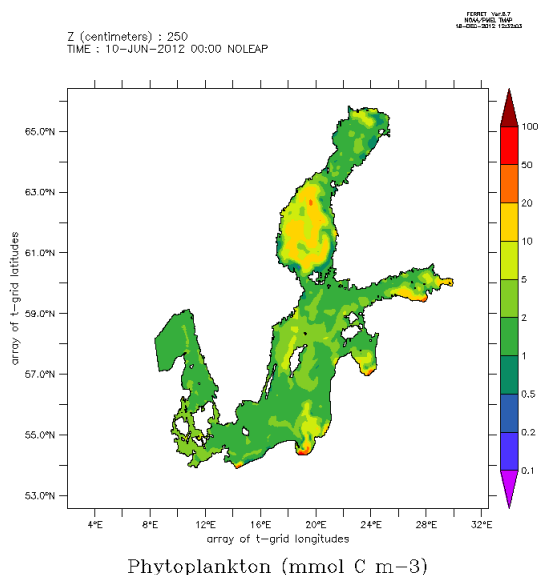

Fig. 5 Phytoplankton concentration for 10th June 2012

In the second part of the year, in September and October, less intense algal blooms appears throughout the Baltic Sea (Fig. 6). The phytoplankton biomass reflects the availability of biogenic substances, revealing a strong decline in their concentration during spring algal blooms.
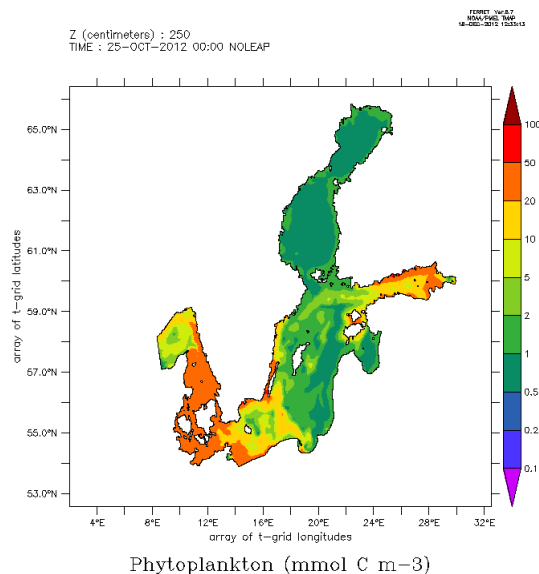

Fig. 6 Phytoplankton concentration for 25th October 2012

The phytoplankton biomass in the Gulf of Gdańsk (Fig. 7) had the highest value in the surface layer and reached the maximum in mid-April. Phytoplankton blooms are correlated with depletion of nutrients in the water, which consequently reduces the plankton growth. In the summer (July and August), the phytoplankton biomass is lower than in the spring, most likely due to the deficit of nutrients. A greater increase in the phytoplankton biomass is observed in the early autumn. This is probably related to the increased concentration of biogenic substances resulting from water mixing in the deeper layers of the water column. In December, when the biomass of phytoplankton decreased to the initial level from January and February, the growing season ends.

Fig. 8 shows that the biomass of phytoplankton in the Gdańsk Bay (station P2) was approximately two times higher compared to Gdańsk Deep (station P1). This situation is caused by the concentration of nutrients near the mouth of the river (where their impact on the values of the studied biological variables is easy to observe), and by the water temperature, which was higher at station P2 compared to station P1.

The phytoplankton biomass increases up to the value of approximately 70 mmol C m^3 in mid-April, but decreases at the end of June to 1 mmol C m^3 and 5 mmol C m^3 at station P1 and P2, respectively. A relatively high value of food is also maintained throughout the summer.

The concentration of available nutrients in the upper water layer remains almost at the same level from June to November.

