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REVIEW PAPER

A North Sea and Baltic Sea Model Ensemble Eutrophication Assessment

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Abstract A method to combine observations and an ensemble of ecological models is suggested to produce a eutrophication assessment. Using threshold values and methodology from the Oslo and Paris Commissions (OSPAR) and the Helsinki Commission (HELCOM), four models are combined to assess eutrophication for the Baltic and North Seas for the year 2006. The assessment indicates that the entire southeastern part of the North Sea, the Kattegat, the Danish Straits, the Gulf of Finland, and the Gulf of Riga as well as parts of the Arkona Basin, the Bornholm Basin, and the Baltic proper may be classified as problem areas. The Bothnian Bay and parts of the Baltic proper, the Bornholm Basin, and the Arkona Basin are classified as potential problem areas. This method is a useful tool for the classification of eutrophication; however, the results depend on the threshold values, and further work is needed within both OSPAR and HELCOM to harmonize these values.

Keywords Eutrophication · OSPAR CP · Assessment · Modelling · North Sea · Baltic Sea

Introduction

Marine eutrophication is defined as the overenrichment of a water body with nutrients, resulting in the excessive growth of organisms and the depletion of the oxygen (O_2) concentration. Nutrient enrichment due to anthropogenic activities has been identified as the main cause of eutrophication in coastal areas (Cloern 2001). This is, in particular, linked to river discharges and enhanced concentrations of inorganic nitrogen (N) in estuaries. In order to combat eutrophication, the Paris Commission Recommendation on reducing nutrients to the North Sea was signed in 1988 by the contracting parties. This article (OSPAR 1988) outlined that the inorganic N and phosphorous (P) inputs to coastal areas should be reduced by 50% of the 1985 concentrations for those areas where nutrients cause, or are likely to cause, pollution. This decision was based on the fact that the loads in many European rivers were extremely high, an increasing frequency of harmful algal blooms seemed to be occurring, and in some areas significant O_2 reductions were occasionally observed in the bottom water (Anonymous 1993). Assessing eutrophication status is a very complex operation. Therefore, OSPAR developed the Common Procedure (OSPAR CP) for the Identification of the Eutrophication Status of Maritime Areas of the Oslo and Paris Convention (1997) which was updated in 2005 (OSPAR 2005a). Also, a set of ecological quality objectives (EcoQOs) and indicators (EQIs) have been accepted as criteria to assess eutrophication status (OSPAR 2005b). The criteria include parameters like winter nutrients, maximum chlorophyll-α (CHL), and minimum O_2 levels.

The Helsinki Commission (HELCOM) aims to protect the marine environment of the Baltic Sea from all sources of pollution and to restore and preserve the ecological balance. As early as 1974, a convention considering all sources of pollution was signed by the seven coastal states around the Baltic Sea (HELCOM, http://www.helcom.fi). Recently, the HELCOM Baltic Sea Action Plan was launched (HELCOM 2007). It is an ambitious program to

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restore the good ecological status of the Baltic marine environment. In order to achieve "good ecological status," the plan concludes that P and N inputs to the Baltic Sea should be reduced by about 42 and 18%, respectively. Integrated ecological status assessments using ecological modeling are addressed as important tools in the process to reach this goal. A pilot project, HELCOM EUTRO (development of tools for a thematic eutrophication assessment), has also been launched to develop harmonized eutrophication assessment tools, criteria, and procedures (including the establishment of reference conditions) for different parts of the Baltic Sea.

A complete assessment based on the measurements of all system parameters with a proper resolution in both time and space would be far too time- and labor-consuming to be desirable due to the complex nature of the system. Therefore, three-dimensional (3D) models have become an important tool for monitoring nutrient and ecosystem dynamics, and an increasing number of ecological models exist. An overview about ecosystem models of the greater North Sea can be found in Moll and Radach (2003). From the comparison between models and observations, it has become clear that ecosystem models should be 3D and should be coupled with or forced by a state-of-the-art circulation model. Several studies have used models to investigate the eutrophication status and the effect of changes in nutrient loads on both the North Sea (Lenhart 2001; Skogen et al. 2004; Wirtz and Wiltshire 2005; Skogen and Mathisen 2009) and the Baltic Sea (Savchuk and Wulff 1999; Neumann et al. 2002; Neumann and Schernewski 2005; Pitkänen et al. 2007; Savchuk and Wulff 2007). The OSPAR Joint Assessment and Monitoring Programme (JAMP) required an assessment by 2006 of the expected eutrophication status of the OSPAR maritime area following the implementation of agreed measures. To assist the delivery of JAMP, OSPAR Eutrophication Committee agreed in 2005 on an Intersessional Correspondence Group for Eutrophication Modelling (ICG-EMO, http://www.cefas.co.uk/eutmod) to produce an assessment in the format of the CP showing the predicted environmental consequences for problem areas of achieving the 50% nutrient reduction target of the North Sea and, where this does not indicate non-problem area status, to predict the reduction target needed to achieve non-problem area status (OSPAR 2008).

All models have to deal with uncertainties due to limitations in both their forcing and process formulations. One way to reduce uncertainty is to add more models in a study and report on the ensemble in a multimodel combination (Weigel et al. 2008). The aim of this study is to illustrate how an integration of observations and an ensemble of ecosystem models can be used to assess marine eutrophication using a set of existing environmental targets for the identification of eutrophication status set by politicians (OSPAR 2005b; HELCOM 2006). Since the accuracy of models differs between parameters and areas, weighted average values of the models have been used to calculate the final assessment. The use of such weights, which are computed from model accuracy based on model validation exercises using observations from distinct areas, illustrates how an ensemble of models can contribute to a reliable eutrophication assessment. It can also serve as a basis for ongoing discussions about the EQIs included in the assessment and the way to merge results from different models and observations for the assessment.

