**Ocean Science
Discussions**

Influence of climate parameters on long-term variations of the distribution of phytoplankton biomass and nutrient concentration in the Baltic Sea simulated by a 3-D model

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.

Abstract

Influence of long term trends in the climate parameters (average temperature, wind speed and solar irradiance) on phytoplankton and nutrient in the Baltic Sea was studied with an integrated three-dimensional coupled sea-ice ecological model. Simple ecosystem has been added to the sea-ice model and it has been used to estimate variability of the phytoplankton and nutrient during long term changes of the main atmospheric forces. Several numerical experiments were conducted to test the sensitivity of the model to changes of the main physical parameters such as temperature, wind speed, solar and thermal radiation (in different configurations). Influences of variability of these parameters on phytoplankton and nutrient (total inorganic nitrogen) is presented and discussion on relevance to expected future climate change is provided.

1 Introduction

Numerous threats and natural disasters elicited by changes in the environment have persuaded experts to radically intensify ecological investigations and forecasts in a regional and global scale. A key part of these changes is played by marine ecosystems, especially the organic matter production processes occurring in them. Marine production is the most important mechanism of carbon exchange between the sea and the atmosphere, and therefore requires to be monitored continuously with traditional methods (from on board ship), as well as with modern remote sensing techniques. This kind of research is extremely expensive and demands the cooperation of interdisciplinary study groups working both in laboratories and on board ship. Nevertheless, effective monitoring of marine production is practically impossible with traditional methods. During the last four decades, another way of solving these problems has been developed using numerical methods describing the bioproductivity of marine basins. Mathematical models of ecosystem also could be used as tools for forecasting and evaluating the influence of human activities, for analysing future changes of a ecosystem and it can be visible as an influence of the external factors (Gordon et al., 1995).

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

L. Dzierzbicka-Głowacka et al.

The Baltic Sea is a semi-enclosed shelf sea bounded by the Scandinavian Peninsula in the north and east, the Jutland Peninsula in the west and continental Europe in the south. The brackish nature of the Baltic, in which salinity decreases in a north-easterly direction, is due to the combination of the high river discharge and the limited inflows of salty water from the North Sea. The Baltic Sea run off drains a catchment area which is approximately four times bigger than the sea itself. Major part of catchment area, especially in the continental part, intensive agriculture is practiced. This means that high loads of nutrients and organic matter eventually could reach the Baltic (HELCOM, 2005), making this sea one of the most productive marine ecosystems in the world (HELCOM, 2006).

The study was conducted as a part of European COastal-shelf sea OPerational observing and forecasting system (ECOOP) Integrated Project. The main goal of this work was to study an influence of atmospheric physical parameters (such as wind speed, air temperature and short wave radiation) on the distribution of phytoplankton biomass, nutrient concentration and sea temperature in the Baltic Sea. However, here the influence of the biogeochemical processes, as e.g. nutrient concentrations increase or decrease through influx of nutrient compounds from rives and the atmosphere, on the investigated variables is not was considered. It has been examined in another study (submitted as a separated paper).

The 3-D Coupled Ecosystem Model of Baltic Sea, has been developed at the Institute of Oceanology PAS, and may be used to estimate: annual, seasonal, monthly and daily variability of investigated characteristics, the impact of various climatic conditions over several years and the influence of different hydrophysical and biochemical processes on the time-spatial distributions.

2 The CEMBSv1 model

The CEMBSv1 model was embedded in the existing 3-D hydrodynamic model of the Baltic Sea. As a part of ECOOP IP WP 10, a sea-ice model (POPCICE) has been use

to implement biological equations for plankton system (see Dzierzbicka-Glowacka et al., 2010a – for POC model, Dzierzbicka-Glowacka et al., 2010b – for copepod model and here – for CEMBSv1). The model consists of Parallel Ocean Program and Community Ice CodE (POPCICE). Both are from Los Alamos National Laboratory (LANL).
POPCICE was forced using European Centre for Medium-Range Weather Forecasts (ECMWF) data: 2 m temperature and dew point, long and short waves radiation (downward), 10 m wind speed and air-ocean wind stress. Ocean model time step is 480 s and ice model time step is 1440 s. Horizontal resolution for ice and ocean model: ∼9 km (1/12 degree). Vertical resolution (ocean model): 21 levels (for the Baltic sea ∼18 levels). Model domain and bathymetry (represented by vertical levels) is presented at Fig. 1. It presents the model coordinates, and the same bathymetry as a geographic projection (rotated relative to model coordinates). Both models, for ice and ocean, work on the same grid, so there are no problems with exchanging fluxes between the models. In this paper, we are focused only on the biological part of the model.

2.1 Conceptual basis

The 3-D ecosystem model is based on 1-D biological model of Dzierzbicka-Glowacka (2005, 2006). In this model, phytoplankton is represented by one state variable and the model formulations are based on a simple total inorganic nitrogen ($NO_3 + NO_2 + NH_4$) cycle (Fig. 2). Nutrient serves initially as a means to trigger the bloom of phytoplankton and later to limit the phytoplankton production. The model is conceptualized for the shallow sea, typical with the replenishment of the mixed layer with nutrients from the bottom. The water column dynamics is implemented in a three-dimensional frame, where phytoplankton and nutrient (nitrogen) are transported by advection and diffusion. The physical frame, including all necessary forcing is presented at Fig. 3.

The biological model incorporates formulations for the primary production mechanism and remineralization mechanisms within the mixed layer, in the lower layer and at the bottom. Primary producers can be transported, die and be utilized by zooplankton

(mesozooplankton). The grazed phytoplankton is divided into three parts: the first one contributes to zooplankton growth, the second is deposited as fecal pellets, and the last one is excreted by zooplankton as dissolved metabolites; thus, it replenishes the nutrient pool. A proportion of the material contributes growing is assumed to be lost immediately, represents dying zooplankton. Proportions of both the fecal and the excreted material are immediately regenerated (Radach and Moll, 1993; Dzierzbicka-Glowacka, 2005). Mortality of phytoplankton is modeled in two ways. One is for grazing by mesozooplankton, which forms the bulk of grazers in the Baltic Sea. In the model it is prescribed by mesozooplankton biomass. All other kinds of mortality, like cell lyses and grazing by zooplankton other than mesozooplankton, are assumed to be proportional to phytoplankton standing stock, with a constant mortality rate, and therefore dynamically coupled to phytoplankton dynamics.

The assumed time scale of sinking of the fecal and dead material of a few days (Jickells et al., 1991) is much less than the time scale for benthic regeneration processes, which is weeks to months (Billen et al., 1991). Therefore, the most of the detrital material sinks onto the bottom where it collects as a benthic pool. Only a small portion of detritus remains suspended in the water column (Postma and Rommets, 1984), i.e. 20 percent of reminarialized dead phyto- and zooplankton and fecal material in water column. The effect of the microbial food web (Azam et al., 1983) is parameterized by converting this portion of detrital material immediately into regenerated nutrients within the water column. The major portion is deposited onto the bottom where it is re-worked by benthic communities. The concept of the detrital pool at the bottom has been introduced to create a lag in remineralization of the majority of detritus and the eventual replenishment of the upper layer with nutrients. This complex process is parameterized by assuming a net remineralization rate for bottom detritus (Billen et al., 1991). Thus, there are two pathways for the regeneration of pelagic and benthic nutrients, each with different time scale. The availability of regenerated nutrients for production in the upper layers is controlled by the physical processes and depth.

Benthic detritus varies according to the input of detrital material from the water column and losses by remineralization. Small biogenic particles, such as individual phytoplankton cells sink very slowly ($<1\,\mathrm{m\,day^{-1}}$) and through various aggregation processes, small particles are repacked into larger detrital particles which are deposited rapidly with sinking velocities of 10–$100\,\mathrm{m\,day^{-1}}$ (see Radach and Moll, 1993). In shallow seas like the Baltic Sea, biogenic particles have a bigger probability of reaching the sediments with much of their organic matter intact than in deep water. In a similar way, zooplankton fecal material was added to the benthic detritus, and nutrient is returned to the water column after remineralization.

