

Influence of wintertime hydrographic conditions on cyanobacteria blooms in the Baltic

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ABSTRACT: The influence of wintertime hydrographic conditions on the inter-annual variability of late summer cyanobacteria (cb) blooms in the Baltic Sea is investigated. A simulation with the 3D ecosystem model ERGOM was carried out with realistic forcing. Further simulations were performed in order to separate the influence of wintertime nutrient conditions from the impact of weather conditions during the growth period. There is strong evidence that the late winter excess phosphorus (eDIP) concentration in the surface layer has a determining influence on late summer cb blooms. The amount of available eDIP in the surface layer is coupled to the wintertime hydrographic conditions by the mixed layer depth. Finally, the simulation results suggest an impact of the large scale wintertime atmospheric conditions, namely the North Atlantic Oscillation (NAO), on the occurrence of cb blooms in the Baltic Sea. For the first time consequences of NAO-related changes in the nutrient availability on the phytoplankton dynamics are outlined. It is hypothesised that the impact of the NAO is transferred by a cause-and-effect chain starting in winter and developing until late summer: high NAO-Index → high wind stress, low ice cover → high mixed layer depth → high surface layer eDIP concentration → (potentially) strong cb bloom and vice versa.

INTRODUCTION

Late summer blooms of diazotrophic, filamentous cb cause strong environmental concern because of both, their potential toxicity and their fertilising effect through increased nitrogen input. Cb blooms are a natural phenomenon in the Baltic Sea which have endured for some

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7,000 yr (*Bianchi et al.*, 2000). Yet, an increase in extent and intensity of cb blooms during the last decades is generally assumed and linked to anthropogenic eutrophication (e.g. *Niemi*, 1979). Trends in cb biomass are however not easily established due to the lack of basin wide long term in-situ observations suitable for the detection of cb blooms with pronounced patchiness and strong inter-annual variability. It is therefore a major task to quantify and explain the inter-annual variability including all spatial scales. *Kahru et al.*, 1994; *Kahru*, 1997 could quantify the inter-annual variability of cb bloom extent during the period 1982 to 1994 from satellite data. No overall increasing trend was found. Instead, two periods with high cb concentrations were detected (1982-1984, 1991-1994), interrupted by a period of almost vanishing concentrations (1985-1989).

There have been a couple of publications dealing with the factors favouring cb blooms in the Baltic Sea (e.g. *Niemi*, 1979; *Kononen*, 1992; *Sellner*, 1997; *Wasmund*, 1997). The variability of one or a combination of these factors causes the inter-annual variability of cb blooms and thus shall be shortly discussed. The spatial distribution of cb in the Baltic Sea is limited by a salinity range from 3.8 to 11.5 PSU (*Wasmund*, 1997). However, only in the transition area between Baltic Sea and Kattegat the salinity variability is strong enough to have a markedly influence on the cb distribution. High growth rates of cb are confined to water temperatures of 16 to 22°C (*Sellner*, 1997) and a global radiation exceeding a daily mean of 120 W m⁻² (*Wasmund*, 1997). Cb gain a competitive advantage from their ability to fix atmospheric nitrogen turning phosphorus into the only limiting nutrient. A low N:P ratio is therefore often assumed as favourable for cb blooms (*Niemi*, 1979). It is generally not sufficient to trigger a bloom but rather can be seen as prerequisite (*Wasmund*, 1997). After *Kononen*, 1992 the N:P ratio is one controlling factor on the time scale of years and space scale of sub-basins. The outcome of simulations with a numerical model for the Gulf of Finland (*Kiirikki et al.*, 2001) indicates that rather the amount of available excess phosphorus than the N:P ratio itself should be regarded as a controlling factor for cb blooms. In conclusion, water temperature and excess phosphorus emerge as the potential main determining factors for the inter-annual variability of cb blooms in the Baltic Sea.

MATERIALS AND METHODS

The applied coupled physical biogeochemical model system is build around the ocean general circulation model MOM (Version 3, *Pacanowski & Griffies*, 2000) adapted to the Baltic Sea. It includes an explicit free surface and an open boundary in the Skagerrak. The model grid

covers the whole Baltic Sea including Kattegat and Skagerrak with a variable horizontal resolution stretching from 3nm x 3nm in the south western part to 9nm x 9nm in the northern and eastern parts of the domain (Fig. 1). With less than 3m up to 90m depth and 77 vertical levels overall, the vertical grid spacing is adapted to resolve the thermal and haline stratification of the Baltic Sea. A thermodynamical ice model completes the physical part of the model system.