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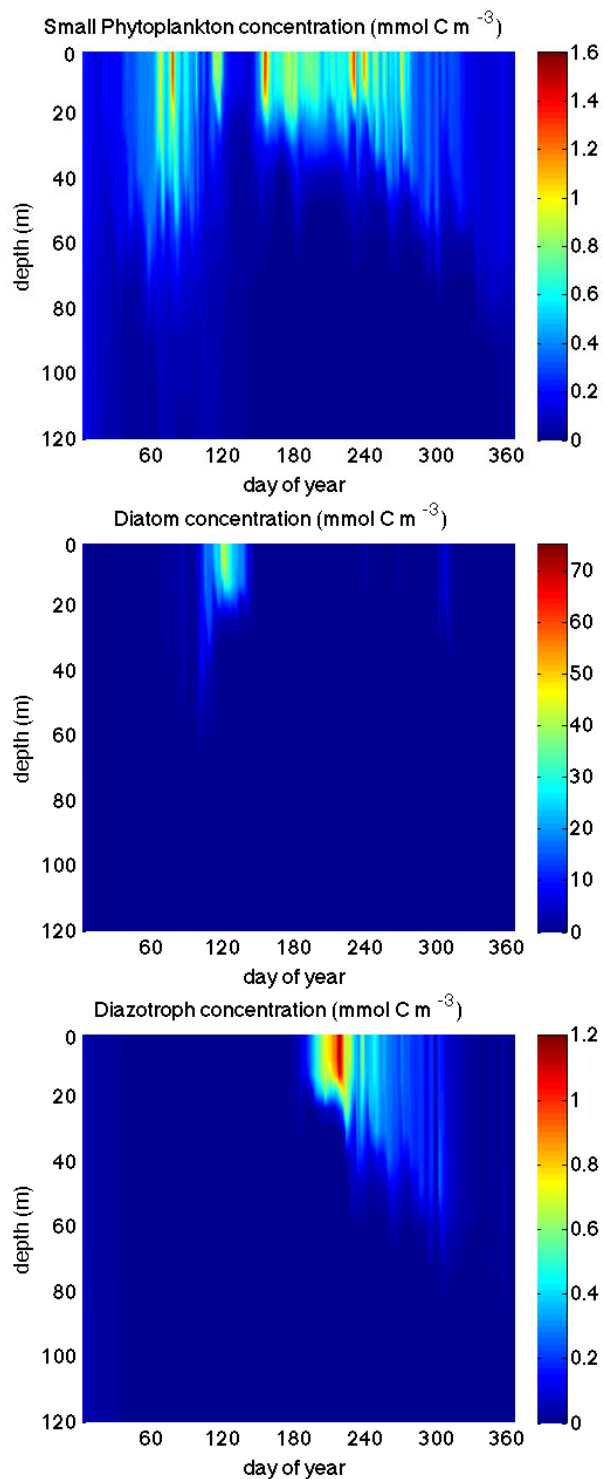Vol:7, No:1, 2013

