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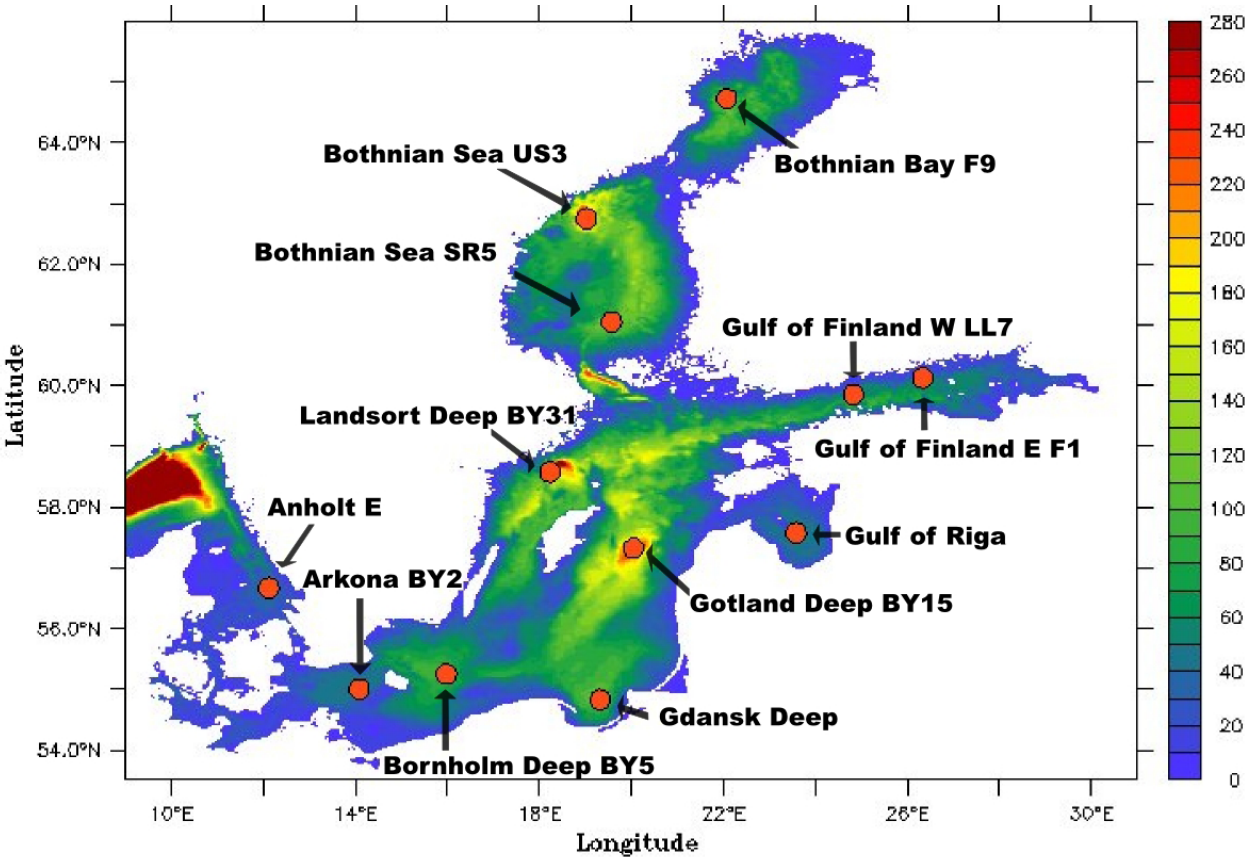
OCEANOGRAFI Nr 101/2010

Quality assessment of state-of-the-art coupled physical-biogeochemical models in hind cast simulations 1970-2005



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Title (and Subtitle/Titel

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Abstract/Sammandrag

The objectives of the project ECOSUPPORT (Advanced modeling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making) are to calculate the combined effects of changing climate and changing human activity (e.g. changing nutrient loads) on the Baltic Sea ecosystem. Three state-of-the-art coupled physical-biogeochemical models (BALTSEM, ERGOM, and RCO-SCOBI) are used to calculate changing concentrations of nitrate, ammonium, phosphate, diatoms, flagellates, cyanobacteria, zooplankton, detritus, and oxygen in the Baltic Sea. The models are structurally different in that ERGOM and RCO-SCOBI are 3D circulation models with uniform high horizontal resolution while BALTSEM resolves the Baltic Sea spatially in 13 sub-basins. This report summarises first results of the quality assessment and model intercomparison within ECOSUPPORT. Results from hindcast simulations are compared with observations for the period 1970-2005. We found that all three investigated models are able to reproduce the observed variability of biogeochemical cycles well. Uncertainties are primarily related to differences in the bioavailable fractions of nutrient loadings from land and parameterizations of key processes like sediment fluxes that are presently not well known.

Avsikten med projektet ECOSUPPORT (Advanced modeling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making) är att undersöka hur klimatförändringar tillsammans med mänsklig aktivitet (förändrad närsaltstillförsel) påverkar Östersjöns ekosystem. Tre kopplade fysiska-biogeokemiska modeller (BALTSEM, ERGOM, and RCO-SCOBI) används för att beräkna hur koncentrationer av nitrat, ammonium, fosfat, diatoméer, flagellater, cyanobakterier, djurplankton, detritus och löst syrgas i Östersjön förändras. Modellerna skiljer sig strukturellt åt genom att ERGOM och RCO-SCOBI är tredimensionella modeller med hög horisontell upplösning medan BALTSEM delar upp östersjön rumsligt i 13 delbassänger. Denna rapport sammanfattar resultaten från en första modelljämförelse och kvalitetsbedömning där modellresultat för tidsperioden 1970-2005 jämförs med observationer från samma period. Alla tre modellerna visar att de kan återskapa den observerade biogeokemiska variabiliteten väl. Osäkerheter är huvudsakligen relaterade till skillnader i andelen av näringstillförseln från land som antas vara biologiskt tillgänglig och till beskrivningarna av viktiga processer, som t.ex. flöden från sedimenten, där kunskapen för närvarande är bristfällig.

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Contents

1 Introduction

Within the project ECOSUPPORT (Advanced modeling tool for scenarios of the Baltic Sea ECOsystem to SUPPORT decision making) a hierarchy of existing state-of-the-art sub-models of the Earth system (Fig.1) are used. The objectives are to calculate the combined effects of changing climate and changing human activity on the Baltic Sea ecosystem (see http://www.baltex-research.eu/ecosupport). This report summarises results from the first ECOSUPPORT model intercomparison within work package 2 (WP 2). The results from hindcast simulations are compared with observations for the period 1970-2005. Three state-of-the-art coupled physical-biogeochemical models are used within ECOSUPPORT to calculate changing concentrations of nutrients and organic matter in the Baltic Sea. These are BALTSEM (Gustafsson, 2003; Savchuk, 2002), ERGOM (Neumann et al., 2002), and RCO-SCOBI (Swedish Coastal and Ocean Biogeochemical model, SCOBI (Eilola et al., 2009) and the Rossby Centre Ocean circulation model, RCO (Meier and Kauker, 2003; Meier et al., 2003)). The models are structurally different in that ERGOM and RCO-SCOBI are 3D circulation models comprising sub-basin scale processes while BALTSEM resolves the Baltic Sea spatially in 13 sub-basins.

All models were supplied with a new common atmospheric forcing and the results presented below show the status of model results after a first rough calibration of the models to the new forcing.

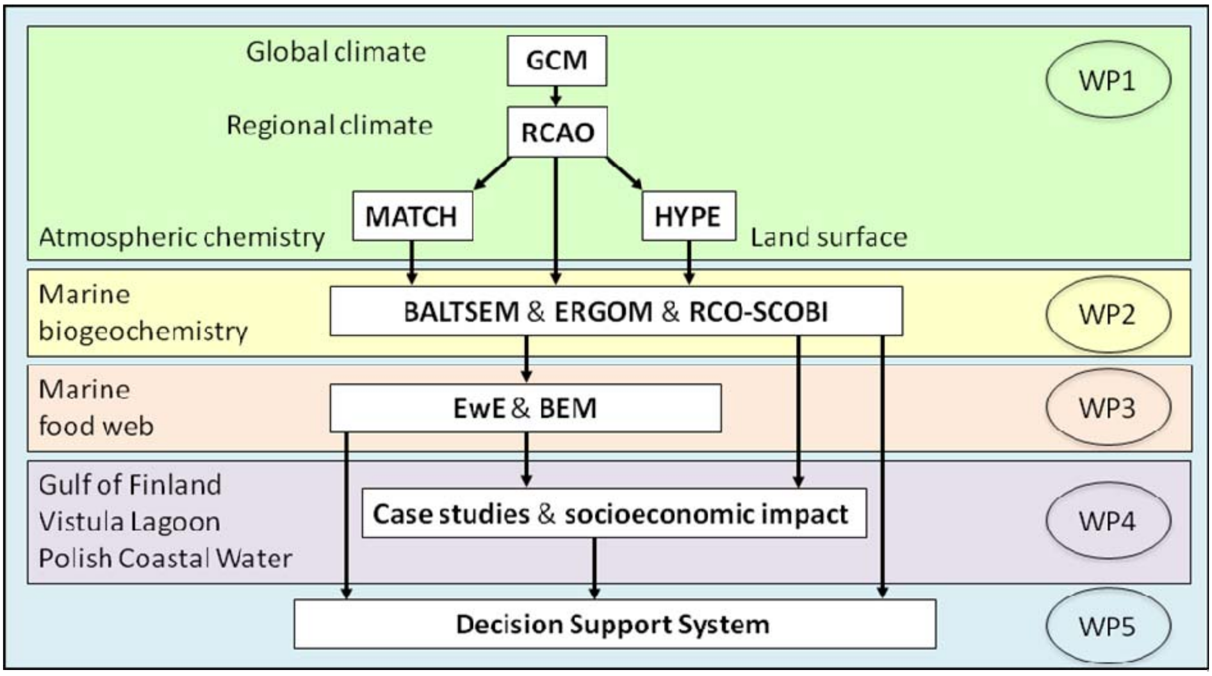

Fig.1: *Model hierarchy in ECOSUPPORT and work package (WP) structure. The schematic is highly simplified neglecting complex interactions (e.g. fish predation pressure on zooplankton, changing society/policy will affect climate and nutrient load scenarios).*

2 Method

Nine countries have their coast lines adjacent to the Baltic Sea located in northern Europe (Fig.2). This shallow sea (mean depth 53m) is connected to the North Sea by a shallow (sill depths of and 8 and 18m) and partly narrow entrance area in the Danish straits that control the inflow of salt water. The Baltic Sea is characterized by large sub-basins separated with sills. The main focus of the present report is the Baltic Proper (coloured area in Fig.2) which is the largest sub-basin by far. The large river runoff to the semi-enclosed Baltic Sea results in brackish water with large horizontal salt gradients and a strong halocline separating the in winter well-mixed surface layer from the saltier bottom layer. More information about the characteristics of the Baltic Sea can be found e.g. in Stigebrandt (2001).

