

## **Eutrophication Status Report of the North Sea, Skagerrak, Kattegat and the Baltic Sea: A model study Present and future climate**

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## 2. Introduction

This joint status report for the North Sea, Skagerrak, Kattegat and the Baltic Sea area (Fig.1) is carried out by SMHI (Swedish Meteorological and Hydrological Institute) Sweden, IMR (Institute of Marine Research) Norway, Department of Bioscience Aarhus University Denmark and SPBIO (St.Petersburg Branch, P.P.Shirshov Institute of Oceanology) Russia, as a part of the project “A Baltic and North sea Model eutrophication Assessment in a future climate” (ABNORMAL), supported by the Nordic Council of Ministers’ Sea and Air Group (NMR-HLG). The present project is a follow-up of two earlier projects funded by NMR-HLG: NO COMMENTS and BANSAL. These projects focused on the establishment and maintenance of operational models for the Baltic and North Seas and the use of these to develop methods for assessing the eutrophication status. Within ABNORMAL these issues are brought forward with a focus also on the use of ecological models for an assessment of marine eutrophication in a future climate. The report is a follow-up of a previous reference report (Eilola et al., 2011) of today’s situation, where marine observations and model simulations were used in an assessment of the eutrophication status in the Baltic and the North Seas for the years 2001- 2005, using the proposed method for assessing eutrophication from an ensemble of models and a set of indicators (Almroth & Skogen, 2010).

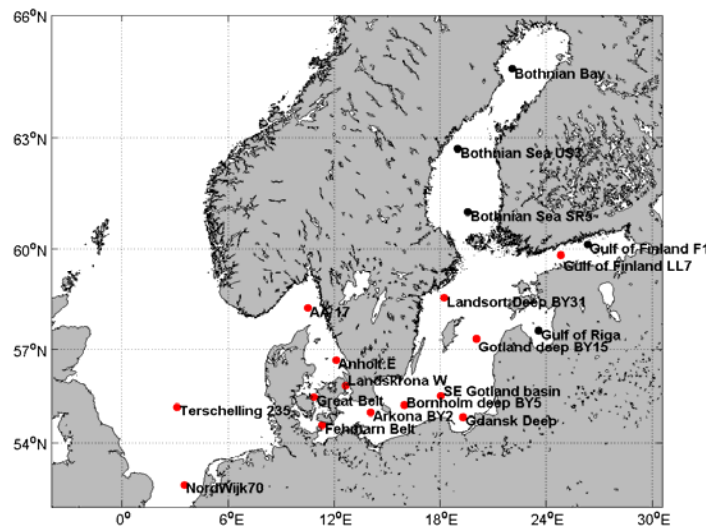


Fig. 1. A map of the North Sea and Baltic Sea area. Monitoring stations with data used for the model validation and estimation of model weights in Eilola et al. (2011) are shown by red dots.

Within HELCOM, eutrophication assessment is based on the method for calculating Ecological Quality Ratio (EQR) (Andersen et al., 2010) for several indicators. The status of the biological quality elements is compared to the reference values, and this gives the Ecological Quality Ratio (Fig.2) and the overall status classification depends on a combination of indicators.

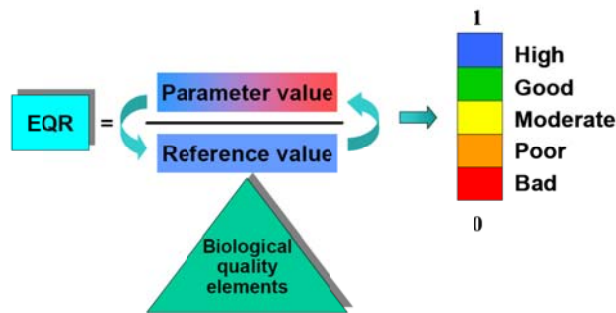


Fig. 2. *Ecological Quality Ratio*

Basically the same method is used in OSPAR, to which the eutrophication assessment of the models in this study is based on. The main difference is in the method of combining the different indicator groups into one assessment. HELCOM uses one-out-all-out principle, which means that the worst value of the biological quality elements is the determining value in each area. OSPAR is using a different approach, where the final assessment is dependent on which parameter that exceeds the limit (see Appendix A for more details).

An assessment of eutrophication status from measurements of all system parameters with a proper resolution in both time and space would be far to time and labour consuming to be desirable due to the complex nature of the system. Therefore, models have become an important tool for evaluating nutrient and ecosystem dynamics. All models have to deal with uncertainties due to limitations in both their forcing and process formulations, and one way to try to reduce uncertainty is to add more models in a study and report on the ensemble mean. For instance in the model-intercomparison study of hydrodynamic models in the Baltic Sea (Eutrophication-Maps, an NMR-funded project) the best results was gained by the ensemble of the 6 participating models (Myrberg et al., 2010). Similar results were obtained for the biogeochemical models evaluated by Eilola et al. (2011b). In BANSAL an integration of observations and a weighted ensemble mean of ecosystem models was used to assess marine eutrophication in the Baltic Sea and North Sea using a set of existing environmental targets for identification of the eutrophication status set by politicians (HELCOM, 2006, OSPAR 2005b). The weights were computed from model accuracy based on model validation exercises using available observations from distinct areas/boxes in the area (Almroth & Skogen, 2010).

The present status report includes assessments both for a control period (1970-2000) and in a future climate situation (2070-2100). The assessment is based on winter nutrients N and P, the winter N:P ratio, summer average chlorophyll and oxygen minimum levels, and a final assessment based on the procedure of Integration of Categorized Assessment Parameters (OSPAR, 2005b). Finally the eutrophication assessment of a future climate is compared to that for the control run. Estimations of region specific background concentrations and threshold values (Almroth & Skogen, 2010) gathered from the literature (Helcom, 2006; OSPAR, 2005b) have in the present study been updated by Oleg Savchuk (BNI Sweden) in personal comm. with Jesper Andersen (DHI, Denmark) to be in accordance with the thematic assessment of Baltic Sea eutrophication status by the HELCOM Eutrophication Assessment Tool (HEAT) (Andersen et al., 2010).

The models, climate scenarios, forcing data and methods of the assessment are described in Section 3. An inter comparison between the hindcast (Eilola et al., 2011), and the weighted



means of the models for the future and control period are presented in Section 4 and the model assessment of eutrophication status is done in Section 5. The results are discussed further in Section 6, while Section 7 is concluding the report and presenting the key messages from the assessment.

### 3. Methods

#### Model descriptions

The model systems used for the joint assessment (Fig. 3) cover different parts of the North Sea, Skagerrak, Kattegat and the Baltic Sea area.

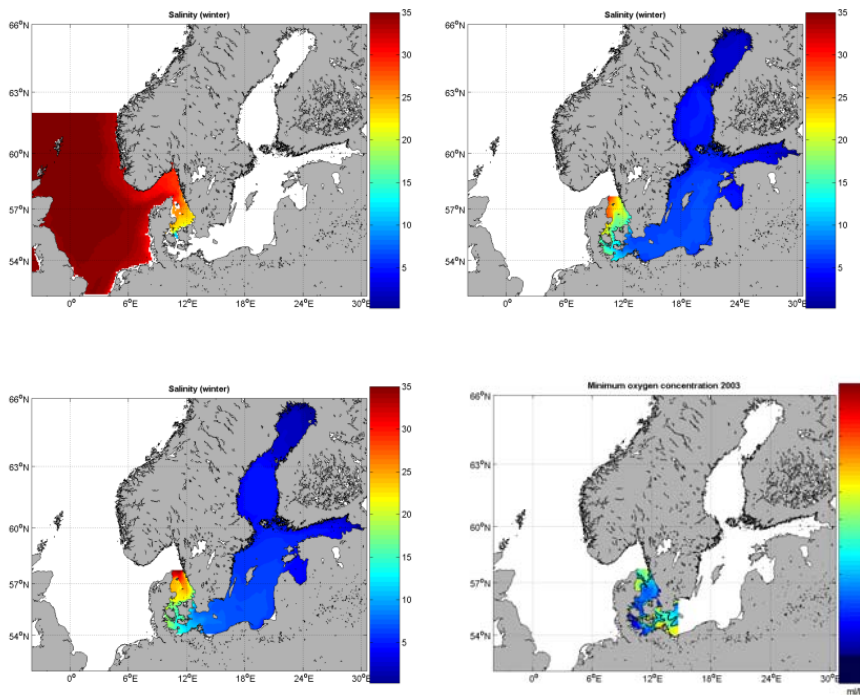


Fig.3. Overview of model domains. The colours indicate salinity in the winter 2001 and summer oxygen (lower right) (Eilola et al., 2011). Upper left: IMR – Norwecom model, upper right: SMHI – RcoSobi model, lower left: SPBEM – model, lower right: Bioscience – model

#### NORWECOM

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical, chemical, biological model system (Skogen et al., 1995; Skogen and Søiland, 1998) applied to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been validated by comparison with field data in the North Sea/Skagerrak in e.g. Søiland and Skogen (2000); Skogen et al. (2004); Skogen & Mathisen (2009) and Hjøllø et al. (2009). The physical model is based on the three dimensional, primitive equation, time dependent, wind and density driven Princeton Ocean Model (POM). In the present study the model is used with a horizontal resolution of 10 km. In the vertical, 20

bottom following sigma layers are used. The chemical-biological model is coupled to the physical model through the subsurface light, the hydrography and the horizontal and the vertical movement of the water masses. The prognostic variables are dissolved inorganic nitrogen (DIN), phosphorous (PHO) and silicate (SI), two different types of phytoplankton (diatoms and flagellates), meso zooplankton, micro zooplankton, two detritus (dead organic matter) pools (N and P), diatomaceous silica (biogenic silica) and oxygen. The simulations started in January 1, 1970 and 2070 respectively with no spin-up. The forcing variables are atmospheric pressure fields and wind stress from the ECHAM5 model (see below), four tidal constituents at the lateral boundaries and freshwater and nutrient river runoffs. Surface heat fluxes are calculated using data available from the ECHAM5 forcing, while initial values and open boundary conditions are taken from monthly climatologies (Martinsen et al., 1992). The river data are monthly means (or climatologies if not available) for the main European rivers for the period 1970-2000, and the same data is used for the 2070-2100 period (only shifted by 100 years).

#### *RCO-SCOB*

RCO-SCOB is a coupled physical-biogeochemical model for the Baltic Sea consisting of the Swedish Coastal and Ocean Biogeochemical model (SCOB) and the Rossby Centre Ocean model (RCO) (Eilola et al., 2009; Meier et al., 2011a). RCO is a Bryan-Cox-Semtner primitive equation circulation model with a free surface (Killworth et al., 1991) and open boundary conditions following Stevens (1991) in the northern Kattegat (Fig.3). In the present study, RCO was used with a horizontal resolution of 3.7km (2 nautical miles) and with 83 vertical levels with layer thicknesses of 3m. SCOB describe the dynamics of nitrate, ammonium, phosphate, phytoplankton, zooplankton, detritus, and oxygen. Phytoplankton consists of three algal groups representing diatoms, flagellates and others, and cyanobacteria (corresponding to large, small and nitrogen fixing cells). The growth rates depend on nutrient concentrations, irradiance, and water temperature. The modeled cyanobacteria also have the ability to fix molecular nitrogen. Organic matter sinks and enters the sediment containing benthic nitrogen and phosphorus. The sediment processes include oxygen dependent nutrient regeneration and denitrification as well as permanent burial of nutrients. With the help of a simplified wave model the combined effect of waves and current induced shear stress is considered to calculate resuspension of organic matter (Almroth-Rosell et al., 2011). The run with RCO-SCOB started in 1961 and finished in 2099. For the description of nutrient and freshwater loads: See SPBEM description.

#### *SPBEM*

The St. Petersburg Baltic Eutrophication Model (SPBEM) is an existing eco-hydrodynamic model that includes 3D hydrodynamic ocean-sea ice module (Neelov et al., 2003; Myrberg et al., 2010) and biogeochemical (BGC) module developed by Savchuk (2002). The hydrodynamic module includes original *k-l* turbulent closure scheme for vertical mixing and uses Arakawa B spherical grid. The BGC module describes nutrient cycling in the coupled pelagic and sediment sub-systems and contains 12 pelagic (zooplankton, diatoms, cyanobacteria, flagellates, nitrogen, phosphorus and silica detritus, ammonium, nitrite + nitrate, phosphate, silicate and dissolved oxygen) and 3 sediment (benthic nitrogen, phosphorus and silica) state variables. The model version used to simulate the state of the Baltic Sea had horizontal resolution 5 nm and 71 levels with  $dz=2m$  in the layer (0, 100m),  $dz=5m$  in the layer (100 m, bottom).