The biogeochemical part of the model consists of nine state variables and is suited to simulate a nitrogen cycle. Dissolved ammonium, nitrate and phosphate provide the nutrients for three functional groups of phytoplankton: diatoms, flagellates, and cyanobacteria. Diatoms represent larger cells that grow fast under nutrient-rich conditions. Flagellates represent smaller cells with an advantage at lower nutrient conditions. The cyanobacteria are able to fix atmospheric nitrogen and, hence, model phosphate is their only limiting nutrient. The ability of nitrogen fixation make the cyanobacteria an essential nitrogen source for the system. A dynamically developing zooplankton variable provides grazing pressure on the model phytoplankton. The cycle is closed by a detritus and a sediment variable. In order to simulate the impact of variable redox conditions on the nutrient cycle oxygen is treated explicitly. A detailed model description can be found in *Neumann, 2000; Neumann et al., 2002*.

Several data sets are needed as initialisation, boundary and forcing data. The atmospheric forcing, consisting of 10m-wind, air pressure, 2m-temperature, dew point temperature, and cloudiness, is taken from the ERA-15 project (*Gibson et al., 1996*). River runoff, nutrient loads, and atmospheric deposition is provided by the Baltic Sea Environmental Database of the University of Stockholm. Initial fields as well as open boundary values for temperature and salinity are taken from climatological data (*Janssen et al., 1999*). Initial data for the biogeochemical variables had to be taken from the model run of *Neumann et al., 2002* because of too sparse observations.

RESULTS

Long-term simulation

The simulation spans the 15-year period 1979-1993. The analysis of the model results is restricted to the time span and region where the satellite observations by *Kahru, 1997* and the simulation overlap, i.e., the period 1982-1993 and the region 13 to 24.5°E , 53.9 to 60.3°N. As a detailed description of model results from a similar simulation including validation against observations is given in *Neumann et al., 2002* the results shown here are restricted to

the variables directly linked to cb blooms and without further extensive comparison with observations.

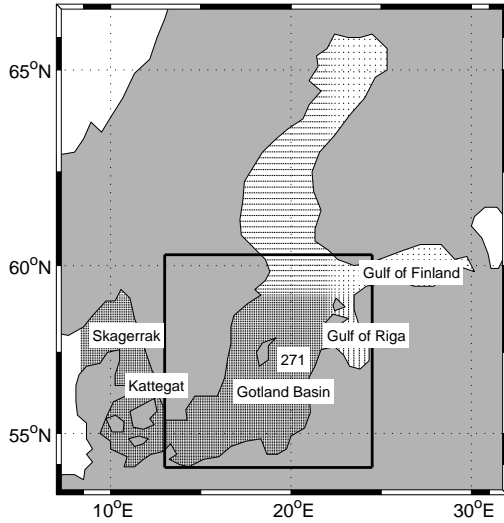


Fig. 1 Model grid. Dots indicate grid cells. The investigation area is marked by the box.

The sea surface temperature (SST) acts as a key variable for phytoplankton growth because it combines the influence of several factors, e.g. solar radiation, wind induced mixing, thermocline depth and turbidity of the surface layer. The physical conditions during the simulation period will therefore be characterized by the SST averaged over the investigation area (Fig. 2). The SST shows a pronounced annual cycle with a minimum near the midst of February and a maximum in early August. During the three very cold winters 84/85-86/87 the minimum temperature was near 0°C indicating that large parts of the Baltic Sea were covered by ice. Cold summers were simulated in 1985/87/93. The SST anomaly in Fig. 2 shows that the year 1987 was outstanding in that it was colder than average during all seasons.