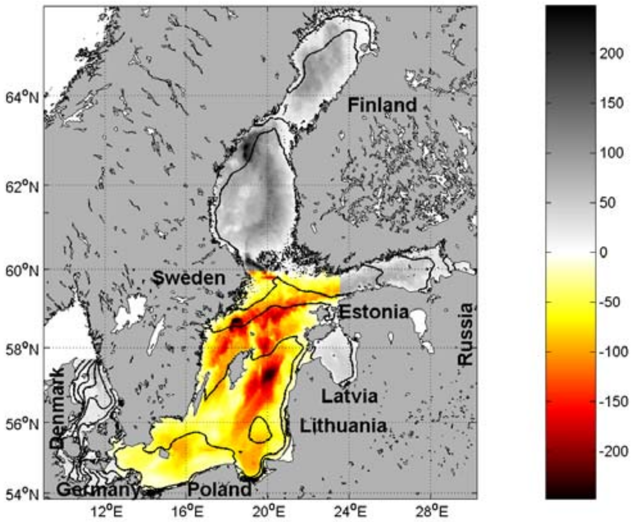

Fig.2: *The RCO model area showing the model bathymetry and for illustration some isolines of salinity that indicate the large salinity gradient between the Baltic Proper and the Kattegat. The area of the Baltic Proper is indicated by negative depth values with ranges in meter shown by the red-yellow scale of the colour bar. The depths of the other Baltic Sea areas are positive and shown by the grey colour scale. Note: RCO and BALTSEM both have their open boundary in Kattegat while ERGOM has its boundary in the western Skagerrak.*

The atmospheric forcing is based on dynamical down-scaling of the ERA40 atmospheric forcing with a high-resolution regional atmosphere model (the Rossby Centre Atmosphere model, RCA; see e.g. Kjellström et al., 2005). The resolution of the atmospheric forcing grid is 25x25 km. The atmospheric wind have been improved using a gustiness parameterization following Höglund et al. (2009).

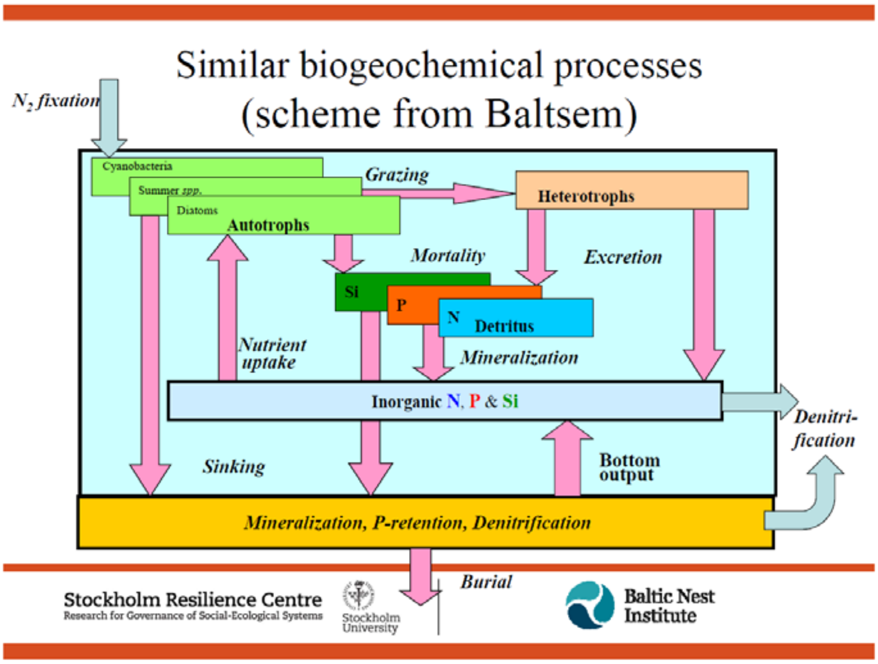

Fig.3: *A highly simplified description of model components and nutrient fluxes exemplified from the BALTSEM model.*

The ERGOM, RCO-SCOBI and BALTSEM models are similar in that they handle dynamics of nitrogen, oxygen and phosphorus including the inorganic nutrients, nitrate, ammonia and phosphate (and also silicate in BALTSEM and inorganic carbon in ERGOM), and particulate organic matter consisting of phytoplankton (autotrophs), dead organic matter (detritus) and zooplankton (heterotrophs). Primary production assimilates the inorganic nutrients by three functional groups of phytoplankton, diatoms, flagellates and others, and cyanobacteria. Organic material may sink and accumulate in the model sediment as benthic nitrogen and phosphorus (and silicate in BALTSEM). The cycling of nutrients within different compartments of the biogeochemical system is illustrated in Fig.3.

In brief, the key differences between the state-of-the-art models at the beginning of the project are described by:

- Differences in treatment of dead organic matter: one state-variable for each nutrient vs. a single variable with constant N/P ratio
- Differences in parameterizations of P sediment dynamics, in particular redox dependent P processes
- Resuspension and sediment transport: mechanistic description (from waves and currents) vs. simple parameterization
- Resolving coastal boundary and deep pits vs. large-scale horizontally integrated sub-basins
- Different vertical resolution

In addition there are other “minor” quantitative (relationships) and qualitative (numerical values of constants) differences in parameterizations of similar pelagic and sediment biogeochemical processes that have not been listed and analyzed yet. For more detailed descriptions of the models the reader is referred to the references listed above.

The models were run with different nutrient supplies, especially for the supply of phosphorus, and were initialized from different initial conditions produced from model dependent spin-up periods. In Fig.4 the differences between model loadings in the 1970’s, 1980’s and 1990’s are shown by the spread relative to the ensemble mean supply. The spread between the different models nitrogen and phosphorus supplies during the three periods are in the ranges 14-25 % and 42-56 % of the ensemble average supply, respectively.

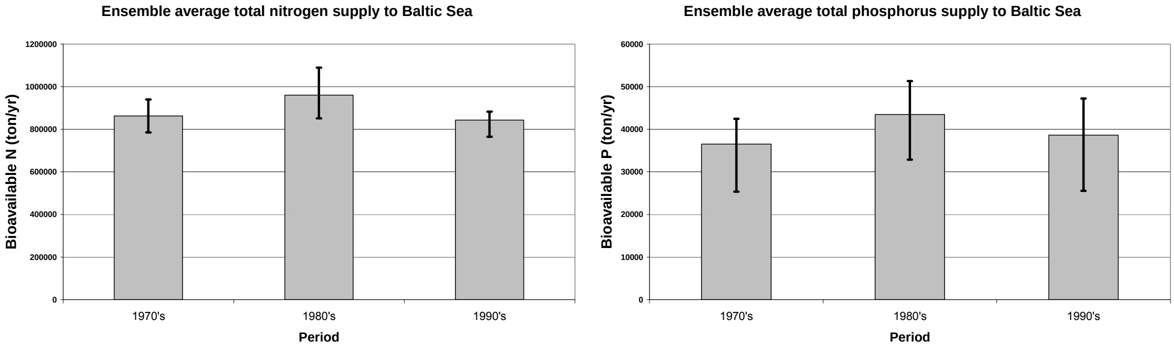

Fig.4: *The total supply (10^3 kg yr^{-1}) of bioavailable nutrients from land and atmosphere to the Baltic Sea are shown as an average for the three models. The nitrogen and phosphorus supplies during the 1970s, 1980s and 1990s are shown in the left and right panels, respectively. The spread between the maximum and minimum of the different model supplies is shown by the error bars.*

The results from the end of the spin-up were used as initial conditions in the beginning of the 1960s. The first years of the period were left out from the analysis. Thus the results cover the period 1970-2007 when the coverage of observations data was found to be satisfactory enough for the validation.

The observational data were extracted from the Baltic Environmental Database (BED) and have so far only been briefly checked for inconsistent data. The average and standard deviation were computed at standard depths without taking into account varying temporal sampling frequency. This will be refined in coming revisions of the validation exercise, although significant differences for these well-sampled monitoring stations are not expected. Pools and surface concentration fields were computed using the DAS data interpolation software (Sokolov, 2003).

For the comparisons below we define the "ensemble mean" as the mean value of results from all three models and the "ensemble spread" as the range defined by the maximum and minimum values of the three models.

As an example: All models first compute vertical profiles of the long term mean value of modeled phosphate at the monitoring station BY15 (Fig.5). The three profiles are then interpolated to a common vertical grid resolution of 1 meter. From these profiles the mean, the maximum and the minimum values are computed for all depths. The ensemble mean profile and spread are then compared to the vertical mean profile computed from the BED data and its statistical range given by the ±1 standard deviation of data.