Bearing in mind the fact that the intention was to make the model as simple as possible, and also to avoid the necessity of including several nutrient components, the model is based on total inorganic nitrogen. This is the main factor which controls the biomass of phytoplankton in the Baltic Sea (Shaffer, 1987), although cyanobacteria overcome N shortage by N-fixation, so primary production is limited by available phosphorus.

In this model, phytoplankton was modelled with the aid of only one state variable represented by diatoms. Cyanobacteria bloom were not incorporated at this stage of the model development. Therefore, in this case nutrient may be represented by one component, total inorganic nitrogen (Shaffer, 1987).

2.2 Equations

Two partial differential equations describe the spatial and temporal evolution in the total inorganic nitrogen $\mathrm{Nutr}(x,y,z,t)$ ($\mathrm{mmol\,N\,m^{-3}}$) and phytoplankton $\mathrm{Phyt}(x,y,z,t)$ ($\mathrm{mg\,C\,m^{-3}}$) pools, and an ordinary differential equation describes the benthic detritus $\mathrm{Detr}(x,y,t)$ ($\mathrm{mg\,C\,m^{-2}}$) pool. Mathematically, the pelagic variables in the model are described as:

$$\frac{\partial \mathrm{Phyt}}{\partial t} = -\left(u\frac{\partial \mathrm{Phyt}}{\partial x} + v\frac{\partial \mathrm{Phyt}}{\partial y}\right) + \frac{\partial}{\partial x}\left(K_x\frac{\partial \mathrm{Phyt}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial \mathrm{Phyt}}{\partial y}\right)$$

Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

$$-(w + w_z)\frac{\partial \text{Phyt}}{\partial z} + \frac{\partial}{\partial z}\left(K_z \frac{\partial \text{Phyt}}{\partial z}\right) + \text{PRP} - \text{RESP} - \text{MORP} - \text{GRZ} \tag{1}$$

$$\frac{\partial \text{Nutr}}{\partial t} = -\left(u\frac{\partial \text{Nutr}}{\partial x} + v\frac{\partial \text{Nutr}}{\partial y}\right) - w\frac{\partial \text{Nutr}}{\partial z} + \frac{\partial}{\partial x}\left(K_x \frac{\partial \text{Nutr}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \text{Nutr}}{\partial y}\right)$$
$$+ \frac{\partial}{\partial z}\left(K_z \frac{\partial \text{Nutr}}{\partial z}\right) + + g_\text{N}\left[-(\text{PRP} - \text{RESP}_{\text{light}}) + \text{RESP}_{\text{dark}} + p_\text{M}\text{MORP} + p_\text{F}\text{FEC}\right.$$
$$\left. + p_\text{Z}(\text{MORZ} + \text{PRED}) + \text{EXCZ}\right] \tag{2}$$

$$\frac{\partial \text{Detr}}{\partial t} = D - \text{REMD} \tag{3}$$

$$D = \int\left[(1 - p_\text{M})\text{MORP} + (1 - p_\text{F})\text{FEC} + (1 - p_\text{Z})(\text{MORZ} + \text{PRED})\right]dz$$

The first four terms on the right-hand side of Eq. (1) describe the horizontal and vertical advection and diffusion of phytoplankton, where u, v and w are the time-dependent velocities obtained from our model for the Baltic Sea (POPCICE), K_x, K_y, K_z are the horizontal and vertical diffusion coefficients, and the following terms describe gross production (PRP), respiration (RESP), mortality (MORP) and grazing (GRZ). Gross primary production (PRP) is calculated from the nutrient and light limitation functions $- f_\text{N}$ and f_I. Steele's function, (Steele, 1962) where optimal light intensity I_{opt}, is used as a light limitation function which includes photoinhibition. For nutrient limitation the Michaelis-Menten formula is applied with a constant K_N as the half-saturation constant. Respiration (RESP) consists of basal maintenance and photorespiration, each being proportional to phytoplankton biomass, where the basic dark respiration proportion is r_{BR} as a proportionality factor to the maximum photosynthetic rate, and the photorespiration proportion r_{PR} is proportional to gross primary production. The temperature dependence f_T is modeled according to $f_T = \exp(0.0769(T - 10))$ with the constant 0.0769 expressing the respiration change f_T with temperature, yielding a doubling by

an increase of 10° C in temperature and $f_T(T_0) = I$ at $T_0 = 10$° C. Mortality of phytoplankton (MORP) is assumed to be proportional to the phytoplankton standing stock, with mortality rate mp. Copepod grazing (GRZ) is assumed to be proportional to copepod biomass Zoop with rate g_{max}, but this rate is modified by a Michaelis-Menten function of phytoplankton biomass with the half-saturation constant k_{Phyt} subject to a threshold $Phyt_0$, below which grazing ceases.

The state Eq. (2) for nutrient includes the first four terms on the right-hand side expressing the horizontal and vertical advection and diffusion of nutrient, where the same velocities and diffusion coefficients are used as for phytoplankton, and the four processes nutrient uptake (UPT), dark respiratory release (RELE), remineralization in the water column (REM) and zooplankton excretion (EXCZ). Nutrient uptake (UPT) appears in the nitrogen equation for positive net production in the euphotic zone only. The constant g_N is the N:C ratio according to the Redfieid ratio. Respiration in the dark consumes particulate organic matter. To conserve matter, the respiration term in the equation for phytoplankton carbon must be balanced by a nutrient release term (RELE) in the equation for nitrogen. This term parameterizes the contribution of respiration to the nutrient pool at the given fixed ratio g_N. For light intensities below the compensation intensity, the respiratory release is regenerated immediately into nitrogen. Fractions of dead phyto- and zooplankton and of fecal pellets that are instantaneously remineralized within the water column by the microbial food web (REM) are given by proportionality factors p_M for phytoplankton, p_Z for zooplankton and p_F for fecal pellets. Excretion of dissolved (EXCZ) and particulate material is parameterized as fixed proportions of zooplankton grazing (ez), fecal pellet production (f) and zooplankton mortality (mz), with the condition $ez + f + mz = 1$.

The benthic detritus Eq. (3) consists of two terms, sedimentation out of the water column to the bottom (indicated by the integration from the surface to the bottom H, simultaneously from all depths) and regeneration at the bottom. Deposition of detrital material out of the water column consists of dead phytoplankton, fecal pellets and dead zooplankton, which are not remineralized in the water column by the microbial

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

food web. Remineralization at the bottom is assumed to be proportional to the amount of available benthic detritus, with a constant rate r_D.

2.3 Parameters

The set of constants is given in Table 1. A few remarks will be made concerning the choice. For the grazing formulation, the threshold value $Phyt_0$ and the half-saturation value k_{Phyt} were changed according to data reported by Dzierzbicka-Glowacka (2005). The nitrogen to carbon ratio g_N was assumed as $0.013 \, \text{mmol N} \, (\text{mg C})^{-1}$. The half-saturation constant for total inorganic nitrogen is $0.5 \, \text{mmol N m}^{-3}$. The optimal light intensity for the phytoplankton community was set to $60 \, \text{W m}^{-2}$.

For the remineralization rates in the water and at the bottom (following Postma and Rommets, 1984): about 20% of the average labile particulate organic carbon (POC) is mineralized daily. Thus, from the POC created as detritus, 20% are instantaneously remineralized ($p_F = p_M = p_Z = 0.2$), and the remaining amount of 80% is transported immediately to the bottom. There is no explicit sinking of living phytoplankton, because this is already included in the instantaneous transfer to the bottom (Fig. 2). The ingested material is divided equally between dead zooplankton, fecal pellets and soluble excretion following Steele (1974). The benthic nutrient mineralization r_D is taken as $0.0005 \, \text{day}^{-1} \exp(0.005° \text{C}^{-1} T)$ (Savchuk and Wulff, 1996).