The prescribed mean monthly riverine discharges in the period considered (1961-2100) were calculated using a statistical model for 5 different basins (Bothnia Bay, Bothnia Sea, Gulf of

Finland, Central Baltic, Kattegat) on the basis of the difference of precipitation minus evaporation for corresponding watershed obtained from RCAO (Meier et al., 2011c). River loads are calculated as the product of concentration of nutrients and the riverine discharge and are prescribed as mean monthly values in the period 1961-2007 in the accordance with (Stålnacke et al., 1999) and more recent estimates of O.Savchuk (personal message). Concentrations in rivers and point sources are assumed constant after 2007 and equal to their average values in the period 1995 -2002. Atmospheric deposition of nitrogen and phosphorus were set equal to their climatic averages. The run with SPBEM started in 1961 and finished in 2009. The initial fields of temperature, salinity, phosphate, nitrate+nitrite, silicon were constructed from the data available in the Baltic Environmental Database (<http://nest.su.se/bed>) for three wintertime months (December – February) of four consecutive years (1961 – 1965).

#### *Bioscience model*

The Bioscience model (Bendtsen et al 2009) is a nested high resolution circulation model covering the Kattegat, the Belt Sea and the western Baltic Sea e.g. the transition zone between the North Sea and the Baltic. The model is based on the COHERENS model (Luyten et al., 1999), which is a primitive equation three dimensional circulation model. The model is formulated on a 2 x 2 nautical mile horizontal spherical grid (approximately 3700 m x 3700 m) with 30 vertical sigma layers and covers the region from northern Kattegat to the Arkona Sea. The water level along the open boundaries is determined from a regional 4 x 4 nautical mile resolution model of the whole North Sea and Baltic Sea area. Temperature and salinity at the open boundaries are determined from observations at sta.1004 (58.9 °N, 11.3 °E) just north of the model domain and data from a station in Hanöbugten (55.62 °N, 14.87 °E) close to the eastern open boundary. Measurements for about every month in the period have been interpolated linearly in time and in the vertical and are also horizontally uniform along the boundaries. Vertical mixing is based on a  $k-\epsilon$  turbulence scheme and a convective adjustment scheme when the water column becomes unstable. The model setup has been analyzed for the period 2001 – 2003 and validated against temperature, salinity, and water level in the area (Bendtsen et al. 2009).

In addition to temperature and salinity, the model also solves transport equations for a conservative tracer ( $c$ ), an age tracer ( $a$ ) and oxygen ( $O_2$ ) (Bendtsen et al. 2009). The Oxygen dynamics in the 3D model is based on a model of the OXYgen CONsumption; OXYCON which is a much simplified relative to oxygen calculations in the biogeochemical models. OXYCON parametrises pelagic and benthic oxygen sinks as described in detail in Hansen and Bendtsen (2012) and Bendtsen and Hansen (2012).

The model considers the oxygen consumption that results from an annual primary production of  $160 \text{ g C m}^{-2} \text{ yr}^{-1}$  and the control runs 2001-2003 show a very good correspondence with observations (Hansen and Bendtsen 2012). The climate scenarios consider a 3 °C warmer climate compared to the present day conditions. This is more or less in the middle of the range of projected temperatures by 2100 (IPCC 2007) and the resulting water column temperature also corresponds fairly well with previous model studies of the transition zone (BACC 2008). Appendix B.

#### **Regional climate data sets**

Two climate change scenario simulations have been available to force the ecosystem models. The forcing was calculated applying a dynamical downscaling approach using the regional climate model RCAO, Rossby Centre Atmosphere Ocean model (Döscher et al., 2002). The lateral boundary data was from two GCMs, ECHAM5/MPI-OM from the Max Planck Institute for Meteorology in Germany (Roeckner et al. 2006; Jungclaus et al. 2006) and

HadCM3 from the Hadley Centre in the UK (Gordon et al. 2000). HadCM3 and ECHAM5 simulations were both forced with the A1B greenhouse gas emission scenario. All ecosystem models were used to run simulations forced by the ECHAM5 model and results are reported for two 30 year periods (1970-2000 and 2071-2100). In addition the SPBEM and RCO-SCOB models were also run using the HadCM3 model to investigate the robustness of the results. The details of the downscaling method and the quality of the atmospheric forcing fields are discussed by Meier et al. (2011b). The climate scenario in the Bioscience model describes a situation where the water column was 3 °C warmer but the hydrography was otherwise identical to the reference conditions 2001-2003.

### Weighted ensemble mean

Since the accuracy of models differs between parameters and areas, a weighted average value of the models has been used to calculate the environmental assessments (Almroth & Skogen, 2010). The weighted model average value (WMA) between the models is defined as:

$$WMA = C \times \sum_{i=1}^N (W_i \times M_i),$$

Where  $M_i$  is defined in all points (x,y) and is the value from model  $i$ , and  $C$  is defined as:

$$C = \frac{1}{\sum_{i=1}^N W_i}.$$

$W_i$  is the corresponding weight defined as  $W_i = 1/(C_i+B)$ , where  $C_i$  is the cost function value (Anon., 1998) for model  $i$  for the actual assessment parameter and area, and  $B$  is a constant used to avoid the weight of one or several models going to infinity when  $C_i$  becomes small. In our example, we have used  $B = 0.1$ . The weighted average value was calculated for all assessment parameters. In areas without observations a simple average between the models was used hence assuming that  $W$  is equal for all models in these areas.

In the lack of data in a future climate to compute the individual cost functions (and thereby the weights), the values estimated and used in Eilola et al. (2011) have been used for all models, parameters and areas. Data for these computations are taken from various databases, and positions are shown in Figure 1. For more details please refer to Eilola et al., (2011).

### Eutrophication assessment

To assess eutrophication the OSPAR CP (OSPAR 2005a) distinguishes between parameters in four different categories (see Almroth & Skogen, 2010): degree of nutrient enrichment (Cat. I), direct effects of nutrient enrichment (II), indirect effects of nutrient enrichment (III), and other possible effects of nutrient enrichments (IV). Several of these (winter DIN and DIP and the DIN:DIP ratio (Cat. I), chlorophyll\_a (II), and oxygen (III)) can easily be explored by models and, in accordance with current management practices, these parameters have been investigated and reported in this study. The agreed EcoQO for eutrophication is that winter DIN and DIP should be below elevated levels, defined as >50% above the background/reference concentration, and that chlorophyll\_a mean value during the growing season should remain below elevated levels, defined as >50% above the spatial (offshore) or historical background concentration. For oxygen, the agreed EcoQO is that the concentrations should be above oxygen deficiency levels. In this study, reference and threshold values for the Baltic Sea, the Danish Straits, the Öresund, and the Kattegat are from HELCOM (2006). For Skagerrak and the North Sea, the reference values and threshold values are from OSPAR (2005b), except for DIN and DIP for the central and northern North Sea, which are taken from

NSTF (1993). For the N:P ratio, a few area specific reference values are found in HELCOM (2006), whereas OSPAR uses the Redfield ratio (16:1) as reference for the whole North Sea (OSPAR 2005b). In areas without an N:P reference value, the Redfield ratio has been used, and the EcoQO for the N:P ratio are set to  $\pm 50\%$ , in accordance with the OSPAR CP. Table 1 provides an overview of the assessment levels that have been used in this study. In total, 23 different areas are classified. The assessment areas with separate threshold values are described by colors and basin numbers in Fig. 4. The average salinity from the models is used where the area specific threshold value is within a salinity range. The final classification of eutrophication status in the different basins in the model area is done using three categories: problem area, potential problem area, and non-problem area. An area is said to be a potential problem area if there are elevated levels of nutrients (Cat. I) relative to the actual threshold values used in that assessment area. To become a problem area, there has to be an elevated level in the direct (chlorophyll) or indirect (oxygen) effects. This classification is based on the procedure of Integration of Categorized Assessment Parameters as suggested in the OSPAR CP (OSPAR 2005a), except that in this study, the HELCOM classification (HELCOM 2006) is used for the oxygen status.

For the evaluation of results the following definitions will be used:

- *Surface layer* = Average for the depth interval 0-10m. For the model results we use the 5m model value to represent the surface layer.
- *Winter* = Average for the period January-February
- *Summer (production period)* = Average for the period March-October
- *Late summer for oxygen* = Average for the period August-September

The assessment has been based on two 30 year periods (control period 1970-2000 and future climate 2070-2100), and the results presented is the individual weighted means over these periods. In the Skagerrak and North Sea only values from IMR were used. In the Kattegat IMR, SMHI and SPBEM models are included, while in the Danish Straits, Öresund and the Baltic Sea only the SMHI and SPBEM model values were used. The assessment areas with separate threshold values are described by colors and basin numbers (Bnr) in Fig.4.

The NERI model that covers Kattegat, Öresund and Baltic east of Bornholm is conceptually very different from the other models. It has not been included directly in the assessment, but the predicted oxygen changes have been included in the discussion to investigate the sensitivity of that assessment.

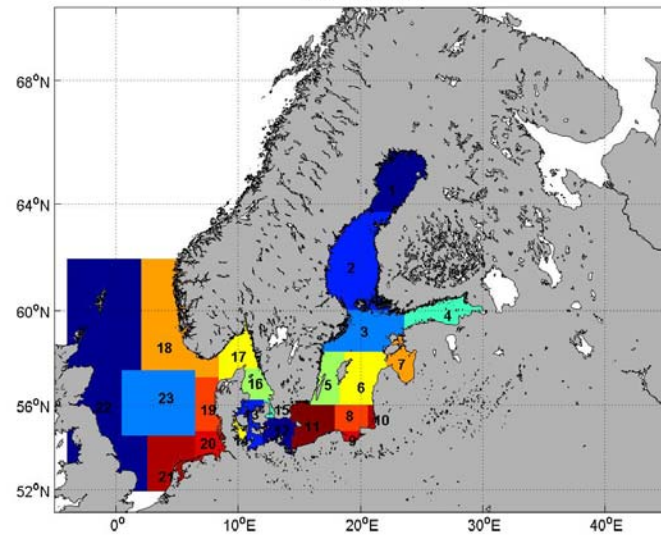


Fig. 4. *The North Sea, Skagerrak, Kattegat and the Baltic Sea are divided into 23 sub-basins with separate threshold values for the ecological quality indicators. Areas in each basin have same assessment threshold values. Areas west of Great Britain are not included in the assessment.*



Table 1. Reference values and threshold values used in the present report with origin from Helcom (2006) and OSPAR (2005b) and Almroth and Skogen (2010) and revision by O. Sachuk in pers. comm. with Jesper Andersen.

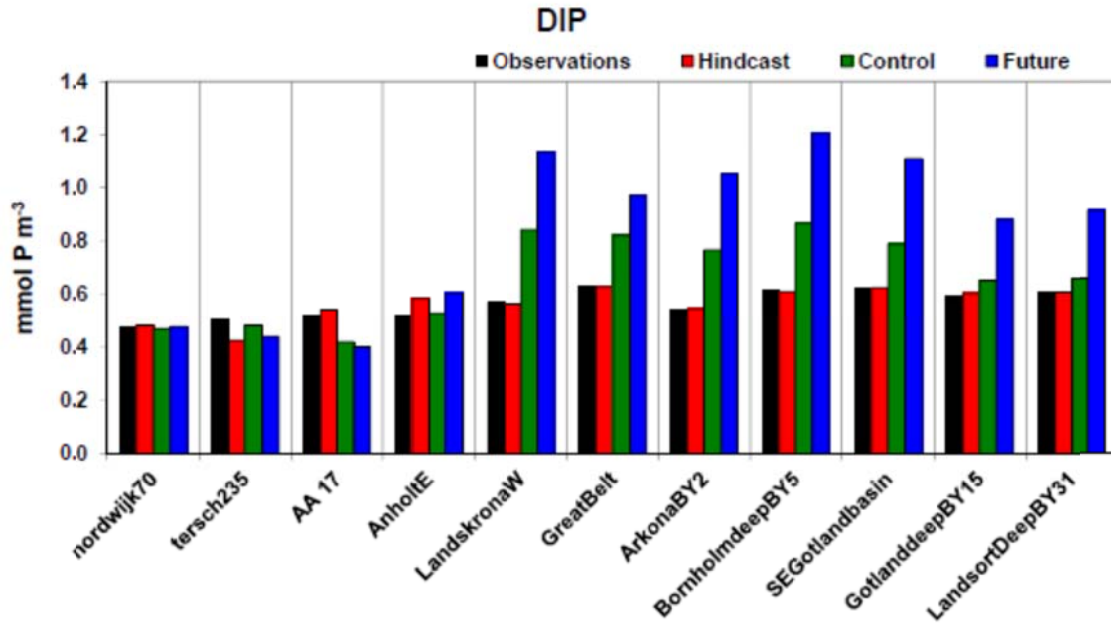
			DIN	DIP	N/P	CHL	DIN	DIP	N/P	CHL
			Winter	Winter	Winter	Summer	Winter	Winter	Winter	Summer
Basin	Basin	Salinity	ref.	ref.	Ref.	ref.	thres.	thres.	thres.	thres.
Nr.	Names	range	value	value	value	Value	value	value	value	value
		psu	μmol/l	μmol/l	-	μg/l	μmol/l	μmol/l	Hi/Lo	μg/l
1	Bothnian Bay	>0	3.50	0.10	16.00	1.30	5.25	0.15	24.0/8.0	1.95
2	Bothnian Sea	>0	2.00	0.20	16.00	1.00	3.00	0.30	24.0/8.0	1.50
3	Northern Gotland Basin	>0	2.00	0.25	16.00	1.10	3.00	0.38	24.0/8.0	1.65
4	Gulf of Finland	>0	2.50	0.50	16.00	1.20	3.75	0.75	24.0/8.0	1.80
5	Western Gotland Basin	>0	2.00	0.25	16.00	1.00	3.00	0.38	24.0/8.0	1.50
6	Eastern Gotland	>0	1.40	0.20	16.00	1.20	2.10	0.30	24.0/8.0	1.80
7	Gulf of Riga	>0	6.60	0.13	16.00	1.80	9.90	0.20	24.0/8.0	2.70
8	South east Gotland B	>0	2.50	0.25	10.00	0.70	3.75	0.38	15.0/5.0	1.05
9	Gdansk deep	>0	4.25	0.25	17.00	-	6.38	0.38	25.5/8.5	4.50
10	Lithuanian water	>0	5.00	0.30	16.00	3.00	7.50	0.45	24.0/8.0	4.50
11	Bornholm basin	>0	2.00	0.25	16.00	1.20	3.00	0.38	24.0/8.0	1.80
12	Arkona Basin	>0	2.25	0.27	16.00	1.20	3.38	0.41	24.0/8.0	1.80
13	Danish straits	>0	1.83	0.22	16.00	0.55	2.74	0.33	20.0/12.0	0.82
14	Danish straits	>0	1.25	0.48	16.00	0.90	1.56	0.60	20.0/12.0	1.13
15	Oeresund	>0	-	-	16.00	1.70	1.56	0.60	20.0/12.0	2.13
16	KattegatS	>0	3.70	0.51	11.25	0.80	5.55	0.76	14.1/8.4	1.20
17	Skagerrak	>0	10.00	0.60	16.00	1.50	15.00	0.90	25.0/8.0	2.00
18	NorthSeaNE	>0	-	0.60	16.00	3.00	13.50	0.80	25.0/8.0	4.50
19	NorthSeaDenmark	< 34.5	15.00	0.60	16.00	6.00	26.00	0.80	25.0/8.0	9.00
19	NorthSeaDenmark	>= 34.5	10.00	0.65	16.00	3.00	12.50	0.80	25.0/8.0	4.50
20	NorthSeaSE	< 34.5	12.50	0.55	16.00	3.00	19.00	0.83	25.0/8.0	4.50
20	NorthSeaSE	>= 34.5	8.50	0.60	16.00	2.00	13.00	0.90	25.0/8.0	3.00
21	NorthSeaSV	< 34.5	19.00	0.60	16.00	10.00	28.50	0.80	25.0/8.0	15.00
21	NorthSeaSV	>= 34.5	-	-	16.00	3.00	15.00	0.80	25.0/8.0	4.50
22	NorthSeaV	< 34.5	15.50	0.80	16.00	10.00	21.00	1.20	25.0/8.0	20.00
22	NorthSeaV	>=34.5	10.00	0.80	16.00	7.50	15.00	1.20	25.0/8.0	10.00
23	NorthSeaC	> 0	8.00	0.60	16.00	-	12.00	0.90	25.0/8.0	10.00