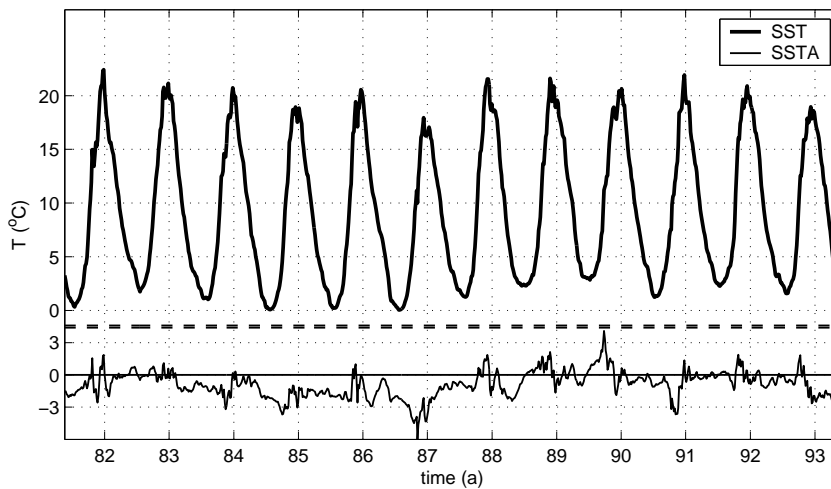


Fig. 2 Simulated area mean sea surface temperature (SST) and anomalies from the mean annual signal (SSTA). Time marks refer to Aug. 15 of the year.

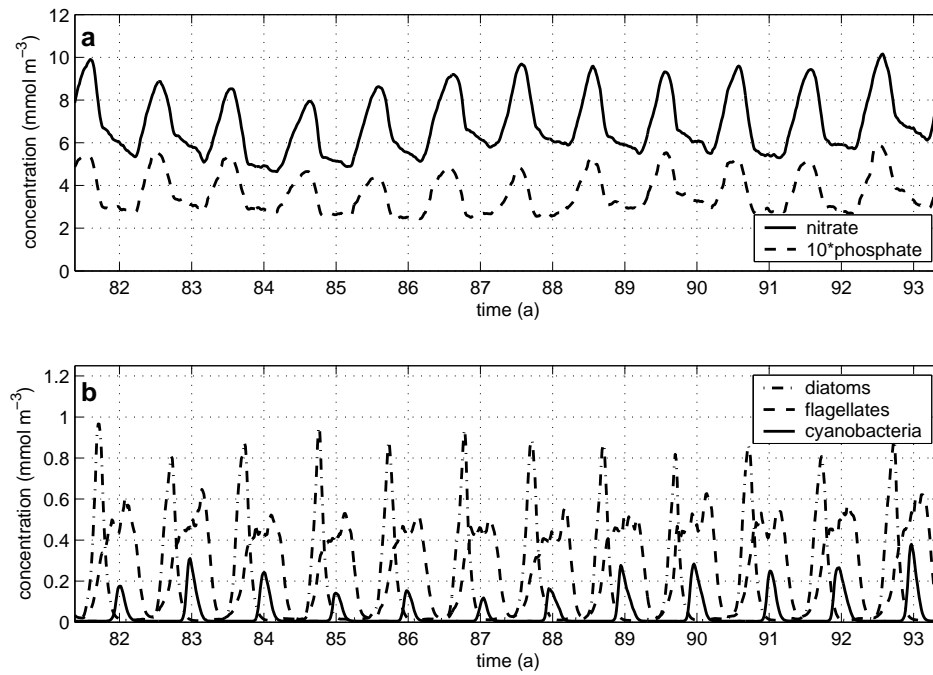


Fig. 3 Simulated area mean concentrations in the surface layer (0-40 m) of (a) nutrients and (b) phytoplankton. Time marks refer to Aug. 15 of the year.

Under the influence of the physical conditions the simulation reproduces the typical annual cycle of phytoplankton development in the Baltic (Fig. 3b). Diatoms dominate at the beginning of the spring bloom in February/March and are superseded by flagellates when the nutrient concentrations start to decline (Fig. 3a). In August the nutrients have almost reached their annual minimum and nitrogen-fixing cb make up a considerable part of the phytoplankton biomass. A strong inter-annual variability in cb blooms becomes apparent with reduced concentrations during the years 1985-1988.

The long term mean pattern of cb concentration in Fig. 4a shows a pronounced east-west gradient with very high concentrations along the Swedish coast and at the entrance to the Gulf of Finland. Nearly absent are cb at the east coast of the simulation area and in the Gulf of Riga. The simulated pattern is in good qualitative agreement with that derived from satellite data (Fig. 3.5 in *Kahru, 1997*). The nutrient conditions during summer are characterized by the mean concentration of 'excess phosphorus' (eDIP) defined as:

$$\text{eDIP mmol m}^{-3} = \text{DIP mmol m}^{-3} - \text{DIN mmol m}^{-3} / 16.$$

The eDIP concentration characterises the amount of remaining phosphorus when all nitrogen is consumed by phytoplankton under the assumption that the nutrient uptake occurs at the Redfield ratio of C₁₀₆:N₁₆:P₁. For this study the eDIP concentration is the preferable measure of nutrient conditions in comparison with the N:P ratio because it includes the information

about the amount of available nutrients and maintains its meaning under very low nutrient conditions.