2.4 Forcing

The intention was to simulate production within a physical environment which will be as realistic as it possible. The actual oceanic forces are required for reliable simulations of the phytoplankton dynamics (Fig. 3). The external forcing are from ECMWF (ERA 40 reanalysis, www.ecmwf.int). The biological reaction terms are not implemented within the circulation model. The primary production model is an independent transport model that uses the circulation model output, so there is no feedback from the biology to the physics, and it makes simulations easier to implement.

Another important force for primary production simulations is solar radiation with its own daily cycle. The total irradiance at the surface is calculated using the model by Rozwadowska and Isemer (1999). The local weather conditions were made on board Voluntary Observing Ships and those data has been used to estimate climatological characteristics of the solar radiation flux at the surface of sea. The monthly irradiation values were interpolated to give daily values.

The nutrient contributions by the rivers are not included in this model, but the initial values for nutrients are based on SCOBI 3-D-model. Phytoplankton production is limited in the model by light and total inorganic nitrogen. The phytoplankton biomass is restricted by zooplankton grazing due to mezozooplankton. The zooplankton biomass is prescribed as a force and it uses the abundance data from the Mańkowski (1978), Ciszewski (1983) and Mudrak (2004) for the southern Baltic Sea. Using these observed biomass values and the abundances, the annual cycles of abundances were transformed to carbon biomass cycles. Trigonometric polynomial has been used to assign values at any model time and for all of the grid points.

2.5 Initial and boundary values

Phytoplankton initial values for January and December are very limited, therefore a constant value of $0.1 \, \text{mg} \, \text{C} \, \text{m}^{-3}$ was defined – but the model is not sensitive to the initial conditions of phytoplankton concentration (in January). Also the data for the detritus content at the bottom were not available, and the instantaneous sinking of detritus is a more arbitrary model assumption. The initial amount of detritus at the bottom was prescribed as $200 \, \text{mg} \, \text{C} \, \text{m}^{-2}$ for the whole Baltic Sea. The initial values for total inorganic nitrogen are taken from SCOBI 3-D-model for January.

The initial vertical distributions of nutrient, phytoplankton, zooplankton and detritus pool are known:

$$\{\text{Phyt}\} (x,y,z,0) = \{\text{Phyt}\}_0 (x,y,z) \, 0 \leq z \leq H$$

$$\{\text{Nutr}\} (x,y,z,0) = \{\text{Nutr}\}_0 (x,y,z) \, 0 \leq z \leq H \, \{\text{Detr}\} (x,y,H,0) = \{\text{Detr}\}_0 (x,y,H) \, z = H$$

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The vertical gradients of phytoplankton and nutrient concentration flux are zero at the sea surface ($z = 0$):

$$F_{\text{Phyt}}(x,y,0,t) \equiv K_z \frac{\partial \{\text{Phyt}\}(x,y,z,t)}{\partial z}|_{z=0} - w_z \{\text{Phyt}\}(x,y,0,t) = 0$$

$$F_{\text{Nutr}}(x,y,0,t) \equiv K_z \frac{\partial \{\text{Nutr}\}(z,t)}{\partial z}|_{z=0} = 0$$

5 The bottom flux condition for phytoplankton and nutrient is given by:

$$F_{\text{Phyt}}(x,y,H,t) \equiv -w_z \{\text{Phyt}\}(x,y,H,t) \, ,$$

$$F_{\text{Nutr}}(x,y,H,t) \equiv K_z \frac{\partial \{\text{Nutr}\}(x,y,z,t)}{\partial z}|_{z=H} = g_N \text{REMD}$$

This flux $F_{\text{phyt}}(H)$ enters the benthic detritus equation as a source term. The boundary condition provides the mechanism by which the water column is replenished by
10 nutrients derived from benthic remineralization.

3 Results and discussion

3.1 Examples of results for 2004 year

For a large area, biogeochemical processes strongly depend on hydrodynamics of the sea. In Figs. 4 and 5 the monthly model output for the surface layer is shown for the
15 different model variables (temperature, salinity, phytoplankton and nutrient). Figure 5a shows the map of nitrogen concentrations in different months while Fig. 5b presents corresponding chlorophyll concentrations calculated from the model It shows that the simulated spring bloom begins in the Skagerrak-Kattegat area earlier than in the Baltic Proper. When the spring bloom starts at temperatures above 4° C (Fig. 4a) in the Baltic
20 Proper it firstly develops in the coastal zone and southern part and then it is spread

northwards. In late spring/early summer the spring bloom starts in the Gulf of Finland and Bothnian Sea and finally it reaches the Bothnian Bay. In the second part of year, in September and October, blooms of smaller intensity appears throughout the Baltic, but in the northern regions and coastal zone of the sea they are higher than in the southern Baltic Sea.

Following the annual nutrient dynamics (Fig. 5a), the season begins with high total inorganic nitrogen concentrations in the whole column water. As the spring starts the nutrient is consumed. The phytoplankton prefers ammonia to nitrate, so as long as ammonia is available, ammonia is consumed. As soon as the ammonia pool in the surface layer is emptied, the phytoplankton turns towards the nitrate for assimilation. It is also noticeable that when the spring bloom has started, and the total inorganic nitrogen concentrations turn low, the bloom is maintained by the external supply of inorganic nitrogen. At the end of June, when the system is depleted of nitrate, the nitrogen fixation starts and phosphorus pool is regained, it is not included in this model. However, winds are strong enough in September to replenish the full water column with abundant nutrients. In the autumn, there is a slightly rise in the phytoplankton biomass. This is caused by the increase in nutrient concentrations resulting from the deeper mixing of the water. However, the growing season terminates in December, when the phytoplankton biomass dropped to the January-February level.

3.2 Comparison of measurements with model results

The modelled values were compared with those measured at the surface layer for temperature and chlorophyll-*a* concentration in the southern Baltic Sea for five years (2000–2004). The calculated mean value errors are in the southern region of Baltic Sea of ca. 1.4° C for temperature and ca. 2.5 mg Chl m^{-3} for chlorophyll concentration.

Figure 6a present results of the validation of model for sea surface temperature. The figure compares the modelled values of this temperature (T_{mod} – the value from the first layer – 5 m) with values measured in situ (T_{exp} – the mean value from 0–5 m layer) at particular measurement stations. The calculated mean error is in the southern region

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

of Baltic Sea of ca. 1.4° C. As far as diagnosing the state of the Baltic ecosystem is concerned, this level of accuracy is satisfied because the model state parameters are calculated for the whole cell (an area of $9 \times 9 \, km^2$) not for the particular points at sea where in situ measurements were performed.

The analysis of the modelled surface concentration of chlorophyll-a Chl_{mod} (value for the first of 5 m layer) was carried out jointly for the entire experimental material, i.e. for 196 points from the southern region of Baltic Sea (measurements data are available in our institute database). In order to guess the errors for all data in the sets of empirical material, validation was performed. The results of the error analysis are presented on the Fig. 6b. One reason for these errors is that the CEMBSv1 model only accounts for a fixed C:Chl ratio of 50:1. In reality, the biomass during the secondary bloom is usually high, while the chlorophyll content in the cells is low. To fully take into account this effect, it should be necessary to introduce a variable C:Chl ratio in the model. Second reason is that in this 3-D model, phytoplankton is represented by one state variable and the model formulations are based on a simple total inorganic nitrogen ($NO_3 + NO_2 + NH_4$) cycle. Another reason is that the model calculates the surface concentration of chlorophyll-a of a whole pixel (an area of $9 \times 9 \, km^2$), and not that of particular point at sea where in situ measurement was made. This effect is reduced by increasing the horizontally and vertically resolution, which will be the next obvious step in the near future model development in addition to the improvement of the mixing parameterisation.