Fig. 7 The annual cycle of phytoplankton concentration (small phytoplankton, diatom, diazotroph) at Gdansk Deep (station P1) during the year 2011
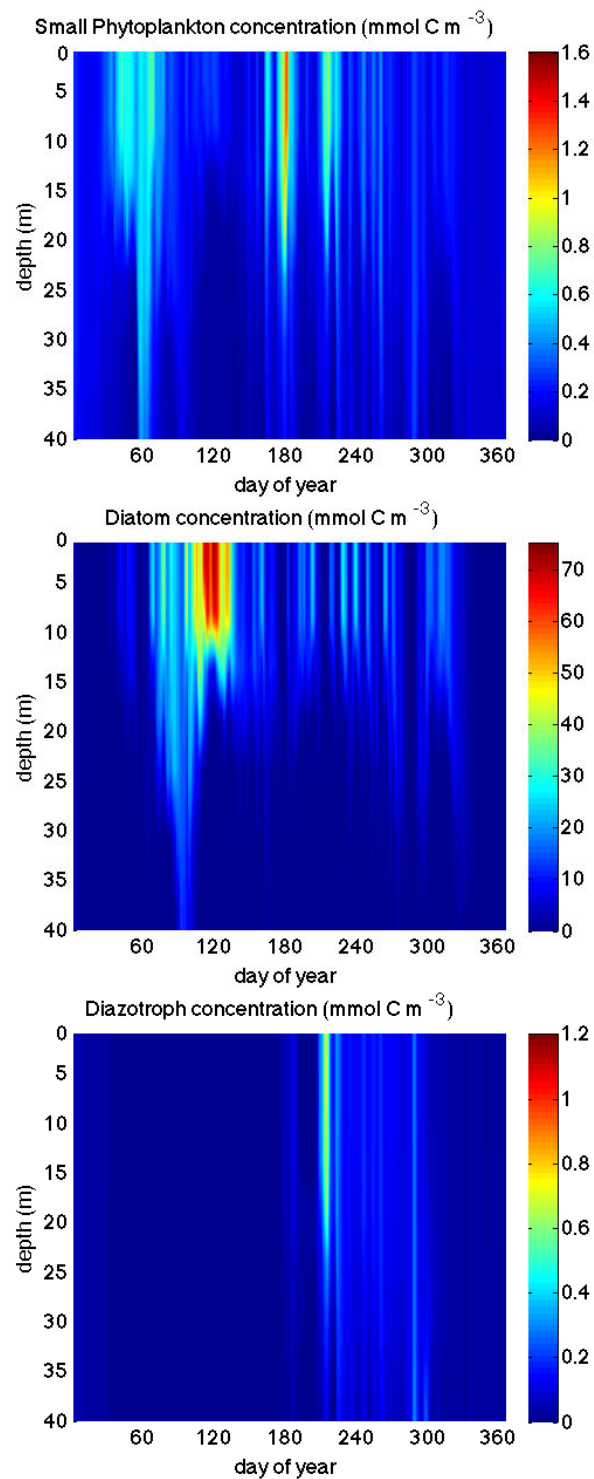

Fig. 8 The annual cycle of phytoplankton concentration (small phytoplankton, diatoms, diazotroph) at Gdansk Bay (station P2) during the year 2011

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V. Summary

Due to the complexity of hydrophysical and biological processes in the marine environment and their interrelations, modern research techniques – mathematical modelling and computer simulations of phenomena are required for their identification, including the current state of research. The research in the sea that provides the most reliable information about the mechanisms and processes, requires long-term, comprehensive and expensive in situ observations in different hydrometeorological conditions to collect relevant „statistics" of a given situation, necessary for appropriate assessment of the environmental state and its possible changes. Results of remote satellite measurements provide significant help, but despite a considerable progress in this field, it is still a future tool. Even extremely skillful interpolation of these results determines only the changes occurring in the upper layer of the seawater column. Most often they are interpolated into deeper areas, hence they are burdened with a pretty big error, because the Baltic ecosystem has a strongly stratified vertical structure.

It is obvious that mathematical models have certain constraints resulting from the state of knowledge about individual processes, parameterization methods, their interrelations, and possibilities of their appropriate implementation in the form of the model. The above facts explain the current common application of mathematical models and computer simulations as new methods of identifying the laws governing the natural world. This particularly applies to issues incorporating several scientific disciplines, which is a rule in oenological studies.

The operational model of the Baltic ecosystem (3D-CEMBS) was launched in 2012 on the 2 km grid with rivers at the Institute of Oceanology PAS.