To summarize the statistical results a cost function (*C*) is computed from: $C = \left| \frac{M - D}{SD} \right|$

where the ensemble mean bias of the model results (M) relative to observations (D) is normalized to the standard deviation (SD) of observations. The following ranges are used for the interpretation of C: $0 \leq C < 1$ (good), $1 \leq C < 2$ (reasonable), and $2 \leq C$ (poor). Observations and model results are interpolated to a vertical grid resolution of 1 meter.

In order to exclude the effects of differences in volumes between models and the database when comparing pools of nutrients in the water, they were adjusted to the volume given by the BED data base. That is, we first compute the volume average concentration in each of the models and then multiply this value by the volume used for the BED data. In a similar manner for the comparison of sediment pools, the bottom areas were adjusted according to the bottom area of the BALTSEM model.

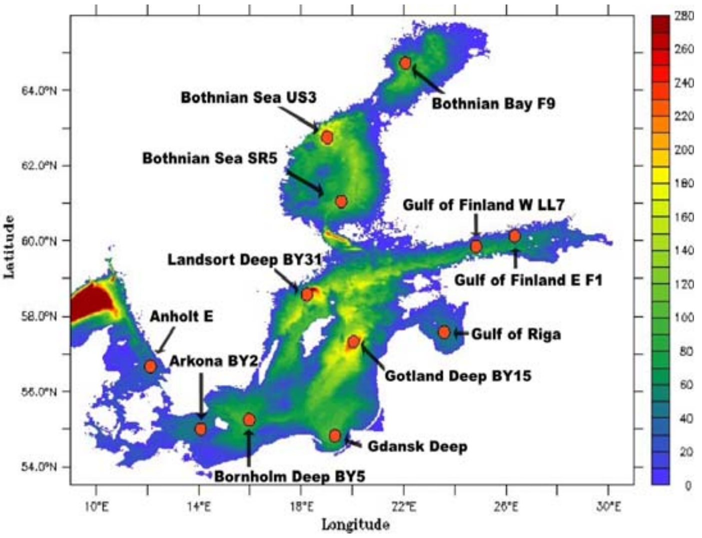

Fig.5. *Positions of Baltic Sea stations.*

In the present report data from the monitoring stations BY5, BY15, LL7 and Anholt E in Kattegat (Fig.5) are used for the long term statistical comparison of plotted profiles. For the computation of the cost function we also consider results from SR5 in the Bothnian Sea, F9 in the Bothnian Bay. The stations positions and station numbers used in the report are defined in Table 1.

Table 1. *List of monitoring station used for the statistical comparison.*

Station Number	Station name	Lat	Lon	Lat°	Lon°
1	Anholt E	5640	1207	56.67	12.12
2	Bornholm Deep BY5	5515	1559	55.25	15.98
3	Gotland Deep BY15	5720	2003	57.33	20.05
4	Gulf of Finland W LL07	5951	2450	59.85	24.83
5	Bothnian Sea SR5	6103	1934	61.05	19.57
6	Bothnian Bay F9	6444	2204	64.73	22.07

3 Results

3.1 Long-term annual statistical comparison

The ensemble means of the long-term (1970-2005) average profiles are compared to statistics from observations at Anholt E, BY5, BY15 and LL07 in Figs.6 to 10. The cost function for the ensemble mean is illustrated in Fig. 11. The ensemble means of the modelled results are in fairly good agreement with the BED data as can be seen from the figures. The results are less good in the deepest Baltic Proper but one should also mention that the volume below 150m occupies only a few percent of the entire Baltic Proper volume.

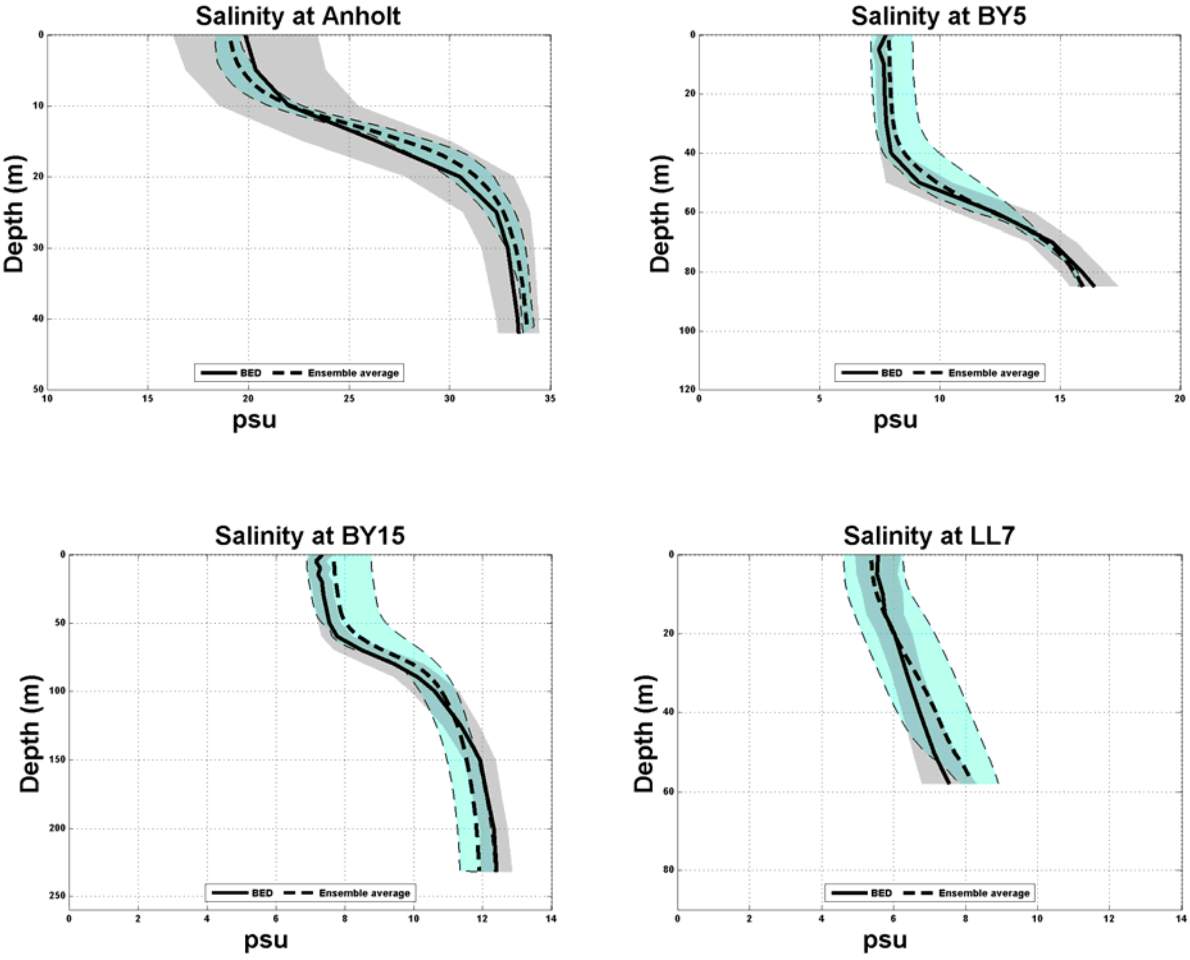

Fig.6. *Average (1970-2005) salinity (psu) at Anholt E, BY5, BY15 and LL07. The black solid line and the grey shaded area indicate the mean value and ±1 standard deviation of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

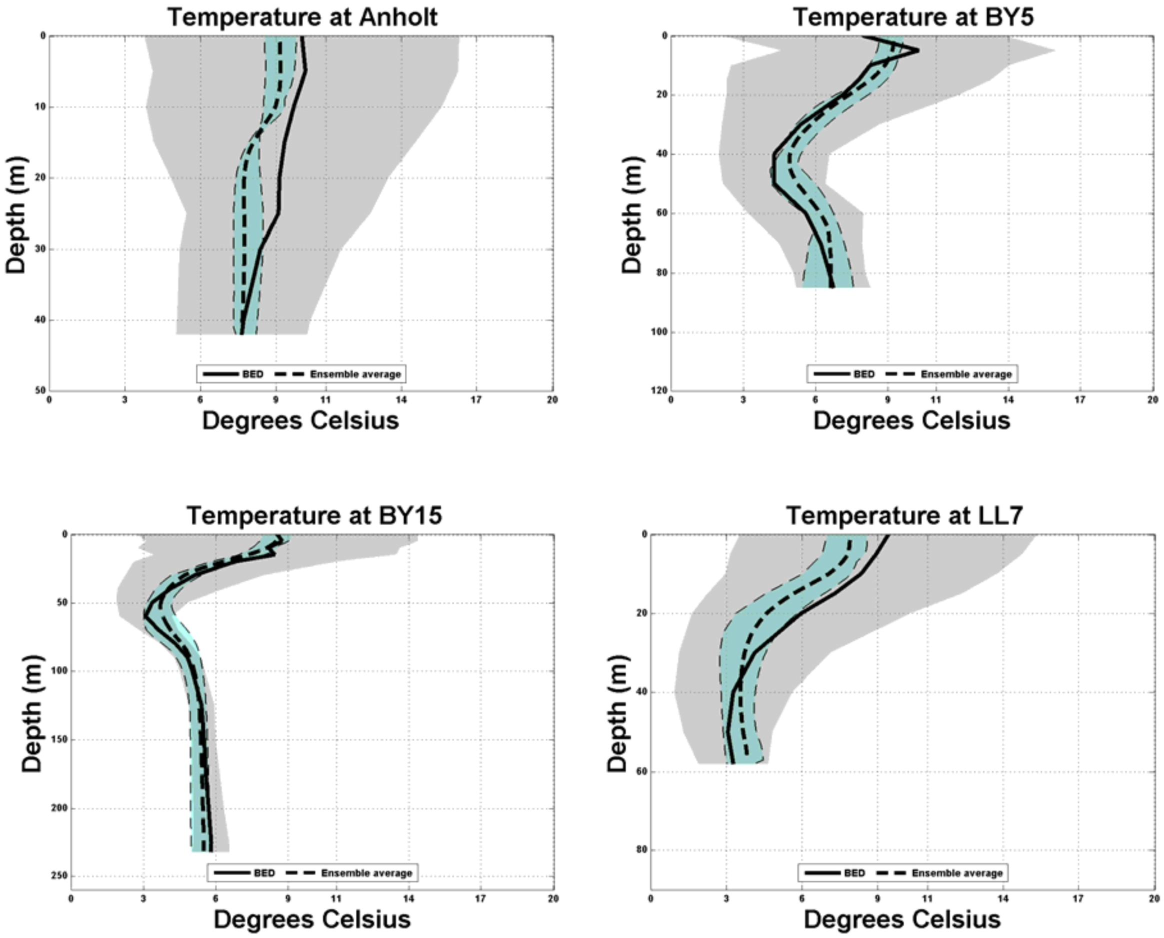

Fig.7. *Average (1970-2005) temperature (°C) at Anholt E, BY5, BY15 and LL07. The black solid line and the grey shaded area indicate the mean value and ±1 standard deviation of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