3.3 Long term variability

The calculations were carried out assuming the following three scenarios following ECOOP Project (ECOOP Annual Report Part I, p. 141, http://www.ecoop.eu/ecoop_docs.php). All scenarios are based on A1B IPCC (Intergovernmental Panel on Climate Change) climate scenarios. It assumes average emission of the CO_2, where averaged were two extreme scenarios (A1 – mostly pessimistic and B1 – mostly optimistic, http://www.ipcc-data.org/ddc_co2.html). The three scenarios involved changing linearly the

anomalies of air temperature, wind speed and shortwave radiation until, after 45 yr they reach the following values:

1. Air temperature increased by 3 degrees;

2. Air temperature increased by 3 degrees, wind speed increased by 30% and short wave radiation increased by 20%;

3. Air temperature increased by 3 degrees, wind speed increased by 30% and short wave radiation decreased by 20%.

The assumed increase of the temperature during next 45 yr is in the upper range of the IPCC predictions (IPCC, 2007) but it has been chosen to cover all the possible temperature change zone. The second scenario involves continuation of the decrease trend in aerosol optical depth and cloudiness over Europe (Philipona et al., 2009) and therefore over the Baltic area. This would have to imply further decrease of atmospheric pollution and may be difficult to achieve. Therefore the third scenario assumes decrease in shortwave radiation to cover all the possible range of irradiance change.

Both the second and third scenarios assume increase in wind speeds (and therefore storminess) over the Baltic. This assumption is caused by the widely predicted change in the average winter North Atlantic Oscillation (NAO) index values. NAO is the index of zonal atmospheric circulation in the mid-latitudes. It controls the winter storm tracks, temperatures and precipitation over the North Europe (Hurrell, 1995). More specificiely, it is highly correlated to the Baltic mean winter sea level (Andersson, 2002). Because NAO controls not only the zonal circulations but also storm tracks. However, its influence over the storminess over the Baltic area is not uniform, namely weaker in the North (Bärring and von Storch, 2004) and stronger in the South (Różyński, 2010). However for simplicity we have assumed uniform increase in wind speed over the whole Baltic. This increase is consistent with the predicted increase of NAO and other zonal indices over the North Hemisphere over the next decades (Yin, 2005; Miller et al., 2006; IPCC, 2007). A word of causion is needed here because

recently, after the record low values of NAO during the winter of 2009/10 (e.g. Cattiaux et al., 2010) this future increase of the zonal indices has been questioned (Francis et al., 2009; Overland and Wang, 2010).

Daily, biweekly, monthly, seasonal and annual variability of investigated variables were calculated for the 45 yr (1, 2 and 3 scenarios). The starting-point of the numerical simulations was assumed to be the end of 2004 with the continue repeating of all ERA 40 yr. For the repeated forcing data the three scenarios were performed.

We have chosen nine locations within our domain to present phytoplankton biomasses. These stations are: Gulf of Gdańsk, Gdańsk Deep, Gotland Deep, Bornholm Deep, Gulf of Finland, Gulf of Riga, Gulf of Bothnian, Bothnian Sea, Danish Straits and are shown on Fig. 7.

Based on these scenarios, the long-term variabilities of temperature, phytoplankton and nutrient in different areas of the Baltic Sea are calculated for 45 yr.

Taking into account earlier assumptions given for three scenarios, the distributions of one year of the maximum sea surface temperature T_{max} (Fig. 8) at selected stations we got the same shapes for all of scenarios; this means that the maxima and minima of temperatures appear in this same time. The calculations also shows that differences in T_{max} between 1, 2 and 3 scenarios for the first 20 yr are insignificantly and the distributions of T_{max} are very similar in each scenario. In first scenario, small average increasing (ca. 0.8° C) of T_{max} for whole region of the Baltic Sea for investigated period is observed. Increasing of T_{max} from 22.08° C (in the first year) to 24.12° C (after 45 yr) in case 2 and decreasing T_{max} to 19.91° C (after 45 yr) in case 3 are evident. A difference in T_{max} between these cases is ca. 2° C. Comparing to case 1, increasing and decreasing of T_{max} is ca. 1.3° C and 3° C in case 2 and 3, respectively. It is an influence of the short wave radiation which compensates changes in temperature. As well as the results of numerical investigations demonstrate that an increasing of wind speed and western component of wind speed, cause a higher drop in T_{max} in case 3 than rise in case 2 (20% decreased and increased short wave radiation, respectively).

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Time series of the one year averaged $Phyt_{ave}$ and year maximum $Phyt_{max}$ of phytoplankton biomass at selected stations are shown on Figs. 9 and 10. Comparing the $Phyt_{ave}$ and $Phyt_{max}$ of phytoplankton biomass for subsurface layer proved that differences between results of 2 and 3 scenario in $Phyt_{ave}$ and $Phyt_{max}$ are slight. It means that short wave radiation has negligible influence on the distribution of phytoplankton biomass. As well as, the numerical results indicate that in the gulfs (Gulf of Gdańsk, Finland, Riga and Bothnia) distributions of $Phyt_{ave}$ and $Phyt_{max}$ for three scenarios differ little. Taking into account the other investigated regions such as Gdask Deep, Gotland Deep, Bornholm Deep, Bothnia Sea and Danish Straits, the differences in $Phyt_{ave}$ and $Phyt_{max}$ between 1 and 2 (or 3) scenarios are evident. They are higher in cases 2 and 3 than in the case 1, i.e. for $Phyt_{ave}$, ones are ca. $10\,\mathrm{mg\,C\,m}^{-3}$ and $Phyt_{max}$ are from 100 to $250\,\mathrm{mg\,C\,m}^{-3}$. It coresponds to the depth of the regions and for Bornholm Deep $Phyt_{max}$ increases by 20% (ca. $100\,\mathrm{mg\,C\,m}^{-3}$) and Gotland Deep – 50% (ca. $250\,\mathrm{mg\,C\,m}^{-3}$).

The results show significant changes in phytoplankton biomass Phyt distributions, which take place in areas (open sea), where there is a considerable increasing in currents. With the parameter values in scenarios 2 and 3, for increasing turbulence (mixing) (30% increased wind speed and western component of wind speed), the results demonstrate an increasing in distributions of phytoplankton biomass. It is the result of the rise in nutrient concentration Nutr (Fig. 11) in the upper layer caused by the increasing of the wind speed, i.e. by mixing deep. The phytoplankton biomass reflects the availability of nutrients, showing a strong increasing with rising total inorganic nitrogen concentration. It shows that increasing of the wind speed causes an increasing influence of the currents on the Nutr which in turn influence on Phyt distributions. This is evident in the regions of open sea and Gulf of Gdańsk, where an increasing of the currents is observed.

Increasing in primary production and phytoplankton biomass cause increasing in zooplankton biomass and pelagic detritus concentration. In consequence it cause increasing of the biomass of zooplankton consumed i.e. by fishes. Excess of the

produced organic matter, which sinks on the bottom, is mineralized. It causes loss of oxygen in the bottom layer. In other way, excess of the primary production contributes to appearance the complete oxygen depletion in the benthic waters leading to the occurrence of hydrogen sulfide.

Our study demonstrates that ecosystem models have the potential for analyzing distribution and dynamics of primary production. It could also produce a quantitative, regional description and assess variations of the organic and inorganic matter in the sea water. The temporal resolution produced by the model cannot be achieved by field observations, so the model provides a useful tool for the interpretation of physical and biogeochemical variables and a valuable supplementation for field studies. The estimation of primary production (phytoplankton biomass) is one of the most important aim in marine ecology, elucidating the amount of energy, which is transferred within communities and ecosystems and provided for higher trophic levels.

4 Conclusions

The results of the numerical simulations are consistent with in situ observations for temperature and chlorophyll-*a* for five years (2000–2004). Differences between the modelled and mean observed phytoplankton biomasses are not small in the subsurface layer and the difference depend on the month and place where the calculations have been made. They also depend on the C/Chl-*a* ratio for converting simulated carbon contents to chlorophyll-*a*, which is assumed as constant for the whole Baltic.

