Eutrophication in the Baltic Sea and shifts in nitrogen fixation analyzed with a 3D ecosystem model

THOMAS NEUMANN and GERALD SCHERNEWSKI
Baltic Sea Research Institute Warnemünde
Seestr. 15, 18119 Rostock, Germany
thomas.neumann@io-warnemuende.de

Abstract

Since the middle of the last century the Baltic Sea ecosystem has undergone a strong change. An obvious indicator is the increase of winter nutrient concentrations. This increase is attributed to increased anthropogenic nutrient loads to the Baltic Sea.

With a 3D ecosystem model we made a hindcast simulation of eutrophication from 1960 to 2000. The model system was able to reproduce the main hydrographic and ecologic features of this period. However, the observed strong increase in winter nutrient concentrations was underestimated by the model.

The simulated nitrogen fixation shows a pronounced interdecadal variability. Nitrogen fixation increased in the early 1990 at the same time nutrient loads to the Baltic Sea were decreasing. The changes in nutrient loads cannot fully explain the increased nitrogen fixation; in fact, the primary trigger for this increase is an intensified wind speed in winter, which is correlated with changes in the North Atlantic oscillation (NAO).

1 Introduction

The Baltic Sea is one of the largest brackish water ecosystems in the world. During the last 50 years, the time span of regular observations, the system obviously has changed (e.g. Larsson et al., 1985; Sanden and Rahm, 1993; Omstedt et al., 2004). Previous studies have documented an increase in winter phosphate and nitrate concentrations in sea surface waters (which, in turn, yields an increase in net primary production) between 1965 and 1985 (e.g. Nehring and Matthäus, 1991). Understanding the complex interrelations of changes is an indispensable prerequisite for any prediction of possible future changes. Now we have the opportunity to build model systems that can provide predictive capabilities. Long-term observations serve as a sound basis for model validation and calibration. The understanding of single processes and even more complex
subsystems have reached a level which allows formulating the basic processes of the ecosystem in a quantitative mathematical form. Homogeneous atmospheric forcing data are available from about 1960 (Uppala et al., 2005), and runoff and load data can be compiled from several sources (e.g. Schernewski and Neumann, 2005).

In this paper we present a 40 years hindcast simulation of the Baltic Sea ecosystem with our 3D ecosystem model. The discussion is focused on interdecadal variability of nitrogen fixation.

2 The ecosystem model

As a starting point, we use the model system described in Neumann et al. (2002). This model has been successfully applied to 15-year time slices to explore different nutrient load scenarios (Neumann and Schernewski, 2005).

Fig. 1 shows the model topography with some geographic notations to which we refer later in the text.

The biogeochemical model consists of nine state variables. The nutrient state vari-
ables are dissolved ammonium, nitrate, and phosphate. Primary production is provided by three functional phytoplankton groups: large cells, small cells, and cyanobacteria. Large cells grow rapidly in nutrient-rich conditions, while small cells have an advantage at lower nutrient concentrations, especially during summer conditions. The cyanobacteria are able to fix and utilize atmospheric dinitrogen and therefore the model assumes that phosphate is the only limiting nutrient for cyanobacteria. Owing to their ability to fix nitrogen, cyanobacteria are a nitrogen source for the system. A dynamically developing bulk zooplankton variable provides grazing pressure on the phytoplankton. Dead particles are accumulated in a detritus state variable. The detritus is mineralized into dissolved ammonium and phosphate during the sedimentation process. A certain amount of the detritus reaches the bottom, where it accumulates in the sedimentary detritus. Detritus in the sediment is either buried in the sediment, mineralized, or re-suspended into the water column, depending on the velocity of near-bottom currents. The development of oxygen in the model is coupled to the biogeochemical processes via stoichiometric ratios. The oxygen concentration controls processes such as denitrification and nitrification. A detailed description of the model can be found in Neumann (2000) and Neumann et al. (2002).