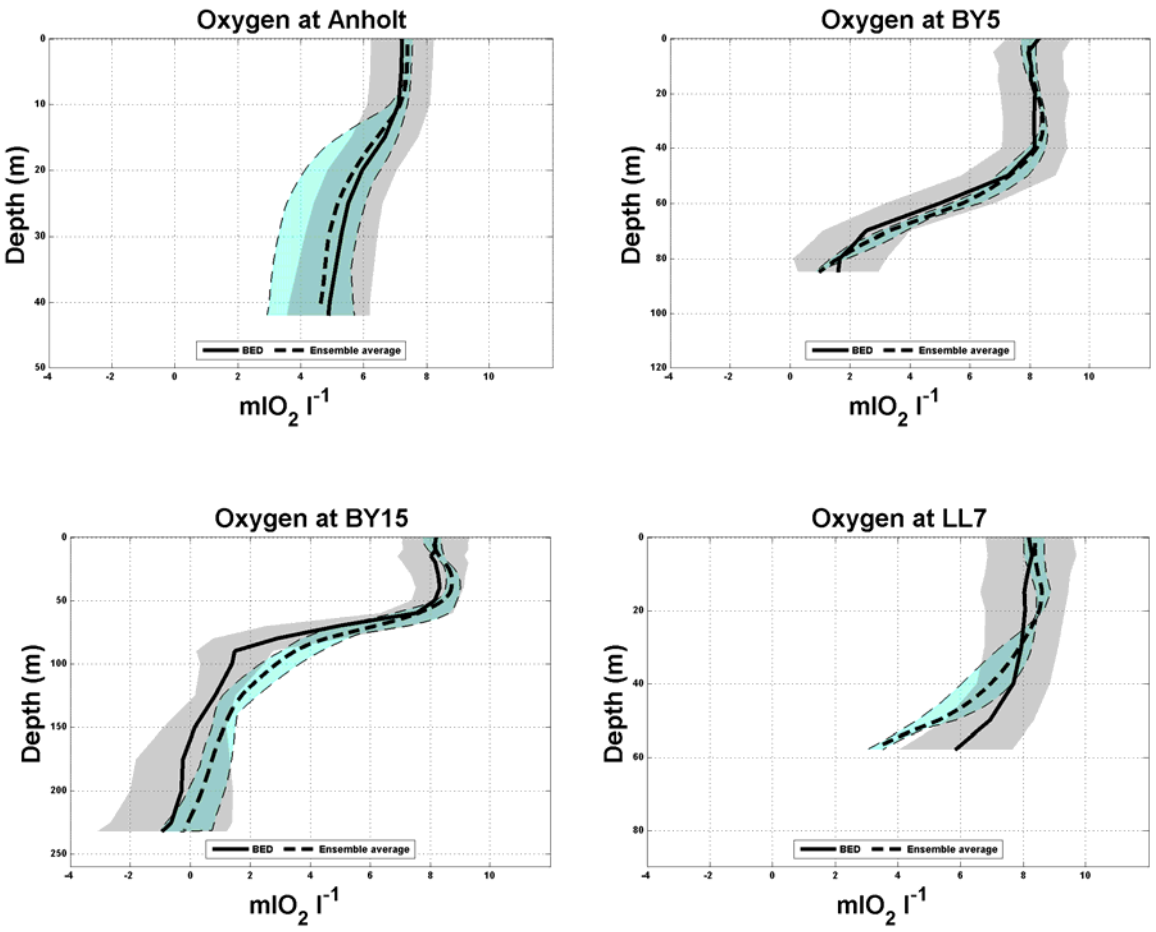

Fig.8. *Average (1970-2005) oxygen (mlO$_2$l^{-1}) concentrations at Anholt E, BY5, BY15 and LL07. The black solid line and the grey shaded area indicate the mean value and ±1 standard deviation of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

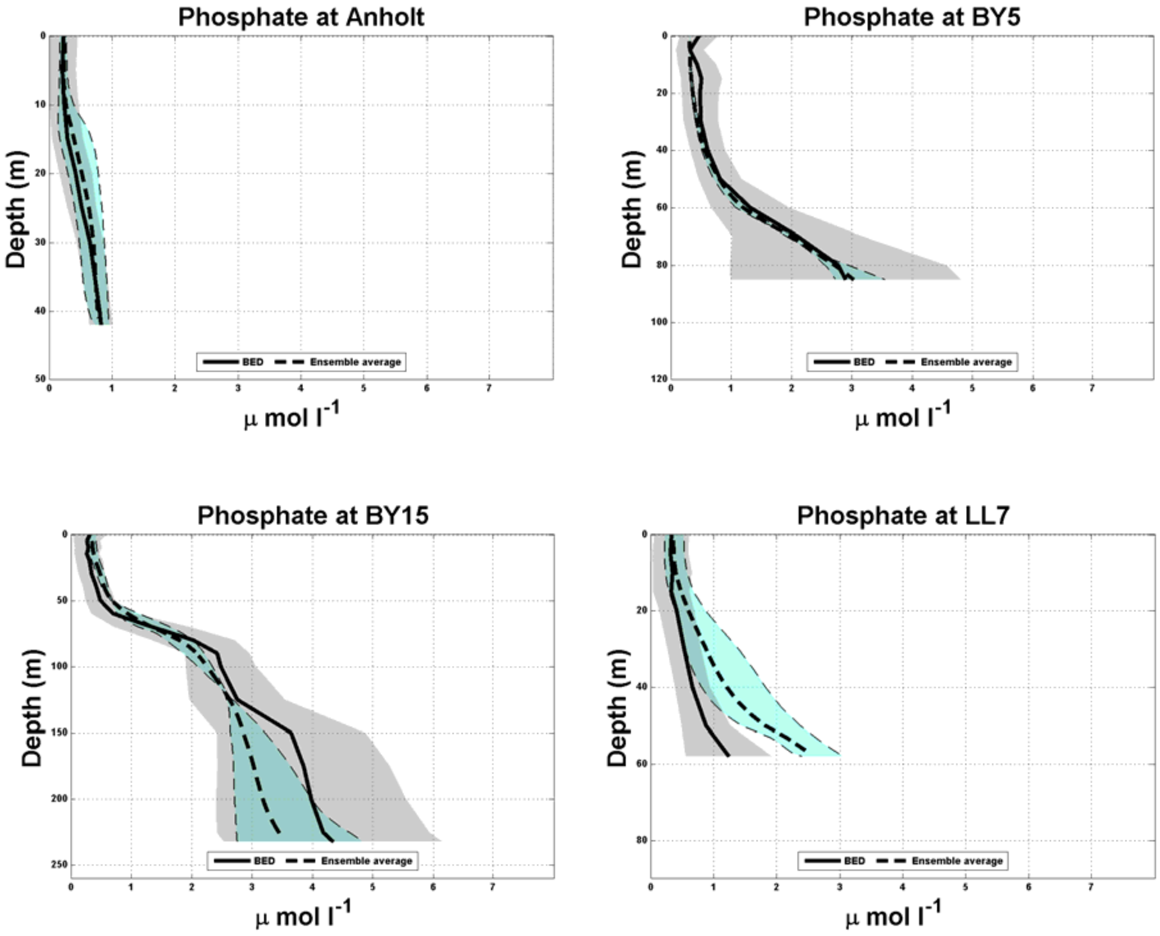

Fig.9. *Average (1970-2005) phosphate (µmolPl^{-1}) concentrations at Anholt E, BY5, BY15 and LL07. The black solid line and the grey shaded area indicate the mean value and ±1 standard deviation of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