For reduction of discrepancies between simulated and observed results for future improvements in this model should include additionally state variables for a few groups of phytoplankton assuming the floating C/Chl-*a* ratio, including nutrients – not only for nitrogen but also phosphate and silicate as well as zooplankton and pelagic detritus.

The results of the numerical simulations for long-term variability for the different areas of Baltic Sea were presented for the 45 yr. The simulations show a general variation in investigated distributions in time. The results present significant changes in

phytoplankton biomass distributions, which took place in the regions where were a significant increasing in currents (up to $100\,\mathrm{cm\,s^{-1}}$). This rise was caused by increased nutrient concentration which is driven by wind speed here. The calculations also show influence of short wave radiation on temperature in the sea. The fact that the wind
5 speed turned out to be more important than both temperature and irradiance values means that the future changes in the modelled parameters will depend on the still uncertain future trajectory of NAO index changes (see Overland and Wang, 2010 for a discussion of possible influence of Arctic Ocean sea-ice loss on weakening of the zonal indices).
10 Currently we are developing the 3-D Coupled Ecosystem Model of Baltic Sea (to next version of CEMBS), which consists of three groups of phytoplankton ("diatoms", "flagellates and others" and "cyanobacteria"), zooplankton, nutrients (such as PO_4, NO_3, NH_4 and SiO_4), and pelagic detritus for two classes (small and large). The next step in our modeling work is to increase horizontal and vertical resolution. We also are
15 going to run the ecosystem model (version 2) to study the impact of climate changes on the development of the biogeochemical variables in the Baltic Sea.

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Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.

Printer-friendly Version

Interactive Discussion

Table 1. Parameterisation of the CEMBSv1 3-D model.

F_S	Mathematical formulation
primary production	$PRP = f_{max} f_I f_N$ Phyt $\\$ $f_I = \frac{I_{PAR}}{I_{opt}} \exp\left(1 - \frac{I_{PAR}}{I_{opt}}\right)$ $\\$ $I_{PAR} = I_0 \exp(-kz)$, $k = 0.17 + 25(\text{Phyt} \times 10^{-3}/g_{Chl})$, $\\$ $g_{Chl} = gC/gChl = 50/1$ (*), $I_{opt} = 60\,W\,m^{-2}$, $f_{max} = 1.5\,day^{-1}$ $\\$ $f_N = \frac{\text{Nutr N}}{K_N + \text{Nutr N}}$; $K_N = 0.18\,mmol\,N\,m^{-3}$,
zooplankton grazing	$GRZ = g_{max} \frac{\text{Phyt} - \text{Phyt}_0}{k_{Phyt} + \text{Phyt} - \text{Phyt}_0} \text{Zoop}$ $\\$ $g_{max} = 0.3\,day^{-1}$, $k_{Phyt} = 100\,mg\,C\,m^{-3}$, $\\$ $\text{Phyt}_0 = 10\,mg\,C\,m^{-3}$
mortality of phytoplankton	$MORP = mp\,\text{Phyt}$, $mp = 0.05\,day^{-1}$,
respiration of phytoplankton	$RESP = f_{max}(r_{PR} f_I f_N + r_{BR}) f_T$ Phyt $\\$ $r_{PR} = 0.05$, $r_{BR} = 0.1$, $f_T = \exp(0.0769(T - 10))$
faecal pellets	$FEC = f\,GRZ$
excretion of zooplankton	$EXCZ = ez\,GRZ$
mortality of zooplankton	$MORZ = mz\,GRZ$, $f = 0.33$, $ez = 0.33$, $mz = 0.3$
predation by another zooplankton	$PRED = p_{max} \frac{\text{Zoop}}{k_z + \text{Zoop}} \text{Zoop}$ $p_{max} = 0.1\,day^{-1}$, $k_z = 1\,mg\,C\,m^{-3}$
phytoplankton uptake release	$UPT = PRP - RESP_{light}$ $\\$ $RELE = RESP_{dark}$
benthic regeneration	$REGD = g_N r_D$ Detr, $g_N = 0.013$ (mmol N(mg C)$^{-1}$)

* Carbon-to-chlorophyll-*a* ration in phytoplankton.