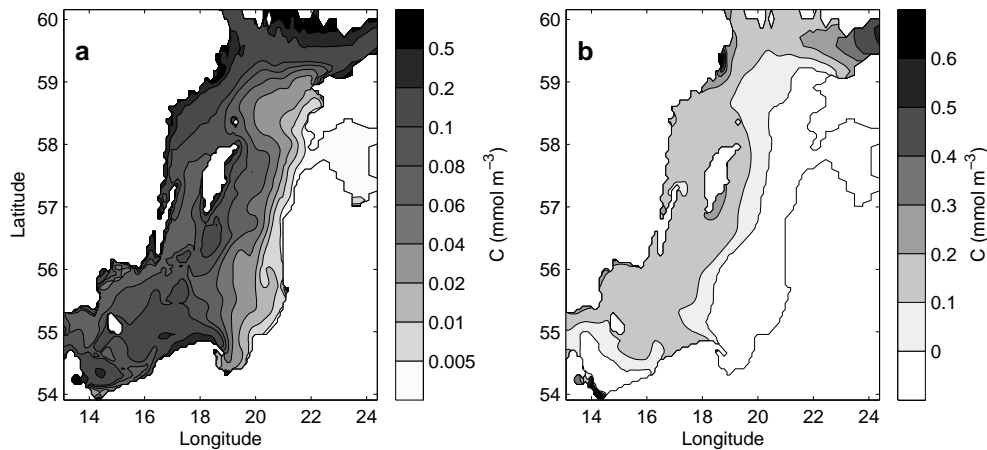


Fig. 4 Simulated summer mean (June-September) values in the surface layer (0-40 m) of (a) cyanobacteria concentration and (b) eDIP concentration. Negative eDIP concentrations are set to zero.

The pattern of eDIP concentration in Fig. 4b bears a strong resemblance with the cb pattern suggesting that the low cb concentrations in the eastern part of the domain are due to phosphorus limitation. The negative eDIP concentrations in this region can be explained by the large riverine nitrogen input from river Vistula, Daugava and Odra which cannot be utilized by phytoplankton due to the lack of phosphorus.

In order to validate the inter-annual variability of simulated cb concentrations at least in a qualitative manner the extension of simulated cb blooms is opposed to the estimates derived from satellite data (*Kahru, 1997*) in Fig. 5. Obviously, the simulated area covered by cb exceeds the observed area to a great extent. A large part of this discrepancy can be attributed to the different properties of simulated and observed data. The satellite data are derived by visible satellite imagery and thus cb blooms are detected not until strong surface accumulations are formed and only under nearly cloudless conditions. Most open water cb blooms in the Baltic are composed of *Aphanizomenon sp.* and *Nodularia spumigena* whereof only the latter forms satellite-detectable surface accumulations. Strong surface accumulations form only under calm and sunny weather conditions and in an advanced stage of the bloom. The ERGOM model in contrast simulates cb concentrations spread over the water column depending on the environmental conditions. The model does not take changes in buoyancy of cb during the development of a bloom in account. The model results are therefore not restricted to surface accumulations of a single species. Cb concentrations are simulated during the entire growth period even if the weather conditions are not favourable for surface accumulations. It is therefore to be expected that the simulated area covered by cb largely exceeds the estimates from satellite data. Besides this discrepancy in the magnitude there is a

striking resemblance in the course of the inter-annual variability. A strong drop between 1984 and 1985 separates a three year period of strong cb blooms (1982-1984) from a four year period (1985-1988) of largely reduced blooms. The cb blooms recovered beginning in 1989 and reach the observed maximum in 1992. The recovering is simulated more abrupt than it was observed.