Materials and Methods

The Models

Four models are used in the assessment: NORWECOM (Skogen and Søiland 1998), RCO-SCOBI (Marmefelt et al. 1999; Meier et al. 2003; Eilola et al. 2009), MIKE III (DHI 2001), and BalEco (Stipa et al. 2003). All of the models cover different parts of the Baltic and/or North Sea. None of the models covers the whole area of interest. The different model domains are shown in Fig. 1. All models are run using their best available forcing (meteorology, river inputs, open boundaries) and set-up (spin-up, resolution); thus, no effort has been made to harmonize the results. The models have been run for the year 2006 in an attempt to produce the most realistic results possible based on the experiences and numerous validation studies performed at each institute.

The In Situ Data

To validate the models, and thereby compute the weights used for the modeled averages, observational data for the period 2001–2006 from stations situated in the North Sea, Skagerrak, Kattegat, Great Belt, Öresund, Arkona Basin, Bornholm Basin, Southeast Gotland Basin, East Gotland Basin, and North Gotland Basin (Table 1) are used. Mean values for a selected set of variables from the year 2006 are computed together with a 6-year (2001–2006) average and standard deviation. The parameters used are the surface (0–10 m) winter (January–February) observations of dissolved inorganic N and P (DIN and DIP), the DIN:DIP ratio, and the mean CHL for the production period (March–October). In addition, the late summer lower layer O_2 concentrations are computed from a depth below 40 m at Anholt, West Landskrona, and BY02; from 80 m at BCSIII-10; from 90 m at BY05; from 200 m at Å17 and BY15; and from 250 m at BY31 in the period August–September.

To compare the model results with observations, a cost function (Anonymous 1998) that gives a nondimensional

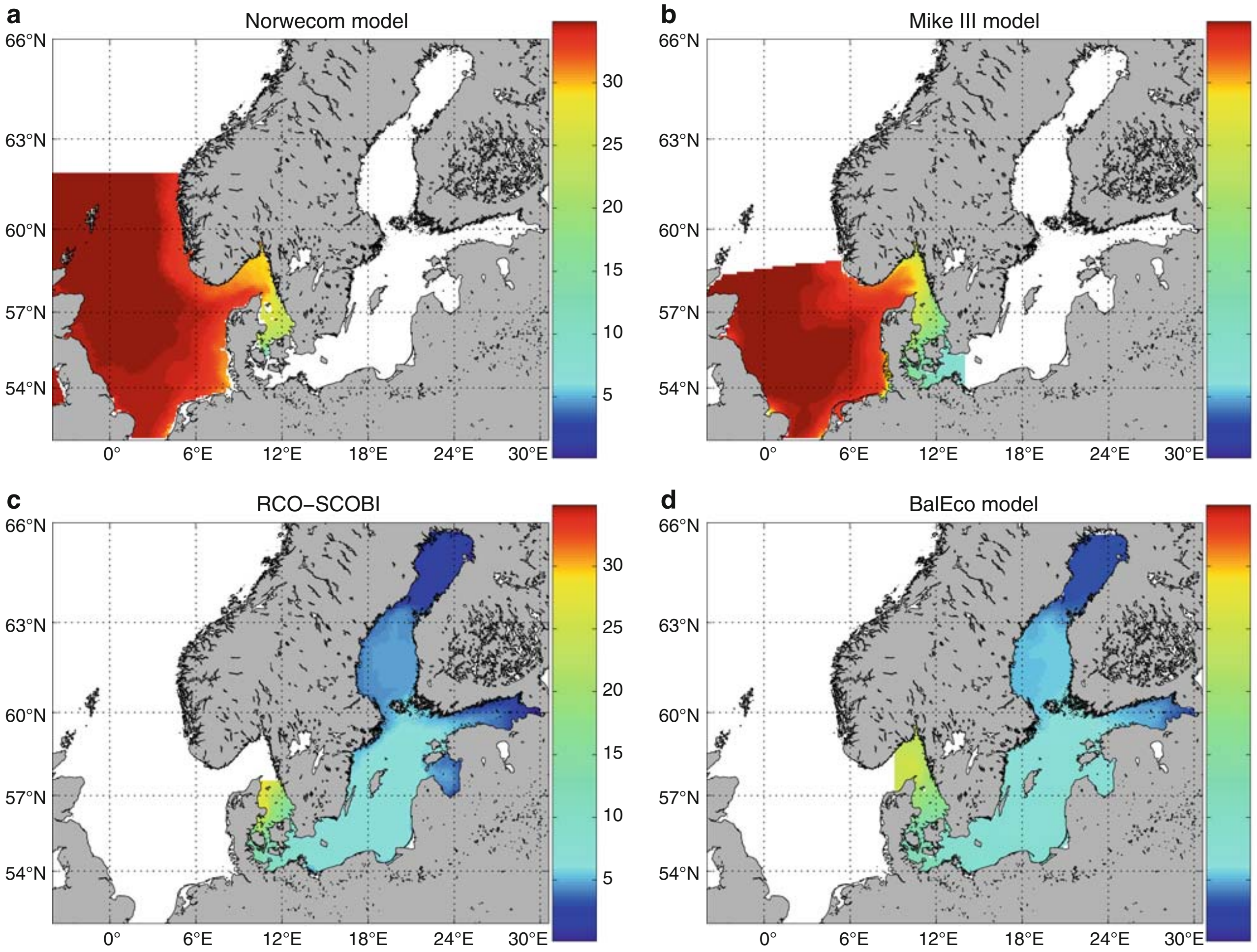


Fig. 1 Areas of influence of the four models used in the assessment. The modeled winter averages of salinity from the IMR–NORWECOM model (**a**), DHI–Mike III model (**b**), SMHI–RCO-SCOBI model (**c**), and FIMR–BalEco model (**d**) are given according to the *color bar*