Long-term simulations require a more sophisticated description of processes with longer time scales, particularly processes connected with physical transport and sediments. In the model version of Neumann et al. (2002) we do not consider iron-oxide-related fate of phosphate. In the revised version, we allow phosphate in the sediment layer to bind iron-oxide under oxic conditions. These complexes form particles which sink out and accumulate in the sediment layer. Erosion events can re-suspend phosphate-rich particles and currents transport them toward the deposition areas. Under anoxic conditions, iron-oxide becomes reduced and phosphate is liberated and available as dissolved phosphate. These processes are implemented in this model version for long-term studies. Furthermore, we have taken into account the effect of bioturbation. In an oxygenated environment, benthic animals populate the sediment. Their activity reduces the cohesive forces in the sediment and injects sedimentary material into the water column and, hence, contributes to re-suspension.

The effects of model extensions are illustrated in Fig. 2. Clearly can be seen the improvement of phosphate dynamics in the Eastern Gotland Sea (EGS).

3 Nutrient loads and atmospheric forcing

We attributed riverine loads into the Baltic Sea to the 20 most important rivers. The load of all smaller rivers, point sources, and diffusive loads has been calculated for 9 regions and we have assumed an evenly distributed diffuse entry of these loads into the coastal waters of every region. In the model this is implemented by according an atmospheric nutrient flux to each grid point of the coast line. Load data are based on HELCOM reports and catchment simulations. For atmospheric forcing, we used data from the ERA40 project (Uppala et al., 2005) and atmospheric loads are derived again

3
Figure 2: Simulated and observed dissolved inorganic phosphorus (DIP) in the central Eastern Gotland Sea. The solid line is a simulation with iron-phosphate and bioturbation, the dashed line is from a simulation with a model without these extensions and the dotted line refers to observations. a) surface; b) near bottom (235 m)
Figure 3: Comparison of simulated data to observed data from the Eastern Gotland Sea. The parameters are temperature (T), salinity (S), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). s and b indicate surface and bottom values, respectively. Observations are represented by 1 at the x axis.

from HELCOM reports.

4 Model performance

In this section we will briefly present a few aspects how the model is able to reproduce the long-term variability of the Baltic Sea ecosystem. We have summarized the models strengths for the EGS station in a Taylor diagram (Taylor, 2001) shown in Fig. 3. The model performs quite well, however simulated variability is less and DIN in deep water is an outlier due to inflow dynamics which we will show below.

As an example for the oxygen dynamics we show a time series from the EGS in Fig. 4. Since the general tendency agrees, consequences of a missed inflow in 1976, which in the model did not reach the deep water, become obvious. The stagnation period starts in the model already in the mid 1970. Another divergence from the observations is the weaker vertical gradient in the simulated oxygen distribution. In Fig. 5
Figure 4: Oxygen time series from the central Eastern Gotland Sea. Observations are shown in the upper panel and simulated oxygen in the lower panel. Shaded areas indicate hydrogen sulfide counted as negative oxygen equivalents.
we show winter nutrient concentrations at different stations in the surface water. In particular we consider dissolved inorganic nitrogen (DIN: ammonium and nitrate) and phosphate. Fig. 5 gives examples for central regions, the Bornholm Sea and the Gotland Sea. In general the simulated nutrient concentrations follow the eutrophication trend with a considerable increase in the 1970. However, compared to observations, the simulated increase is less pronounced. This is reflected in the lesser variability represented in Fig. 3, while the correlation is quite reasonable. In general the model system is able to reproduce interannual and decadal variability of the physical and biogeochemical variables. The latter tend to show less variability than the physical variables compared to the observations. On a decadal time scale, the model reproduces stagnation periods and periods with frequent saltwater inflows. However, single events, in particular in the deep water of the central Baltic Sea, are under- or overestimated by the model.

The observed increase of winter nutrient concentrations during the eutrophication period is underestimated by the model; nevertheless the tendency of a concentration
increase is reproduced. There are several possible explanations for the discrepancies. We cannot be sure that all important, so-called first-order processes are included in the model. Furthermore, parameterizations for the unresolved processes may not be suitable. On the other hand, observations also have weaknesses as shown in Voss et al. (2005). A further uncertainty comes from forcing data and especially from nutrient load data.

5 Nitrogen fixation

Nitrogen fixation is a substantial internal source for nitrogen in the Baltic Sea. Reported fixation rates range up to 318 mmol m$^{-2}$ year$^{-1}$, which corresponds to 1000 kt year$^{-1}$ (e.g. Rolff et al., 2007). This almost is in the order of riverine nitrogen loads and atmospheric deposition. In this section we will discuss nitrogen fixation estimates from our ecosystem model.