Climate influence on Baltic phytoplankton

L. Dzierzbicka-Głowacka et al.
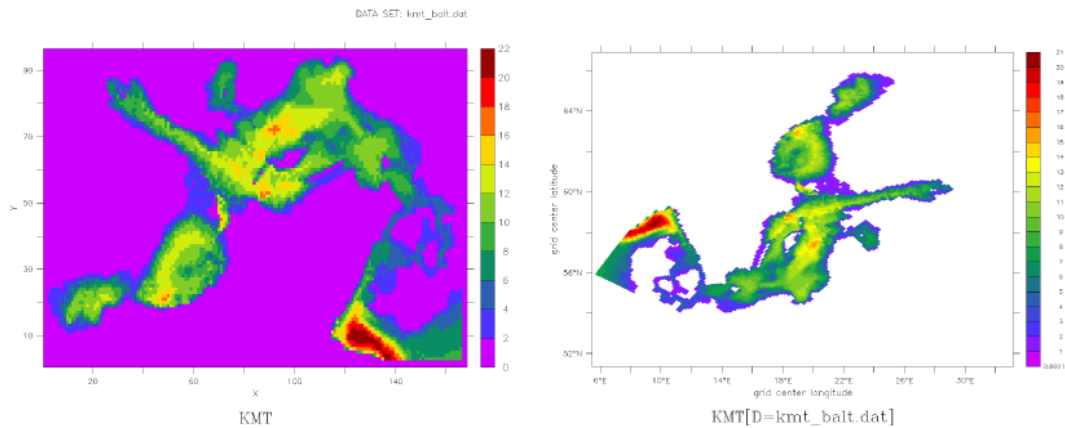
Fig. 1. Model domain and bathymetry (model coordinates – left panel, stereographic coordinates – right panel). Color scale represents model levels (not depth).
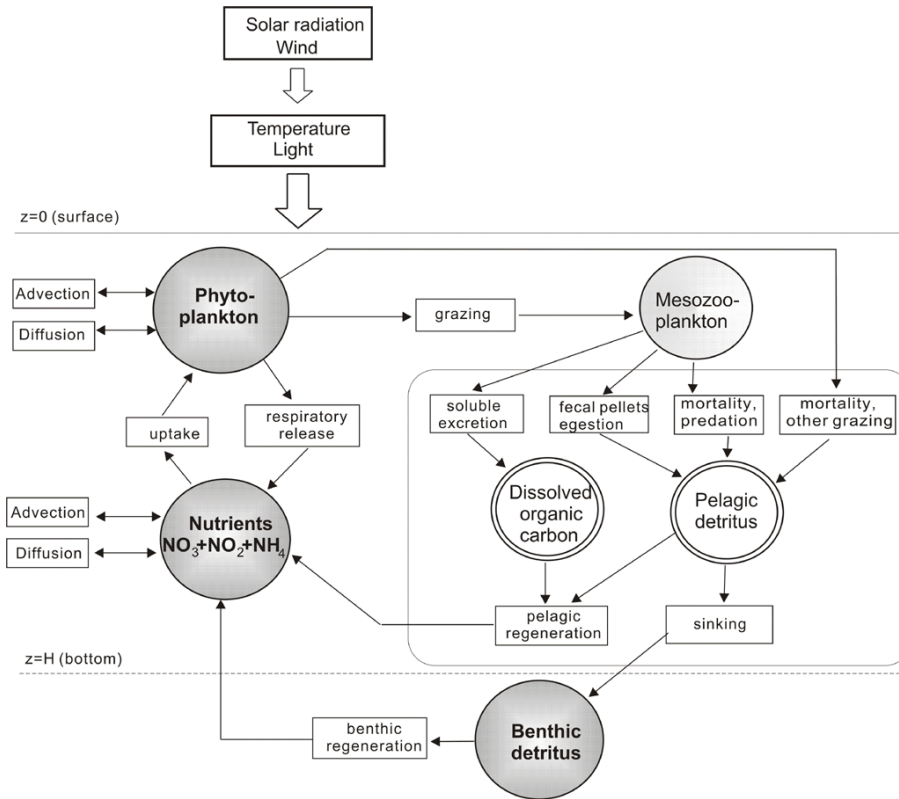
Fig. 2. Schematic diagram of the CEMSv1 processes.
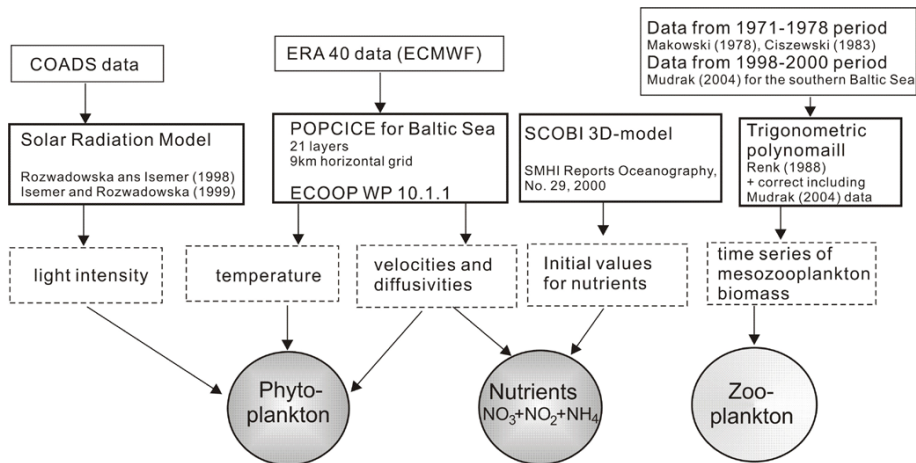
Fig. 3. Schematic diagram of the forcing data and related state variables in the model.
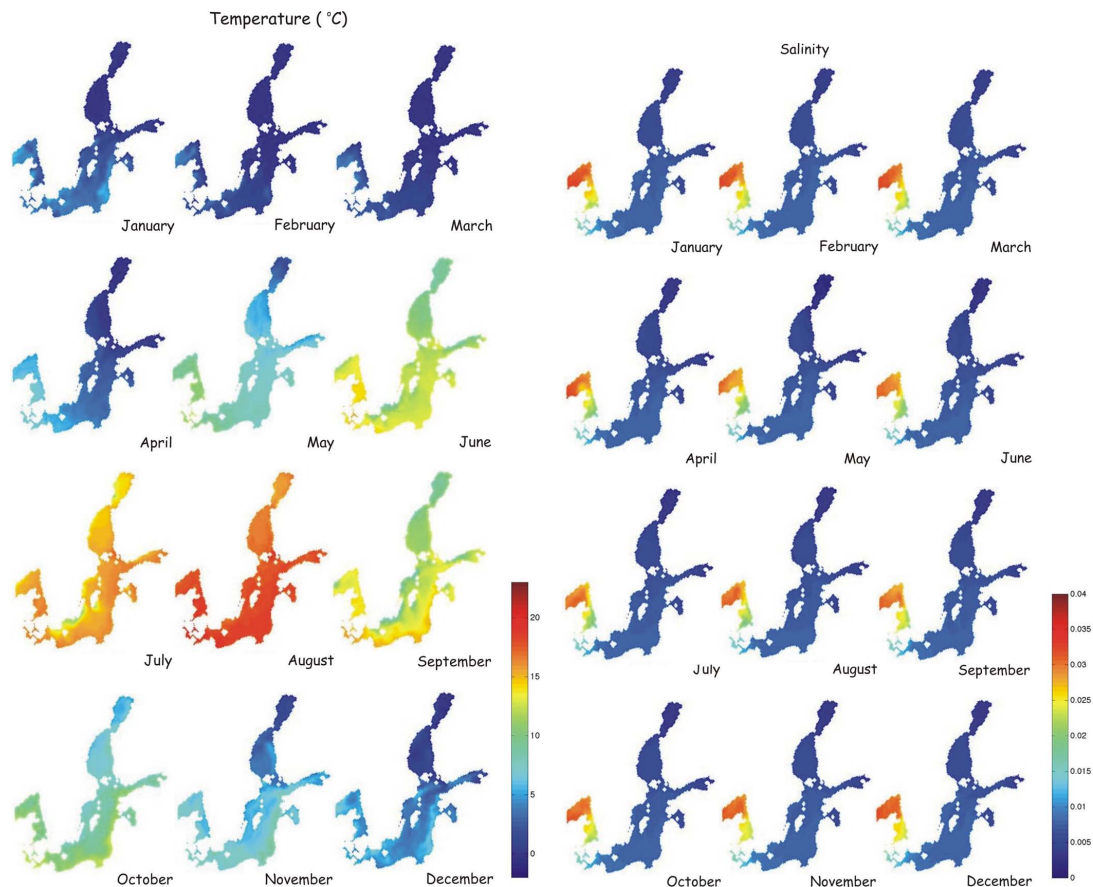
Fig. 4. Monthly averaged temperature (°C) and salinity for the surface layer during January–December 2004.
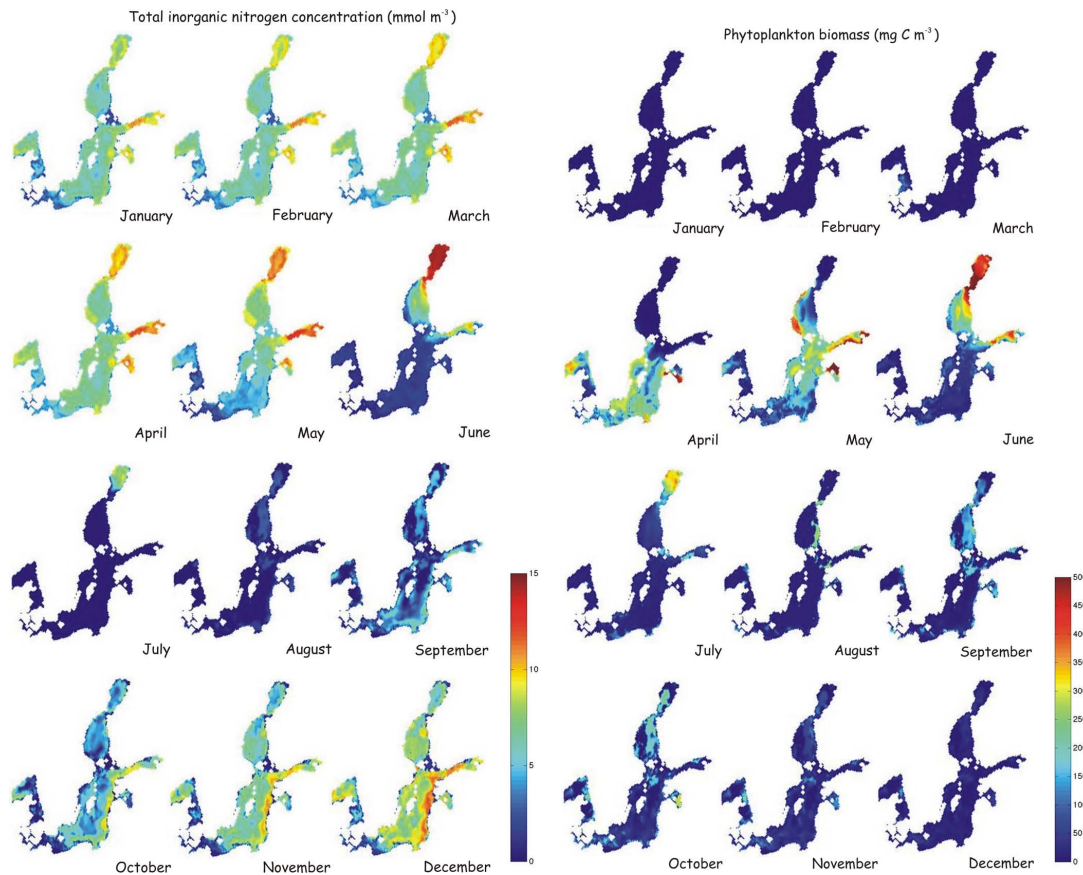
Fig. 5. Monthly averaged total inorganic nitrogen concentration (mmol m^{-3}) and phytoplankton biomass (mg C m^{-3}) for the surface layer during January–December 2004.
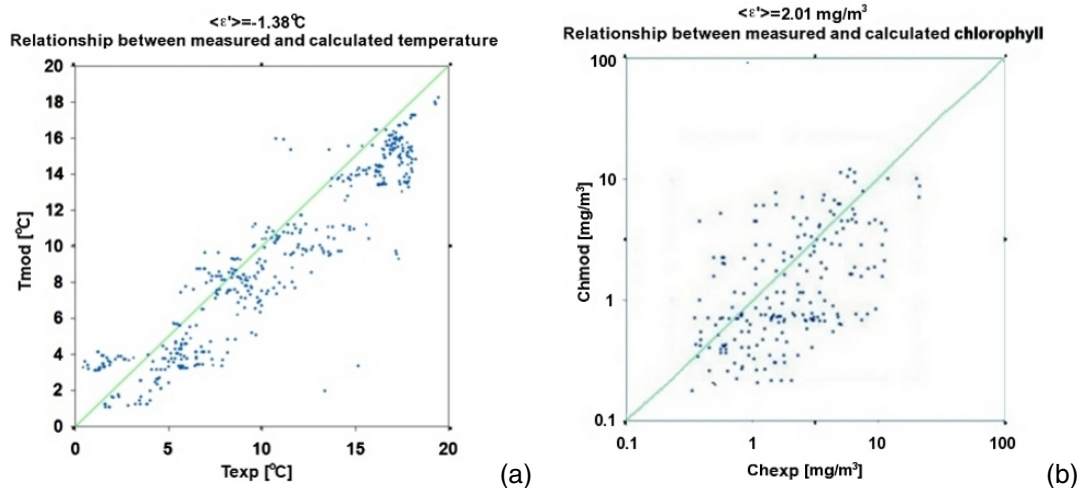
Fig. 6. Comparison of the sea surface temperatures **(a)** and surface chlorophyll-*a* concentrations **(b)**: measured (T_{exp}, CH_{exp}) and calculated (T_{mod}, CH_{mod}) from CEMBSv1 model.
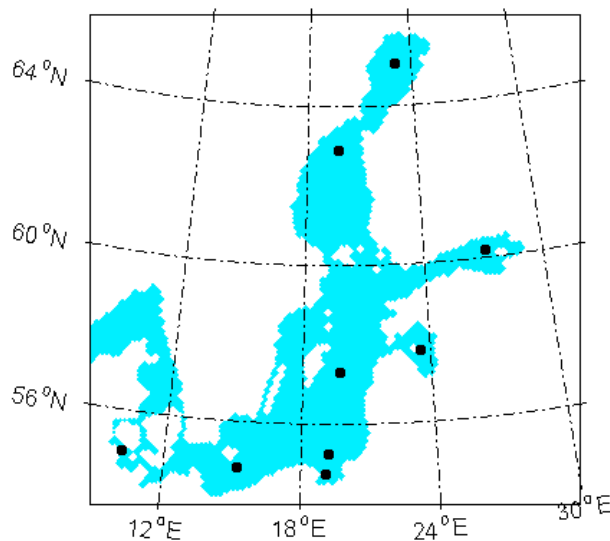
Fig. 7. The locations within model domain to present modeled results.
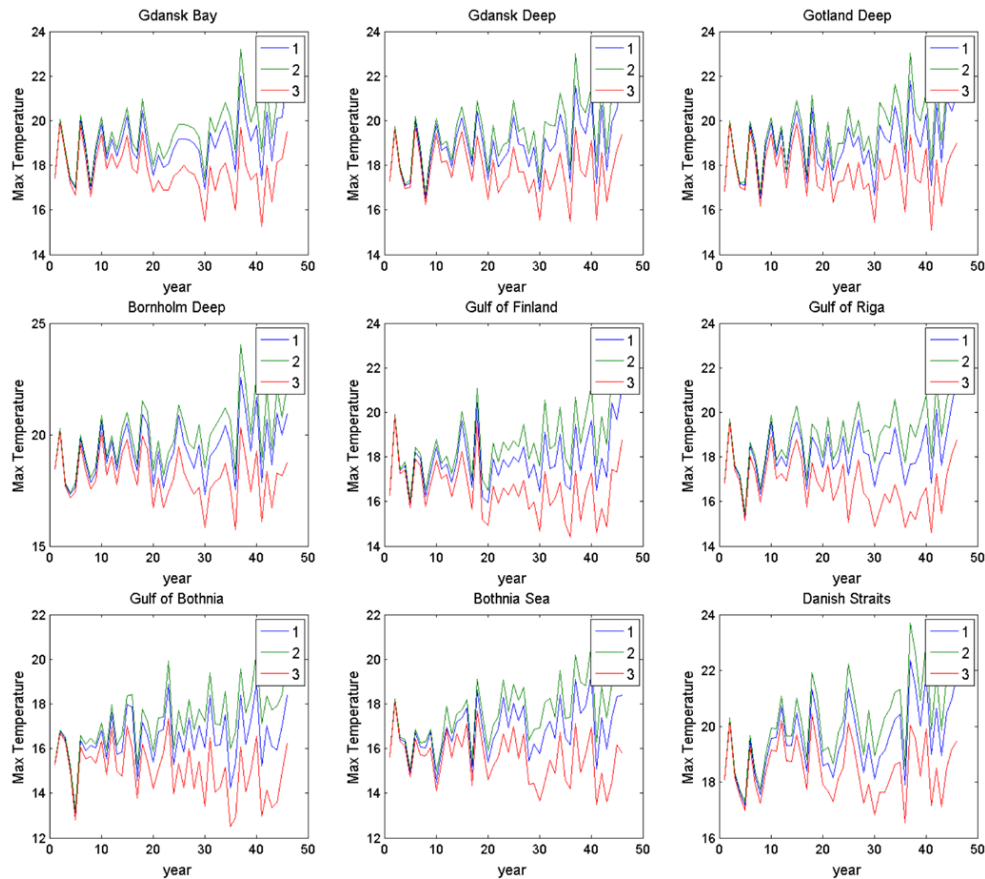
Fig. 8. One year maximum of the sea surface temperature (SST) (°C) at selected stations.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