Table 1 The stations used in the comparison of model results and in situ data, their positions, and the source from which the data are extracted

Sea area	Station name	Latitude	Longitude	Data source
North Sea	Noordwijk70	+52 35.1	+03 31.9	(Waterbase http://www.waterbase.nl).
Skagerrak	Å17	+58 16.5	+10 30.8	SMHI database, SHARK
Kattegat	Anholt East	+56 40.0	+12 07.0	SMHI database, SHARK
Great Belt	FYN, 6700053	+55 30.5	+10 51.8	(Danmarks Miljøundersøgelser http://www.dmu.dk)
Öresund	W Landskrona	+55 52.0	+12 45.0	SMHI database, SHARK
Arkona Basin	BY02	+55 00.0	+14 05.0	SMHI database, SHARK
Bornholm Basin	BY05	+55 15.0	+15 59.0	SMHI database, SHARK
SE Gotland Basin	BCS III-10	+55 33.3	+18 24.0	SMHI database, SHARK
E Gotland Basin	BY15	+57 20.0	+20 03.0	SMHI database, SHARK
N Gotland Basin	BY31	+58 35.0	+18 14.0	SMHI database, SHARK

SHARK The Swedish Ocean Archive (Svenskt HavsARKiv)

value indicative of the goodness of fit is used. The cost function is computed as:

$$C_i = \left| \frac{M_i - D}{Sd} \right| \qquad (1)$$

where C_i is the cost function (i.e., the normalized deviation in Sd units between model results and in situ data) for the model i, M_i ithe mean value of the 2006 model results for model i ($i =$ Institute of Marine Research (IMR), Danish

Hydrological Institute (DHI), Swedish Meteorological and Hydrological Institute (SMHI), or Finnish Institute of Marine Research (FIMR)), D the mean value of the 2006 in situ data, and Sd is the long-term (2001–2006) standard deviation of the in situ data.

In Radach and Moll (2006), the following criteria for performance are used: $C < 1$ = very good, $1 < C < 2$ = good, $2 < C < 3$ = reasonable, and $C > 3$ = poor. One may note that the value of C_i becomes large if the modeled mean value differs much from the mean value of the in situ data. The cost function may also obtain high values when the standard deviation is very small; this could be the case if the number of observations is too low to be representative for the time and area in question. Finally, one should bear in mind that the model data are sampled every day, while the sampling frequency of in situ data may vary between variables and among different seasons, locations, and years.

The Weighted Model Average

Since the accuracy of the models differs between parameters and areas, weighted average values of the models have been used to calculate the environmental assessments. The weighted average value between the models is defined as:

$$\text{Model Average} = C \cdot \sum_{i=1}^{4} (W_i \cdot M_i) \tag{2}$$

where M_i defined in all points (x, y) is the value from model i, W_i is the corresponding weight defined as $W_i = 1/(C_i + B)$, where C_i is the cost function value 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 $B = 0.1$. Finally, C is defined as:

$$C = \frac{1}{\sum_{i=1}^{4} W_i}.$$

The weighted average value is calculated for all assessment parameters and areas except for the lower layer minimum O_2 concentration. For this value, the minimum value from the different models is used. In areas where no observations—and therefore no cost function values—could be calculated, a simple average between the models is used. In the Skagerrak and North Sea, only values from IMR and DHI are used. In the Kattegat area, model values are used from all models. In the Danish Straits and Öresund, model values are used only from DHI, SMHI, and FIMR. From the Baltic Sea, only the SMHI and FIMR model values are used.

The Assessment Threshold Values

To assess eutrophication, the OSPAR CP (OSPAR 2005a) distinguishes between parameters in four different categories: 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), CHL (II), and O_2 (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 CHL mean value during the growing season should remain below elevated levels, defined as >50% above the spatial (offshore) or historical background concentration. For O_2, the agreed EcoQO is that the concentrations should be above O_2 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 Anonymous (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 ±50%, in accordance with the OSPAR CP. Table 2 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. 2. 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 (CHL) or indirect (O_2) 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 O_2 status.