#### 4. Model validation

A validation of the individual models was done in Eilola et al., (2011) where the cost functions were computed for the stations in Table 1. These cost functions were then used to compute the individual weights as described in the previous section. For completeness the cost functions for the hindcast period that are used in the present assessment are given in Tables 2-6. A validation of the control period based on the same data is difficult since the atmospheric forcing from the climate model should only represent the correct statistics of the period. The quality of the ECHAM5 forcing has been investigated by Meier et al. (2011b), and their conclusion was that the mean winter air temperature especially in the northern Baltic Sea was generally too warm. Otherwise, the results were satisfactory. This limitation in the forcing (compared to the *real* situation) will of course have an impact on the quality of the simulation for the control period. Also the fact that the 30 years control period and the 5 years hindcast period do not overlap, and that the river runoffs are different will make a difference. To get an idea of the integrated effects of these differences, the weighted means of the models for some stations have been compared to observations and the weighted mean of the hindcast simulations in Figures 5-9. Finally, the weighted mean for the future climate is given for comparison.

Generally, the DIP values in the control period are too high from the Danish straits and towards the south of Gotland (Figure 5) compared to the hindcast and observations, while the DIN values are too low in the straits and the Bornholm deep and too high in the Gotland and Landsort deeps (Figure 6). Chlorophyll values (Figure 8) are up a factor two higher in the control compared to the hindcast in the North Sea and Skagerrak, while it is down around 50% in the Baltic stations. Comparing the control and the future climate values the general pattern, with a few exceptions, is that the nutrients and the chlorophyll increase, while oxygen is reduced.

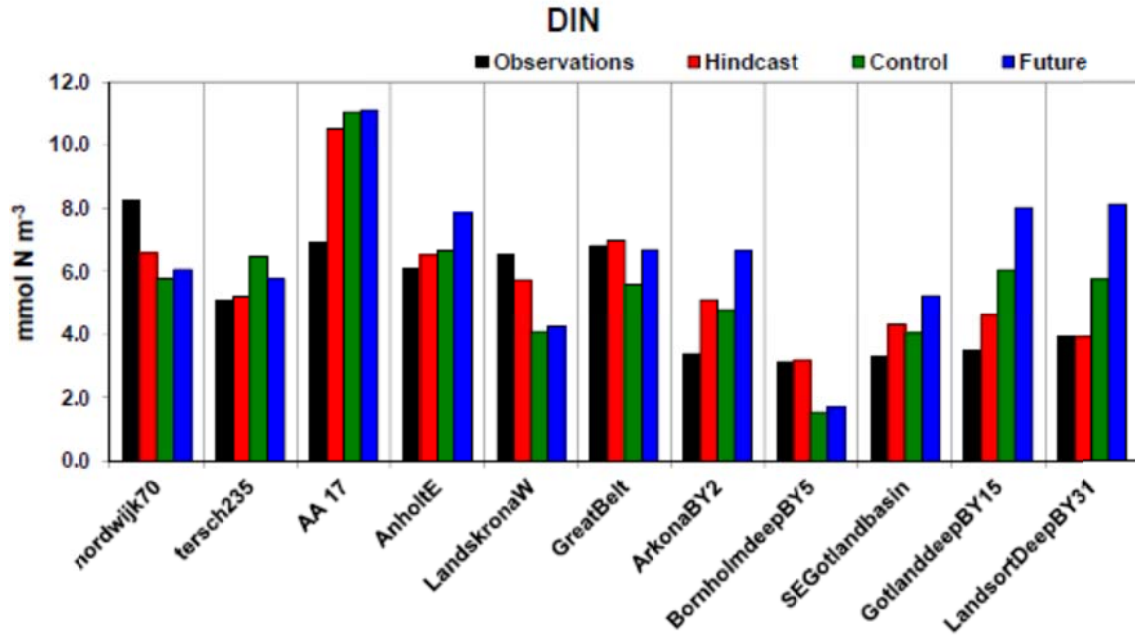




Observations 0-10m in January-February		DIP	DIP	Model values DIP Mv			Cost function values DIP		
Period	Station	Mv	Sd	SMHI	IMR	SPBIO	SMHI	IMR	SPBIO
2001-2005	AA 17	0.52	0.04	-	0.54	-	-	0.6	-
2001-2005	AnholtE	0.51	0.06	0.67	0.46	0.56	2.7	0.9	0.7
2001-2005	ArkonaBY2	0.54	0.16	0.45	-	0.67	0.6	-	0.8
2001-2005	BornholmdeepBY5	0.61	0.17	0.38	-	0.78	1.4	-	1.0
2001-2005	GotlanddeepBY15	0.59	0.18	0.51	-	0.89	0.5	-	1.7
2001-2005	GreatBelt	0.63	0.12	0.73	0.60	0.62	0.8	0.3	0.1
2001-2005	LandskronaW	0.57	0.09	0.47	-	0.57	1.1	-	0.0
2001-2005	LandsortDeepBY31	0.60	0.19	0.36	-	0.93	1.3	-	1.7
2001-2005	nordwijk70	0.48	0.09	-	0.48	-	-	0.1	-
2001-2005	SEGotlandbasin	0.62	0.18	0.55	-	0.72	0.4	-	0.6
2001-2005	tersch235	0.50	0.11	-	0.42	-	-	0.7	-

Fig. 5. Average surface layer winter DIP ( $\mu\text{mol P l}^{-1}$ ) of the observations (black), weighted model mean of hindcast from Eilola et al. (2011) (red), weighted model mean of control period (green) and weighted model mean of future climate (blue). See Fig. 1 for location of stations.

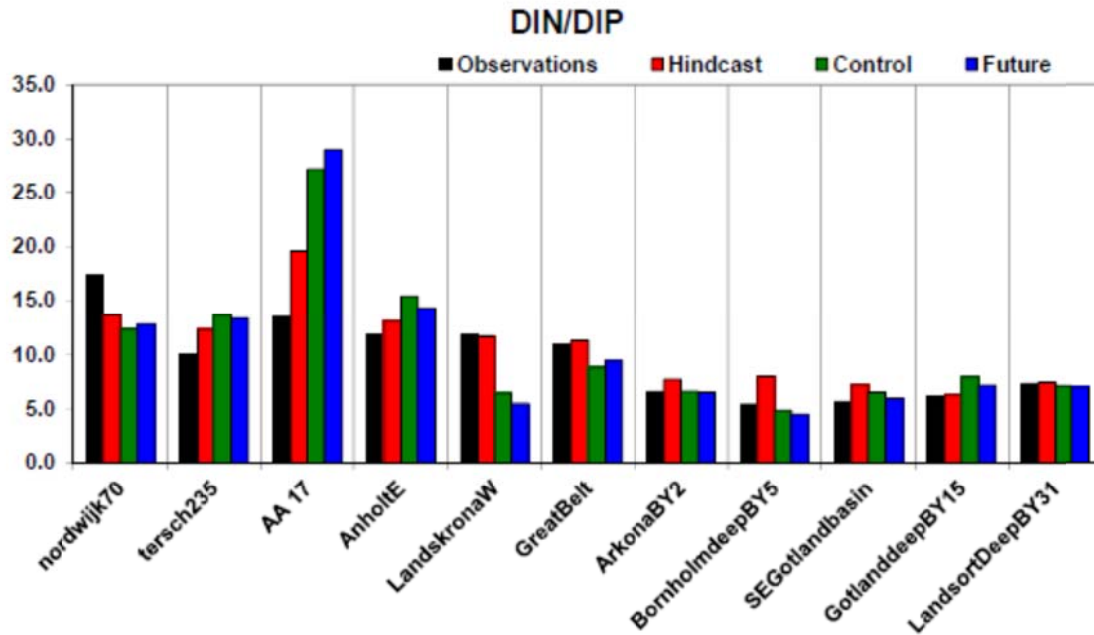
Table 2. Average surface layer winter DIP ( $\mu\text{mol P l}^{-1}$ ) of the observations (yellow header) and the individual models (blue header) is shown with the corresponding cost function values (golden header) in the right columns, from Eilola et al., 2011.



Observations 0-10m in January-February		DIN Mv	DIN Sd	Model values DIN Mv			Cost function values DIN		
Period	Station			SMHI	IMR	SPBIO	SMHI	IMR	SPBIO
2001-2005	AA 17	6.90	1.02	-	10.53	-	-	3.5	-
2001-2005	Anholte	6.07	0.62	10.68	10.30	5.63	7.4	6.8	0.7
2001-2005	ArkonaBY2	3.39	0.86	5.24	-	4.96	2.2	-	1.8
2001-2005	BornholmdeepBY5	3.13	0.64	2.98	-	6.06	0.2	-	4.6
2001-2005	GotlanddeepBY15	3.45	0.42	4.71	-	4.52	3.0	-	2.6
2001-2005	GreatBelt	6.82	1.22	10.10	7.03	6.31	2.7	0.2	0.4
2001-2005	LandskronaW	6.55	1.12	6.08	-	4.18	0.4	-	2.1
2001-2005	LandsortDeepBY31	3.91	0.40	4.27	-	3.68	0.9	-	0.6
2001-2005	nordwijk70	8.27	2.52	-	6.57	-	-	0.7	-
2001-2005	SEGotlandbasin	3.30	0.37	4.05	-	4.85	2.0	-	4.2
2001-2005	tersch235	5.07	1.84	-	5.19	-	-	0.1	-

Fig. 6. Average surface layer winter DIN ( $\mu\text{mol N l}^{-1}$ ) of the observations (black), weighted model mean of hindcast from Eilola et al. (2011) (red), weighted model mean of control period (green) and weighted model mean of future climate (blue). See Fig. 1 for location of stations.