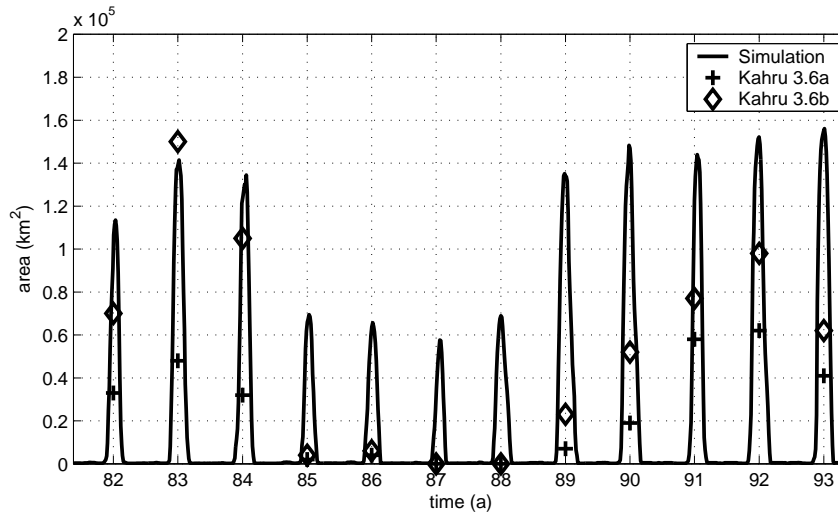


Fig. 5 Simulated area and observed annual cumulative area (from *Kahru, 1997*; Fig. 3.6) covered by cyanobacteria accumulations in the Baltic Sea. ‘Kahru 3.6a’ refers to the observed series and ‘Kahru 3.6b’ to the series corrected for the unequal number of available satellite images (for details see *Kahru, 1997*). Time marks and observations refer to Aug. 15 of the year.

Scenario simulations

Several simulations were carried out in order to test the influence of atmospheric forcing (i.e. the weather conditions) and model initialisation (see below) on the development of cb blooms. Each simulation started in the midst of February of the specific year and ended at the end of October covering the annual growth period of cb in the Baltic Sea. At the beginning of each simulation all model variables have to be initialised, i.e., all variables must be filled with meaningful values at all grid points. The values can be estimated from observations or taken from a previous simulation. With the objective of separating the influence of the weather conditions during the growth period from environmental conditions before the start of the growth period different initialisation data sets were extracted from the results of the long-term simulation. Two years, 1983 (before the strong drop in cb concentration from 1984 to 1985) and 1986 (after the drop), were selected. The mean annual cb concentration in 1983 declined to one third of its magnitude in 1986 (Fig. 6a,d) with the strongest decline in the southern part

of the area. The model was rerun with the forcing and boundary conditions from 1983 but with the initialisation from February 1986. If case 6b is compared to case 6a,d it is obvious that the annual mean concentration as well as the pattern bear a much stronger resemblance to case 6d indicating that the initialisation in February has by far the dominating influence compared to the weather conditions during the course of the year. To provide more confidence in this finding the experiment was rerun the other way round, i.e., forcing and boundary conditions were taken from 1986 and the initialisation from 1983. Pattern and mean annual concentration in case 6e show smaller differences with respect to case 6a than to case 6d. This result confirms the outcome of the first experiment in that it is again the initialisation and not the forcing that has the strongest impact on the development of the cb bloom.