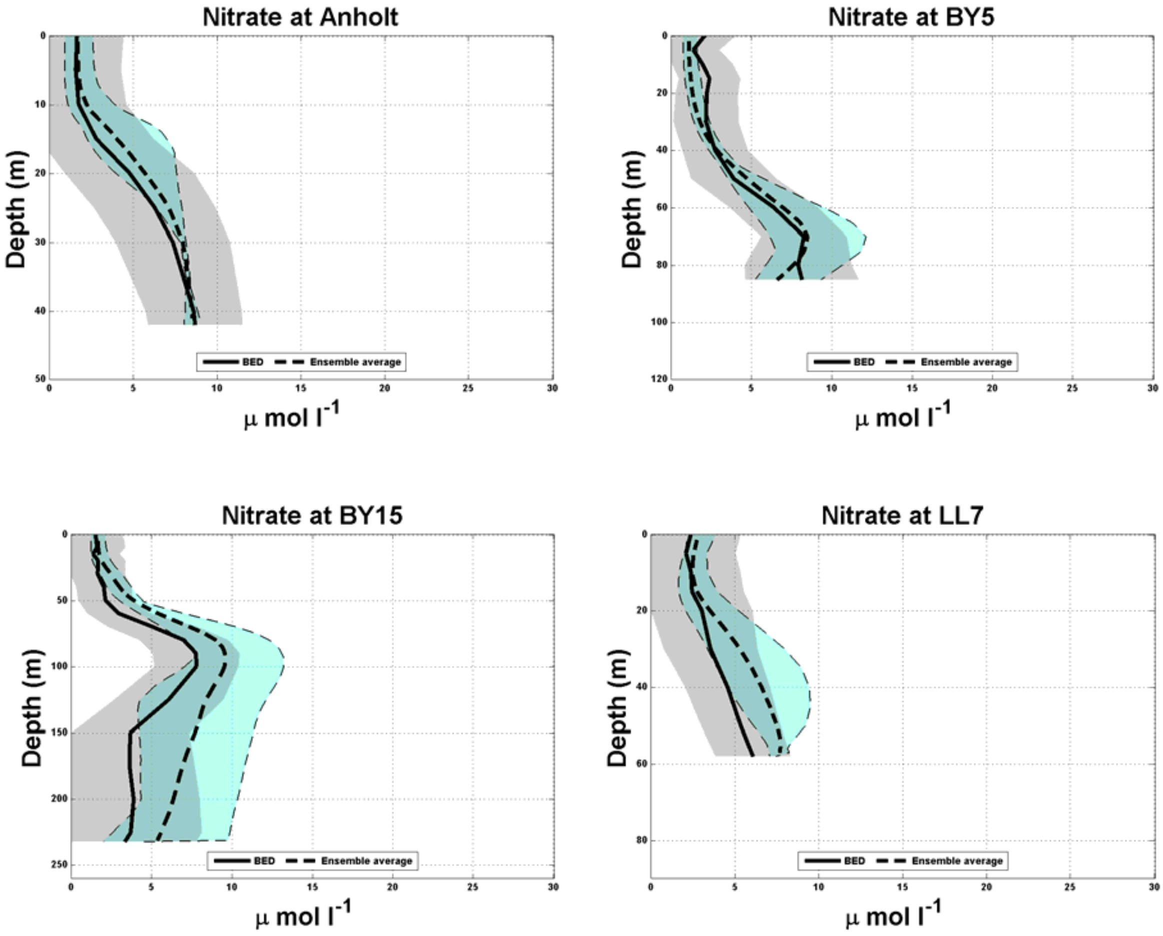

Fig.10. *Average (1970-2005) nitrate (µmolNl^{-1}) concentrations at Anholt E, BY5, BY15 and LL07. The black solid line and the grey shaded area indicate the mean value and ±1 standard deviation of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

The cost function gives a quick way to look at the quality of the ensemble average of the models and point out regions where more efforts are needed in order to obtain accurate results. According to the cost function analysis, the results are generally good or reasonable. In the figures the colour scales for the good, reasonable and poor results are split into two intervals. This gives an idea about which end of the quality classification the results lie in. One may point out some poor results in the northern stations SR5 (No 5) and F9 (No 6). Here phosphate is overestimated as is the case also for the deeper part of LL07. Nitrate is also overestimated in the deeper parts of SR5 and F9, which is reflected by the high cost function number here.

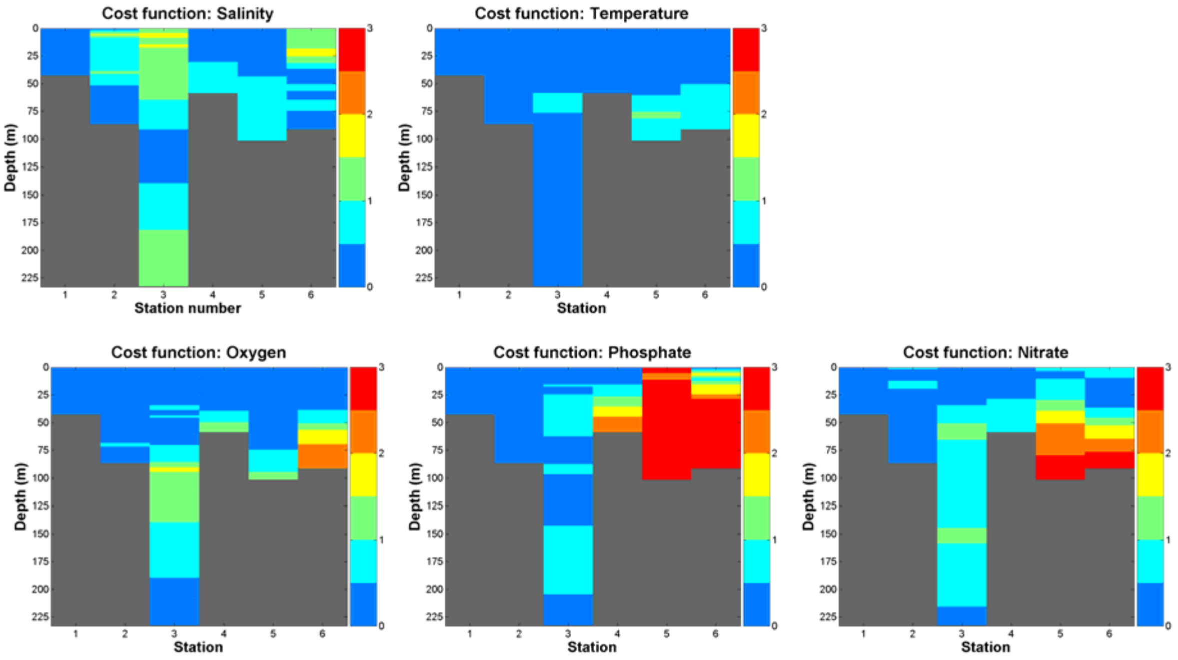

Fig.11. *Vertical profiles of cost function values for the ensemble averages (1970-2005) of salinity, temperature, oxygen, phosphate, nitrate at 6 stations (Table 1) ranging from Kattegat in the west to the Bothnian Bay in the north. Light and dark blue colors (0-1) indicate good results, green and yellow colors indicate reasonable results (1-2) and orange and red colors indicate poor results (>2).*

3.2 Long-term average seasonal cycle

In order to investigate the seasonal characteristics of the models, the long-term (1970-2005) monthly average properties are compared to statistics from BED observations at BY15 (Figs.12 to 14).

The long-term average seasonal cycle of temperature and phosphate and nitrate are well reproduced by the models. All models and hence the ensemble mean results seems to have a too shallow depth of nutrient depletion in late spring and summer compared to the BED data. One should however note that the observations are based on data from standard depths (0, 5, 10, 15, 20, 30, 40, 50 and 60 m) while models results have a higher vertical resolution. The largest spread of model averages are mainly correlated to time periods and depth layers where the spread of observations given by the ±1 standard deviation of the BED data also are largest.

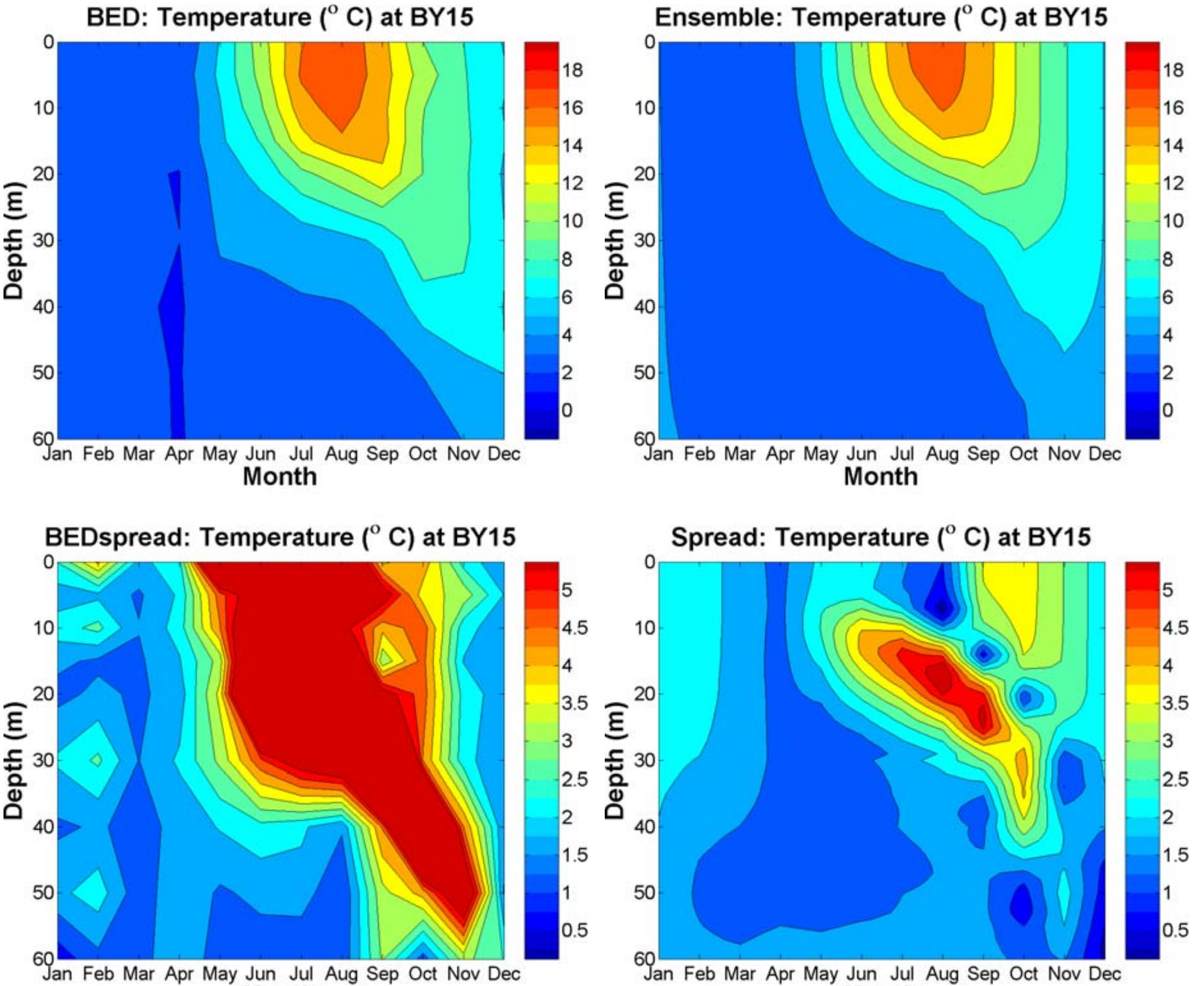

Fig.12. Annual cycle of monthly average (1970-2005) temperature (℃) at BY15 (upper panels). Results from BED and the ensemble average are shown in the left and right panels, respectively. The corresponding spread of BED data (BEDspread=2 x standard deviation) and the spread between models are shown in the lower panels, respectively.