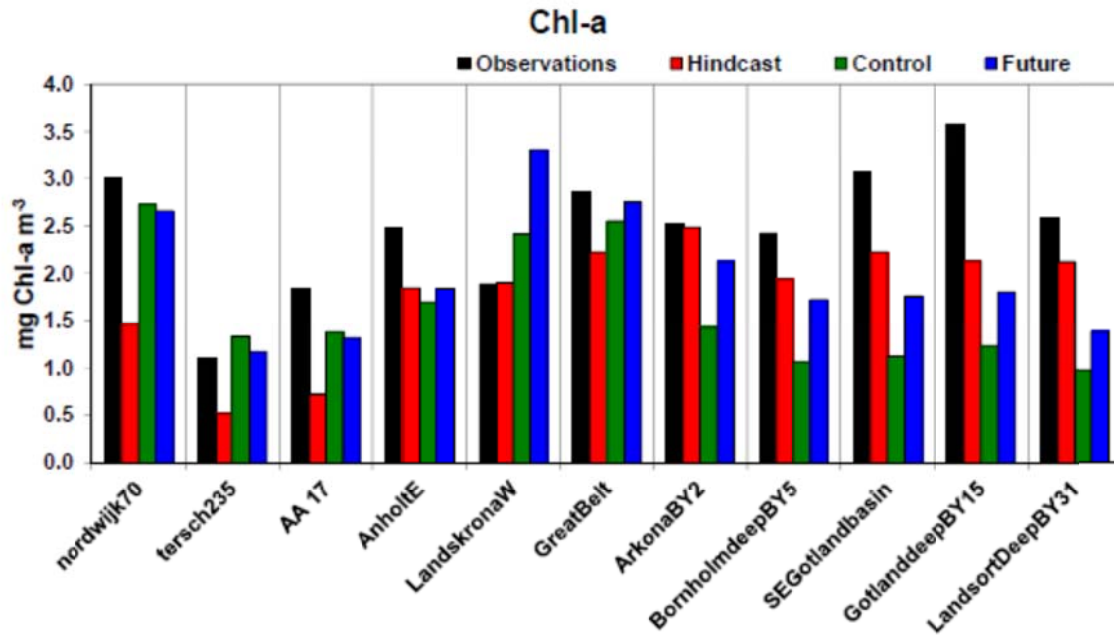
Table 3. Average surface layer winter DIN ( $\mu\text{mol N l}^{-1}$ ) of the observations (yellow header) and the individual models (blue header) is shown with the corresponding cost function values (golden header) in the right columns, from Eilola et al., 2011.



Observations 0-10m in January-February		DIN/DIP		Model values DIN/DIP Mv			Cost function values DIN/DIP		
Period	Station	Mv	Sd	SMHI	IMR	SPBIO	SMHI	IMR	SPBIO
2001-2005	AA 17	13.43	2.05	-	19.59	-	-	3.0	-
2001-2005	Anholte	11.86	1.39	16.24	22.37	10.10	3.2	7.6	1.3
2001-2005	ArkonaBY2	6.54	1.72	11.32	-	7.11	2.8	-	0.3
2001-2005	BornholmdeepBY5	5.32	1.36	8.10	-	7.81	2.0	-	1.8
2001-2005	GotlanddeepBY15	6.09	2.12	9.47	-	5.13	1.6	-	0.5
2001-2005	GreatBelt	10.86	1.19	13.94	11.71	10.04	2.6	0.7	0.7
2001-2005	LandskronaW	11.81	2.93	13.19	-	7.11	0.5	-	1.6
2001-2005	LandsortDeepBY31	7.27	3.17	13.25	-	4.06	1.9	-	1.0
2001-2005	nordwijk70	17.31	3.25	-	13.67	-	-	1.1	-
2001-2005	SEGotlandbasin	5.62	1.38	7.88	-	6.78	1.6	-	0.8
2001-2005	tersch235	9.90	1.50	-	12.29	-	-	1.6	-

Fig. 7. Average surface layer winter DIN:DIP ratio of the observations (black), weighted model mean of hindcast from Eilola et al. (2011) (red), weighted model mean of control period (green) and weighted model mean of future climate (blue). See Fig. 1 for location of stations.

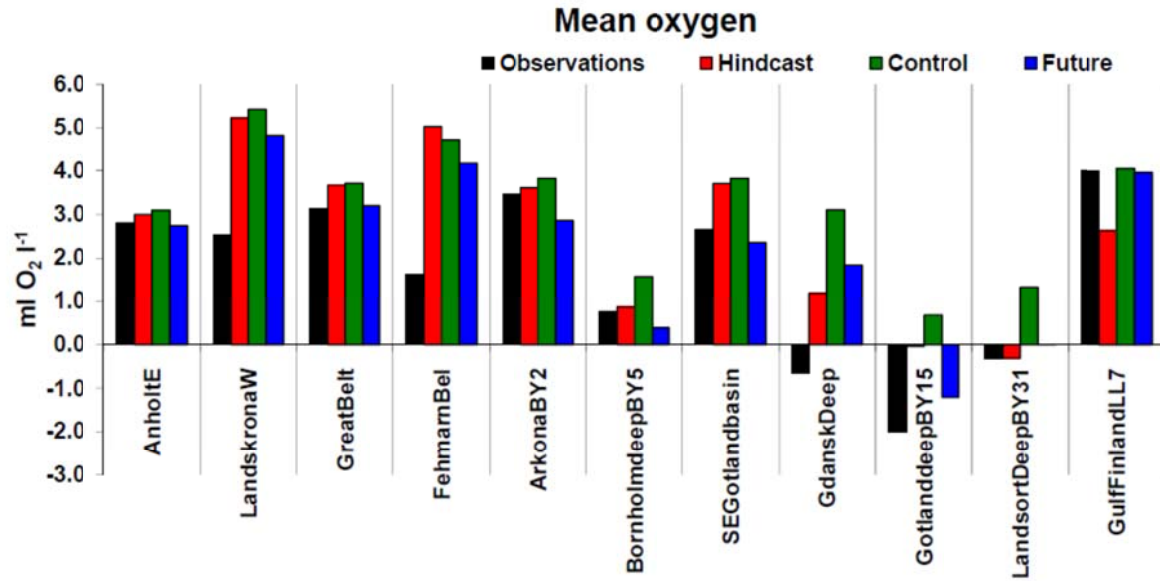
Table 4. Average surface layer winter DIN:DIP ratio of the observations (yellow header) and the individual models (blue header) is shown with the corresponding cost function values (golden header) in the right columns, from Eilola et al., 2011.



Observations 0-10m in March-October		Chl	Chl	Model values Chl Mv			Cost function values Chl		
Period	Station	Mv	Sd	SMHI	IMR	SPBIO	SMHI	IMR	SPBIO
2001-2005	AA 17	1.84	1.02	-	0.72	-	-	1.1	-
2001-2005	AnholtE	2.47	0.60	4.17	0.53	0.51	2.9	3.2	3.3
2001-2005	ArkonaBY2	2.51	0.53	2.94	-	0.66	0.8	-	3.5
2001-2005	BornholmdeepBY5	2.42	0.73	2.17	-	0.50	0.3	-	2.6
2001-2005	GotlanddeepBY15	3.58	0.75	2.66	-	0.36	1.2	-	4.3
2001-2005	GreatBelt	2.86	0.23	4.77	1.19	0.68	8.5	7.4	9.7
2001-2005	LandskronaW	1.89	0.42	4.05	-	0.68	5.2	-	2.9
2001-2005	LandsortDeepBY31	2.58	0.25	2.34	-	0.29	1.0	-	9.3
2001-2005	nordwijk70	3.01	0.77	-	1.47	-	-	2.0	-
2001-2005	SEGotlandbasin	3.07	0.32	2.58	-	0.41	1.5	-	8.3
2001-2005	tersch235	1.10	0.32	-	0.52	-	-	1.8	-

Fig. 8. Average surface layer summer Chlorophyll-a ( $\mu\text{g Chl-a l}^{-1}$ ) of the observations (black), weighted model mean of hindcast from Eilola et al. (2011) (red), weighted model mean of control period (green) and weighted model mean of future climate (blue). See Fig. 1 for location of stations.

Table 5. Average surface layer summer Chlorophyll-a ( $\mu\text{g Chl-a l}^{-1}$ ) of the observations (yellow header) and the individual models (blue header) is shown with the corresponding cost function values (golden header) in the right columns, from Eilola et al., 2011.



Observations in August-September		Depth (m)	Oxygen		Model values Oxygen Mv			Cost function values Oxygen		
Period	Station		Mv	Sd	SMHI	IMR	SPBIO	SMHI	IMR	SPBIO
2001-2005	Anholte	50	2.81	0.85	2.79	6.27	5.19	0.0	4.1	2.8
2001-2005	ArkonaBY2	40	3.47	0.56	3.52	-	4.68	0.1	-	2.2
2001-2005	BornholmdeepBY5	85	0.77	1.46	0.48	-	2.69	0.2	-	1.3
2001-2005	FehmarnBel	26	1.63	1.02	4.47	-	5.84	2.8	-	4.1
2001-2005	GdanskDeep	100	-0.66	2.59	1.28	-	1.12	0.7	-	0.7
2001-2005	GotlanddeepBY15	240	-2.00	3.28	0.92	-	-0.56	0.9	-	0.4
2001-2005	GreatBelt	33	3.14	0.71	2.53	7.06	6.39	0.9	5.5	4.6
2001-2005	GulfFinlandLL7	70	3.99	0.86	3.04	-	1.54	1.1	-	2.8
2001-2005	LandskronaW	50	2.52	0.72	4.45	-	6.95	2.7	-	6.2
2001-2005	LandsortDeepBY31	250	-0.31	0.46	0.16	-	-0.82	1.0	-	1.1
2001-2005	SEGotlandbasin	80	2.67	0.66	4.47	-	3.39	2.7	-	1.1

Fig. 9. Average deep water late summer mean oxygen ( $\text{ml O}_2 \text{ l}^{-1}$ ) of the observations (black), weighted model mean of hindcast from Eilola et al. (2011) (red), weighted model mean of control period (green) and weighted model mean of future climate (blue). See Fig. 1 for location of stations. Hydrogen sulfide concentrations are shown as “negative oxygen” equivalents ( $1 \text{ ml H}_2\text{S l}^{-1} = -2 \text{ ml O}_2 \text{ l}^{-1}$ ).

Table 6. Average deep water late summer mean oxygen ( $\text{ml O}_2 \text{ l}^{-1}$ ) of the observations (yellow header) and the individual models (blue header) is shown with the corresponding cost function values (golden header) in the right columns, from Eilola et al., 2011.

## 5. Models weighted mean assessment

The model results for the variables used in the assessment of ecological quality indicators are presented here. The weighted average values of the variables are used for the classification of the eutrophication status according to the threshold values valid for each area (Fig.4). For the control period the model means 1970-2000 are used, while the future climate figures are the 2070-2100 mean. Where possible, the results of the assessments are presented. First the threshold values used are presented in Figure 10.

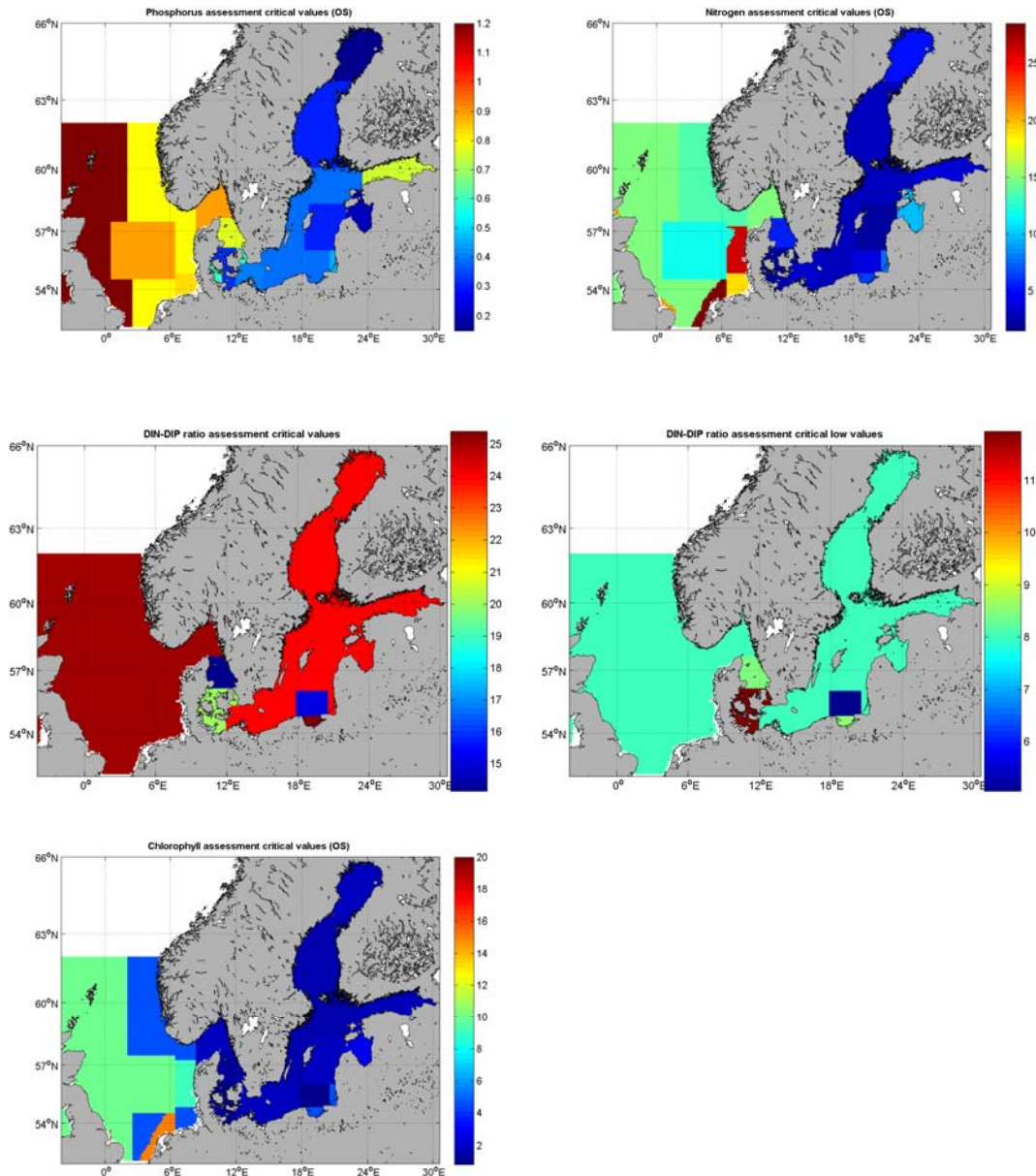


Fig. 10. Critical threshold values used for the ecological quality indicator of DIP ( $\mu\text{molP l}^{-1}$  - upper left), DIN ( $\mu\text{molN l}^{-1}$  - upper right), DIN:DIP ratio high (middle left) and low values (middle right) and chlorophyll a ( $\mu\text{g Chl-a l}^{-1}$  - lower ).