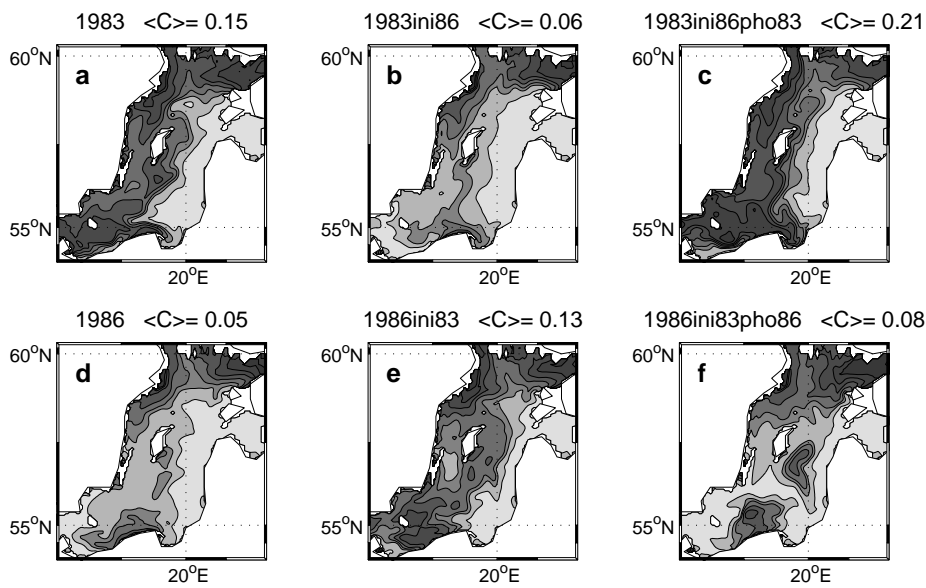


Fig. 6 Annual mean cb concentrations. Dark shading indicates high concentration. The title of each subfigure specifies (from left to right) the simulation year (determined by atmospheric forcing and boundary conditions), the initialisation year (ini), the initialisation year for phosphate (pho) if different from ini and the mean annual concentration C in mmol m^{-3} with square brackets standing for the spatial mean. Further explanations are given in the text.

The results support the hypothesis that the decline in cb concentrations from 1983 to 1986 can mainly be attributed to changes in the environmental conditions in February and not to differences in the weather conditions during these years. However, the dominating factor causing the variability in the simulated cb blooms has still to be separated as the initialisation consists of all model variables. Results from simulations with a simpler model for the Gulf of Finland (*Kiirikki et al., 2001*) indicate that the wintertime eDIP concentration is crucial for the cb development. One variable, namely phosphate, was therefore isolated from the initialisation data and two further simulation experiments were carried out. For the first

experiment (case 6c) the setup of case 6b was changed in such a way that forcing and initial phosphate were taken from 1983 and the rest of the initialisation was taken from 1986. This results in cb concentrations that are more than three times higher than in case 6b and are even higher than in case 6a. Obviously, the February phosphate concentration has a very strong impact on the cb development and it can be assumed that other factors in the initialisation are of minor importance. These findings are confirmed by the results of the second experiment (Fig. 6f). In this case the cb bloom is reduced with regard to Fig. 6e but slightly increased over the concentrations in Fig. 6d.

It must be stressed that in case 6e,f not only the phosphate concentration itself was changed, but by keeping the nitrogen concentration fixed the N:P ratio respectively the eDIP concentration was changed too. In order to explain the inter-annual variability of cb blooms the question remains so far which mechanism forces the inter-annual variability of phosphate respectively eDIP.

DISCUSSION

The inter-annual variability of cb blooms in the Baltic Sea as observed from satellites is described in *Kahru et al., 1994; Kahru, 1997*. But the factors causing this variability are still not clear.

Obviously, late summer atmospheric and hydrographic conditions have an impact on the development of cb blooms. Calm, sunny weather causes a strong, shallow thermocline and high sea SST, the favourable conditions for large cb blooms with pronounced surface accumulations. Even a positive feedback mechanism between high SST and high cb concentration has been reported (*Kahru et al., 1993*).

The influence of the wintertime hydrographic conditions half a year in advance of the bloom dominating the variability in the presented simulations is not that obvious and shall thus be outlined: Phytoplankton growth starts each year in March in the southern Baltic Sea from the wintertime nutrient concentrations. During the course of spring and summer diatoms and flagellates consume the nutrients at the Redfield ratio. Growth stops when one of the limiting nutrients, either phosphorus or nitrogen, is depleted (see Fig. 3). Large parts of the Baltic Proper and the Gulf of Finland are limited by nitrogen leaving behind an excess of phosphorus in the surface layer in late summer (Fig. 4). This eDIP pool bears the potential for blooms of nitrogen fixing cb. Under the assumption that deviations from the Redfield ratio in nutrient uptake of diatoms and flagellates play a minor role this suggests the possibility to estimate the potential for late summer cb blooms from the knowledge of surface layer nutrient

concentrations before the onset of stratification in March/April. In other words, the potential of a late summer cb bloom is determined as early as February by the eDIP concentration in the surface layer. The actual strength of the bloom is of course affected by other factors especially whether summertime weather conditions permit exhaustion of the eDIP pool or not. That this chain of events is crucial in order to explain the magnitude of cb blooms in the Gulf of Finland was demonstrated in a model study of *Kiirikki et al., 2001*. This leads to the conclusion that the key to an explanation of the inter-annual variability of cb blooms is an understanding of the factors controlling the variability of wintertime surface layer eDIP concentrations. A cause-and-effect chain suitable to explain the eDIP variability and linking it to the large scale atmospheric situation, namely the North Atlantic Oscillation (NAO), is outlined in Fig. 7.