Table 2 Reference and threshold values from HELCOM (2006) and OSPAR (2005b)

Basin no.	Basin name	Salinity range (psu)	DIN ref. (μM)	DIP ref. (μM)	N:P ref.	CHL ref. $(\mu\ \mathrm{l}^{-1})$	DIN thres. (μM)	DIP thres. (μM)	CHL thres. $(\mu\ \mathrm{l}^{-1})$
1	Bothnian Bay	>0	3.50	0.10	16.00	1.00	5.25	0.15	1.50
2	Bothnian Sea	>0	2.00	0.20	16.00	1.00	3.00	0.30	1.50
3	N Gotland Basin	>0	2.00	0.25	16.00	1.00	3.00	0.38	1.50
4	Gulf of Finland	>0	2.50	0.30	16.00	1.20	3.75	0.45	1.80
5	W Gotland Basin	>0	2.00	0.25	16.00	1.00	3.00	0.38	1.50
6	E Gotland	>0	2.29	0.35	16.00	1.90	3.44	0.53	2.85
7	Gulf of Riga	>0	6.50	0.40	16.00	2.00	9.75	0.60	3.00
		>0	4.00	0.13	16.00	1.10	6.00	0.20	1.65
8	SE Gotland B	>0	2.50	0.6	10.00	–	3.75	0.90	2.85
9	Gdansk deep	>0	4.25	0.25	17.00	–	6.38	0.38	4.50
10	Lithuanian water	>0	5.00	0.30	16.00	3.00	7.50	0.45	4.50
11	Bornholm Basin	>0	1.70	0.34	16.00	1.90	2.55	0.44	2.85
12	Arkona Basin	>0	2.44	0.29	16.00	1.90	3.66	0.44	2.85
13	Danish Straits	>0	2.10	0.52	16.00	1.20	2.63	0.65	1.50
14	Danish Straits	>0	1.25	0.48	16.00	0.90	1.56	0.60	1.13
15	Öeresund	>0	–	–	16.00	1.70	1.56	0.60	2.13
16	Kattegat	>0	4.50	0.40	11.25	1.25	5.63	0.50	1.56
17	Skagerrak	>0	10.00	0.60	16.00	1.50	15.00	0.90	2.00
18	North Sea NE	>0	–	0.60	16.00	3.00	13.50	0.80	4.50
19	North Sea Denmark	<34.5	15.00	0.60	16.00	6.00	26.00	0.80	9.00
		≥34.5	10.00	0.65	16.00	3.00	12.50	0.80	4.50
20	North Sea SE	<34.5	12.50	0.55	16.00	3.00	19.00	0.83	4.50
		≥34.5	8.50	0.60	16.00	2.00	13.00	0.90	3.00
21	North Sea SV	<34.5	19.00	0.60	16.00	10.00	28.50	0.80	15.00
		≥34.5	–	–	16.00	3.00	15.00	0.80	4.50
22	North Sea V	<34.5	15.50	0.80	16.00	10.00	21.00	1.20	20.00
		≥34.5	10.00	0.80	16.00	7.50	15.00	1.20	10.00
23	North Sea C	>0	8.00	0.60	16.00	–	12.00	0.90	10.00

Results

Comparison to In Situ Data

In situ data from 2006 indicate lower concentrations of winter DIN, DIP, and DIN:DIP ratios in all of the studied sea areas relative to the 6-year average. The summer CHL concentrations in 2006 are on the same level as the average value or a little less. The lower layer O_2 concentrations were improved in the Kattegat, Danish Straits, Öresund, Arkona, and Bornholm Basins relative to the 6-year average.

All models were compared to the available 2006 data, and the cost function values were computed. The model results from 2006 indicate good or very good (Radach and Moll 2006) cost function values for most variables in the different areas. The best results are seen for the summer CHL, which are found to be very good in almost all models and areas, while the lower layer O_2 concentrations have the highest number of poor results (Table 3). It should be noted that the model results in the Skagerrak and Kattegat areas in the SMHI and FIMR models are highly affected by the open boundary conditions. The computed cost function values are further used in the weights of the model averages (Eq. 2) in the following section.

Model Assessment

The assessments are computed from the weighted model averages using the cost function values or from the simple model mean for areas and parameters where no observations, and thereby no cost function values, were available as previously described. The final model averages are then compared to the thresholds. When the values from the model ensemble are above the threshold, the status is assumed to be bad, whereas it is said to be good when the values are below the threshold. The assessment of eutrophication status

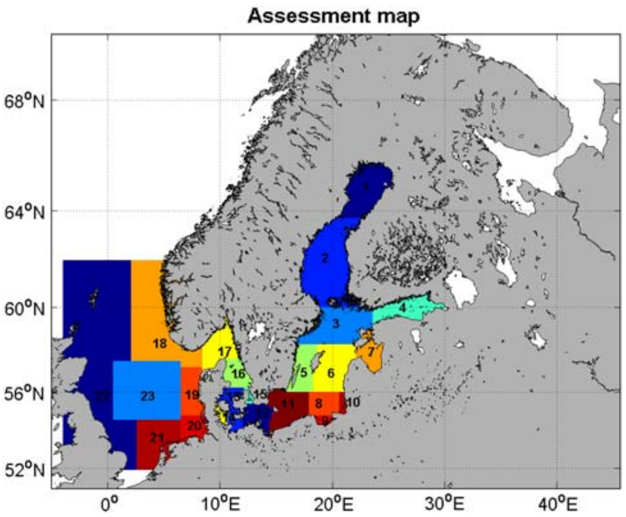


Fig. 2 The North Sea, Skagerrak, Kattegat, and the Baltic Sea are divided into 23 subbasins with separate threshold values for the EQIs. Areas in each basin have the same assessment threshold values. Areas west of Great Britain are not included in the assessment

according to the threshold values for winter DIN, DIP, and DIN:DIP (Cat. I) is shown in Fig. 3. The assessment indicates elevated levels of DIP in large parts of the Baltic proper, the Riga Bay, and the Gulf of Finland. For DIN, elevated levels are indicated for some coastal regions of the southern North Sea, in the Danish Straits, in the eastern and northern Baltic proper, in the Gulf of Finland, in the Bothnian Bay, and along the coasts in the Riga Bay and in the Bothnian Sea. The N:P ratio shows elevated or lower values along the southern coasts of the North Sea and in large areas of the Baltic Sea, with an exception for parts of the Bothnian Sea, the Gulf of Finland, the Gulf of Riga, and the eastern parts of the Eastern Gotland Basin.