### **Nutrients (DIP, DIN and DIN:DIP):**

In the North Sea the winter nutrient levels (Figures 11 and 12) are high in the Atlantic inflow and along the southern North Sea coast where the large rivers are transporting large amounts of nutrients into the sea. The nutrient levels are also elevated in the Skagerrak and along the Norwegian coast, due to the transport of excess nutrients with the ocean currents from the southern North Sea. In the North Sea there is a minor increase in the levels in the future climate simulation. The N:P ratio is increasing 1-2 units in most areas of elevated nutrients. In the Baltic there are high nutrient values in the southern and eastern coastal areas, with a decrease northwards and westwards. In the future climate there is a significant and almost uniform increase in the levels all over, except for the Bothnian Bay and in the Gulf of Finland where the changes are relatively small. The N:P ratio is only slightly changed, except for the coastal Bothnian Bay where a marked increase is seen. The situation in the Bothnian Bay is consistent with the picture shown from the nutrients (high N and low P), while the N:P ratio in the rest of the Baltic indicates a situation where the P levels generally are high and N values are low.

### *Assessment*

The winter nutrients assessment levels are high in the Baltic Sea all years (Figures 11 and 12). For the control run, the phosphorous levels are bad, i.e. above the threshold in all areas except for some small parts of the Bothnian Bay, while nitrogen is low in the Bothnian Bay and the Bornholm Basin. In the future climate the situation is almost identical. In the North Sea phosphorous is high on the Danish east coast and close to the outlets of the main European continental rivers, while nitrogen is high in Kattegat and in a narrow strip along the coast from Skagen to the English Channel. In the future climate there is a slight increase in bad phosphorous levels along the continental coast, while nitrogen is unchanged. For the N:P ratio (Figure 13) the picture is different. In the control run, the Bothnian Bay is below the threshold except for some coastal areas. The remaining parts of the Baltic Sea show levels below the threshold along the coast to the south and east, and above elsewhere. In the North Sea part the N:P ratio is elevated in the Skagerrak, Kattegat, Thames estuary and along the continental coast. In the future climate the situation is slightly worse in the Gulf of Finland and the Eastern Gotland, while there is an improved N:P ratio in the Kattegat.



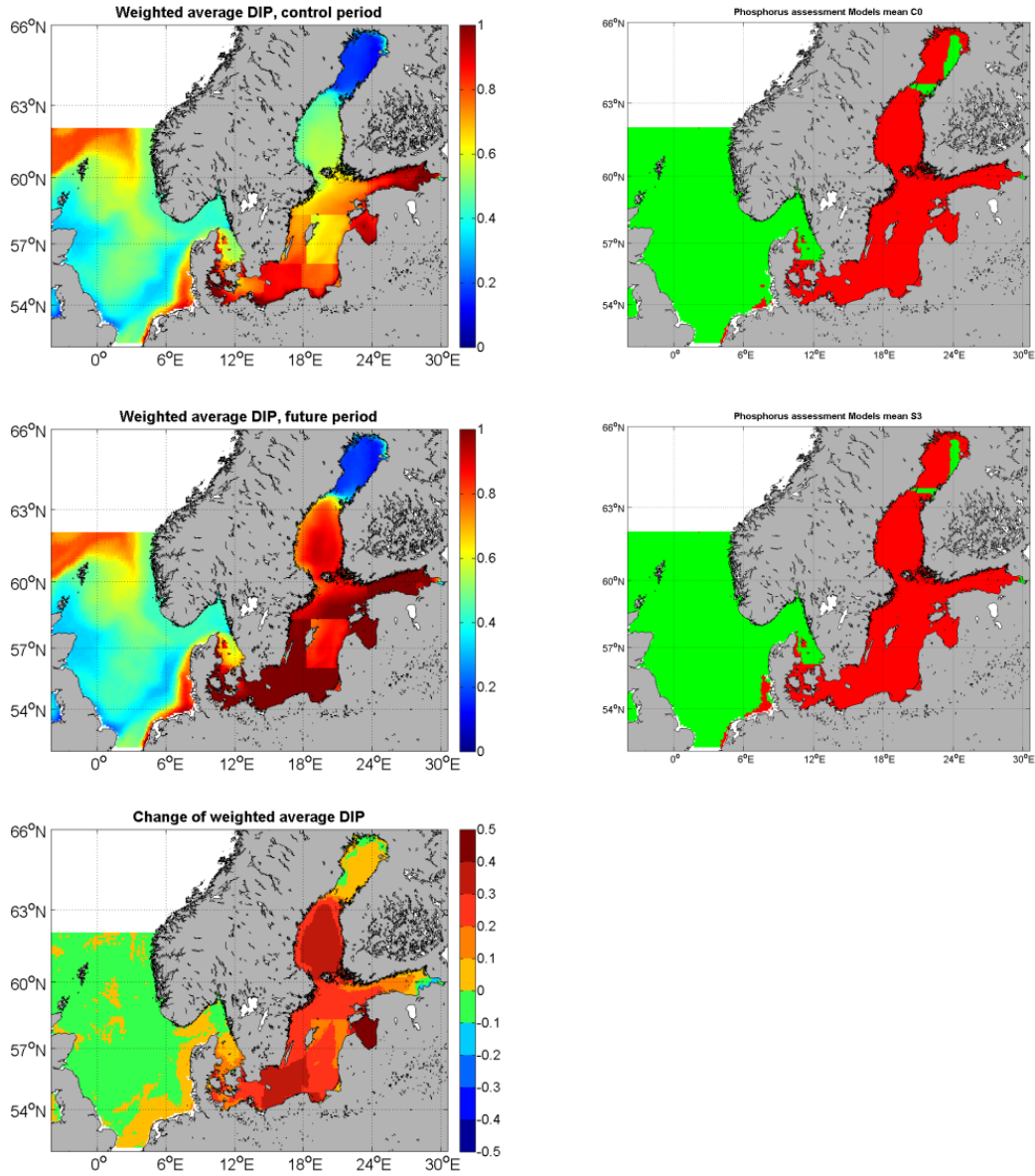


Fig. 11. Average surface layer DIP ( $\mu\text{mol P l}^{-1}$ ) of the ensemble weighted means in winter (left) and the corresponding assessment (right). Control period (c0) are in upper panels, and future climate (s3) in lower panels. The assessment levels are indicated by colours, green (good), red (bad).



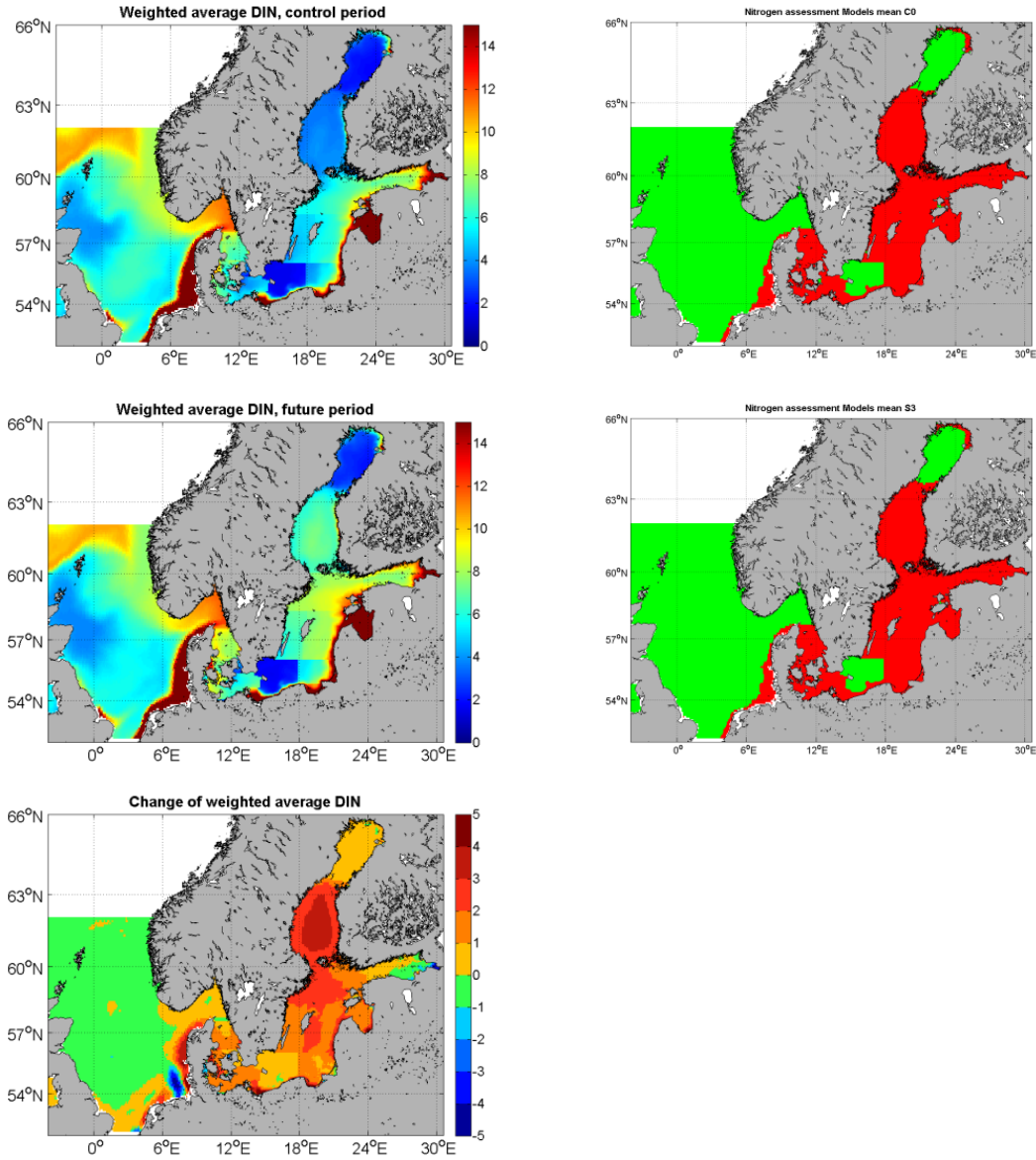


Fig. 12. Average surface layer DIN ( $\mu\text{molN l}^{-1}$ ) of the ensemble weighted means in winter (left) and the corresponding assessment (right). Control period upper panels, and future climate middle panels. The future change is shown in the lowermost panel. The assessment levels are indicated by colours, green (good), red (bad).