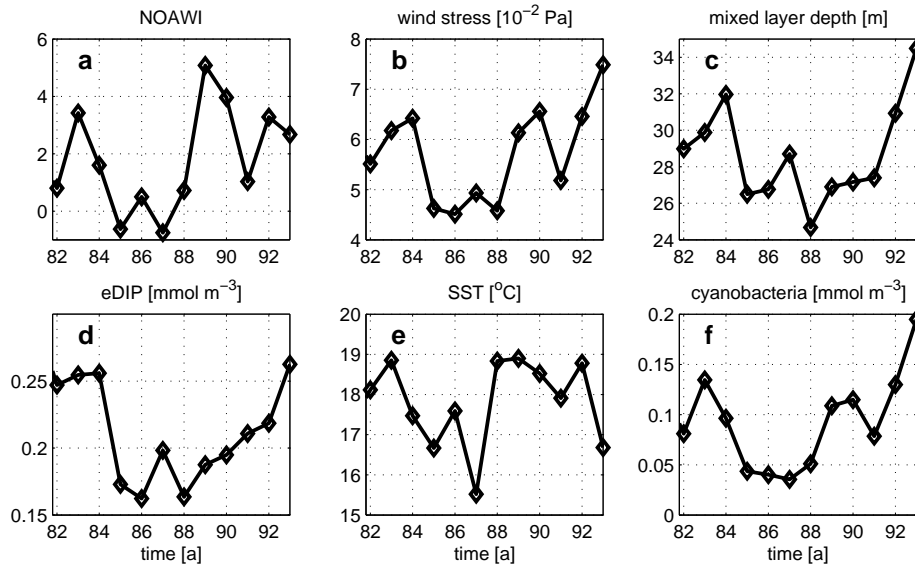


Fig. 7 Inter-annual variability of (a) NAO winter index after Hurrell 1995, (b) wind stress, (c) mixed layer depth, (d) eDIP concentration, (d) SST, (e) cb concentration. (b-f) Simulation results from the long-term simulation. (c-f) Results are averaged over surface layer. Time averaging covers different periods: (b, c) October-April, (d) January-February, (e, f) July-September

The NAO is the dominating mode of atmospheric variability in the northern hemisphere. It controls a large portion of wintertime climate variability in northern Europe (Hurrell et al. 2003). Comparing Fig. 7a and b this influence is obvious. Fig. 7b shows the simulated mean winter wind stress to the water surface, i.e., it combines the influence of surface winds and ice cover, strongly damping the direct wind input. Wintertime variability of both variables, surface wind and ice cover, are determined by the NAO to a large extent (*Omstedt & Cheng, 2001*). Wind stress in turn has a strong (but not exclusive) influence on the simulated mixed layer depth (Fig. 7c). The next element in the chain is the link between mixed layer depth and surface layer eDIP concentration which becomes manifest in the strong correlation visible in

Fig. 7c,d. Prerequisites for the functioning of this link are (1) a nutricline in the appropriate depth and (2) positive eDIP concentrations below the nutricline. Both prerequisites are fulfilled in most parts of the Baltic Sea covered by cb blooms as shown exemplary for a monitoring station in the central Gotland Basin in Fig. 8a.

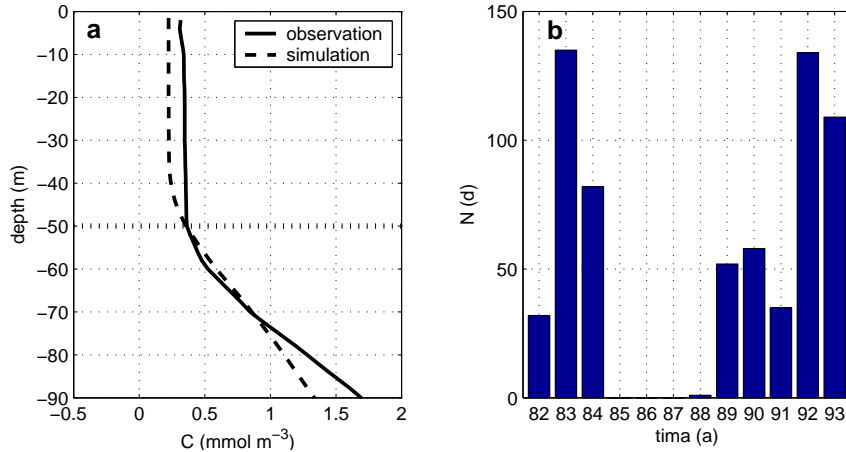


Fig. 8 (a) Mean winter (January-March) vertical profiles of simulated and observed eDIP concentrations at monitoring station 271 (For the location of station see Fig. 1.) (b) Simulated number of days N when mixed layer depth exceeded 50 m.