The 3D-CEMBS model determines the temporal and spatial distributions of oxygen and nutrients concentrations, biomass of phytoplankton and zooplankton, as well as pelagic detritus deposits. The presented 3D-CEMBS model is the right tool for monitoring the state and bio productivity of the ecosystem and forecasting the physical and ecological changes in the studied sea. This model allows prediction of long-term changes in the main characteristics of the Baltic ecosystem, both in time and space, by adopting the assumptions related to scenarios of the economic development and the extent of environmental pollution

Appendix

Change in phytoplankton biomass:

$$\frac{d(Phyt)}{dt} = photoC - graze - loss - agg$$

where:

$Phyt$ – small phytoplankton / diatom / diazotroph concentration

$photoC$ – carbon-fixation (mmol C/ m^3/sec)

$graze$ – grazing rate (mmol C/ m^3/sec)

$loss$ – non-grazing mortality (mmol C/ m^3/sec)

agg – aggregation loss (mmol C/ m^3/sec)

$$photoC = PCphoto \cdot Phyt$$

$$PCphoto = PC\max \cdot light\_lim$$

$$PC\max = PCref \cdot f\_nut \cdot Tfunc$$

$$f\_nut = \min(VNtot, VFeC, VPO4)$$

$$VNtot = \frac{\dfrac{NO3}{kNO3} + \dfrac{NH4}{kNH4}}{1 + \dfrac{NO3}{kNO3} + \dfrac{NH4}{kNH4}}$$

$$VFeC = \frac{Fe}{Fe + kFe}$$

$$VPO4 = \frac{PO4}{PO4 + kPO4}$$

$$VSiO3\_diat = \frac{SiO3}{SiO3 + diat\_kSiO3}$$

$$light\_lim = 1 - e^{\frac{-alphaChl \cdot thetaC \cdot PAR\_avg}{PC\max + epsTinv}}$$

$$thetaC = \frac{PhytChl}{Phyt + epsC}$$

$$Tfunc = 2^{\frac{(T+273.16)-(30+273.16)}{10}}$$

Grazing and losses:

$$graze = u\max \cdot zooC \cdot \frac{reduceV}{reduceV + z\_grz}$$

where:

$umax$ – max zooplankton growth rate at local temperature (1/sec)

$reduceV$ – factor in nutrient uptake (mmol C / m^3)^2

$ZooC$ – zooplankton concentration (mmol C / m^3)

$$u\max = u\max\_0 \cdot Tfunc$$

$$reduceV = Pprime^2$$

$$Pprime = \max(Phyt - C\_loss\_thres, 0)$$

$$C\_loss\_thres = f\_loss\_thres \cdot loss\_thres$$

$$loss = mort \cdot Pprime \cdot Tfunc$$

$$agg = \min(agg\_max \cdot dps \cdot Pprime, mort2 \cdot Pprime^2)$$

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TABLE I
PHYTOPLANKTON EQUATIONS PARAMETERS

Parameter	Unit	Small phytoplankton	Diatom	Diazotroph
PCref	1/day	9.4	9.4	2.5
kNO3	mmol N / m^3	0.25	0.5	0
kNH4	mmol N / m^3	0.25	0.5	0
kPO4	mmol P / m^3	0.05	0.1	0.5
kFe	mmol Fe / m^3	$0.03 \cdot 10^{-3}$	$0.08 \cdot 10^{-3}$	$0.06 \cdot 10^{-3}$
kSiO3	mmol Si / m^3	0	0.25	0
alphaChl	mg Chl W sec	0.34	0.3	0.17
umax_0	1/day	2.5	1.95	0.9
z_grz	mmol C / m^3	1.0	0.7	1.0
loss_thres	-	0.001	0.02	0.01
mort	1/day	0.15	0.15	0.17
mort2	1/day/(mmol C / m$^{3)}$)	0.0035	0.0035	0
agg_max	1/day	0.75	0.75	0
epsC	mmol C / m^3	$1.0 \cdot 10^{-8}$	$1.0 \cdot 10^{-8}$	$1.0 \cdot 10^{-8}$
epsTinv	(1/year)(1/sec)	$3.17 \cdot 10^{-8}$	$3.17 \cdot 10^{-8}$	$3.17 \cdot 10^{-8}$
dps	-	1/86400	1/86400	1/86400

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