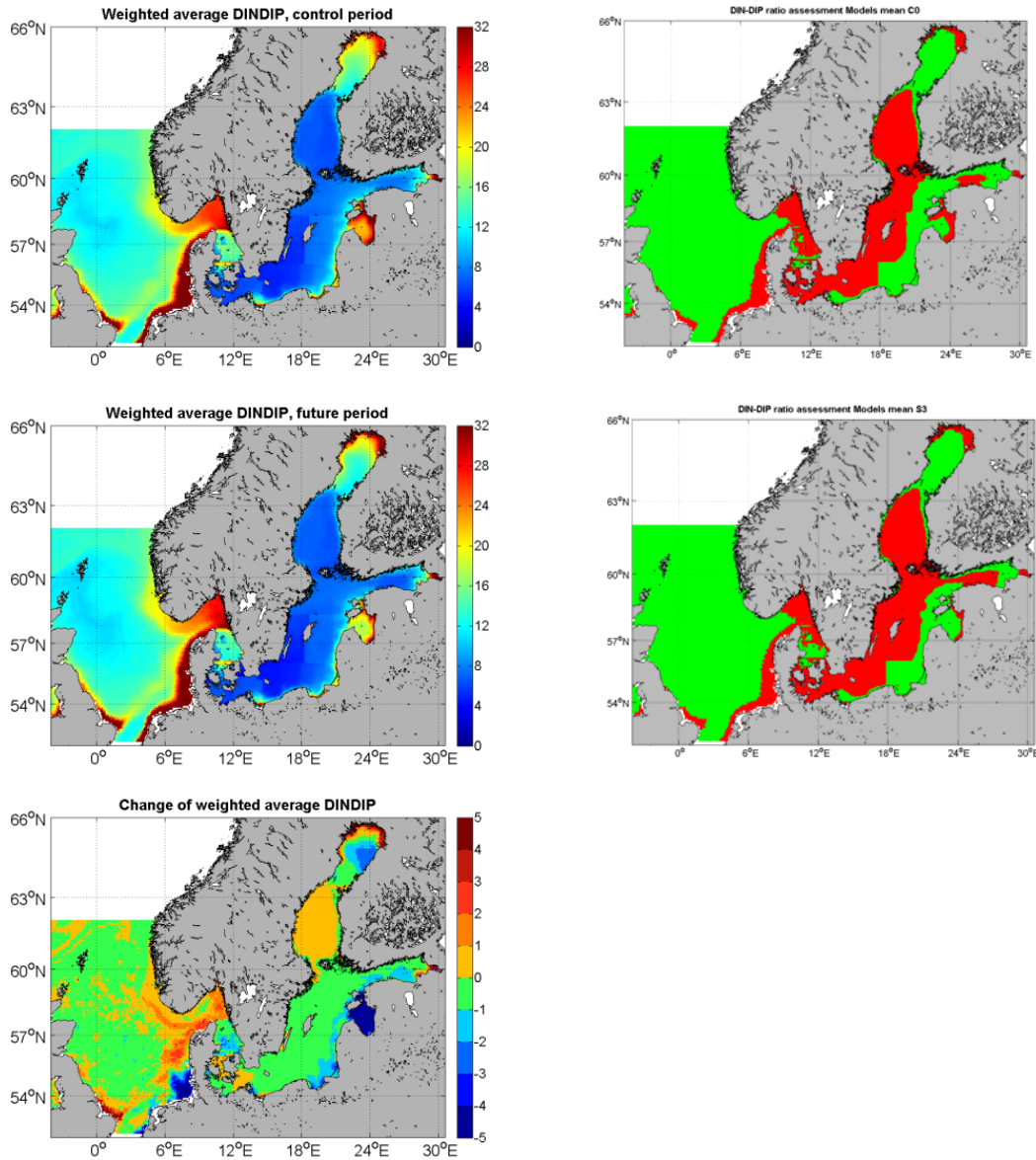


Fig. 13. Average surface layer DIN:DIP of the ensemble weighted means in winter (left) and the corresponding assessment (right). Control period upper panels, and future climate middle panels. The future change is shown in the lowermost panel. The assessment levels are indicated by colours, green (good), red (bad).

### Chlorophyll-a

The average summertime surface layer Chlorophyll-a shows values  $0.2 \mu\text{g Chl- a l}^{-1}$  to more than  $6.0 \mu\text{g Chl- a l}^{-1}$  (Fig.14) with highest values in the coastal zone of the south-eastern North Sea, of the western Kattegat, and in the coastal southern and eastern Baltic Sea. In the future climate there is an increase in the levels in the German Bight, Kattegat and almost the entire Baltic Sea. The increase in the Baltic is  $0.5\text{-}1.0 \mu\text{g Chl a l}^{-1}$  all over except for the Bothnian Bay and the southern part of the Gulf of Finland where a slight decrease is seen. The changes in the Baltic Sea are consistent with the changes seen in the modeled winter nutrients.

### Assessment

For the control run, the corresponding assessment of the eutrophication status is good (non-problem area) for the North Sea and Skagerrak, Gdansk Deep, SE Gotland Bay, the Lithuanian water, Bornholm Basin, the Gulf of Riga, East Gotland and North Gotland Basin, the Bothnian Sea and the Bothnian Bay. In the remaining areas the assessment is problem area. In the future climate the Bothnian Sea, Gulf of Riga, Bornholm Basin and parts of the North Gotland Basin and East Gotland Basin have turned into problem areas as well.

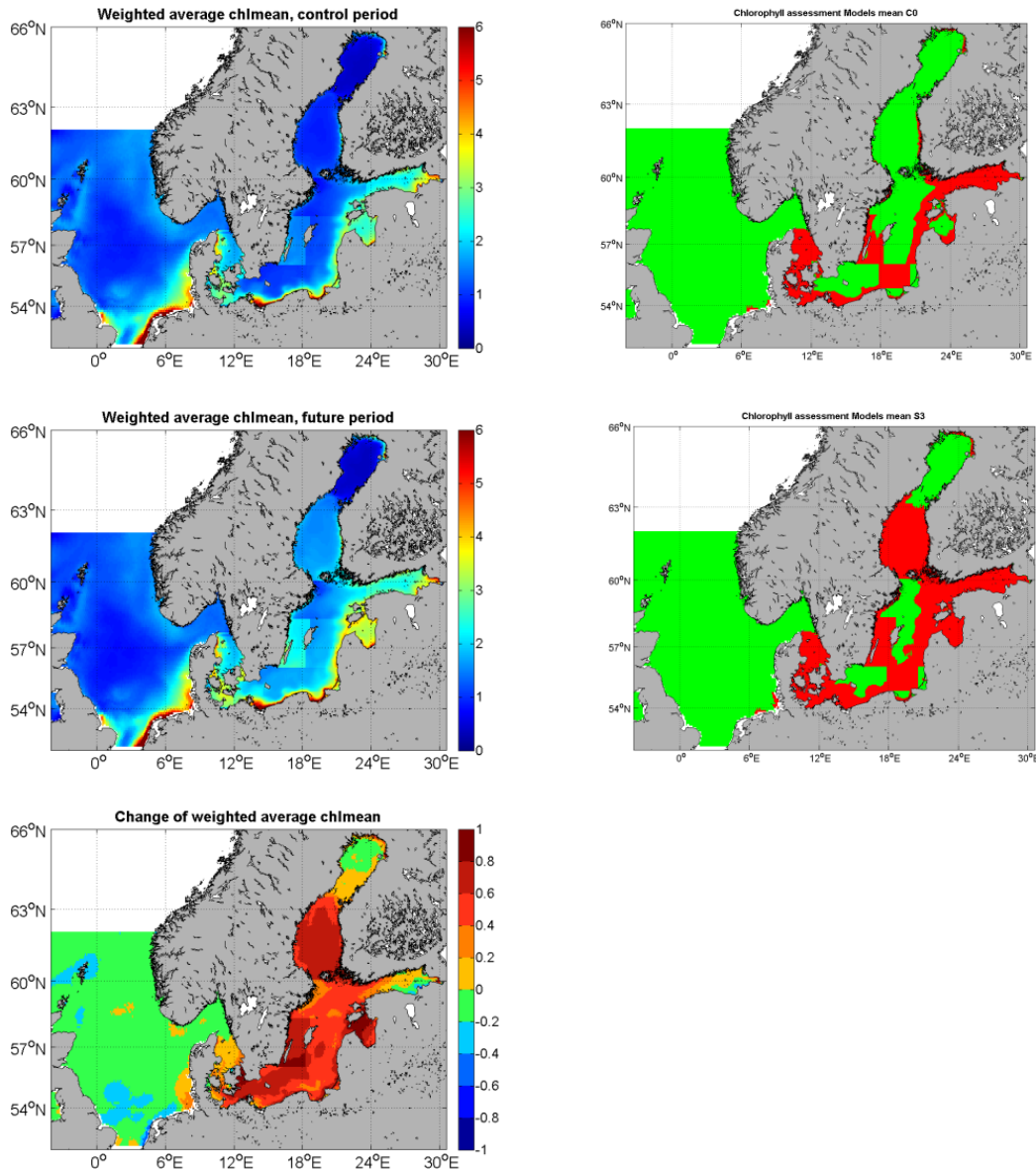


Fig. 14. Average surface layer Chlorophyll-a ( $\mu\text{g Chl-a l}^{-1}$ ) of the ensemble weighted means in summer (left) and the corresponding assessment (right). Control period upper panels, and future climate middle panels. The future change is shown in the lowermost panel. The assessment levels are indicated by colours, green (good), red (bad).

## Oxygen conditions

The distribution of annual bottom layer oxygen minimum (Figure 15) in general follows the bathymetry and depth of the pycnocline in each of the basins in the Baltic Sea as well as in the Kattegat and Belt Sea. In contrast the distribution of oxygen in the North Sea correlates with high nutrient concentration and chlorophyll concentrations. The strong correlation with water depth is due to the estuarine stratification of Baltic Sea as well as the transition zone in the Danish straits. There are however differences between the Baltic Sea and The Danish straits in the temporal dynamics of the oxygen concentration. The Danish straits is characterized by short term changes in the oxygen condition during the critical period from August to October. The Kattegat and the Belt Sea are persistently stratified and in the transition zone between the North Sea and the Baltic Sea where there is a strong gradient in oxygen declining from North to South (from the border in the Skagerrak to the western Baltic Sea). Short term variation in the oxygen concentrations arises from barotropic in and outflows of the bottom water and during such events the entire bottom water volume may be renewed with oxygen rich Skagerrak water (Bendtsen et al., 2009, Jonasson et al., 2012). The water depth is generally shallower in the Kattegat and in the Belt Sea and mixing events may also add to the short term dynamics - especially in the straits where current speeds are high. In the deep basins of the central Baltic and the Bornholm deep the short term dynamic of oxygen is less pronounced because the water column is deeper, more stable and less influenced by advection. Due to the highly dynamics oxygen conditions in the Kattegat and Belt Sea oxygen minimum concentration could be somewhat misleading when compared to minimum oxygen conditions in the central Baltic Sea where oxygen minima refer to longer lasting hypoxic conditions. With respect to the environmental quality experienced by benthic life, it would be more relevant to describe these conditions as the bottom oxygen concentration average over a period from a few weeks or one month. The distribution of oxygen in the North Sea reflects to a larger extent the spatial pattern in the productivity, which in turn, leads to locally enhanced respiration.

Comparing the control and future climate simulation, the oxygen minimum in the North Sea and the Kattegat is almost unchanged. South of the Belts and in the Baltic Sea, there is a general decrease in oxygen levels all over, with the smallest changes in the Bothnian Bay and the Gulf of Finland, similar to the patterns seen for nutrients and chlorophyll.

## Assessment

In the control run the Kattegat is either defined as problem or potential problem area. This is also the case for all deeper parts of the Baltic (except for the Bothnian Sea and Bothnian Bay). In the future climate the situation has worsened in the way that most of the potential problem areas has become problem areas. The assessment of eutrophication status is done according to the annual minimum oxygen concentrations (indirect effects) ranges defined by decreased oxygen levels ( $O_2 < 2.8 \text{ ml l}^{-1}$ ) and toxic levels ( $O_2 < 1.4 \text{ ml l}^{-1}$ ). However, as described above the longevity of the hypoxic events is an equally important descriptor for environmental quality and there may be local differences in how long the benthic community can withstand hypoxic condition. This should be taken into account when further harmonizing the description of the eutrophication status of the entire area.