The assessment of eutrophication status according to the threshold values for summer CHL concentrations (direct effects) (Fig. 4a) indicates elevated levels in the river mouth areas in the southeastern North Sea, the Baltic Sea, the whole Kattegat, Danish Straits, Riga Bay, and Gulf of Finland, and in small areas south of Gotland and east of Öland.

The assessment of eutrophication status according to the annual minimum O_2 concentrations (indirect effects) (Fig. 4b) indicates decreased O_2 levels ($O_2 < 2.8$ ml l^{-1}) in large parts of the eastern North Sea and at some locations in the southern Baltic Sea. Toxic levels ($O_2 < 1.4$ ml l^{-1}) are found in the southeastern North Sea, in the Bornholm Basin, and in the Baltic proper. Also some local areas in the Danish Straits show toxic levels of O_2 concentrations.

The assessment of eutrophication status according to the integration of the categorized assessment parameters (OSPAR 2005b) indicates that the entire southeastern part of the North Sea, the Kattegat, the Danish Straits, the Gulf of Finland, and the Bay of Riga area as well as parts of the Arkona Basin, the Bornholm Basin, and the Baltic proper may be classified as problem areas (Fig. 5). The Bothnian Bay and parts of the Baltic proper, the Bornholm Basin, and the Arkona Basin are classified as potential problem areas. Elevated primary production seems to be the main problem in the Gulf of Finland, the Bay of Riga, Danish Straits, Kattegat, and at some of the river mouths; this categorizes the areas as problem areas. In the North Sea, Bornholm Basin, and the Baltic proper, the low bottom layer minimum O_2 concentration seems to categorize the areas as problem areas.

Table 3 Cost function value (C_i) of the year 2006 for the four models where available

Model CF station	2006 Year	DIN	DIP	N:P	CHL	O_2
N70	DHI	*1.13*	2.56	**0.44**	*1.61*	–
	IMR	**0.43**	**0.33**	**0.48**	**0.35**	–
Å17	DHI	2.01	2.61	*1.56*	***7.32***	*1.20*
	IMR	***3.47***	*1.51*	***3.50***	**0.08**	***3.77***
	FIMR	**0.05**	***3.95***	**0.93**	1.39	–
Anholt	DHI	*1.99*	**0.20**	2.85	**0.38**	*1.62*
	IMR	2.77	**0.20**	***4.35***	**0.48**	***3.36***
	SMHI	**0.22**	**0.16**	**0.51**	**0.39**	***7.50***
	FIMR	*1.09*	*1.79*	**0.81**	**0.11**	–
Great Belt	DHI	**0.47**	*1.15*	–	**0.42**	**0.86**
	IMR	**0.53**	**0.38**	–	*1.67*	2.92
	SMHI	2.75	*1.71*	–	**0.49**	2.91
	FIMR	*1.64*	**0.20**	–	*1.16*	–
W Landskrona	DHI	*1.81*	*1.12*	*1.85*	**0.50**	**0.75**
	SMHI	*1.46*	2.18	**0.41**	**0.11**	***4.54***
	FIMR	**0.42**	**0.67**	**0.06**	**0.24**	–
BY02	DHI	***4.78***	*1.90*	***5.47***	**0.80**	**0.81**
	SMHI	*1.18*	*1.73*	**0.42**	**0.004**	***3.28***
	FIMR	**0.17**	*1.09*	**0.58**	**0.30**	–
BY05	SMHI	**0.60**	*1.07*	**0.93**	**0.30**	*1.42*
	FIMR	**0.85**	**0.68**	**0.88**	**0.23**	–
BCSIII	SMHI	**0.41**	**0.11**	**0.42**	**0.57**	***3.68***
	FIMR	*1.55*	**0.02**	*1.19*	**0.49**	–
BY15	SMHI	**0.39**	**0.22**	**0.33**	**0.48**	**0.33**
	FIMR	*1.68*	**0.89**	2.15	**0.48**	–
BY31	SMHI	**0.88**	*1.10*	**0.36**	**0.47**	*1.56*
	FIMR	*1.39*	*1.22*	*1.32*	**0.76**	–

The typeface refers to the criteria set by Radach and Moll (2006). *Boldface* ($C < 1$) = very good, *italic* ($1 < C < 2$) = good, *lightface* ($2 < C < 3$) = reasonable, and *boldface* and *italic* ($C > 3$) = poor

Discussion

The main finding of this study is the proposed way of combining observations and an ensemble of ecological models to make an assessment of the eutrophication status