The average nitrogen fixation pattern is shown in Fig. 6. We found the highest rates in the western part of the Gulf of Finland (GoF). Another region with elevated fixation rates is around the Island Gotland and at the Middle Bank. Wasmund et al. (2001) reviewed literature and found fixation rate estimates from 1 to 263 mmol m$^{-2}$ year$^{-1}$. From a carbon dioxide budget approach, Schneider et al. (2003) estimated a fixation rate of 318 mmol m$^{-2}$ year$^{-1}$, which amounts to about 1000 kt nitrogen per year. Referring to observation-based estimates, our simulated rates are in a reasonable range. The lower panel of Fig. 6 shows the time evolution of nitrogen fixation. From the beginning of the simulation until 1990, nitrogen fixation shows a downward trend from about 400 kt year$^{-1}$ to about 200 kt year$^{-1}$. Between 1988 and 1992 nitrogen fixation rapidly increased to about 700 kt year$^{-1}$. A hint at increased nitrogen fixation in the 1990 is given in Kahru et al. (2007).

The slight decreasing trend in the 1970 and 1980 can be explained with increasing nutrient loads. Nutrient loads to the Baltic Sea deliver excess nitrogen to the system, which reduces nitrogen fixation. The relation between reduced nutrient loads and increased nitrogen fixation and vice versa has been demonstrated in Neumann et al. (2002) and Neumann and Schernewski (2005).

At the same time nitrogen fixation levels rapidly increased (starting about 1990) nutrient loads decreased. To determine whether decreased nutrient loading was the mechanism behind increased nitrogen fixation, we reran the model starting in 1987 with riverine, atmospheric, and point and diffusive source nutrient loads constant at 1987 levels. This was termed the "high load experiment". The annual nitrogen fixation in the high load experiment was approximately 200 kt less than in the control experiment. However, nitrogen fixation has more than doubled between 1988 and 1992 (Fig. 7). Consequently, the nitrogen fixation increase cannot be explained by decreasing nutrient loads alone; hence, internal dynamics or meteorological forcing must have contributed to the shift in nitrogen fixation. From the simulation data we did not find any hints of internal dynamics; neither the pool of phosphorus stored in sediments
Figure 6: Nitrogen fixation rate averaged over the entire study period (upper panel) and horizontally integrated nitrogen fixation (lower panel).
Figure 7: Annual nitrogen fixation in the control experiment (solid line) and the high load experiment, wherein, nutrient loads were held at 1987 levels (dashed line).
nor the pools of phosphorus and nitrogen in the water column changed significantly. Therefore, we conclude that it is most likely that meteorological forcing has caused the increased nitrogen fixation. To highlight the cause-effect chain from the meteorological forcing to nitrogen fixation we applied an EOF (empirical orthogonal function) analysis to different data sets. All data used for the EOF analysis have been de-trended, weighted by area, and standardized by standard deviation. EOFs and principal components have been normalized that each EOF varies between $-1$ and $+1$. In Fig. 8a the first EOF of nitrogen fixation is shown. The corresponding principal components (lower panel) has the same time tendency as the nitrogen fixation in Fig. 6. This fact yields the conclusion that the EOF pattern shows the interdecadal variability. The most pronounced variability can be seen in the western part of the Baltic proper.

Excess phosphate is considered to play an important role for nitrogen fixation (e.g. Laamanen and Kuosa, 2005; Kahru et al., 2007) because the lack of oxidized nitrogen provides a competitive advantage to nitrogen fixing cyanobacteria. Usually excess phosphate is defined as the amount of phosphate which is in excess compared to dissolved inorganic nitrogen with respect to the Redfield ratio ($eP = DIP - \frac{DIN}{16}$). In the simulated data, we found (especially for the winter months January, February, and March) a signal in the surface excess phosphate corresponding to the interdecadal nitrogen fixation variability. The first EOF mode of the winter surface excess phosphate is shown in Fig. 8b. Pattern and time evolution are similar to the patterns of nitrogen fixation. Enrichment of the surface water with nutrients (especially excess phosphate) in winter is due to upwelling, convection, and vertical mixing. We diagnosed the vertical flux of nutrients through a horizontal cross section in 15 m depth. Fig. 8c shows the first EOF pattern of the vertical excess phosphate flux in winter. Again, the principal components change drastically at the beginning of the 1990. A positive sign in the pattern refers to an upward flux. The pattern suggests that the upward flux has increased in the western part and decreased in the eastern part. However, the horizontally integrated flux increases as well.