Observed as well as simulated eDIP profiles show a remarkable increase in concentration below around 50m depth. Surface layer eDIP concentrations will increase if the mixed layer depth reaches the nutricline indicating a strong upward mixing of eDIP. If on the other hand the wintertime mixed layer depth does not reach the nutricline the surface layer eDIP concentrations will remain at the low late summer level of the preceding year. The number of days when the mixed layer depth exceeded 50m in Fig. 8b shows a strong drop from 1984 to 1985. During the years 1985-1988 the depth of 50m was almost never exceeded indicating strongly reduced upward mixing of eDIP. Although the results from an isolated grid point are not representative for the spatial mean, they are consistent with Fig. 7 and illustrate the suggested mechanism. The simulated eDIP variability is confirmed by an analysis of the observed phosphate concentration in the eastern Gotland Basin (*Nehring, 2001*). His results show the maximum wintertime surface layer phosphate concentration in 1984 and a strong decline during the years 1985/86 in agreement with the simulated results in Fig. 7d.

As aforementioned high wintertime surface layer eDIP concentrations are a prerequisite for strong late summer cb blooms. However, eDIP concentrations will yield only strong cb blooms if the weather conditions are favourable and the eDIP pool can be completely utilized. The limiting influence of unfavourable weather conditions is obvious in the extraordinary cold summer of 1987 (Fig. 7e) when cb concentrations remain on the low level of preceding years although eDIP concentrations are markedly increased. Responsibility of the weather

conditions for the cb concentrations below the potential limit in 1987 can be verified by a further simulation similar to case 6e. This time the atmospheric forcing is taken from 1987 and the initialisation from 1983. In contrast to case 6e, where the increase with respect to case 6d was almost threefold, the magnitude of the cb bloom is less than doubled in 1987 when the initialisation is taken from 1983. This result is a strong indication that the very unfavourable weather conditions in 1987 do not admit the complete utilisation of the wintertime eDIP pool, forcing a cb bloom below the potential limit.

By the two step simulation approach summarised in Fig. 6 it could be demonstrated that: (1) the late winter environmental conditions, represented by the February initialisation data, have major influence on the formation of cb blooms, (2) model phosphate concentration is a crucial variable within the initialisation data set with respect to cb variability. This approach takes advantage of the power of numerical simulations to establish causal relationships, impossible by analysis of observations because the influence of a combination of many factors influencing cb blooms (e.g. salinity, temperature, turbulence, solar radiation, nitrogen, phosphate, grazing) cannot be separated. Once the crucial factor controlling the variability of cb blooms is separated the task is to explain the variability of this factor. In order to explain the inter-annual variability of cb blooms in the Baltic Sea it is important to understand the variability of the wintertime surface layer eDIP concentration. The mechanism driving the variability of the eDIP concentration is outlined in Fig. 7. It is hypothesised that the impact of the NAO is transferred to the variability of cb blooms by a cause-and-effect chain starting in winter and developing until late summer. This chain was discussed in connection with Fig. 7 and is summarised Fig. 9.

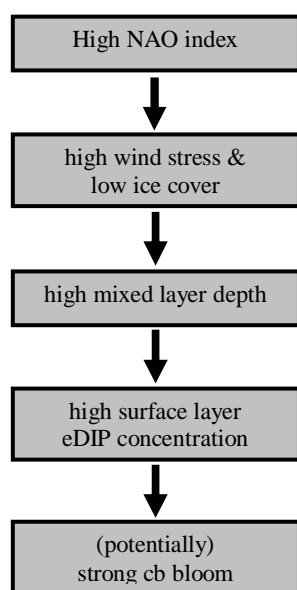


Fig. 9 Cause-and-effect chain for the transfer of NAO variability to cb blooms in the Baltic Sea.

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