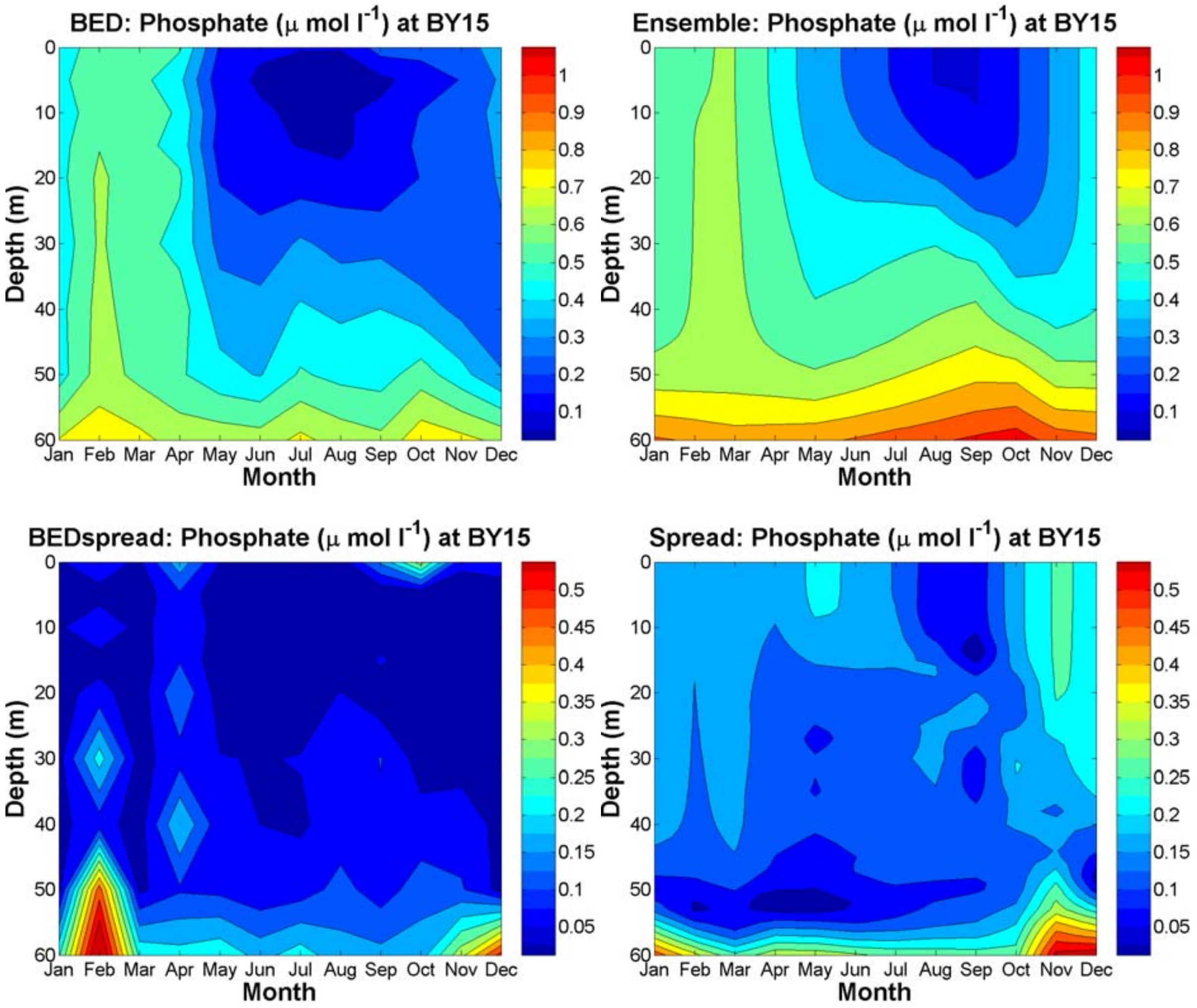

Fig.13. *Annual cycle of monthly average (1970-2005) phosphate (µmolPl^{-1}) concentrations at BY15 (upper panels). Results from BED and the ensemble average are shown in the left and right panels, respectively. The corresponding spread of BED data (BEDspread=2 x standard deviation) and the spread between models are shown in the lower panels, respectively.*

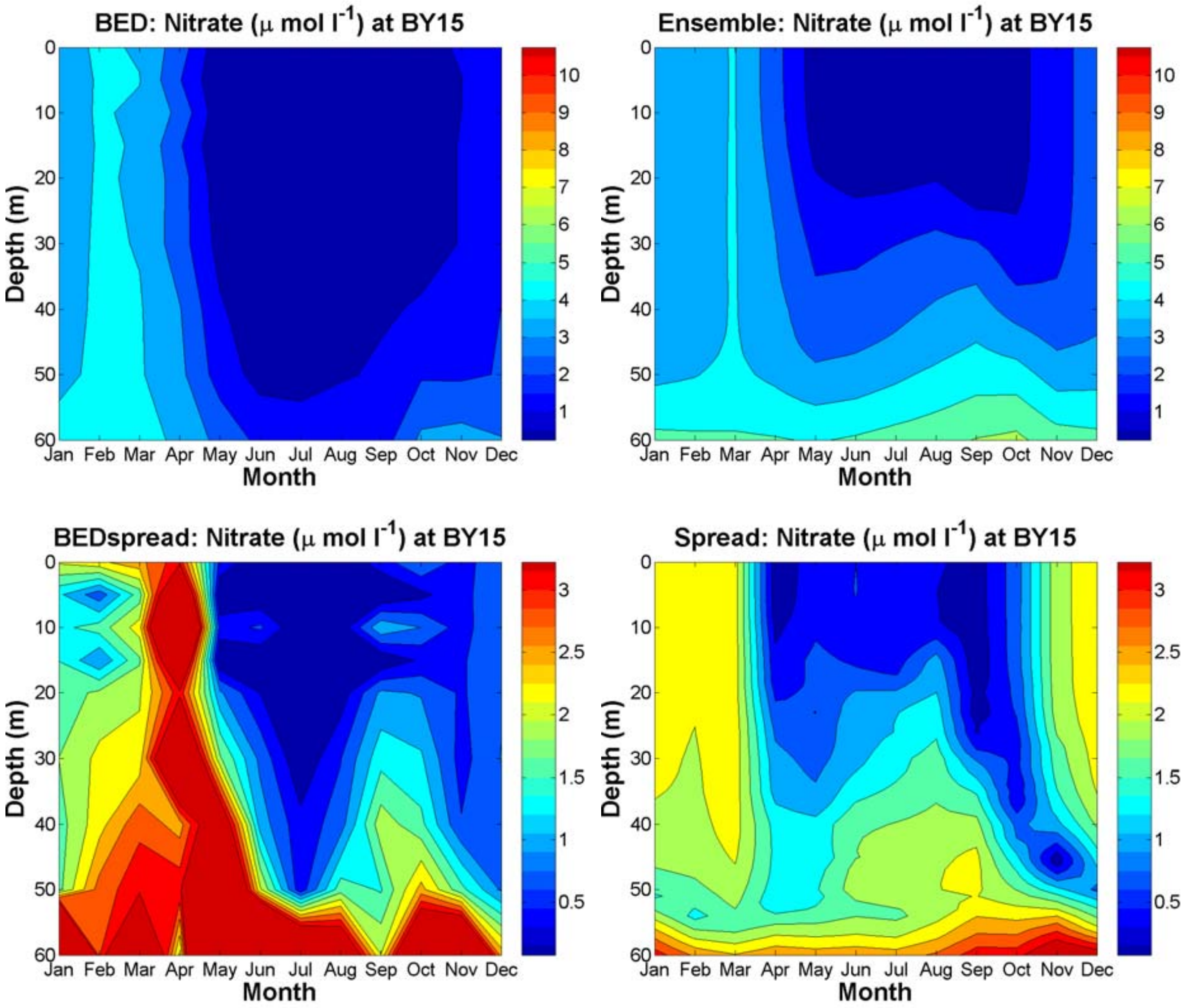

Fig.14. *Annual cycle of monthly average (1970-2005) nitrate (µmolNl^{-1}) concentrations at BY15(upper panels). Results from BED and the ensemble average are shown in the left and right panels, respectively. The corresponding spread of BED data (BEDspread=2 x standard deviation) and the spread between models are shown in the lower panels, respectively.*

3.3 Long-term winter mean average spatial distribution

In order to investigate the spatial variability of the winter nutrient concentrations, the long-term (1995-2005) monthly surface layer (0-10m) mean in March of the different models are compared to comparable statistics from BED observations. For this comparison the ensemble average was not available. The network of monitoring stations that were used for the corresponding computations from BED data are shown in Fig.15.