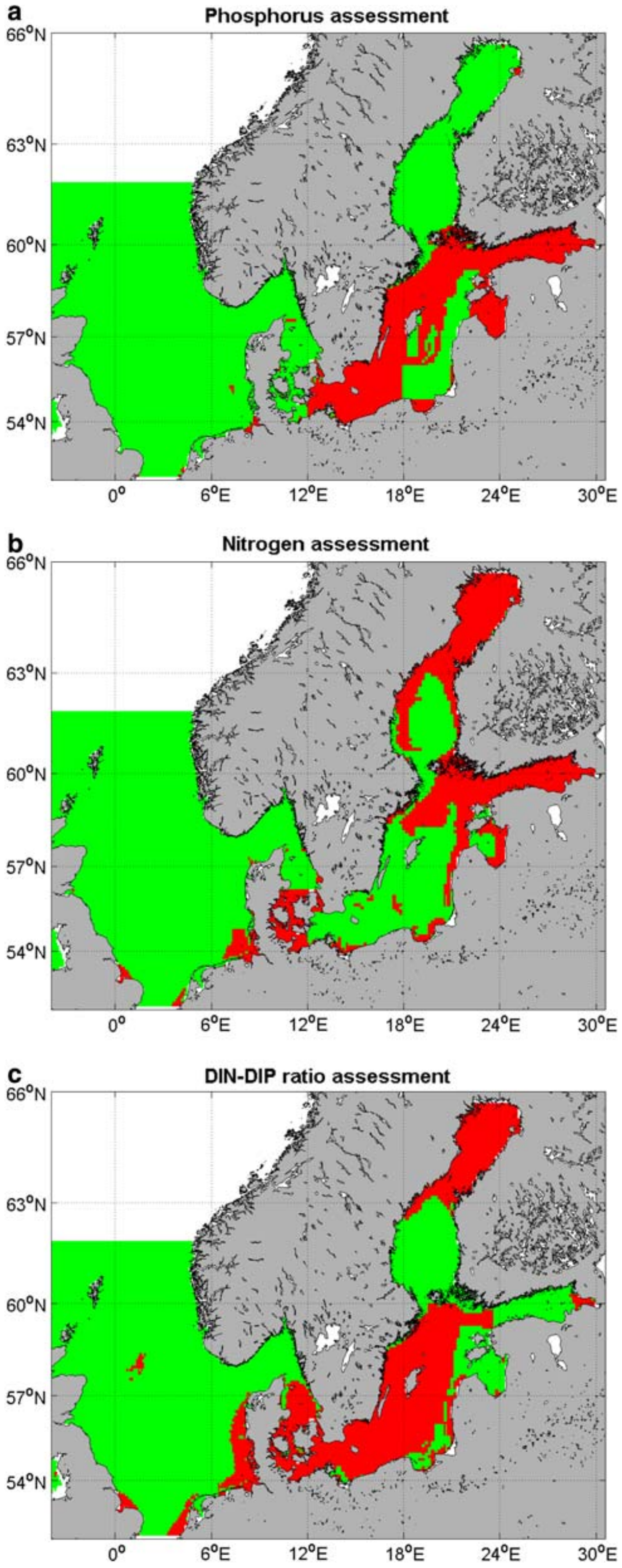


Fig. 3 Assessment results of DIP (**a**), DIN (**b**), and the DIN:DIP ratio (**c**). The assessment levels are indicated by the *colors*: *green* (good) and *red* (bad)