Westerly and southwesterly winds favor upwelling at the western coast and vertical mixing. Since westerly winds prevail in winter over the Baltic Sea, we hypothesized that the wind speed has changed. We analyzed the wind stress, which is the momentum entering the ocean, again with an EOF analysis. The first pattern (Fig. 8d), together with the principal components, also indicates a drastic change between 1988 and 1990, that is, the wind stress increased during this time. The North Atlantic oscillation (NAO) is to a large extent dominating the climate variability in northern Europe (e.g. Hurrell et al., 2003). In Fig. 8d the NAO winter index is shown as a red line. Clearly visible is the correlation between NAO and wind stress.

We can summarize the cause-effect chain as follows: An intensified winter NAO enhances the transport of cyclones towards the Baltic Sea area and, hence, wind speed intensifies. Increased wind stress promotes upwelling and deep mixing, which result in an enlarged upward transport of excess phosphate. This excess phosphate may partly remain in the surface layer or be caught in the intermediate winter water. During summer it becomes available for nitrogen fixing cyanobacteria due to, for example,
Figure 8: Most significant EOF and principal components of various oceanographic and meteorological data sets. The upper of each pair of panels shows the EOF pattern and the lower the respective principal components (bars). The black line is a running mean. All quantities are normalized and dimensionless. 

a) First EOF mode of nitrogen fixation (explained variance: 0.34). 
b) First EOF mode of winter excess phosphate in the surface water (explained variance: 0.23). 
c) First EOF mode of vertical excess phosphate flux in winter (explained variance: 0.29). Positive sign denotes an upward flux. 
d) First EOF mode of the winter wind stress (explained variance: 0.84). Red line shows the winter NAO index. Every higher EOF explains no more than 0.1 of the variance.
mixing or upwelling events. This relationship was first described by Janssen et al. (2004), albeit on a shorter time scale. However, from winter NAO to nitrogen fixation in summer several processes are involved, which modify available excess phosphate and cyanobacteria blooms. These are *inter alia* the concrete wind fields, vertical distribution of excess phosphate and meteorological conditions in summer. Consequently, high NAO index is a precondition for a strong cyanobacteria bloom, but the strength of the bloom may be modified by other processes too.

6 Conclusions and summary

In this study we have presented an ecosystem model of the Baltic Sea that was able to reproduce the eutrophication period of 1960 to 2000. An important step to reach this goal was the inclusion of sedimentary processes in the biogeochemical model of Neumann et al. (2002).

Hindcast simulations are test cases for models which should evolve a predictive capability. On the other hand, hindcast simulations can provide insight into the cause-effect chains of changes and variability of a systems state. This is important especially for marine systems which cannot be sampled sufficiently.

A prominent characteristic of the simulated ecosystem is the increased nitrogen fixation in about 1990. It occurs at the same time that regime shifts were detected in the Baltic and North Sea. Alheit et al. (2005) report about synchronous regime shifts in the North and Baltic Sea visible in almost all trophic levels of the ecosystem and relate the shifts to increased air and sea surface temperatures in winter as the driving forces caused by the NOA.

However, we found for nitrogen fixation that increased wind speed is the main driver of the shift. This highlights that not only temperature effects the ecosystem, in fact all external forcing has to be considered as potential drivers for ecosystem shifts. Here we want to note that the interdecadal variability of nitrogen fixation in the GoF is different from that in the Baltic proper, although it shows the highest fixation rate. Winter mixing and upwelling is not that important for cyanobacteria bloom dynamics in this area.

Interdecadal variability of nitrogen fixation can be attributed to changed nutrient loading and changes in meteorological forcing. Especially the wintertime wind speed has an important influence on the nitrogen fixation.

References