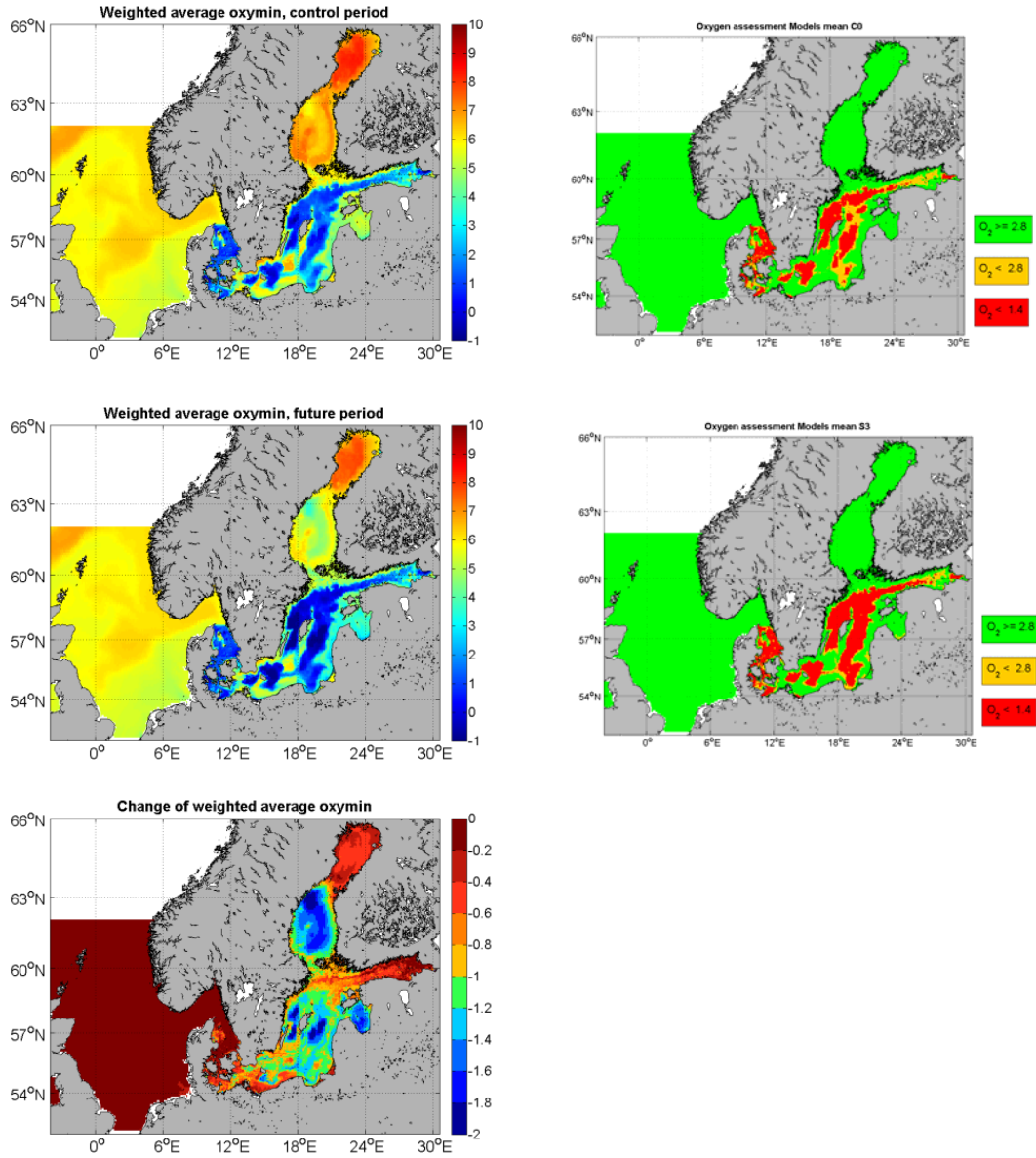


Fig. 15. Annual bottom layer dissolved oxygen minimum concentration (ml O<sub>2</sub> l<sup>-1</sup>) of the ensemble weighted means (left) and the corresponding assessment (right). Control period upper panels, and future climate middle panels. The future change is shown in the lowermost panel. The assessment levels are indicated by colours, green is good (O<sub>2</sub> > 2.8 ml l<sup>-1</sup>), while orange (O<sub>2</sub> < 2.8 ml l<sup>-1</sup>) and red (O<sub>2</sub> < 1.4 ml l<sup>-1</sup>) are bad.

## Eutrophication status

In the control run, the assessment of eutrophication status according to the integration of the categorized assessment parameters indicates that the Kattegat, the Danish Straits, the Gulf of Finland, the Gotland Basin as well as main parts of the Arkona Basin, the Bornholm Basin, and the Baltic proper may be classified as problem areas. The main part of the North Sea and also the Skagerrak are non-problem areas while the main parts of the Gulf of Bothnia, Gulf of Riga and the entire southeastern continental coast of the North Sea may be classified as potential problem areas (Fig. 16). In addition to elevated nutrient levels in the whole Baltic, elevated primary production (chlorophyll-a) seems to be the main problem causing the areas to be classified as problem areas, except for the Western Gotland Basin where low oxygen is the reason for this classification. In the North Sea, the classification as potential problem areas are due to high nitrate and N:P ratio. In the future climate most of the potential problem areas in the Baltic become problem areas, except for the Bothnian Bay where the situation remain unchanged. Also in the North Sea there seems to be no change in the projected future climate.

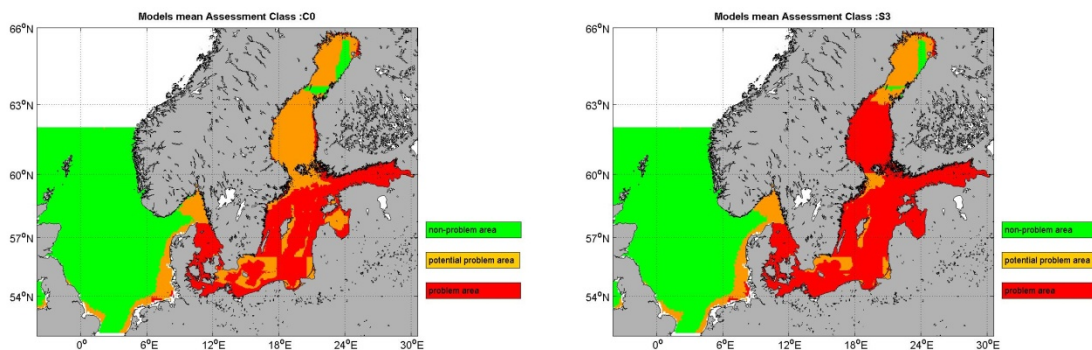


Fig. 16. Assessment results of integrated categorized assessment parameters for the control simulation (left) and the future climate simulation (right). The assessment levels are indicated by colours, green (non-problem area), yellow (potential problem area), and red (problem area).

## Bioscience results

The Bioscience model; OXYCON considers only the transition zone between the Baltic Sea and the North Sea (sub-area 13-16, Fig.4) and is based on a carbon budget parameterised specifically for this area and the simulated oxygen concentrations are validated against observations 2001 – 2003 (Bendtsen and Hansen 2012). In the climate scenario 3 °C boundary conditions has been applied to the air temperature and at the open boundaries of the model domain this results in a 3 °C warmer water column but otherwise similar hydrographical conditions. Under the present day reference conditions the average bottom water oxygen concentrations during the summer are about 180  $\mu\text{M}$  (Fig. 17). However, during the most critical period of the hypoxic season, in September, hypoxia is prevailing in the southern part of the transition zone (Bendtsen and Hansen 2012) with considerable inter-annual differences. The affected area covers up to 20.000  $\text{km}^2$  during years with very calm weather conditions in summer and in the early autumn whereas the affected area is much smaller and restricted to the Little Belt in the Western Baltic Sea during years with strong winds and mixing (Bendtsen and Hansen 2012). A 3 °C warmer climate results generally in lower oxygen concentrations. In the climate scenario (Fig. 17), hypoxia (marked with red) defines the average summer conditions in the southern Kattegat, the Danish Straits and in the Western Baltic Sea. During September, the same areas suffers from severe hypoxia ( $< 62 \mu\text{M}$ ) (Bendtsen and Hansen

2012). The severely hypoxic area expands by 25 % and the duration is extended for about 1 month. In general the average oxygen concentration in the bottom water is reduced by 0.8 ml/l – 1 ml/l.

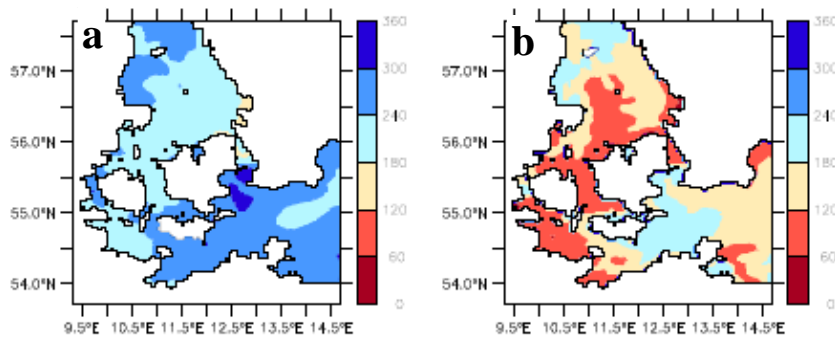


Fig. 17. Output from nested model of the Danish Straits a) average summer bottom oxygen conditions ( $\mu\text{M}$ ) and b) corresponding climate scenario (+ 3°C). For further details see (Bendtsen and Hansen 2012).

## 6. Discussion

The main finding of this study is the way of combining observations and an ensemble of ecological models to make an assessment of the present and future climate eutrophication status. A similar exercise has been done before in a hindcast period (Eilola et al, 2011) with the same models for five different years (2001-2005). Using the OSPAR classifications of areas (OSPAR 2005b), the different parts of the North Sea and the Baltic Sea are categorized as non-problem, potential problem, or problem areas. Also, by using models for such classifications, the assessment is valid in each model grid point, while in e.g. HELCOM (2006) the assessment is valid only for larger areas (coastal waters, transitional waters, and open sea).

Even though there are biases in the control run compared to the hindcast and observations in Figure 5-9, the impact on the assessments are rather small. Comparing the assessments of the control period to that of the hindcast (Eilola et al., 2011), the DIP assessment is comparable except for the Bothnian Bay and the Gulf of Finland, where the assessment has changed from good (hindcast) to bad (control). For DIN it is the opposite, meaning that the Bothnian Bay has changed from bad (hindcast) to good (control), while parts of the Skagerrak has changed from good (hindcast) to bad (control). This also has implications for the DIN:DIP ratio. For chlorophyll, the assessments have similar patterns, except that the bad areas are somewhat larger in the Baltic proper in the hindcast compared to the control. Finally, for oxygen some red areas have turned into orange in the control, except for the Kattegat where the situation in the control has worsened. In summary the final integrated assessment is generally very similar in the control and hindcast, except for the Skagerrak which in the control is potential problem while it was non-problem in the hindcast.

The classification of an area will strongly depend on the threshold values, and the EcoQOs are based on national assessments that can differ quite a lot from region to region. One of the most noticeable differences in the North Sea is the elevated levels of CHL in the neighboring

Areas 20 (German Bight) and 21 (Dutch Coast) of 4.5 and 15 mg m<sup>-3</sup>, respectively (cf. Table 1). With such a large discrepancy between the assessment levels, and the fact that Area 20 is downstream from 21, it will be difficult to achieve the desired goal of combating eutrophication in the German Bight without a further harmonization of the assessment levels. Related to this, areas may show the effects of eutrophication even when there is no evident increased local nutrient enrichment. The effect may instead be a result of transboundary nutrient transports. Therefore, there is a need to understand and quantify the contribution of nutrients from other marine areas relative to the local ones. In order to address this, there is a need for further development of tools (including validated numerical models) to arrive at total nutrient budgets for specific areas (OSPAR 2003). In the CHL assessment method (Category II), modeled phytoplankton biomass is transformed to chlorophyll-a by a constant conversion factor. It should be noted that the ratio between phytoplankton biomass and chlorophyll-a is highly variable during the growth season depending on many factors such as temperature, nutrients, photosynthetic available radiation and others (see, for example, Sathyendranath et al., 2009), and therefore has an impact on the definition of a problem area. Furthermore, the subsequent mineralization and export of phytoplankton biomass also differs considerably among phytoplankton groups and cannot be predicted from Chlorophyll-a. Similarly, the method of using the annual minimum oxygen concentration and the relevant thresholds that should be used for the oxygen assessment (Category II) could be further discussed. Using the minimum of oxygen concentrations that are averaged over some time period relevant for the benthic life might be more relevant for the assessment in highly dynamic areas like in the Kattegat and Belt Sea as compared to the less dynamic deep waters in the central Baltic Sea where many areas are permanently azoic.

Evaluating the assessments of ecological quality indicators for the North Sea in future climate, it should be remembered that they were obtained under the assumption of no changes in the boundary conditions at the open boundaries of the North Sea in 2070-2100 and setting them as the observed climatic averages. Thus, future changes in the characteristics of eutrophication in the North Sea are caused in the model by atmospheric changes only, not considering the influence from changes in rivers, of the open Atlantic Ocean or the exchange with the Baltic. As the nutrient budgets in the North Sea primarily are regulated through water exchange with the open Atlantic even small changes in these background levels due a general warming of the water column in the North Atlantic could have significant effect on the eutrophication level in the future North Sea. The same effect could propagate to the Kattegat and Belt Sea where the nutrient pools to a large extent also are regulated through advection of water from the North Sea and North Atlantic.

In the Baltic there has been a recent revision in threshold values compared to HELCOM (2006) (see Table 1). These corrections have been made by the agencies, especially SEPA, to include better data. However, there are still some remaining issues to be discussed. The reference values for winter DIN is low (generally below 2.5-3 µM). In a 100 years back scenario simulations (Savchuk and Wulff, 2009) annual means were never lower than 3.0 in Danish Straits and Baltic Proper surface box. Thus winter values could be at least 30-50% higher. The value 1.40 µM for winter DIN in the Eastern Gotland Basin is also very low compared to all neighboring areas.

The Bioscience model simulates the oxygen dynamics in the very dynamic transition zone between the North Sea and the Baltic Sea. The temperature increase will cause a reduction in the bottom oxygen concentration between 0.74 - 1 ml/l O<sub>2</sub> in the central Kattegat and in the Belt Seas. However, these figures represent a conservative estimate because the productivity



is maintained at the present day level and thereby the total oxygen consumption remains the same. The reduction in oxygen is due to the lower saturation content of the warmer water and due to a shift between pelagic and benthic respiration which causes a stronger seasonality in the oxygen concentration. The model mechanism is as follows: When the water gets warmer more of the sinking particulate organic material is respired during its descent through the water column and thereby less organic material will be deposited and respired on the sea bottom. As the respiratory oxygen uptake from the bottom is diffusive and depend on the water oxygen concentration in the water phase, this will slow down the oxygen consumption when oxygen concentration is declining in the early phase of hypoxia. In contrast, the pelagic oxygen uptake is largely independent of the oxygen concentration and therefore oxygen declines faster during the hypoxic season and reaches a lower minimum level. Thus a warmer climate will change the temporal dynamics of oxygen consumption and more will be consumed in the critical hypoxic season.