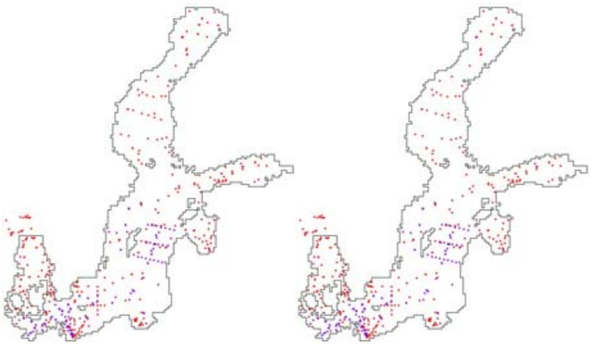

Fig.15. *The stations in BED used for the computation of monthly (March) average (1995-2005) surface layer (0-10m) DIP (left) and DIN (right) concentrations.*

The models reproduce much of the variations characterized by the higher DIP concentrations in the Baltic Proper and especially in the Gulf of Finland as compared to the Bothnian Bay. All models overestimate the DIP concentrations both in the Bothnian Sea. However, the lower DIN concentrations and DIN/DIP ratios in the Baltic Proper as compared to the Bothnian Bay are also in fair agreement with the BED estimation. The model results and BED data differ e.g. in the coastal regions and the differences may be due to both the different horizontal resolution of models, but also to under-sampling of data in the BED data set. Because we use only one month as a reference here, the differences may also be due to regional differences in the onset and temporal evolution of spring phytoplankton production in the models.

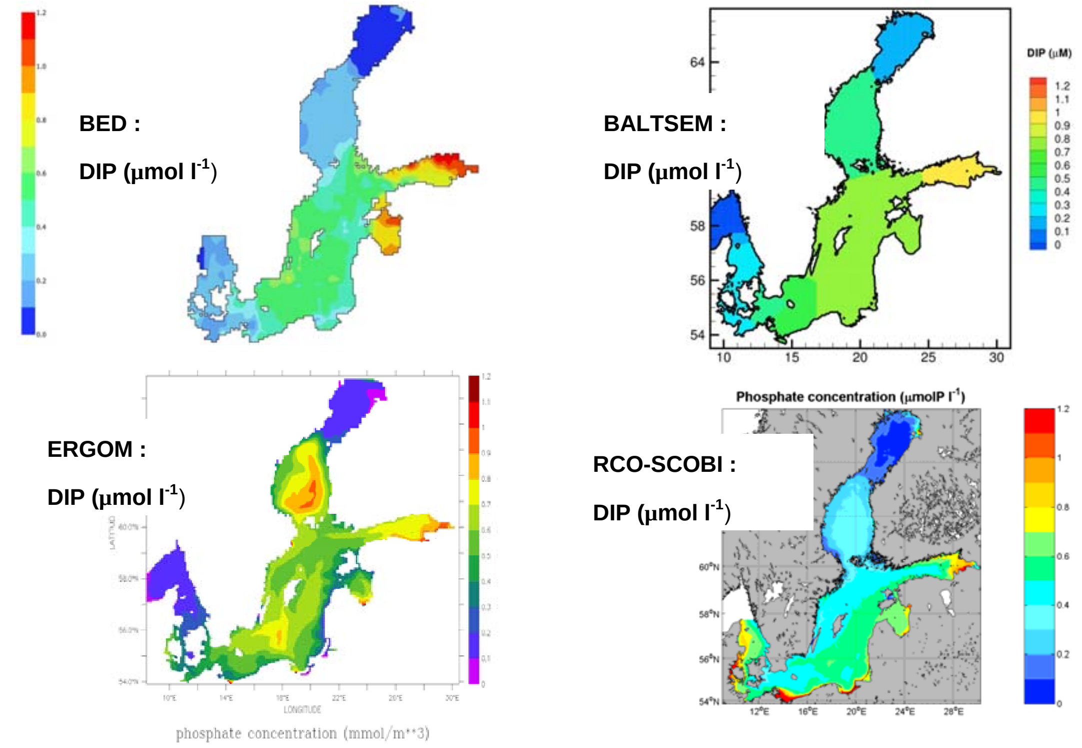

Fig.16. *Monthly (March) average (1995-2005) surface layer (0-10m) DIP (µmolPl^{-1}) concentrations. Results from BED, BALTSEM, ERGOM and RCO-SCOBI are shown in the upper left, upper right, lower left and the lower right panels, respectively. Please, note the different colour scales of the different figures.*

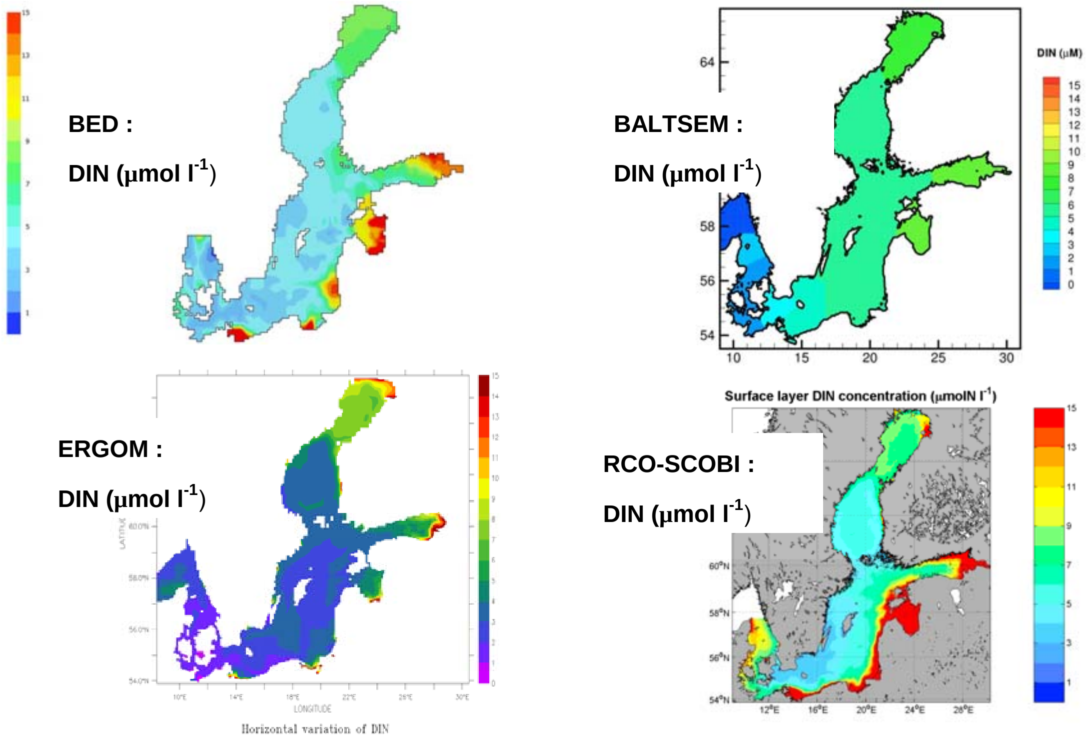

Fig.17. *Monthly (March) average (1995-2005) surface layer (0-10m) DIN (µmolNl^{-1}) concentrations. Results from BED, BALTSEM, ERGOM and RCO-SCOBI are shown in the upper left, upper right, lower left and the lower right panels, respectively. Please, note the different colour scales of the different figures.*

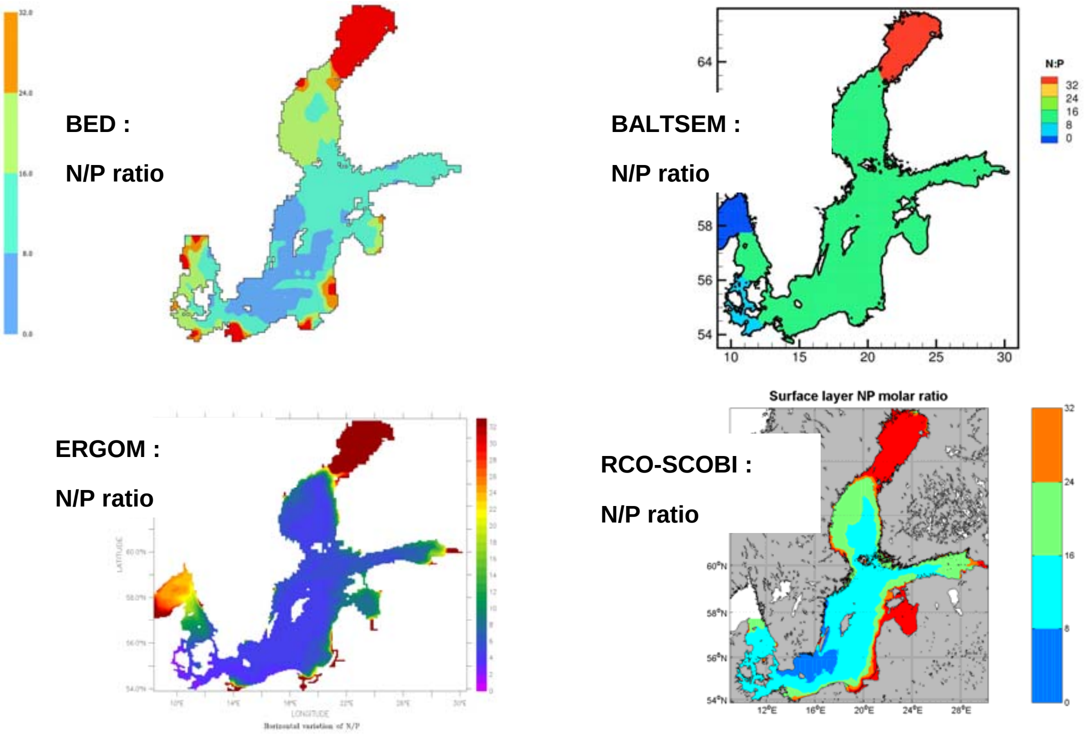

Fig.18. *Monthly (March) average (1995-2005) surface layer (0-10m) DIN to DIP ratio. Results from BED, BALTSEM, ERGOM and RCO-SCOBI are shown in the upper left, upper right, lower left and the lower right panels, respectively. Please, note the different colour scales of the different figures.*

3.4 Nitrogen and phosphorus pools in the Baltic Proper

In order to investigate the interannual variability of the pool of nutrients, the ensemble mean and the spread is compared to the corresponding pools estimated from the BED data. One should mention that the initial conditions of the models were different from the start.