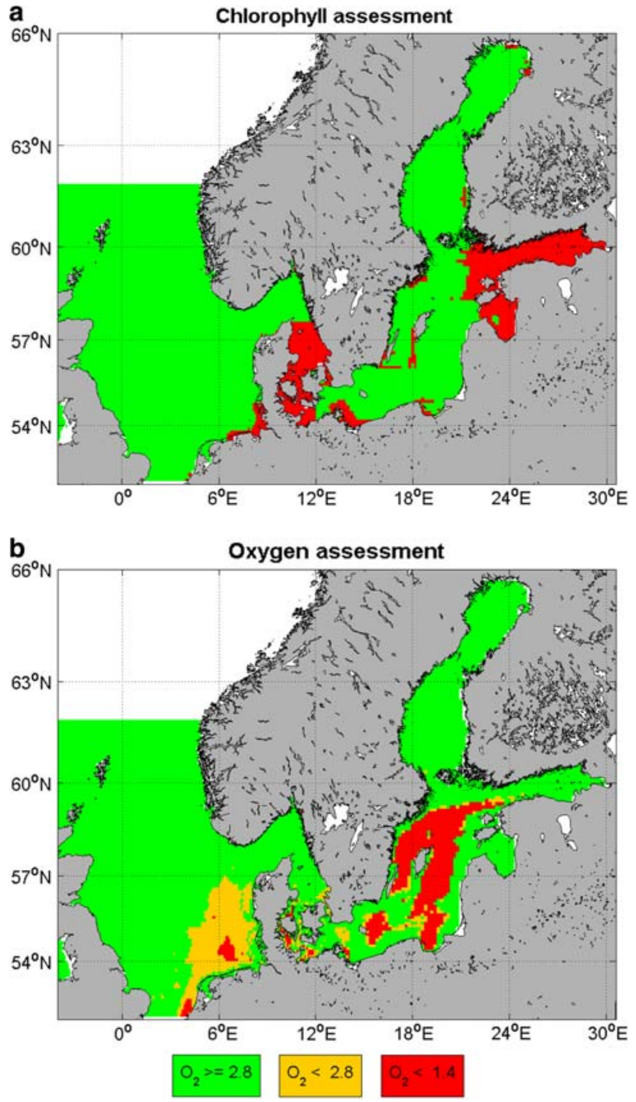
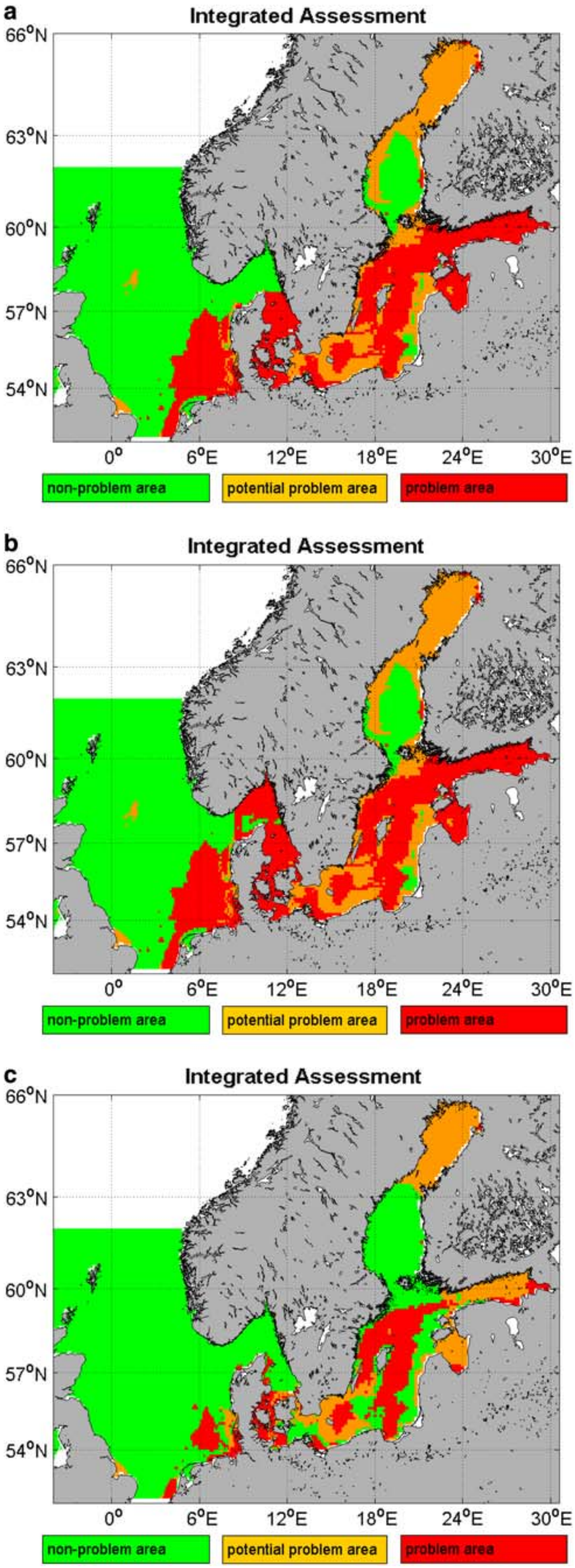


Fig. 4 Assessment results of summertime average CHL (**a**). The assessment levels are indicated by the *colors green* (good) and *red* (bad). Assessment results of annual minimum O_2 concentrations (**b**). The assessment levels are indicated by the *colors*: *green* ($O_2 \geq 2.8$ ml l^{-1}), *orange* ($O_2 < 2.8$ ml l^{-1}), and *red* for the toxic level ($O_2 < 1.4$ ml l^{-1})

in the North Sea and Baltic Sea. 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.

Comparing the present North Sea integrated assessment to that performed by the OSPAR contracting parties in 2002, there is good agreement in the final classification (OSPAR 2003). In both assessments, most of the Dutch, German, Danish, and Swedish coastal and offshore waters in the Kattegat and North Sea are categorized as problem areas. The exception is in the Skagerrak, which in the



◀ **Fig. 5** Assessment results of integrated categorized assessment parameters using the proposed weighted means (**a**), simple model means (**b**), and weighted means with a 50% change in the threshold values (**c**). The assessment levels are indicated by the *colors*: *green* (non-problem area), *orange* (potential problem area), and *red* (problem area)

present assessment is classified as a non-problem area, whereas in the OSPAR assessment, the Danish and Swedish waters are said to be problem areas and the Norwegian coastal area is classified as a potential problem area. The Norwegian classification is mainly due to the transboundary load of nutrients, which is not considered in the present assessment. This is also the case in the Swedish offshore Skagerrak, where region-specific phytoplankton indicator species (not considered in the present assessment) also suggest a problem area. Only in the Danish part of the Skagerrak, an EcoQO considered (CHL) is the reason for the classification as a problem area.

In an interim assessment using the assessment tools from HELCOM EUTRO, all basins in the Baltic Sea were classified as problem areas (Intercessional Correspondence Group on Eutrophication Modelling, http://www.cefas.co.uk/eutmod), while in this study the Bothnian Bay and parts of the Baltic proper, the Bornholm Basin, and the Arkona Basin are classified as potential problem areas and the remaining Baltic Sea as problem areas. In the HELCOM report (HELCOM 2006), the assessment is valid for larger areas than in the model study. The HELCOM basins are divided into coastal waters, transitional waters, and open sea, while in the model study the classification is valid for each grid point. In the HELCOM report, they use the "one out, all out" principle, which means that if one of the categories shows an elevated value compared to the reference value, the area as a whole is classified as a problem area, otherwise it is a non-problem area. In our model study, in contrast, three classes are used—problem area, potential problem area, and non-problem area. In the HELCOM assessment, they also include more parameters than in the model assessment. In the HELCOM report, the Bothnian Sea is classified as a problem area, which is a result of skewed DIN:Silicate (SiO_4) ratios. This parameter is not used in the model study. The Bothnian Bay is classified as a problem area due to the elevated DIN:DIP ratios, but in the model study this is classified as a potential problem area. In eastern part of the East Gotland Basin, the difference in assessment classification is because HELCOM treats the basin as a single area, while the model study uses a more detailed pattern; this is the advantage of using models.