Overall, the results from OXYCON correspond to the other models in the ensemble. However, whereas the changes in oxygen concentration as simulated in the other models mainly results from increasing respiratory oxygen demand due to eutrophication and increased temperature dependent mineralization rates, the declining oxygen modeled in OXYCON is a more conservative estimate because the eutrophication level is kept constant. The effect on the oxygen conditions of OXYCON in the climate scenarios are due to the physical effect of the temperature on the oxygen saturation, and due to a structural “regime shift” in the model ecosystem where the relative balance between pelagic and benthic respiration is assumed to change. This balance is explicitly formulated as a function of the temperature in order to keep the total annual remineralization at a constant level. If the eutrophication level increases this effect will come on top of the direct effect of the temperature (for a more details see Bendtsen and Hansen 2012). Hence, if the climatic changes involve increasing winter DIN concentration, this will further amplify the negative climatic effects on the oxygen conditions. A hindcast study 1975-2010 (Jonasson and Hansen 2012b) using OXYCON implemented in another 3D model have analyzed the relationship between winter DIN concentrations and average bottom oxygen concentrations and found a regression coefficient between molar concentrations of DIN and O<sub>2</sub> between 7.55 and 9.84 for the North Sea-Baltic Sea transition zone. Thereby, the projected increase in DIN from the ensemble modeling of 1-2  $\mu\text{M}$  would further decrease the oxygen concentration by 7.5 - 20  $\mu\text{M}$  O<sub>2</sub> (0.17 – 0.44 ml/l). Thus, by combining the modeled nutrient concentrations and the highly parameterized oxygen model for the transition zone, the expected decrease in the oxygen concentration is estimated to be between 0.9 and 1.44 ml/l. The latter relationship between eutrophication and oxygen was also confirmed by another sensitivity study by Bendtsen and Hansen (2012).

The impact of using different climate scenarios (not shown) was studied by comparing the HadCM3 SPBEM and RCO-SCOB simulations to the ones using ECHAM5. In both sets of simulations the volume averaged water temperature increased with time as a response of the increased air temperature while the volume averaged salinity decreased as a response of the increased runoff during the twenty first century. Sea surface temperature changes between 2070–2100 and 1970–2000 were largest in the Bothnian Bay and Bothnian Sea during summer in both scenarios. However, the magnitude of sea surface salinity (SSS) and temperature (SST) changes differed significantly between the HadCM3 and ECHAM5 driven simulations, with the largest SST increase and smallest SSS decrease found in the HadCM3 driven simulations. The eutrophication status assessment (cf. Fig.16) based on the results

from the two different climate projections showed quite insignificant differences though there were some differences in the responses of the ecological parameters.

In HadCM3 the average surface layer summer chlorophyll-a increased by 0.5-1.0  $\mu\text{g Chl-a l}^{-1}$  and the bottom layer dissolved oxygen was reduced by 0.8-2.0  $\text{ml O}_2 \text{l}^{-1}$  almost everywhere in the Baltic Sea excluding Arkona Basin, Danish straits, Öresund and Kattegat. These changes are greater than corresponding changes in the ECHAM5 driven simulations. The average surface layer winter DIP increases everywhere in the Baltic Sea in both runs and this increase in HadCM3 driven simulations is slightly higher. In ECHAM5 driven simulations winter DIN increased everywhere in the Baltic Sea except in the Bornholm basin and Gulf of Finland, whereas in HadCM3 driven simulations significant increase in surface DIN occurs only in the Bothnian Sea and Bothnian Bay. In the latter one the increase are larger than for ECHAM5.

The reason for such changes is likely the higher water temperature changes in the HadCM3 driven simulations. Higher water temperatures are projected to (1) reduce oxygen concentrations in the water column due to lower solubility of oxygen in warmer water and (2) accelerate organic matter mineralization and oxygen consumption (see Bendtsen and Hansen 2006; Meier et al., 2012). Greatly expanding anoxia will (3) increase phosphorus release rates from the sediments, and amplify the phosphorus recycling which will reduce the permanent removal of phosphorus from the ecosystem. Together with an accelerated pelagic recycling loop (4), this will intensify primary production and increase phytoplankton biomass and chlorophyll-a. It is more difficult to explain the difference in the changes of surface layer winter DIN in ECHAM5 and HadCM3 driven simulations: a detailed analysis of the biogeochemical fluxes of nitrogen in the analyzed periods is needed. In this report, the output of these fluxes has not been provided, so the analysis of this issue is left for the future work.

## 7. Conclusions

An ensemble of models has been used to assess eutrophication in the North Sea and Baltic Sea in the present and the future climate, using a method suggested in Almroth and Skogen (2010). In the control run, the assessment of eutrophication status according to the integration of the categorized assessment parameters indicates that the Kattegat, the Danish Straits, the Gulf of Finland, the Gotland Basin as well as main parts of the Arkona Basin, the Bornholm Basin, and the Baltic proper may be classified as problem areas. The main part of the North Sea and also the Skagerrak are non-problem areas while the main parts of the Gulf of Bothnia, Gulf of Riga and the entire southeastern continental coast of the North Sea may be classified as potential problem areas (Fig. 16). The temperature increase by itself will worsen the oxygen condition throughout the area and on top of this; elevated nutrient levels in the whole Baltic will amplify this effect due to elevated primary production. Therefore declining oxygen condition and increasing phytoplankton biomasses will be the main problem causing the areas to be classified as problem areas. In the Western Gotland Basin low oxygen seems to be the sole reason for this classification. In the North Sea, the classification as potential problem areas are due to high nitrate and N:P ratio. In the future climate scenarios most of the previous potential problem areas in the Baltic Sea have become problem areas, except for the Bothnian Bay where the situation remain fairly unchanged. Also in the North Sea there seems to be no obvious changes in the projected future climate. Comparing the ECHAM5 driven changes to simulations using the HadCM3 forcing show that; all changes except the surface layer winter

DIN in the future climate have the same sign and that; the overall eutrophication status assessment is robust and insensitive to the choice of future scenario.

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## 9. Appendix A; Comprehensive procedure

### **From: OSPAR Integrated Report 2005 on the Eutrophication Status of the OSPAR Maritime Area Based Upon the First Application of the Comprehensive Procedure**

All areas not being identified as non-problem areas with regard to eutrophication through the Screening Procedure are subject to the Comprehensive Procedure which comprises a checklist of qualitative parameters for a holistic assessment (cf. § 4.2.1. in the Common Procedure OSPAR 97/15/1, Annex 24):



The qualitative assessment parameters are as follows:

a. the causative factors

the degree of nutrient enrichment

- with regard to inorganic/organic nitrogen
- with regard to inorganic/organic phosphorus
- with regard to silicon
  - taking account of:
    - sources (differentiating between anthropogenic and natural sources)
    - increased/upward trends in concentration
    - elevated concentrations
    - increased N/P, N/Si, P/Si ratios
    - fluxes and nutrient cycles (including across boundary fluxes, recycling within environmental compartments and riverine, direct and atmospheric inputs)

b. the supporting environmental factors, including:

- light availability (irradiance, turbidity, suspended load)
- hydrodynamic conditions (stratification, flushing, retention time, upwelling, salinity, gradients, deposition)
- climatic/weather conditions (wind, temperature)
- zooplankton grazing (which may be influenced by other anthropogenic activities)

c. the direct effects of nutrient enrichment

i. phytoplankton;

- increased biomass (e.g. chlorophyll a, organic carbon and cell numbers)
- increased frequency and duration of blooms
- increased annual primary production
- shifts in species composition (e.g. from diatoms to flagellates, some of which are nuisance or toxic species)

ii. macrophytes, including macroalgae;

- increased biomass
- shifts in species composition (from long-lived species to short-lived species, some of which are nuisance species)
- reduced depth distribution

iii. microphytobenthos;

- increased biomass and primary production

d. the indirect effects of nutrient enrichment

i. organic carbon/organic matter;

- increased dissolved/particulate organic carbon concentrations
- occurrence of foam and/or slime
- increased concentration of organic carbon in sediments (due to increased sedimentation rate)

ii. oxygen;

- decreased concentrations and saturation percentage
- increased frequency of low oxygen concentrations
- increased consumption rate
- occurrence of anoxic zones at the sediment surface (“black spots”)

iii. zoobenthos and fish;

- mortalities resulting from low oxygen concentrations

iv. benthic community structure;

- changes in abundance
- changes in species composition
- changes in biomass
- v. ecosystem structure;
  - structural changes
- e. other possible effects of nutrient enrichment
  - i. algal toxins (still under investigation - the recent increase in toxic events may be linked to eutrophication)

*Table A 1. The agreed Harmonised Assessment Criteria and their respective assessment levels of the Comprehensive Procedure*

<b>Assessment parameters</b>		
<b>Category I</b>	<b>Degree of Nutrient Enrichment</b>	
	<b>1</b>	<b>Riverine total N and total P inputs and direct discharges (RID)</b> Elevated inputs and/or increased trends (compared with previous years)
	<b>2</b>	<b>Winter DIN- and/or DIP concentrations</b> Elevated level(s) (defined as concentration >50 % above salinity related and/or region specific background concentration)
	<b>3</b>	<b>Increased winter N/P ratio (Redfield N/P = 16)</b> Elevated cf. Redfield (>25)
<b>Category II</b>	<b>Direct Effects of Nutrient Enrichment (during growing season)</b>	
	<b>1</b>	<b>Maximum and mean Chlorophyll <i>a</i> concentration</b> Elevated level (defined as concentration > 50 % above spatial (offshore) / historical background concentrations)
	<b>2</b>	<b>Region/area specific phytoplankton indicator species</b> Elevated levels (and increased duration)
	<b>3</b>	<b>Macrophytes including macroalgae (region specific)</b> Shift from long-lived to short-lived nuisance species (e.g. <i>Ulva</i> )
<b>Category III</b>	<b>Indirect Effects of Nutrient Enrichment (during growing season)</b>	
	<b>1</b>	<b>Degree of oxygen deficiency</b> Decreased levels (< 2 mg/l: acute toxicity; 2 - 6 mg/l: deficiency)
	<b>2</b>	<b>Changes/kills in Zoobenthos and fish kills</b> Kills (in relation to oxygen deficiency and/or toxic algae) Long term changes in zoobenthos biomass and species composition
	<b>3</b>	<b>Organic Carbon/Organic Matter</b> Elevated levels (in relation to III.1) (relevant in sedimentation areas)
<b>Category IV</b>	<b>Other Possible Effects of Nutrient Enrichment (during growing season)</b>	
	<b>1</b>	<b>Algal toxins (DSP/PSP mussel infection events)</b> Incidence (related to II.2)

*Table A 2. Integration of Categorised Assessment Parameters*

	Category I Degree of nutrient enrichment	Category II Direct effects	Category III and IV Indirect effects/ other possible effects	Classification
a	+	+	and/or +	<b>problem area</b>
b	-	+	and/or +	<b>problem area</b>
C	+	-	-	<b>potential problem area</b>
D	-	-	-	<b>non-problem area</b>

(+)= Increased trends, elevated levels, shifts or changes in the respective assessment parameters in Table 1

(-) = Neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters in Table 1

Note:Categories I, II and/or III/IV are scored ‘+’ in cases where one or more of its respective assessment parameters is showing an increased trend, elevated level, shift or change.



## 10. Appendix B; Bioscience 3D-model oxygen sinks

### *Parameterization of oxygen sinks in the 3D-model*

The oxygen dynamics is described for a heterotrophic layer of bottom water. The oxygen concentration is parameterized by a pelagic and a benthic oxygen drain where the pelagic respiration is described by ( $S_p$ ), the benthic faunal respiration ( $S_b$ ) according to:

$$S_p = -f(T)R_1 \frac{O_2}{O_2 + k_1}$$

$$S_b = -f(T)R_2 \frac{O_2}{O_2(sat)} - f(T)R_3 \frac{O_2}{O_2 + k_2}$$

where the pelagic sink is applied to all vertical layers in the model while the benthic sink is only applied to the bottom layer.

The respiration rate constants has been calibrated against a carbon budget for the North Sea-Baltic Sea transition zone where the below halocline carbon mineralization is  $78 \text{ g C m}^{-2} \text{ yr}^{-1}$  where the pelagic respiration mineralizes  $45 \text{ g C m}^{-2} \text{ yr}^{-1}$  and benthic macrofaunal respiration contributes with  $20 \text{ g C m}^{-2} \text{ yr}^{-1}$  and microbial respiration  $13 \text{ g C m}^{-2} \text{ yr}^{-1}$ . Consequently  $R_1 = 0.6 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$ ,  $R_2 = 4.08 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$  and  $R_3 = 2.88 \text{ mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$ ,  $k_1 = 5 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$  is a half saturation constant for pelagic respiration and  $k_2 = 60 \text{ mmol O}_2 \text{ m}^{-3} \text{ d}^{-1}$  is the corresponding half saturation constant for benthic macrofaunal respiration,  $F(T)$  describes the temperature sensitivity and is represented by a  $Q_{10}$  value of 3.



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