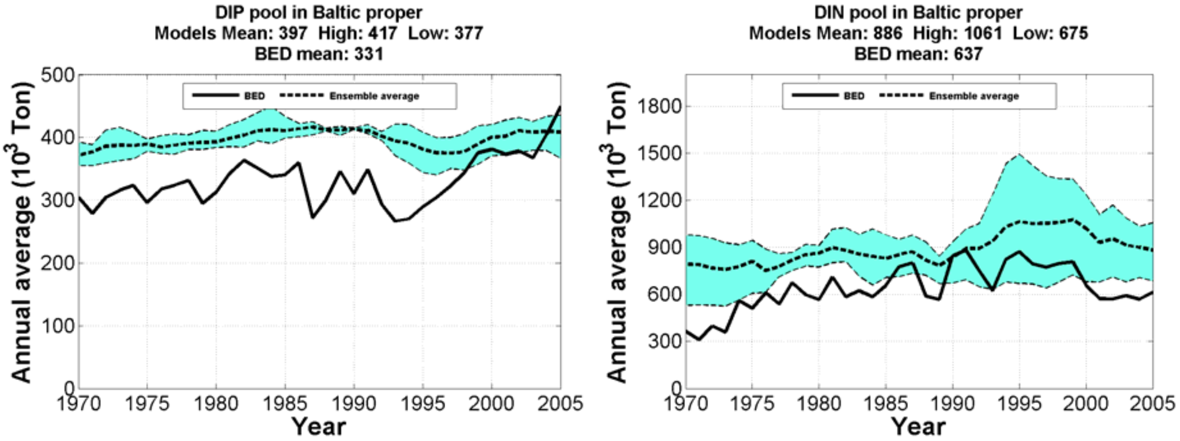

Fig.19. *Annual averages of the integrated pools in the Baltic Proper of DIP (left) and DIN (right). The black solid line indicates the mean value of BED data. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble. The corresponding mean values for the period of the ensemble average, ensemble low range and ensemble high range and the BED data are shown above the figures.*

The ensemble average pools of DIP and DIN in the Baltic Proper are about 400 kton DIP and 890 kton DIN, respectively. The pools of DIP and DIN in the Baltic Proper are on average during the period overestimated relative to the BED estimations by about 20% (70 kton DIP) and 40% (250 kton DIN), respectively. One should mention that the BED estimation of nutrient pools is uncertain to some at present unknown degree since it is based on a restricted number of monitoring stations. The inter-annual variability of the ensemble average is lower than seen from the BED data. The mean ensemble spread is about 10% (40 kton P) and about 40% (390 kton N) of the ensemble average for DIP and DIN, respectively.

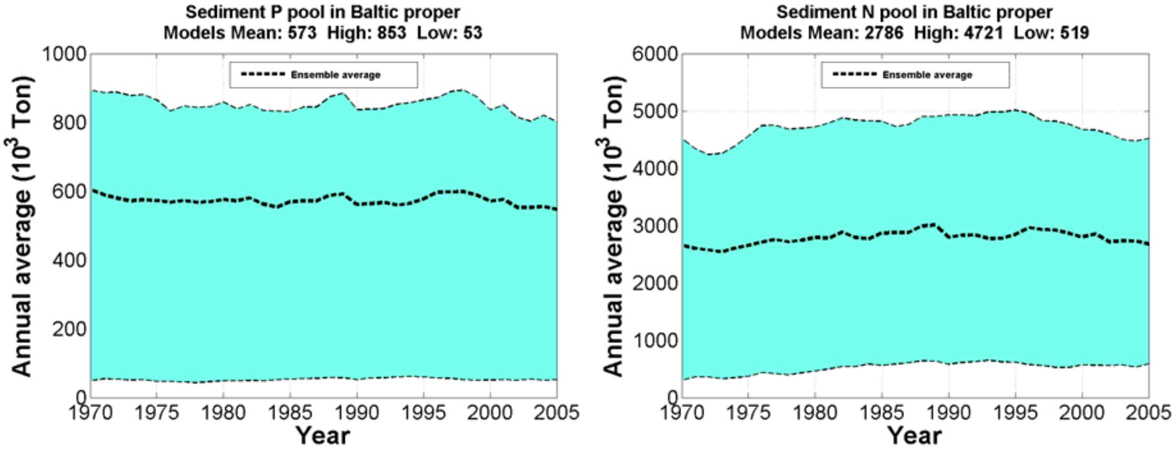

Fig.20. *Annual averages of the integrated pools in the Baltic Proper of DIP (left) and DIN (right). The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble. Observations corresponding to the results are not available. The corresponding mean values for the period of the ensemble average, ensemble low range and ensemble high range are shown above the figures.*

The ensemble average pools of sediment P and N in the Baltic Proper are about 570 kton P and 2790 kton N, respectively. The mean ensemble spread is about 140% (800 kton P) and about 150% (4200 kton N) of the ensemble average for sediment P and N, respectively.

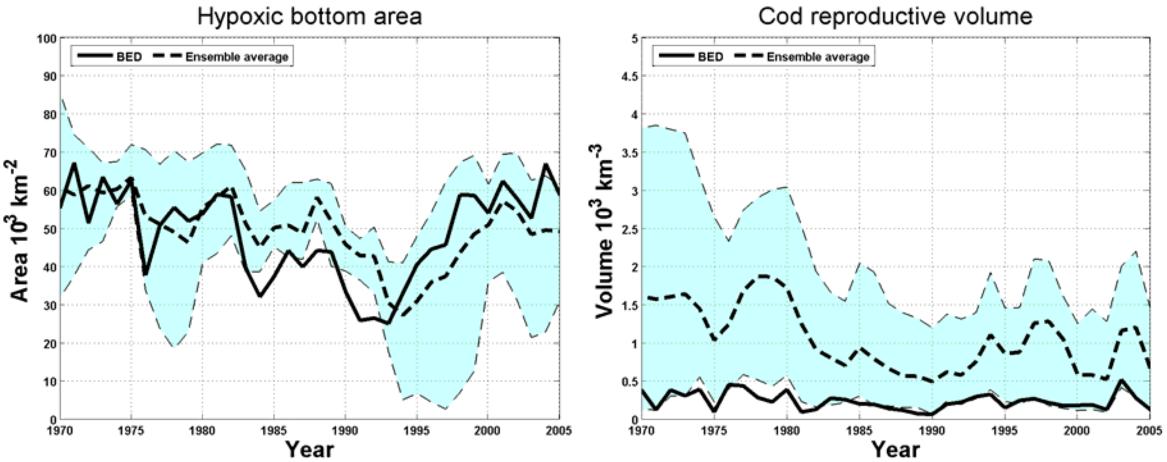

Fig.21 *Annual averages of the integrated area with hypoxic (O_2<2mlO_2l^{-1}) area (left) and the cod reproduction volume (salinity >11 and O_2>2mlO_2l^{-1}) (right) in the Baltic Proper. The black dashed line and the blue shaded area indicate the mean and spread of the model ensemble.*

The variation of hypoxic area in the Baltic Proper is fairly well reproduced by the ensemble mean while the cod reproduction volume and its variability is overestimated relative to BED data. The ensemble spread of hypoxic area is large especially seen during periods of major inflow events. The ensemble spread of cod reproduction area is very large in the beginning of the period but is reduced in the 1980s and forward.

4 Discussion and concluding remarks

This is the first summary of results from the ongoing work with coupled biogeochemical and physical models within the ECOSUPPORT project. The aim of the report was to provide information about the models validation and the state of the art at the start of the project. A second aim was to find new methods on how to describe the results from the model ensemble and how to obtain measures of the uncertainties related to the different model results. The methods will be further discussed and improved if possible during the next coming year of the project.

The results show that all three investigated models as well as the ensemble average are able to reproduce the observed variability of biogeochemical cycles well. One could however point out some poor results for nitrate and phosphate from the ensemble mean in the Gulf of Bothnia and in the deepest parts of the Gulf of Finland. The variation of hypoxic area in the Baltic Proper was reproduced by the ensemble mean while the cod reproduction volume and its variability is overestimated relative to BED data.

A preliminary investigation (not shown) of whether the models ensemble average give better results than the individual models showed that the number of models is hardly sufficient in the present investigation to give any reliable quantitative measure of this. In order to do the quantification it is also necessary to summarize the quality of all variables from each of the models. This task is out of the scope of the present report. The results however indicated that the ensemble mean is relatively strongly influenced by any one model member that by some reason give very poor results in some region.

This first model inter-comparison showed that the differences between the models were found in correlation with time periods and depth layers where the observations had large standard deviations. The most important differences for the uncertainties of modelled processes are however primarily related to differences in the bioavailable fractions of nutrient loadings from land and parameterizations of key processes like sediment fluxes that are presently not well known. The differences between model loadings of N and P in the 1970’s, 1980’s and 1990’s are in the ranges 14-25 % and 42-56 % of the ensemble average supplies, respectively. The spread of the ensemble average pools of sediment P and N in the Baltic Proper are about 140% of the ensemble average for phosphorus and about 150% for nitrogen, respectively.

There are ongoing discussions within the modelling group about the introduction of harmonized nutrient loadings to the models and about the key processes that create uncertainties for the sediment pools and fluxes.

5 Acknowledgement

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