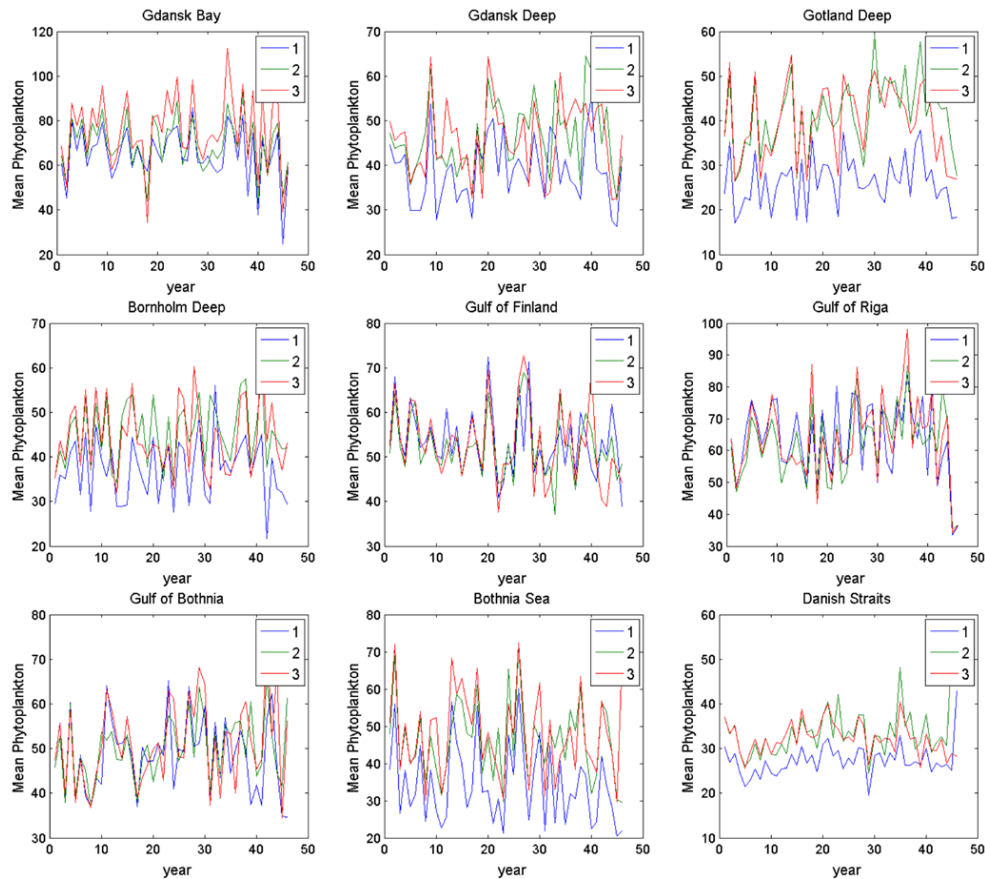Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 9. One year averaged phytoplankton biomass ($mg\,C\,m^{-3}$) of the surface layer at selected stations.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version
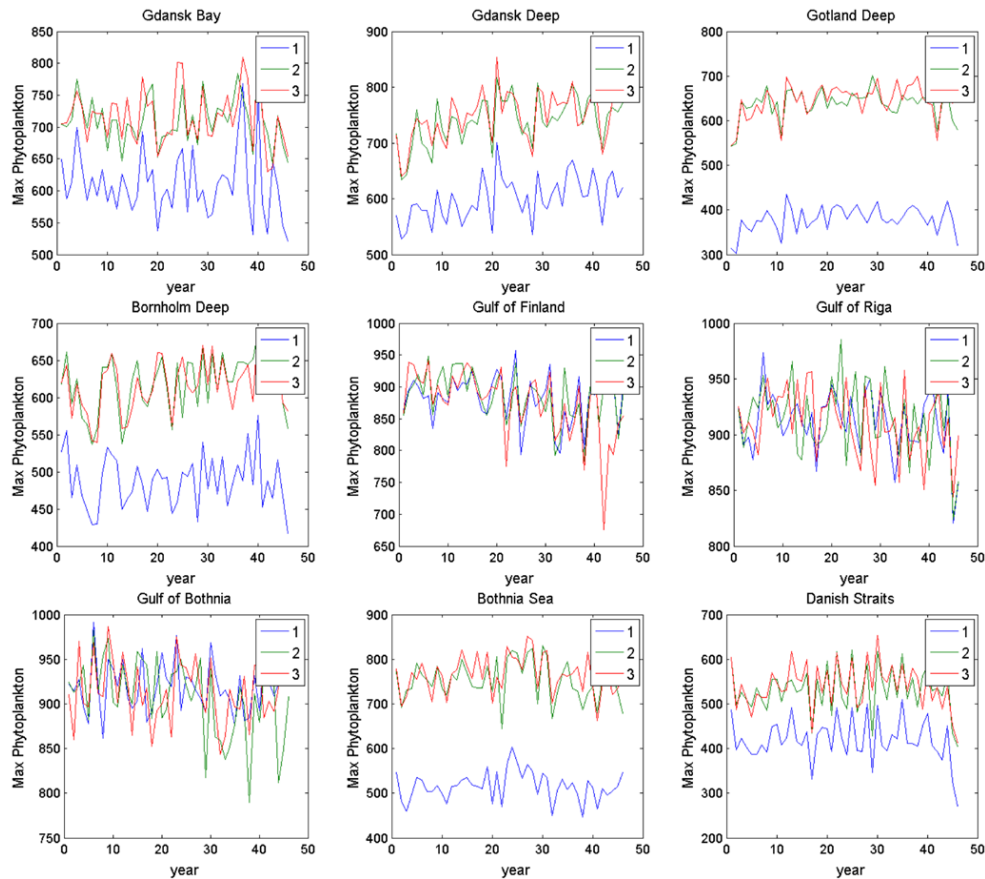
Interactive Discussion