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 is the elevated levels of CHL in the neighboring Areas 20 (German Bight) and 21 (Dutch Coast) in the North Sea of 4.5 and 15 mg m^{-3}, respectively. With such a large deviance 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 nutrient enrichment as 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. This suggests the need for concerted actions to be taken with respect to transboundary-affected areas, and for transboundary nutrient inputs to be considered an assessment parameter especially for downstream areas. 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).

When applying a simple average everywhere instead of using the weighted mean, the largest difference is seen in the Skagerrak (Fig. 5b). The main reason for this is the change in the classification of CHL, which goes from good to bad in large parts of Swedish and Norwegian waters. This is again caused by a larger weight given to the DHI model, which has a very high cost function for CHL in Skagerrak (Table 3). At first sight, turning parts of Skagerrak into a problem area might look like an improvement; however, CHL turned out to be a problem in the OSPAR assessment only in the Danish part of Skagerrak (see above). Thus, using the simple average instead of the weighted mean reduced the quality of the modeled eutrophication assessment.

To test the sensitivity to different assessment levels, a simple test was performed. As the threshold values for DIN, DIP, and CHL were increased by 50%, a large part of the areas formerly classified as “bad” (Figs. 3, 4) were improved and became classified as “good.” However, the integrated classification of the assessment was only improved for smaller areas in the eastern Baltic proper and western Bothnian Sea. As the higher and lower, threshold values for N:P ratios were increased and decreased by 50%, respectively, the assessment for the N:P ratios also showed improvements in large parts of the “bad” areas. The total classification of the assessment showed some further improvements in the Kattegat, the Arkona Basin, east of the Bornholm Basin, and eastern and northern Baltic proper. Finally, as the O_2 thresholds were decreased from 2.8 to 2 ml l^{-1} for the decreased O_2 level and from 1.4 to 0 ml l^{-1} for the toxic level, the total classification of the assessment area was even further improved, mainly in the North Sea (Fig. 5c). Looking at each parameter, the eutrophication assessments seem to be sensitive to an increase as large as 50% (or a decrease of the lower threshold value for the N:P ratio). However, looking at the total classification based on the assessments, including all of the parameters, the main patterns are the same, and the method seems to be a good tool for the classification of eutrophication status.

This study is an attempt to illustrate how models and measurements can be used to make a eutrophication assessment. However, when used in an operational framework, the availability of proper data sets, both temporal and spatial, also has to be discussed further. This is done, for example, in Radach and Pätsch (1997), where three conditions for defining adequate data sets for climatological statistics are suggested. These conditions include considerations for both the number and distribution of the observations. Using these conditions, they were able to produce validation data sets (means and their variances) for the North Sea on a 1° × 1° grid. Such methods should be used to scrutinize available data sets before using them in the assessment. This will also determine whether the number of observations available is sufficient for adopting the cost function technique, or whether a simple average between the models should be used. When the proper data are lacking, an alternative approach could also be to estimate the cost functions based on climatological fields. Such an analysis was not part of this study; therefore, the chosen data sets should only be considered as examples. Further, in a full assessment applying the proposed method, the existence of proper data sets also has to be discussed with respect to the existing thresholds and the division of the area into basins.

Concluding Remarks

The method described in this study seems to be a useful tool for making eutrophication assessments. Combining the results of different models, by using the weighted average values based on the accuracy of the different models, reduces the uncertainty of the integrated model result, and the final assessment becomes more reliable. The assessment indicates that the entire southeastern part of the North Sea, the Kattegat, the Danish Straits, the Gulf of Finland, and the Gulf of Riga area, as well as parts of the Arkona Basin, the Bornholm Basin, and the Baltic proper, may be classified as problem areas. The Bothnian Bay and parts of the Baltic proper, the Bornholm Basin, and the Arkona Basin are classified as potential problem areas.

Nevertheless, when interpreting the results, several limitations should be taken into account. Clearly the horizontal resolution in the different models is a limiting factor with respect to the correct simulation of, for example, near-shore and mesoscale processes. One should also note that the results in some areas may be questionable due to the assessment methods used in the study. The results are based on a pretty rough division of the modeled area into different basins and, in most areas, threshold values are valid for areas covering coastal areas as well as open water. Good reference values are essential for a comprehensive assessment of the eutrophication status, and more threshold values, with a better distinction between coastal areas and open ocean, will clearly improve the quality. For example, many estuaries and near-shore areas rarely achieve the desired ratio due to their naturally high N:P ratio, so rather than using a fixed ratio (Redfield in most areas), one should use a sliding assessment level based on salinity (OSPAR 2003). The lack of harmonization of thresholds between different regions is already mentioned as a problem. Methods to even out sharp gradients between areas with different thresholds should be encouraged. Finally, proper time series of observations as a basis for the calculation of the cost functions and weights used for the assessment are important. At present, there is a lack of such time series that ideally should exist in all areas in order to make high-quality assessments that can be used by managers and politicians for further environmental actions and legislation.

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