Fig. 10. One year maximum of phytoplankton biomass (mg C m^{-3}) of the surface layer at selected stations.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

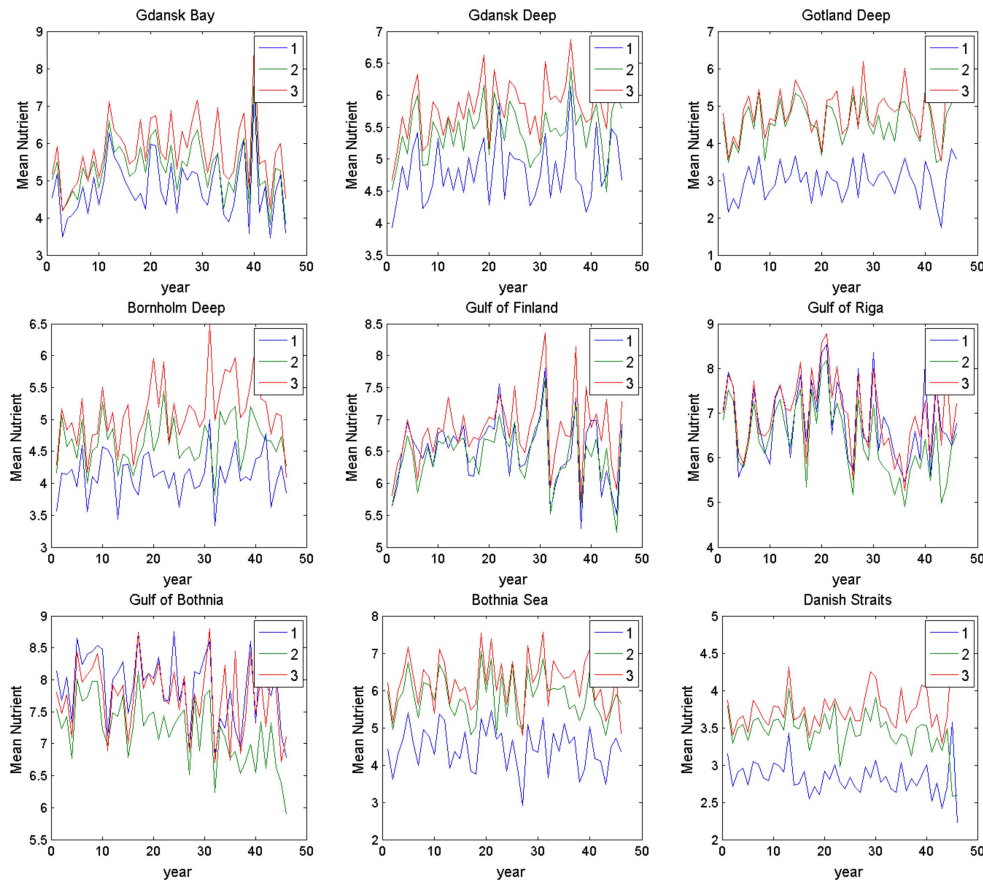Printer-friendly Version

Interactive Discussion

Fig. 11. One year averaged of total inorganic nitrogen concentration (mmol N m^{-3}) of the surface layer at selected stations.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion