BALANCE Interim Report No. 17

Baltic Sea oxygen maps

Baltic Sea Region
INTERREG III B

BALANCE

Baltic Sea Oxygen Maps 2000–2006

BALANCE Interim Report No. 17

November 2007

Project Oxygen Maps for the Baltic Sea		Approved by: Johnny Reker			
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1 PREFACE

This report is written in accordance with the contract “Development of oxygen maps for the Baltic Sea and Kattegat” of July 2007 between the Danish Forest and Nature Agency and DHI Water • Environment • Health.

The scope of work for the study is to combine numerical modelling and in-situ profiling data to provide oxygen maps for bottom conditions in the Baltic Sea and the Kattegat. The targeted period is 2000 to 2006.

The maps produced are developed for use in the BSR INTERREG IIIB project “BALANCE”.

More information about BALANCE can be found at http://www.balance-eu.org

The work is based on a model setup earlier updated and used for the ongoing project BANSAI for the Air and Sea Working Group under the Nordic Council of Ministers.

Acknowledgements
DHI Water • Environment • Health thanks all persons and institutions supplying data for the study, e.g. ICES, HELCOM, Finnish Institute of Marine Research, Institute of Aquatic Ecology (Latvia) and the National Environmental Research Institute (Denmark). The work is funded by the Danish Forest and Nature Agency and the Swedish Environmental Protection Agency as an input to the BSR INTERREG IIIB project BALANCE.

2 INTRODUCTION

The objective of this report is to present oxygen maps illustrating minimum oxygen concentrations in the bottom waters of the Baltic Sea and the transition area to the North Sea during the period 2000-2006.

Oxygen depletion is a major environmental problem in the Baltic Sea and Kattegat and has been so for many decades. Although many institutions and scientists have spent considerable resources on monitoring and assessment of oxygen depletion, no harmonised Baltic Sea-wide maps showing the areas of concern have ever been produced.

The present report presents results from the period 2000-2006.

2.1 Nutrient enrichment, eutrophication and oxygen depletion in the Baltic Sea

The introduction to the Baltic Sea environmental situation shown below is taken from /4/:

The ecological status of most parts of the Baltic Sea is impaired compared to the ecological quality objectives set up by national authorities or international institutions.

The reasons behind the present situation of impaired conditions can be attributed to several, mostly human-generated, causes, e.g. resource exploitation (e.g. fisheries), pollution (nutrients and hazardous substances), physical modification of habitats, introduction of non-native species, and climate change.

Pollution from excessive nutrients (mainly compounds of nitrogen and phosphorus)—nutrient enrichment—is a major concern. This type of pollution is termed ‘eutrophication’. The word ‘eutrophication’ has its root in two Greek words: ‘eu’ which means ‘well’ and ‘trope’ which means ’nourishment’. The modern use of the word eutrophication is related to the inputs and effects of nutrients in aquatic systems.

Many initiatives have been launched and much work has been put into mitigation of the effects and consequences of eutrophication, especially in relation to the reduction of inputs of nutrients from point sources (e.g. towns and industries).

Focusing on nutrients and the reduction of nutrient inputs is sensible because eutrophication is a process being fuelled by excessive nutrient releases from various human-related sources. This increased flow, or flux, of nutrients into a marine ecosystem may increase the concentrations of nutrients which, taken together with the availability of light and certain minerals, may cause an increase in primary production, for example, by microscopic planktonic algae.

Nutrient enrichment thus results in an increase in productivity. Marine systems such as the Baltic Sea can cope with an increase, but only to a certain extent. When the limits are passed, we are confronted with the problem of eutrophication. The faces of this large-scale problem are well known in most parts of the Baltic Sea, e.g. green water due to blooms of planktonic algae, mats of macroalgae at the shores, reduced distribution of rich benthic habitats such as eelgrass meadows, or oxygen depletion resulting in the death of benthic animals or fish.

2.2 The Baltic Sea is very sensitive to eutrophication

The Baltic Sea is the only inland sea in the European Union and is the largest brackish-water basin in the world. It is divided into several sub-regions and a transition zone to the North Sea (the Belt Sea and Kattegat area), consisting of basins separated by sills. The major basins of the Baltic Sea are: (1) the Baltic Proper, (2) the Gulf of Bothnia, comprising the Bothnian Sea and the Bothnian Bay, (3) the Gulf of Finland, (4) the Gulf of Riga, and (5) the Danish Straits, including the Belt Sea, and Kattegat area.

The Baltic Sea has an average depth of 52 m, with a volume of 21 700 km^3 and a surface area of 415 200 km^2. The different basins or sub-areas of the Baltic Sea vary considerably from north to south and from east to west.

The basins differ not only in size, volume, and depth, but also in the salinity of the water, which is a very important factor for biota. In the western parts of the Baltic Sea (Kattegat), salinity normally is 20–25 psu; in the central Baltic Proper, salinity normally is 6–8 psu; in areas like the Bothnian Bay and the Gulf of Finland, salinity may drop to below 1 psu.

The number of naturally occurring species in the different parts of the Baltic Sea is influenced by the salinity. This makes the Baltic Sea very special. The maximum number of species is found at salinities in the range of 25–35 psu. When the salinity decreases, so does the number of marine species. The minimum number of species is found at salinities in the range of 8–10 psu, which is the typical salinity in many parts of the Baltic Sea. At salinities below 8 psu, the number of species increases because species typically living in freshwaters can cope with these low salinities.

Another feature which makes the Baltic Sea very special is the combination of a large catchment area with the associated human activities, and the limited exchange of water with the Skagerrak and the North Sea. This combination makes the Baltic Sea vulnerable to eutrophication. The catchment area of the Baltic Sea is more than 1 700 000 km^2, with a population of approximately 85 million inhabitants. The population density varies from less than 1 person per km^2 in the northern and north-eastern parts of the catchment area to more than 100 persons per km^2 in the southern and south-western parts.

The land-use structure follows the same pattern as the population density, with a high proportion of arable land in the eastern, southern, and western parts, and predominantly forest and wooded land in the northern part.

The combination of a high population density, a well-developed agricultural sector, and other human activities, such as emissions from energy production and transport, has resulted in large inputs of nutrients, mainly compounds of nitrogen and phosphorus, to the Baltic Sea. This has resulted in the eutrophication problems in the Baltic.

2.3 Effects of eutrophication

Nutrient enrichment by nitrogen, phosphorus, and sometimes organic matter can result in a series of undesirable effects. The major effects of eutrophication include changes in the structure and functioning of the entire marine ecosystem and a reduction in stability.

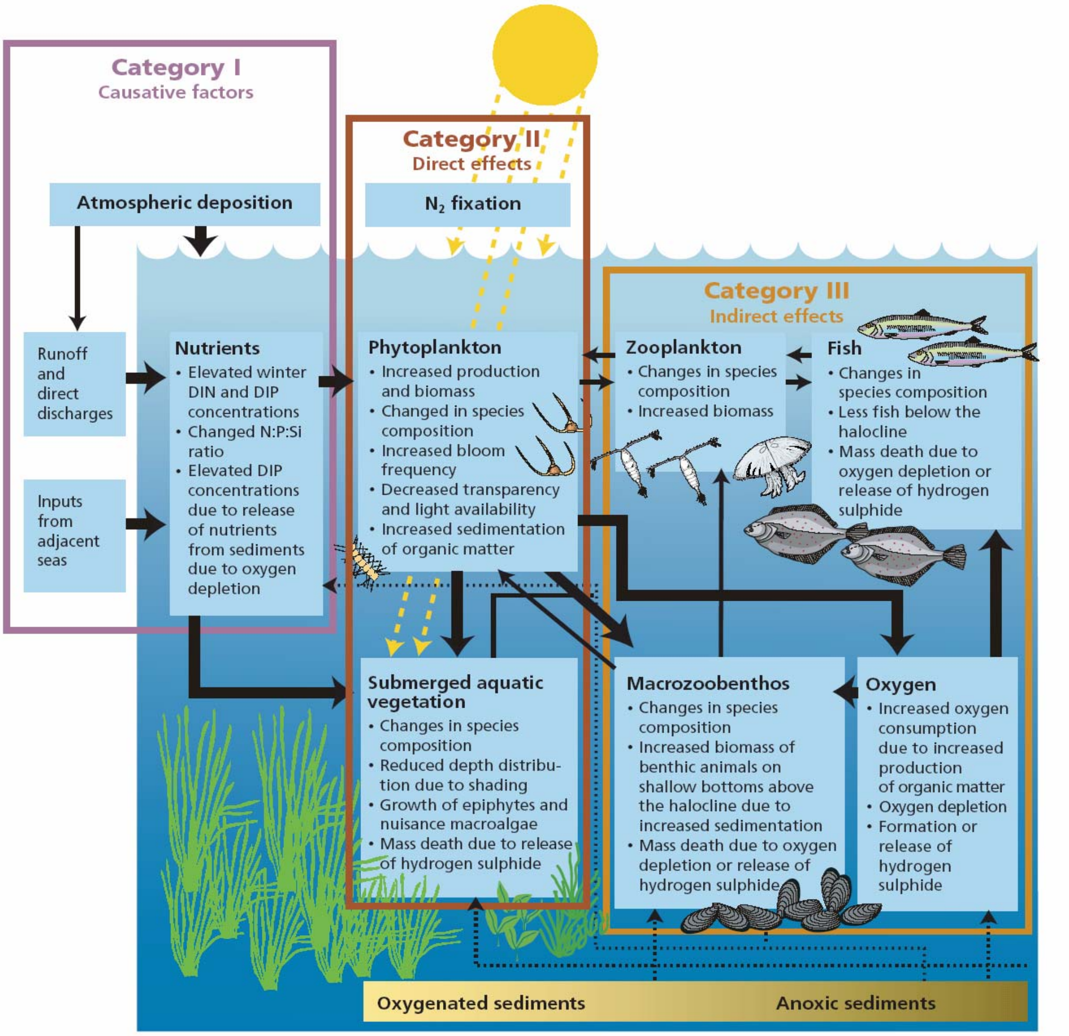

Fig. 2.1 *Conceptual model of eutrophication. The arrows indicate the interactions between different ecological compartments. Nutrient enrichment results in changes in the structure and function of marine ecosystems, as indicated with bold lines. Dashed lines indicate the release of hydrogen sulphide (H_2S) and phosphorus, which is positively related to oxygen depletion.*

Oxygen depletion is sometimes regarded as an ultimate effect of eutrophication leading to kills of benthic invertebrates, fish and sometimes even submerged aquatic vegetation and to release of nutrients, especially phosphorus from sediments. The photo on the front page illustrates a fish kill in Aalborg Bay, Denmark, in 2002 caused by oxygen depletion.

3 METHODOLOGY

The methodology for producing oxygen maps for the Baltic Sea and Kattegat is combining dynamical 3D modelling with data assimilation.

In this way both the actual oxygen status, as available from the sporadic profilings, and the dynamics between the profilings in space and time, as simulated by the model, are included in the description of the oxygen conditions in the area. Thus the strengths of both datasets are utilised.

It should be noted that the method requires both reliable recordings and a proper dynamic model to produce proper results. Therefore, both the model and the recordings have been thoroughly checked before use, removing e.g. outliers from the recordings and using a model that has been checked against recordings at other studies.

3.1 3D modelling

The 3D model applied is a MIKE 3 setup. MIKE 3 is DHI's own numerical modelling system for 3D flows.

The MIKE 3 model is a dynamic finite difference baroclinic model for free surface flows. The hydrodynamic module (HD) provides a full 3D model representation of the water levels, flows, salinities, temperatures and densities within the modelling domain, resulting from the external forcing conditions:

- Water level variations at open boundaries
- Salinity and temperature conditions at open boundaries
- Runoff from land
- Meteorological forcing

The ECOLab eutrophication model provides information on the nutrient levels (NO_x, NH_4 and PO_4), phytoplankton, zooplankton and Chlorophyll conditions, oxygen conditions, H_2S conditions and detritus (C, N, P) conditions. The main external forcing conditions for the eutrophication processes are:

- Hydrodynamics (advection, salinity, temperature, etc.)
- Nutrient loads from land and atmospheric deposition
- Concentration of the state variables at the open boundaries
- Photoactive radiation

For more information on MIKE 3 is referred to www.dhisoftware.com/MIKE3.

The present model setup is a slightly updated version of the model used for the NMR project BANSAI /1/. The updated specifications include mainly:

- Nutrient conditions at the open boundary in the English Channel
- New specifications of a few of the runoff sources
- The specified minimum value for the applied eddy viscosity
- The settings for the vertical dispersion parameters

3.1.1 Model domain and time step

The model domain includes the entire Baltic, the transition area and the North Sea. The model applies a nested grid set-up with a 9 nautical mile horizontal outer grid covering the Baltic Sea and the North Sea, and an inner 3 nautical mile grid covering the seas around Denmark, see Fig. 3.1.

In the vertical direction a 2 m resolution is used, with a maximum of 110 layers depending on the actual depth. However, the surface layer with surface elevation varying with the actual tide has a typical thickness of 5 m. For areas with depths under level -223 m the rest of the water column is included in the lowest layer.

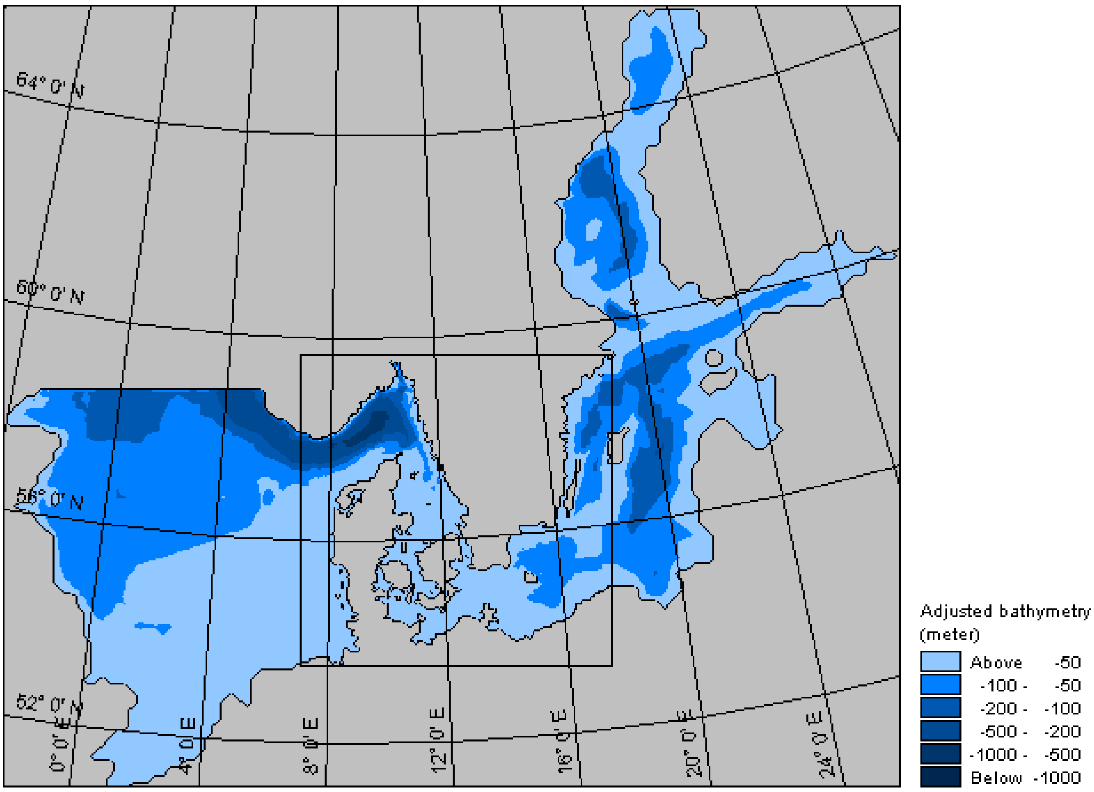

Fig. 3.1 Model domain and bathymetry with the outer 9 nautical mile domain and the inner 3 nautical mile grid

The model runs with a hydrodynamic time step of 300 seconds and an ECOLab time step of 1 hour. The selected saving time step is typically 24 hours.

3.1.2 Boundary forcings

The forcings on the open boundaries against the Northern Atlantic Ocean and the English Channel include:

- Astronomical tide along boundary (actual values for the period 2000-2006)
- Salinity distribution in sections (monthly climatologic)
- Temperature distribution in sections (monthly climatologic)
- Nutrients distribution in sections (monthly climatologic)
- Phytoplankton, chlorophyll, detritus and zooplankton concentration distribution in sections (monthly climatologic)
- Oxygen distribution in sections (monthly climatologic)

3.1.3 Air-sea exchange

The forcing conditions at the air-sea interface include:

- Wind, air pressure and temperature conditions (actual 2D maps with 1 (3) hour resolution delivered by Vejr2 (from 2002) and DMI (before 2002)
- Net precipitation (2D maps of monthly climatologic)
- Photoactive radiation (PAR) (actual daily values for most years in the period 2000-2006)
- Nitrogen deposition (2D maps of annual climatologic)

3.1.4 Runoff

The runoff to the model domain is represented by 82 source points. The position of the runoff sources is illustrated in Fig. 3.2.

The Danish sources are actual runoff discharges and nutrient concentrations taken from the annual reporting from NERI (2006 sources are estimated based on actual rainfall). The Baltic Sea and North Sea sources are mainly made available via the BANSAI /1/ project and the former NO COMMENTS project /3/. Load compilation data from around year 2000 from HELCOM and OSPAR has been applied where actual data has not been available.

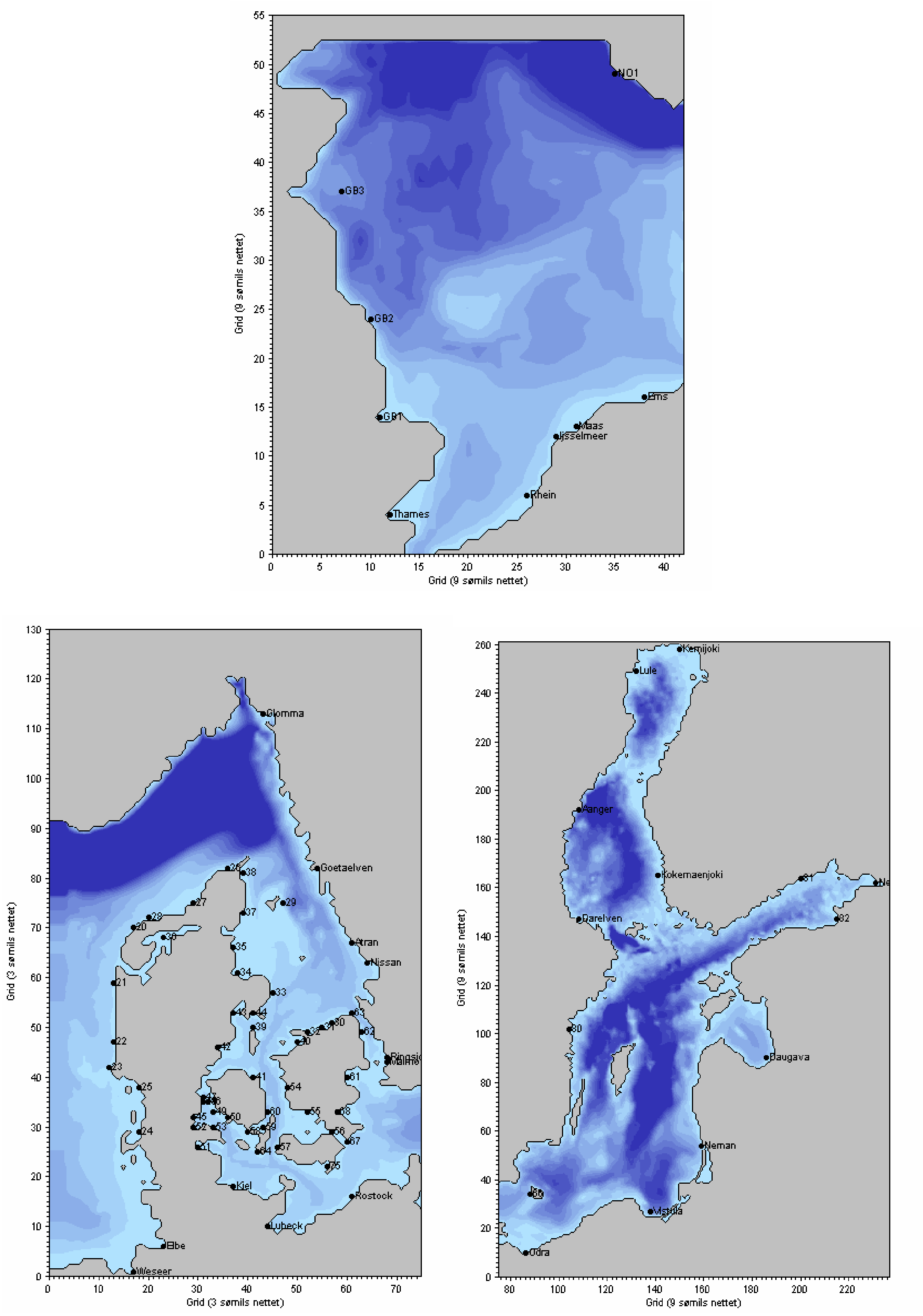

Fig. 3.2 Runoff positions for the 82 freshwater sources

3.2 Data assimilation

DHI has earlier tested data assimilation of oxygen conditions in the OPTIM project /5/. This task focussed on the Danish waters and used a different methodology from the present study, but the present work builds on some of the recommendations from the OPTIM project.

The applied assimilation method is a further development of the scheme used in Havmodellen under NOVANA /2/, where in-situ temperature and salinity data are assimilated into a 3D model. The method can be described as an Optimal Interpolation method, where the model results are being corrected at the position of the in-situ profiling in the direction of the monitoring value already starting a certain time before the date of the in-situ data.

The correction takes place at the position of the in-situ recording, but also in some distance horizontally and vertically around the recording position. The horizontal and vertical correction around the recording position has a Gaussian distribution (top-hat), with the length scale specifying where the correction is 50% of the centre correction and with a maximum extent of the correction of 3 times the length scale.

3.2.1 In-situ data sources

There have been three main types of sources of in-situ data:

- Baltic Sea and Skagerrak profiling data provided by ICES and OSPAR. This data is typically titration data, available with 5 to 25 m level steps
- Danish profiling data from NERI's database MADS. This data is sensor data, available with less than 1 m depth intervals
- Gulf of Riga profiling data from Latvia. This data is assumed being titration data and comes with 5-10 m depth intervals
- Profiling sensor data downloaded from the database of FIMR

In-situ data from the North Sea has not been included as this was outside the focus area for the assessment.

The spatial in-situ data coverage is shown in Fig. 3.3. In total 59 stations are applied. The temporal coverage varies significantly from station to station (5 to 50 profiles each year). For some stations year 2006 data is lacking, else the temporal coverage is more uniform, as shown in Table 3.1.

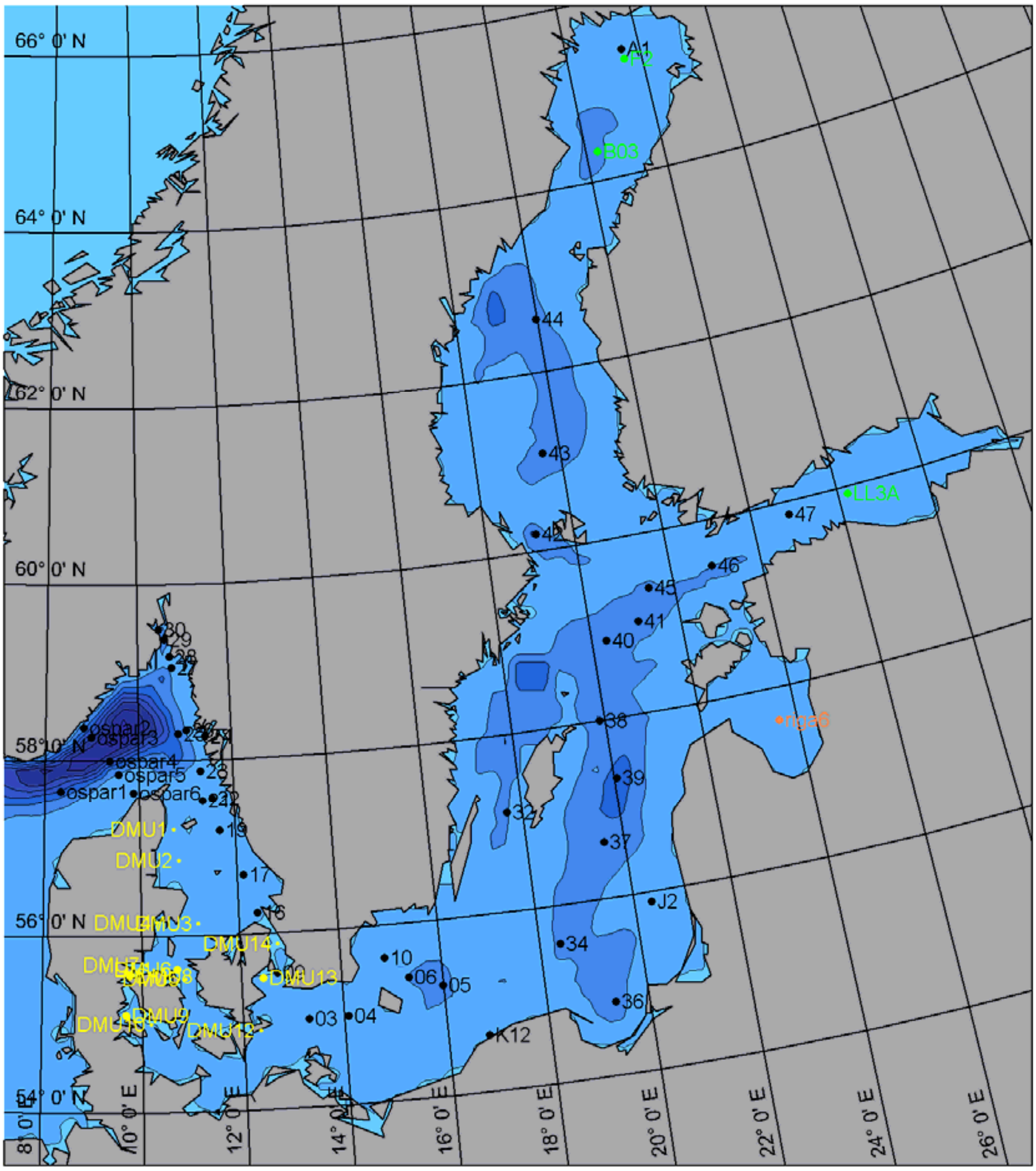

Fig. 3.3 *Position of the profile stations used for data assimilation. Stations used in Fig. 4.1 are also indicated*

Table 3.1 Temporal coverage of the station data used for assimilation A indicates 1-5 profiles per year, B 6-10 profiles, C 11-15 profiles and D >16 profiles per year

Station ID	Station Name	2000	2001	2002	2003	2004	2005	2006
Bothnian Bay:								
A1		A	A	A	A	A	A	A
B03		A	A	A	A	A	A	
F2		A	A	A	A	A	A	
Bothnian Sea:								
ices 44		B	A	A	A	A	A	A
ices 43		B	A	A	A	A	A	A
ices 42		A	A	A	A	A	A	A
Gulf of Finland:								
LL3A		A	A	A	A	A	A	
ices 47		C	C	C	A	A	A	
ices 46		C	B	A	A	A	A	A
Gulf of Riga:								
riga 6		B	C	C	C	B	A	A
Baltic Proper:								
ices 45		A	A	A	A	A		
ices 41		B	A	A	A	A	A	A
ices 40		C	C	C	C	C	C	
ices 39		C	C	C	C	C	C	
ices 38		C	C	C	C	C	C	A
ices 37		C	C	C	C	C	C	
ices 36		B	B	B	B	B	A	
ices 34		C	C	C	C	C	C	
ices 32		C	C	C	C	C	C	A
ices 10		C	C	C	C	C	C	
ices 06		C	C	C	C	C	C	
ices 05		D	D	D	D	D	D	A
ices 04		C	C	C	C	C	C	0
ices 03		D	D	D	D	D	D	A
J2		A	A	A	A		A	
K12		A	B	B	B	B		
dmu 12	STR 0901016Hjelm Bugt	D	D	D	D	D	D	D
Sound:								
ices 09		D	D	D	D	A	A	A
dmu 14	KBH 431 Ven	D	D	D	D	D	D	D
dmu 13	ROS 1727 Køge Bugt, midt	D	D	D	D	D	D	D
Belt Sea:								
dmu 10	FYN 6300043 Sydlige Lillebælt	D	D	D	D	D	D	D
dmu 09	FYN 6200901 Sydlige Lillebælt	D	D	D	D	D	D	D
dmu 08	FYN 6100051 Nordlige Lillebælt	D	D	D	D	D	D	D
dmu 07	VEJ 6870 N. Lillebælt, s.f. Bjørnsknude	D	D	D	D	D	D	D
dmu 06	FYN 6700009 Storebælt ved Fynshoved	D	D	D	D	D	D	D
dmu 05	FYN 6700053 Storebælt ved Romsø	D	D	D	D	D	D	D
dmu 04	ÅRH 170006 Århus Bugt	D	D	D	D	D	D	D
Kattegat:								
dmu 03	VSJ 20925 Gniben	D	D	D	D	D	D	D
dmu 02	NJY 409 Aalborg bugt	D	D	D	D	D	D	D
dmu 01	NJY 40302 Læsø rende	D	D	D	D	D	D	D
ices 16		C	B	B	B	B	B	A
ices 17		D	D	D	D	D	D	A
ices 19		C	D	C	D	C	C	A
ices 21		B	B	B	B	B	A	A
ices 22		B	B	A	B	B	B	A
ices 23		C	C	C	C	C	C	
Skagerrak:								
ices 24		C	D	D	D	D	D	
ices 25		C	C	C	C	C	C	
ices 26		C	C	C	C	C	C	
ices 27		B	B	B	B	B		
ices 28		B	B	B	B	B		
ices 29		B	B	B	B	B		
ices 30		B	B	B	B	B		
ospar 1		B	B	B	B	B		
ospar 2		D	D	D	D	D	D	
ospar 3		C	C	C	C	B		
ospar 4		D	D	D	D	D		
ospar 5		D	D	D	D	D		
ospar 6		D	D	D	D	D		

3.2.2 Processing before assimilation

All in-situ oxygen data has been converted into mg/l, as this is the unit used in the model.

The in-situ data has been lumped vertically before being used for the assimilation. The NERI data has been organised into a set representing the surface layer in the model (data from above -5 m) and then data follows in sets representing each of the underlying 2 m layers in the model.

Data from ICES, OSPAR ,Gulf of Riga and FIMR is also organised with a surface set (data above -5 m) followed by sets representing the ICES standard depths (-10 m, -15 m, -20 m, -25 m, -30 m, -40 m, -50 m, -60 m, -70 m, -80 m, -90 m, -100 m, -125 m, -150 m , -175 m, -200 m, -225 m, -250 m, etc.).

3.2.3 Date assimilation specifications

The model code with the assimilation options has been tested to check the proper functioning and the need for the strength of spatial and temporal footprint in the assimilation. The finally applied data assimilation specifications are generally:

- Start of assimilation 10 days before in-situ data date
- Vertical assimilation length scale 0.2 m and horizontal length scale 10-20 km for NERI sensor station data
- Vertical assimilation length scale (1-)5 m and horizontal length scale 30 km for ICES, OSPAR, FIMR and Gulf of Riga station data

4 RESULTS

Fig. 4.1 shows the development in bottom oxygen concentrations for two stations for the model version with and without data assimilation.

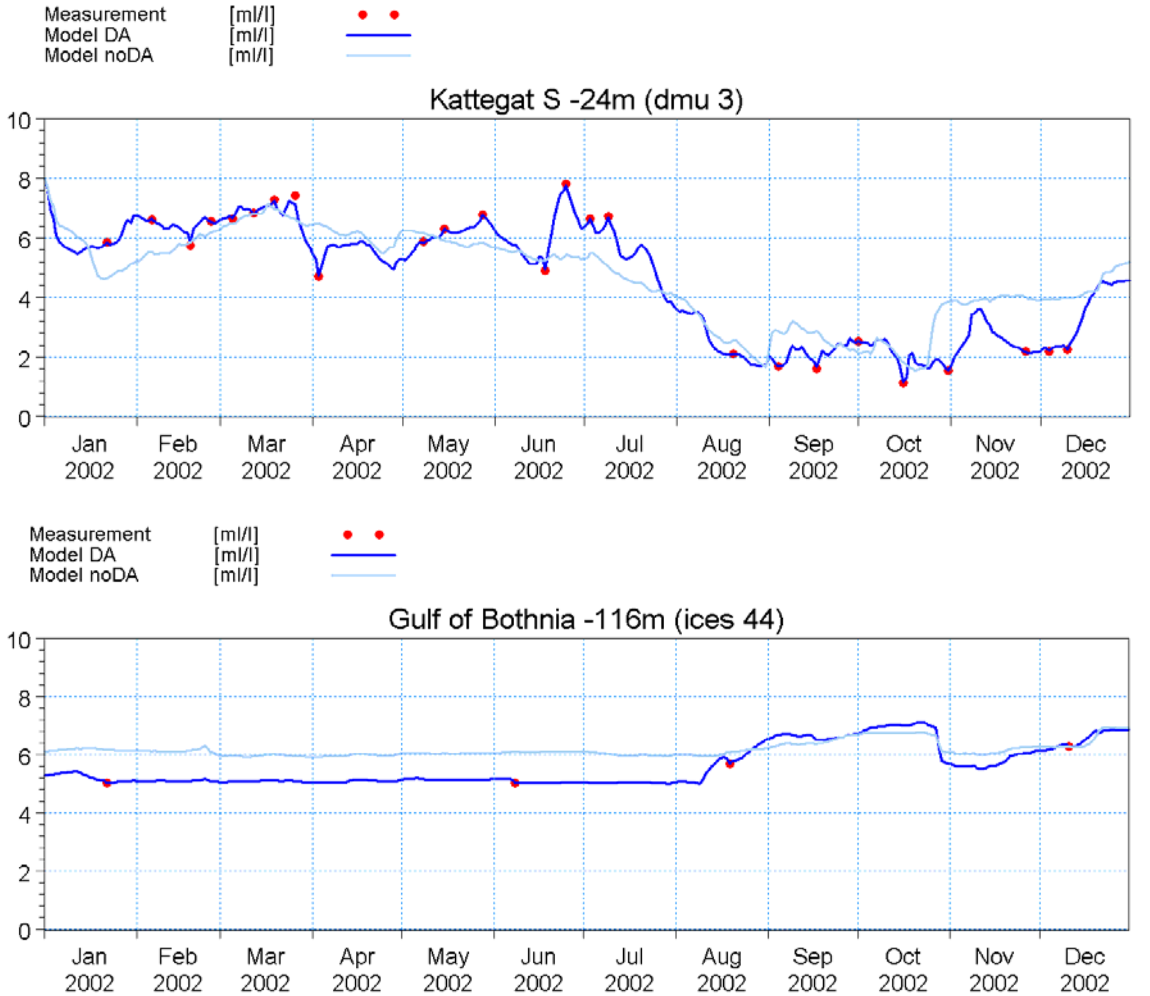

Fig. 4.1 Comparison of model results of bottom oxygen concentrations with (DA) and without (No DA) data assimilation for two positions: Kattegat S (NERI 925) and Gulf of Bothnia (see Fig 3.1 for positions)

4.1 Individual years 2000 to 2006

For each year the minimum oxygen concentration is extracted along the bottom of the model domain. Fig. 4.2 shows the minimum distribution for year 2000. The isolines represent oxygen depletion (less than 3 ml/l), severe oxygen depletion (less than 1.5 ml/l) and practically full depletion (less than 0.3 ml/l).

It should be noted that the minimum plots represent the statistical minimum for each position based on daily values available from the modelling. Thus, the plots are not describing the typical extent of the depletion areas, but show how low the oxygen concentration gets for each position throughout the year.

Similar plots are given for the other years in the period in Figs. 4.3 to 4.8. It should be noted that the 2006 distribution in Fig. 4.8 is based on assimilation of less monitoring data due to a lack of this data, which means that the uncertainty of the 2006 plot is larger than for the other plots.

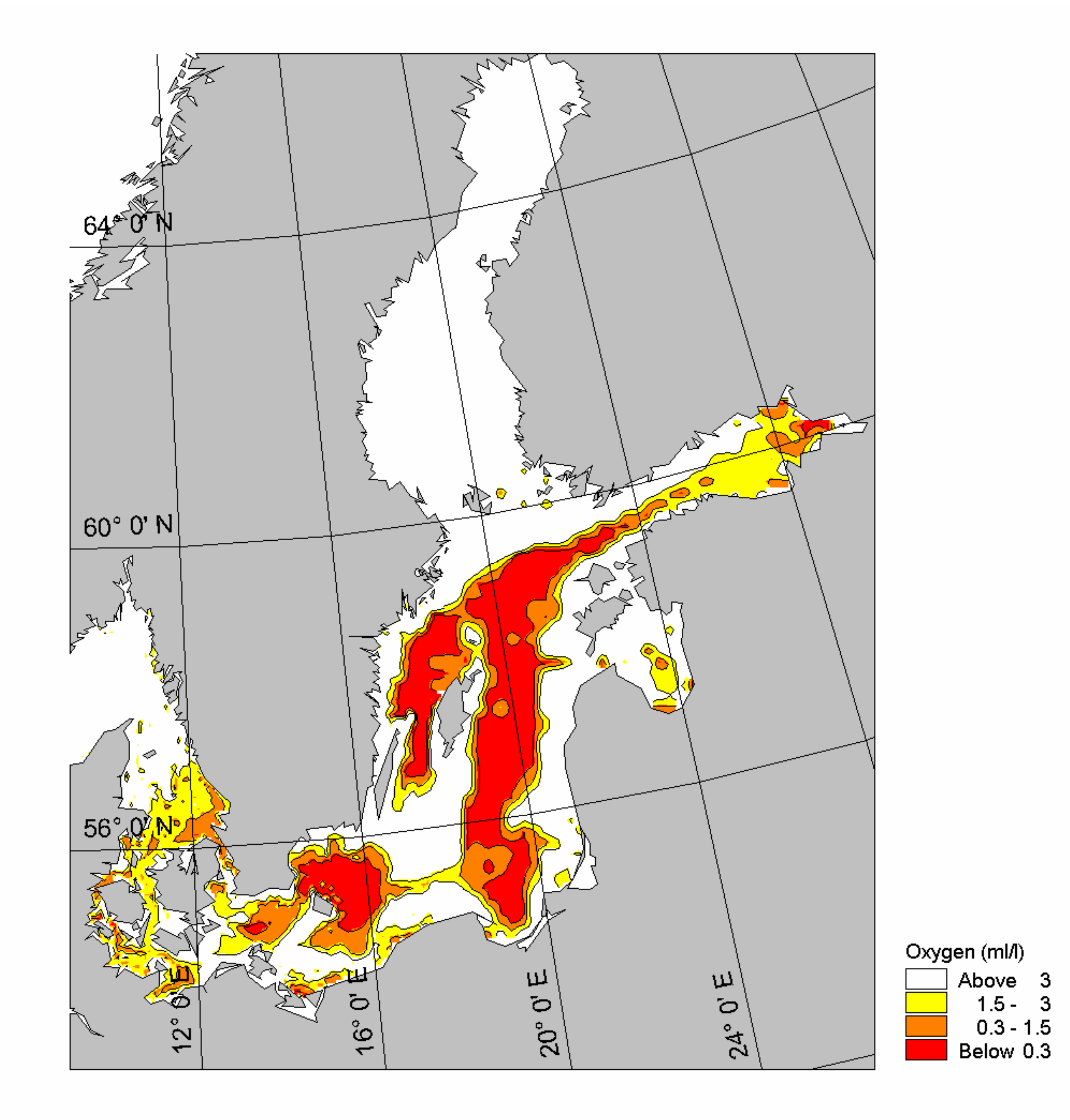

Fig. 4.2 Modelled distribution of minimum bottom oxygen concentrations in year 2000

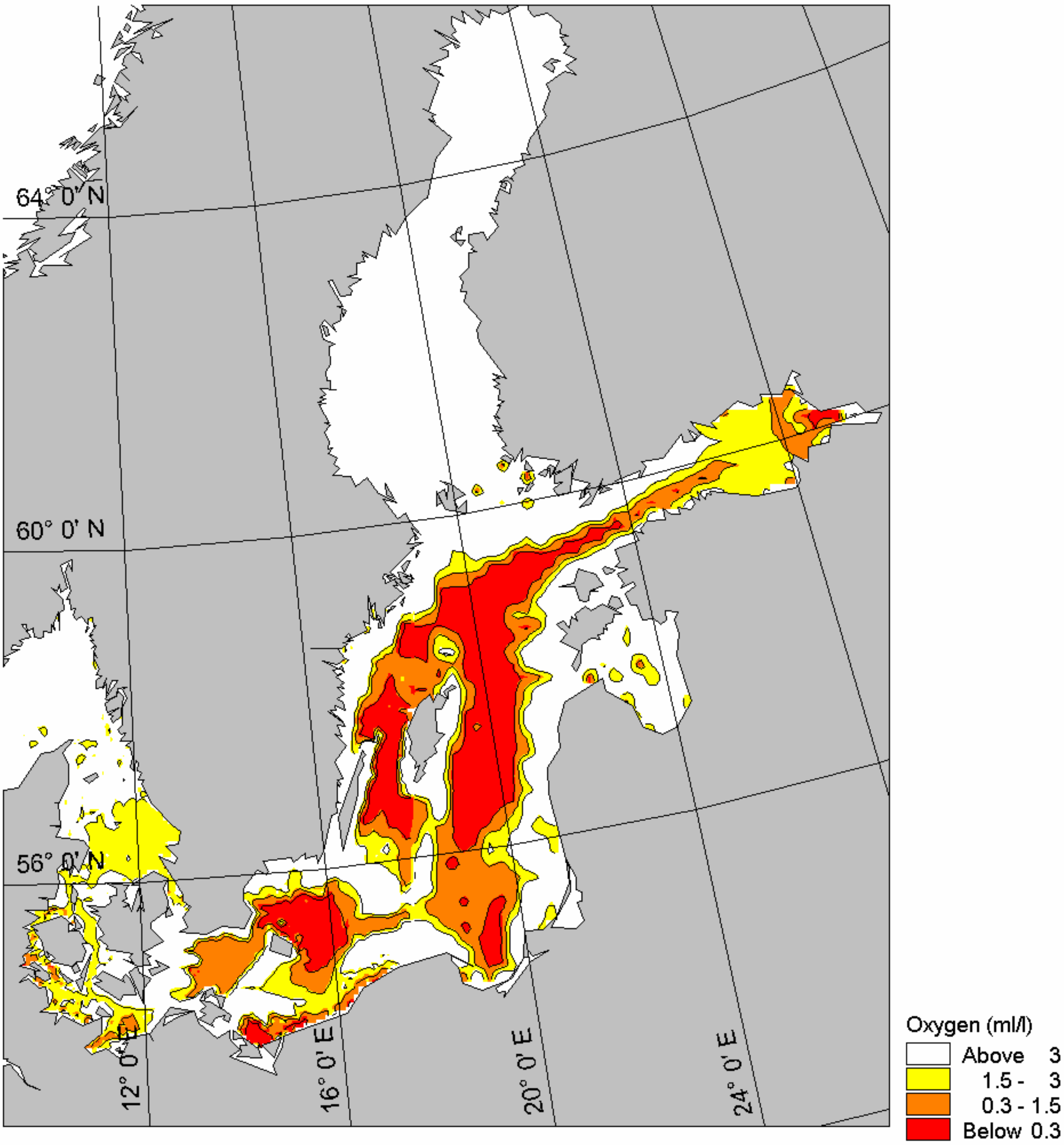

Fig. 4.3 Modelled distribution of minimum bottom oxygen concentrations in year 2001

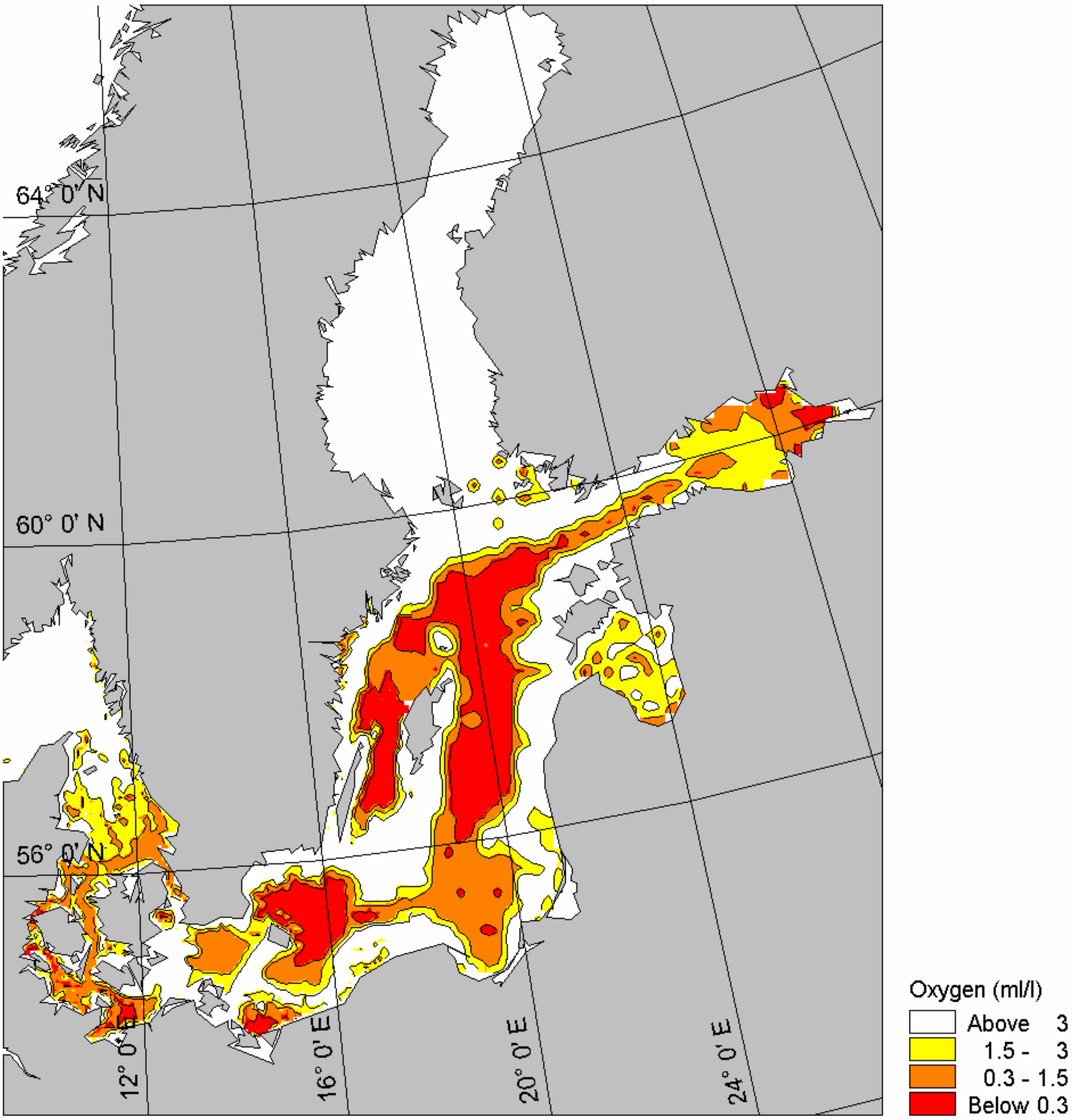

Fig. 4.4 Modelled distribution of minimum bottom oxygen concentrations in year 2002

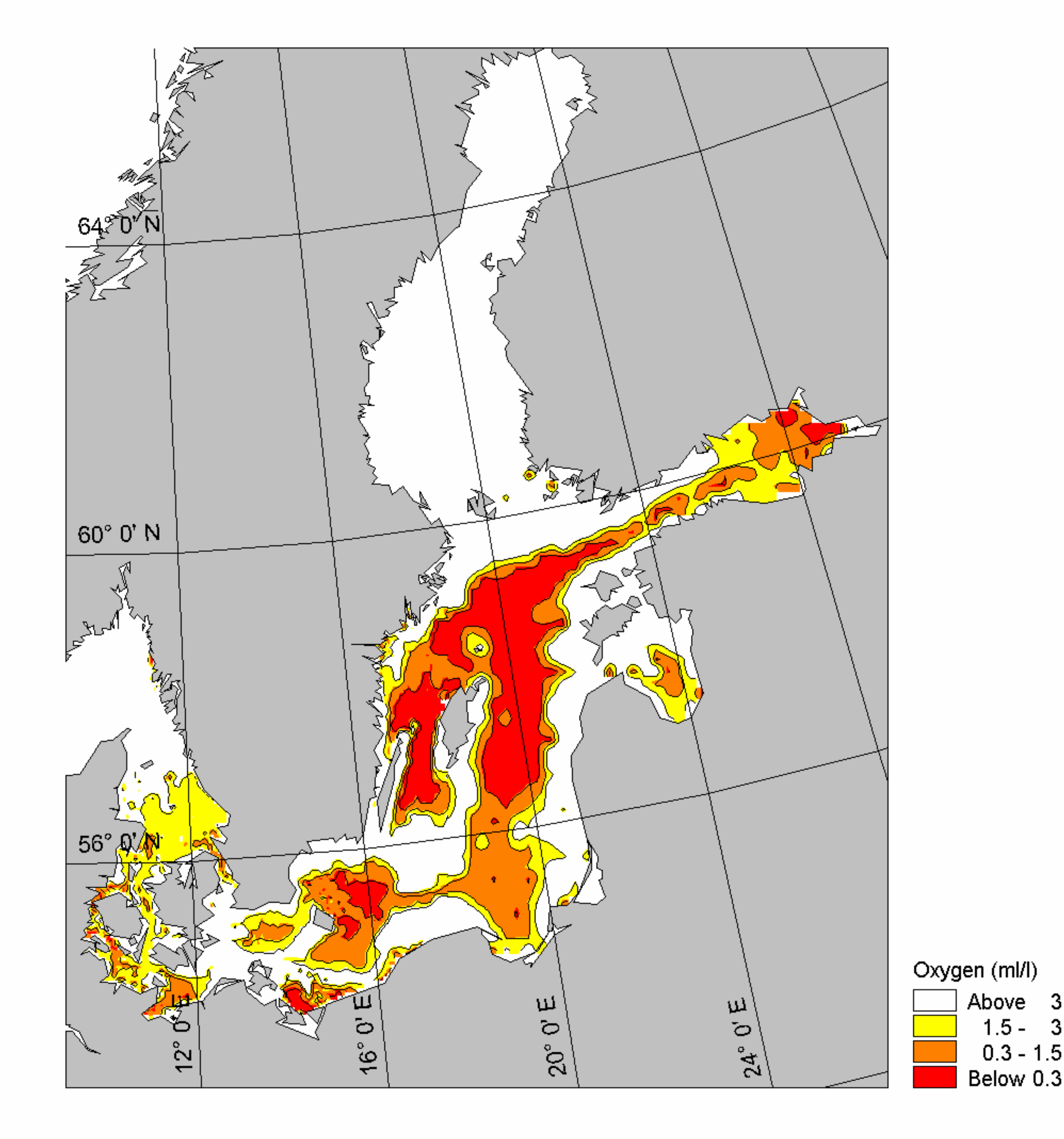

Fig. 4.5 Modelled distribution of minimum bottom oxygen concentrations in year 2003

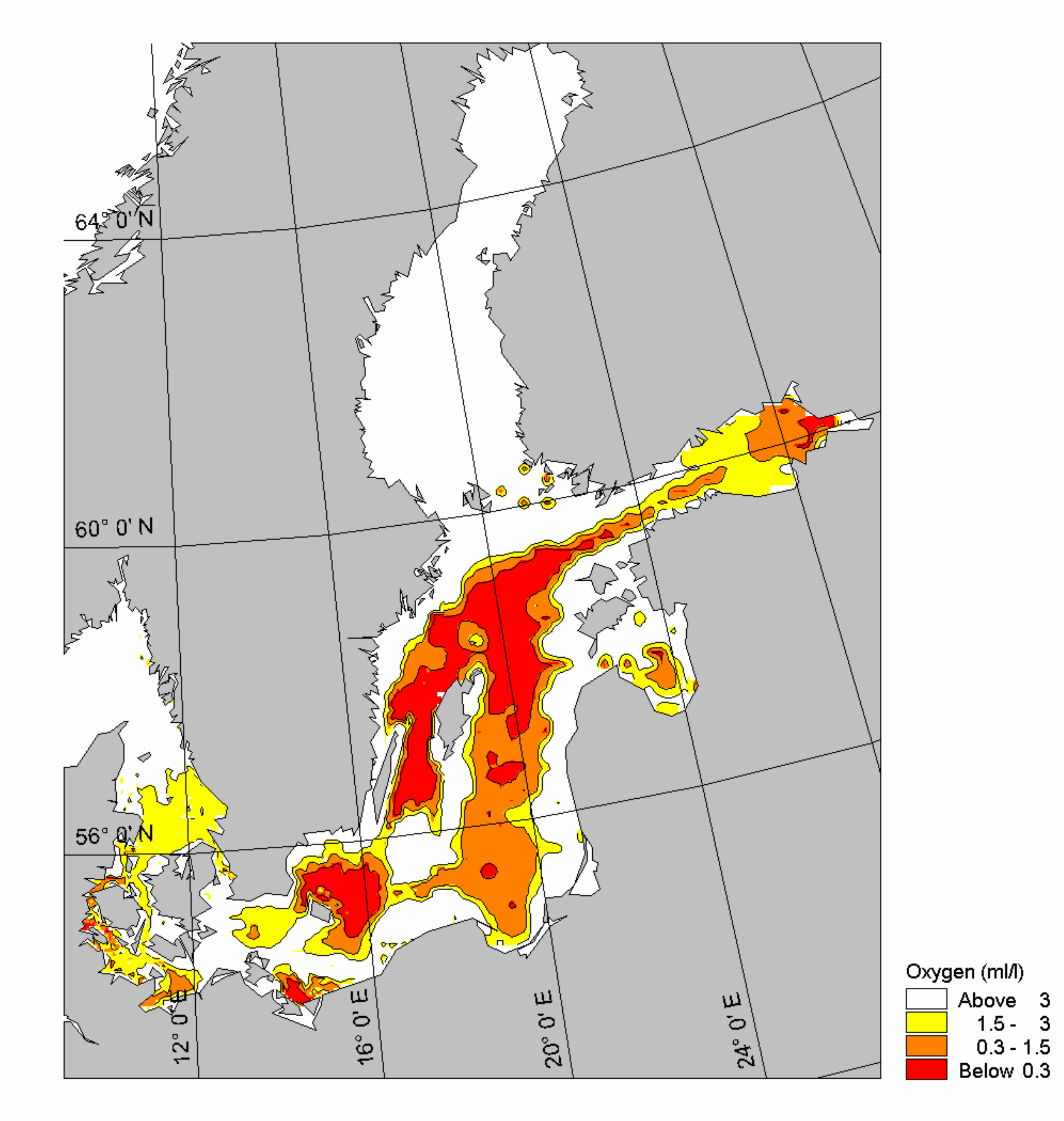

Fig. 4.6 Modelled distribution of minimum bottom oxygen concentrations in year 2004

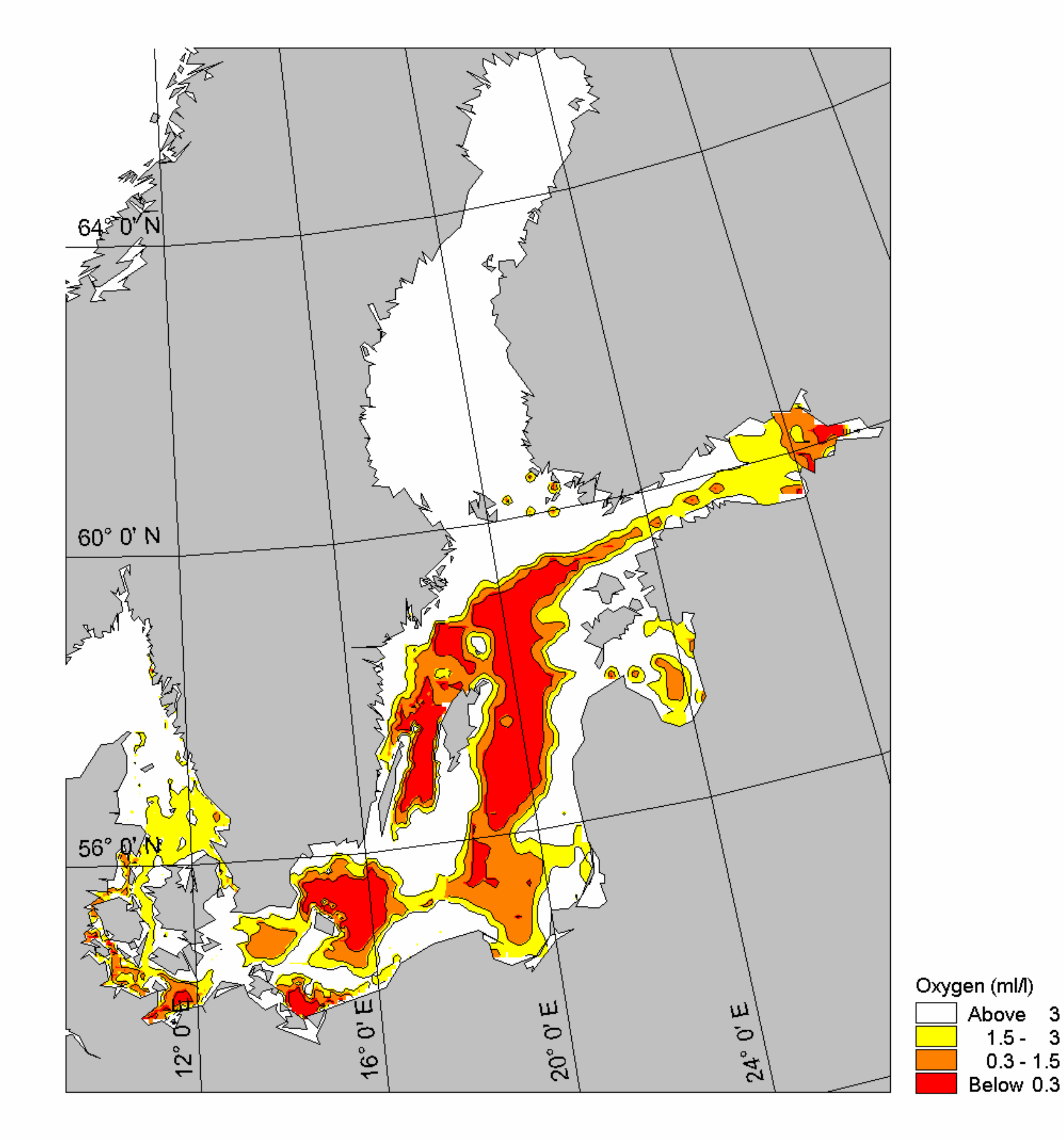

Fig. 4.7 Modelled distribution of minimum bottom oxygen concentrations in year 2005

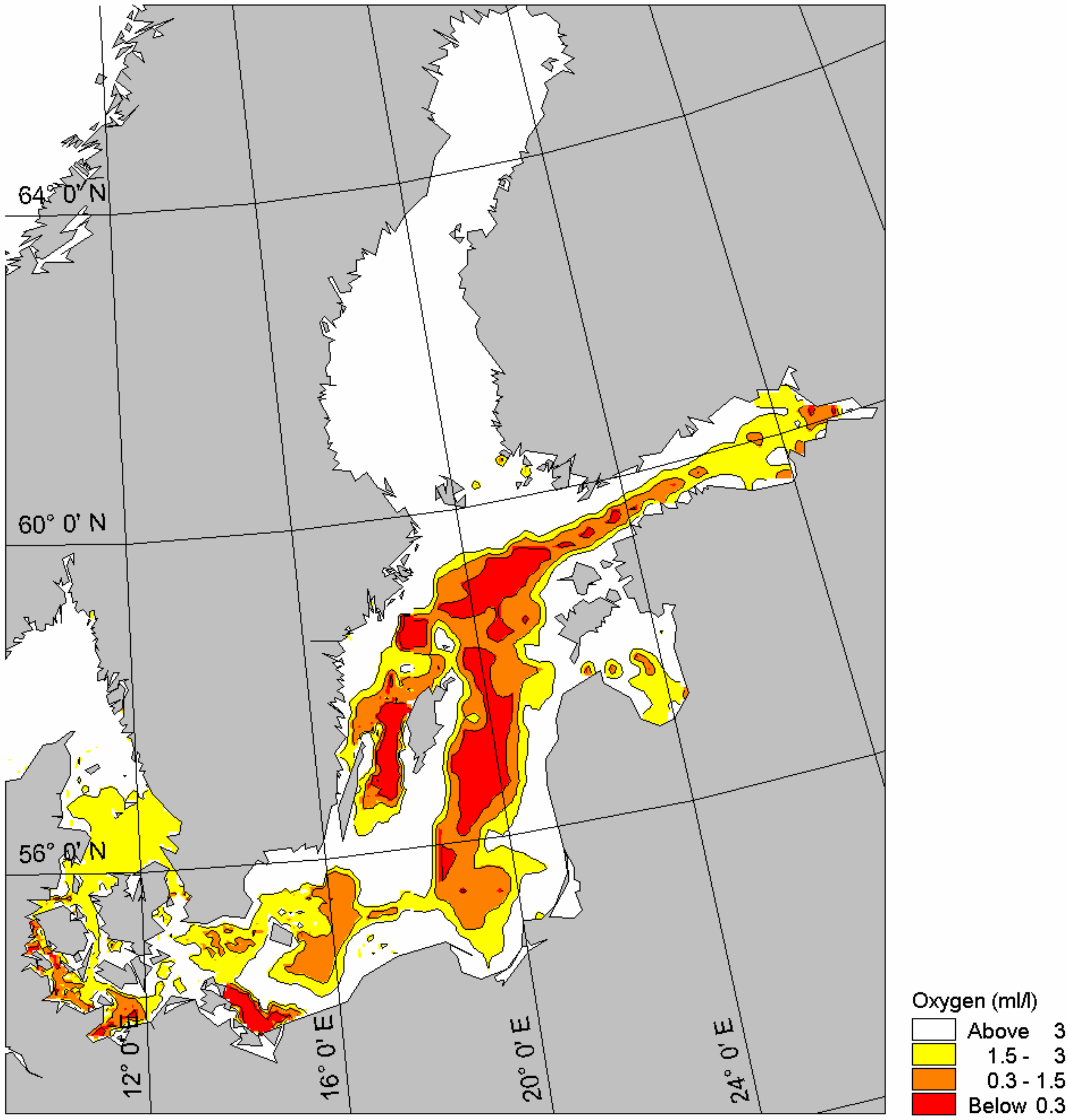

Fig. 4.8 Modelled distribution of minimum bottom oxygen concentrations in year 2006

Appendix A provides time series of 12 bottom positions for the entire assessment period 200-2006, where both the model result and the assimilation data are shown. These plots give an impression of the seasonal variation at these 12 positions.

In Table 4.1 is listed the impacted areas for each individual year.

Table 4.1 Oxygen depletion areas. The areas are insignificant in Bothnian Sea and Bothnian Bay

Area	Oxygen limit	Every year	At least once	2000	2001	2002	2003	2004	2005	2006
	ml/l	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
Skagerrak:	*3*	0	1821	617	648	710	309	494	309	216
	1.5	0	185	0	0	62	93	31	31	0
Kattegat:	*3*	7779	14385	11020	10681	12780	10588	10465	9755	12224
	1.5	0	5803	3396	31	5217	1050	0	154	31
Belt Sea:	*3*	8180	12440	10496	9199	11761	10650	10002	10002	11638
	1.5	1698	9168	4136	0	8612	4970	3519	5001	5063
Sound:	*3*	587	1142	1111	617	1080	648	741	617	1142
	1.5	0	957	833	93	926	463	154	185	154
Baltic Proper:	*3*	93626	152524	113074	126409	117797	121130	120297	119186	113629
	1.5	61954	115852	91126	98627	94460	94737	93904	90014	75012
Gulf of Finland:	*3*	13613	23615	16947	20559	22781	21392	22504	17225	16114
	1.5	2223	16114	6946	9446	12502	13335	11391	6112	5834
Gulf of Riga:	*3*	1111	11669	3334	2778	8057	5279	5001	6112	4723
	1.5	278	5834	1389	556	3612	3056	2778	3056	1111

4.2 Joint results 2000-2006

Based on the annual plots in Figs. 4.3-4.8 three more plots have been produced:

- The minimum plot for the entire period 2000-2006, showing the most severe bottom oxygen condition appearing once throughout the seven year period. This data is calculated as the minimum of the annual minimums

- The every year depletion plot, showing the area suffering from oxygen depletion at least once every year in the period 2000-2006. This data is calculated as the maximum of the annual minimums

- Frequency plot for extent of minimum oxygen condition, showing the percentage of years where minimum bottom oxygen becomes below 3 ml/l

Figs. 4.9-4.11 show the results of the two joint period processings.

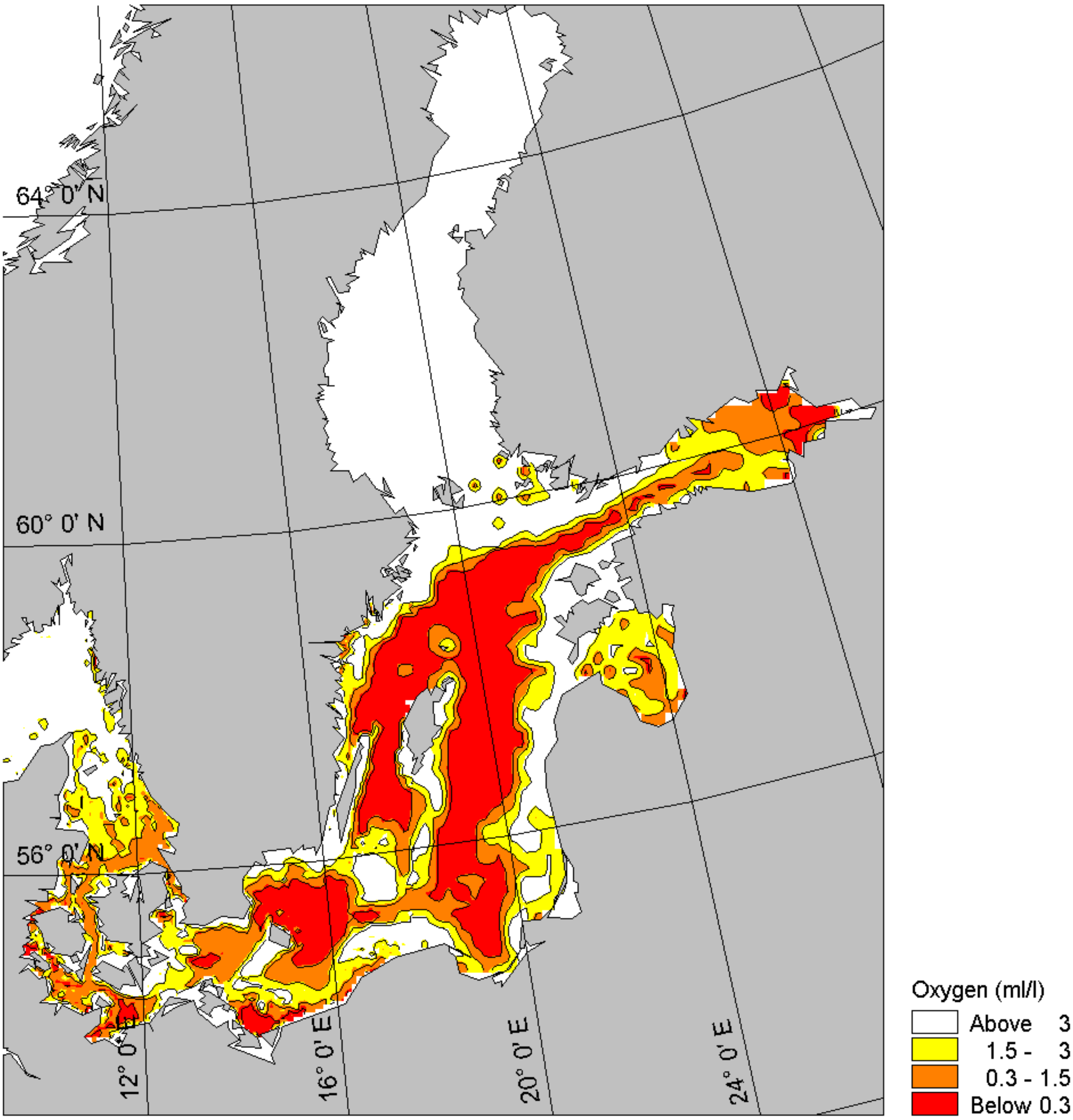

Fig. 4.9 *Modelled distribution of minimum bottom oxygen concentrations for the entire period 2000-2006, showing the lowest concentration appearing at least once (1 day) in the period*

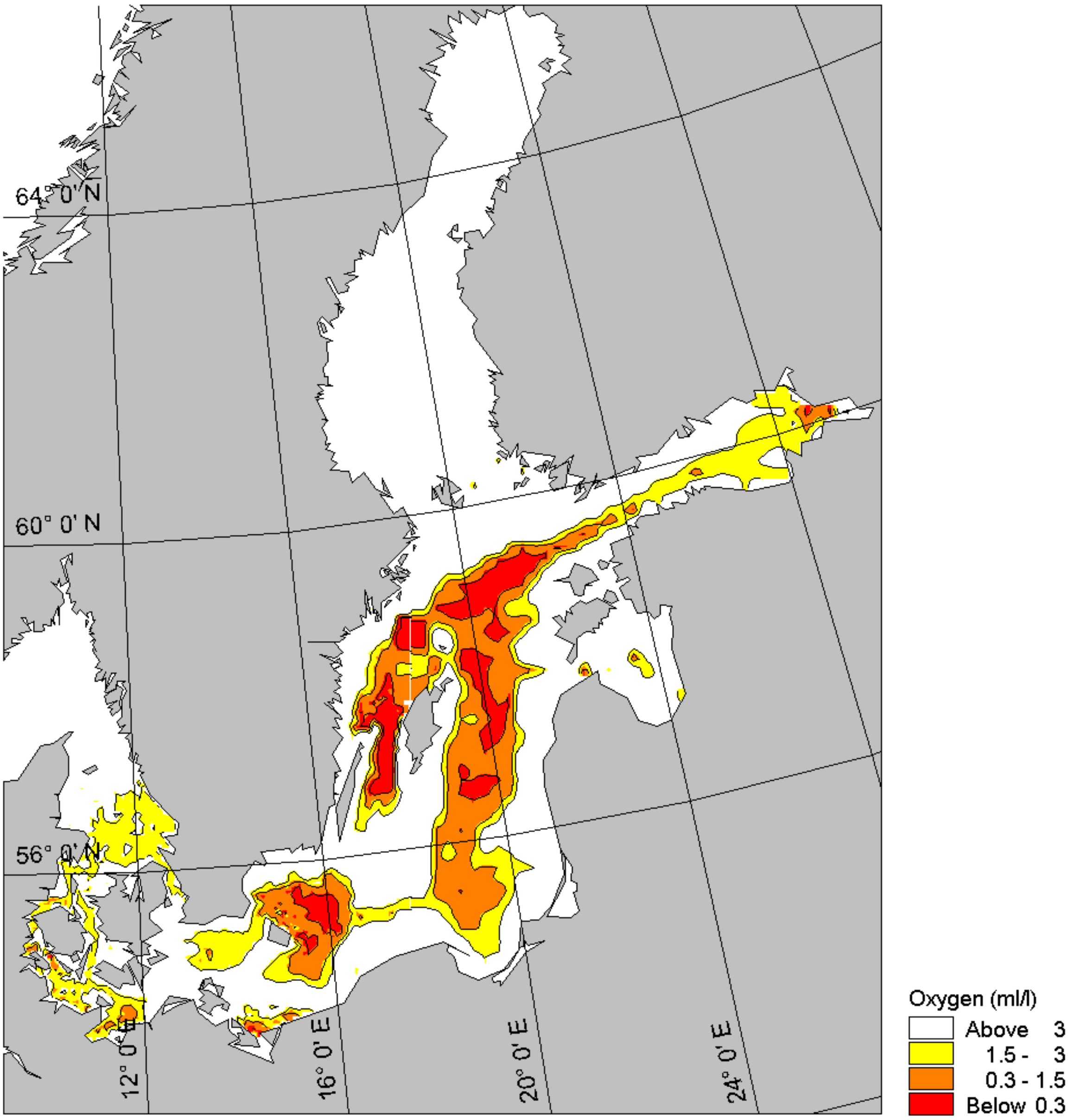

Fig. 4.10 Modelled distribution of every year bottom oxygen depletion area for the entire period 2000-2006, showing where oxygen is low each year in the analysis period

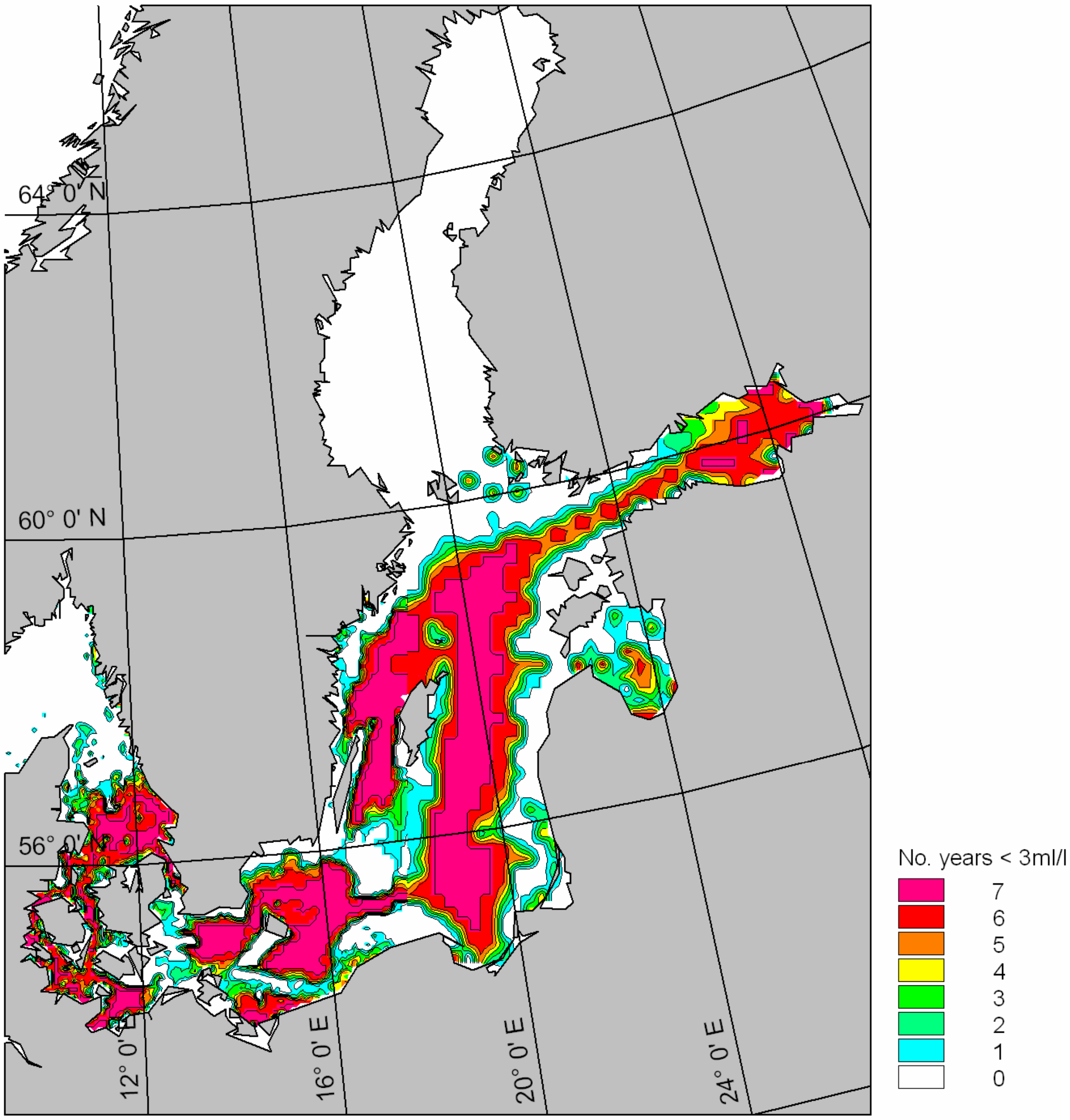

Fig. 4.11 *Modelled distribution of frequency for extent of minimum oxygen condition, showing the number of years within seven years 2000-2006 where minimum bottom oxygen becomes below 3 ml/l*

In Table 4.1 is also listed the impacted oxygen depletion areas from Figs 4.9 and 4.10.

5 DISCUSSION AND RECOMMENDATIONS

5.1 Strengths and limitations

The combined approach of numerical modelling with data assimilation of in-situ profiling data has not been done for the oxygen conditions on a Baltic Sea-wide scale before. Therefore, the results represent a first generation state-of-the-art description of the basin-wide oxygen conditions in the Baltic Sea including the transition area out to the Skagerrak. It should be noted that the available set of in-situ profiling data mainly covers the more open part of the modelling domain and not local fiords, lagoons and near coastal parts. Therefore results are less accurate for these latter areas.

The comparison between assimilated model results, non-assimilated model results and in-situ measurements (Fig. 4.1) documents that the basic model seems appropriate in most areas and that the assimilation method works appropriately. The results can thus be characterised as being of a high quality, displaying spatial differences and temporal differences between the years for the more open parts of the area.

However, the applied assimilation method is a new development at DHI, and there is not yet much experience with the appropriate settings regarding the size of the assimilation foot print. This could probably be optimised further.

There is a tendency to fall-back to the former oxygen level right after assimilation of a monitoring value. This could be related to the size of the foot print, but it could also be due to lack of update of hydrogen sulphide and of the ammonia/nitrate ratio in the applied assimilation method. Furthermore, it could indicate that the basic model (without assimilation) is slightly too dispersive.

5.2 Discussion of results

The results from the individual years document the extent and variability of the oxygen depletion. For the various areas the following conclusions can be drawn:

Skagerrak

The proper of Skagerrak is not suffering from low oxygen conditions in any of the assessment years. Along the Swedish coast of Skagerrak local signs of reduced oxygen are seen in several years and near the Danish coast local signs are seen in 2001.

Kattegat

The assessment shows that most parts of Kattegat have suffered from oxygen depletion once or more times during the assessment period. Only the central part of the northern Kattegat seems not to be affected. The impact includes down to less than 1.5 ml/l in the southernmost part of Kattegat and some way up along the Swedish coast and a large part of this area is subjected to oxygen depletion every year.

Year 2002 is seen to have the most critical depletion in this area.

Belt Sea and The Sound

The offshore parts of the Sound, Great Belt and Little Belt are seen to suffer from oxygen depletion nearly every year. The most critical depletion is seen to have occurred in 2002. In the deeper basin in southern Little Belt the oxygen depletion gets below 0.3 ml/l nearly every year.

The Belt Sea area west of the Darss Sill also suffers from oxygen depletion nearly every year. The most critical depletion is seen to have occurred in 2002, when the large offshore parts were subjected to events with less than 1.5 ml/l.

Arkona Basin

In the Arkona Basin (west of Bornholm) the conditions are very dependent on the inflow of saline water through the Belt Sea. Year 2000 had the most critical oxygen levels in the central part and year 2001 the largest extent of the depletion. After the strong saline inflow event in late January 2003 some improvement is seen in this area, but in 2005 the depletion from before the inflow event is reestablished. The central part is seen to be subject to less than 3 ml/l every year.

In the vicinity of the outflow from the river Oder at the German coast severe oxygen depletion events are also seen every year, with changing extent. Year 2006 seems to have been the most critical year.

Bornholm Basin

The Bornholm Basin (east of Bornholm) is connected in the deep to the Arkona basin via the Bornholm Gap northwest of Bornholm and via the Stolpe Channel to the Baltic Proper. However, both connections are less deep than the Bornholm Basin, thus leaving a hollow subsurface. This hollow is subjected to oxygen depletion every year, with year 2002 being the most critical year. After the strong saline inflow event in later January 2003 is seen some improvement in this area but the effect is reduced from year 2004.

Bay of Gdansk

Every year oxygen depletion occurs in the Bay of Gdansk. The most critical year seems to have been year 2000, when the bottom oxygen got below 0.3 ml/l in a large part.

Eastern Baltic Proper

The Eastern Baltic Proper with its deep part in the centre is a critical area by nature with respect to oxygen. In the assessment period the oxygen content got below 0.3 ml/l in the central deeper part almost every year. In 2003 the larger saline inflow is seen (Appendix A) to have increased the oxygen content in the deepest part to about 3 ml/l, but the complete oxygen depletion is reestablished within 12 months. In the annual plots the year 2004 seems to have the smallest extent of the critical bottom oxygen conditions after the inflow and year 2000 the largest extent.

Western Gotland Basin
The basin west of Gotland is also subjected to very critical oxygen conditions every year with the years 2000, 2003 and 2004 being the most critical years.

Gulf of Riga
Only the central part of the Gulf of Riga seems to be subjected to depletion every year, whereas most of the offshore area is subjected to depletion at least once in the seven year period. Year 2001 seems to have been the less critical year and year 2002 among the most critical years. Some critical concentrations are also seen close to the coast.

Gulf of Finland
In the Gulf of Finland the innermost part and the deeper part all the way out are suffering from depletion every year. The variability from year to year is not large, but the years 2001, 2002 and 2003 seem to have had the most critical conditions.

Åland Sea
The archipelago sea around the Åland islands is probably not sufficiently well resolved in the applied model to assess the bottom oxygen conditions, as the model applied a 9 nm horizontal resolution here. The result showing no significant critical oxygen parts may thus be a too optimistic assessment.

Bothnian Sea
The Bothnian Sea does not seem to have suffered from oxygen depletion in the assessment period, not even in the deepest parts in the northern end.

Bothnian Bay
Similarly the Bothnian Bay does not seem to have suffered from oxygen depletion in the assessment period.

5.3 Recommendations for further work

The established 3D dataset on oxygen conditions in the Baltic Sea appears to be a proper basis for further analysis of the extent and temporal variation of the oxygen conditions.

Among the possible additional post processing options are:

- Development of time series of monthly extent of the bottom oxygen depletion area for the various parts of the Baltic Sea
- Development of time series of monthly size of the pelagic volume of water suffering from depletion for the various parts of the Baltic Sea
- Development of frequency of occurrence of oxygen depletion for the various parts of the Baltic Sea

It is also possible to make a similar analysis for the occurrence of other substances like hydrogen sulphide. Hydrogen sulphide is already a state variable of the model, but the hydrogen sulphide measurements have not yet been prepared for data assimilation.

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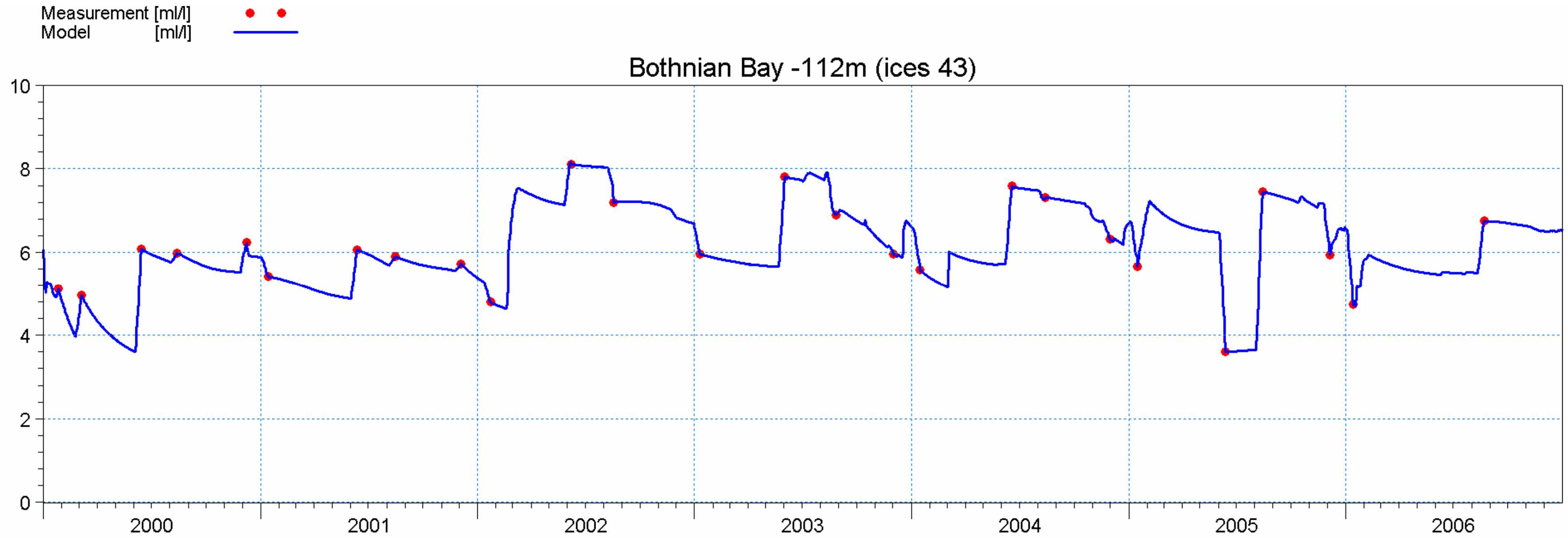
A P P E N D I X   A

Time series of assimilated oxygen results for 12 stations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10
8
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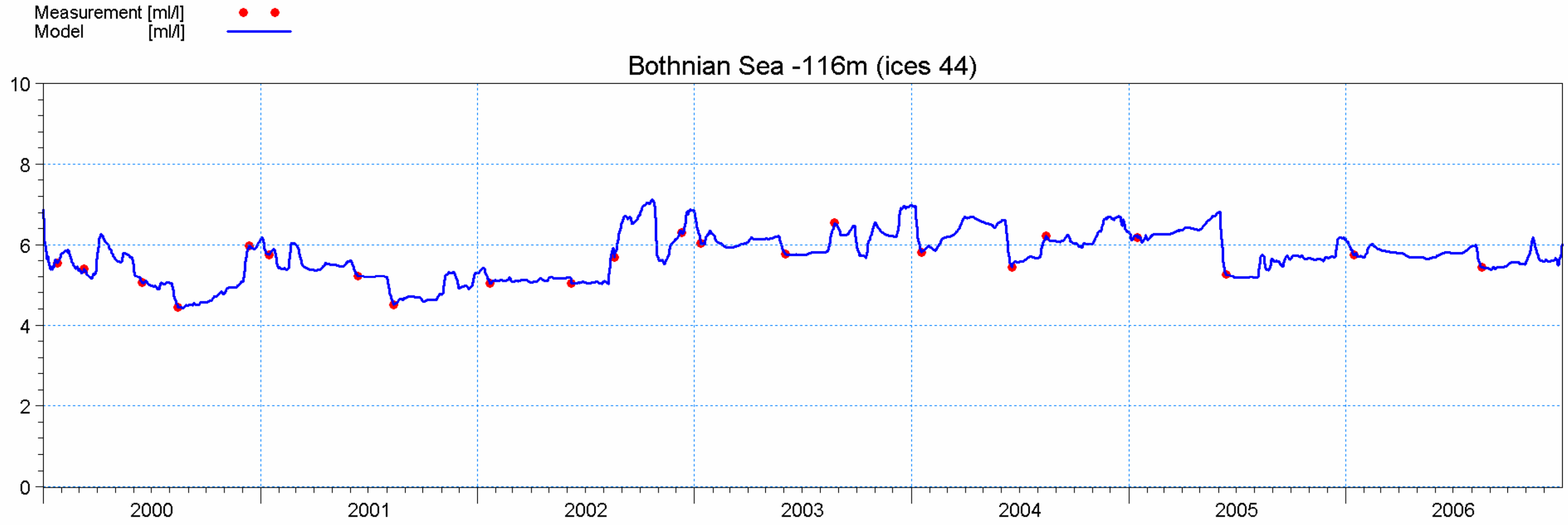
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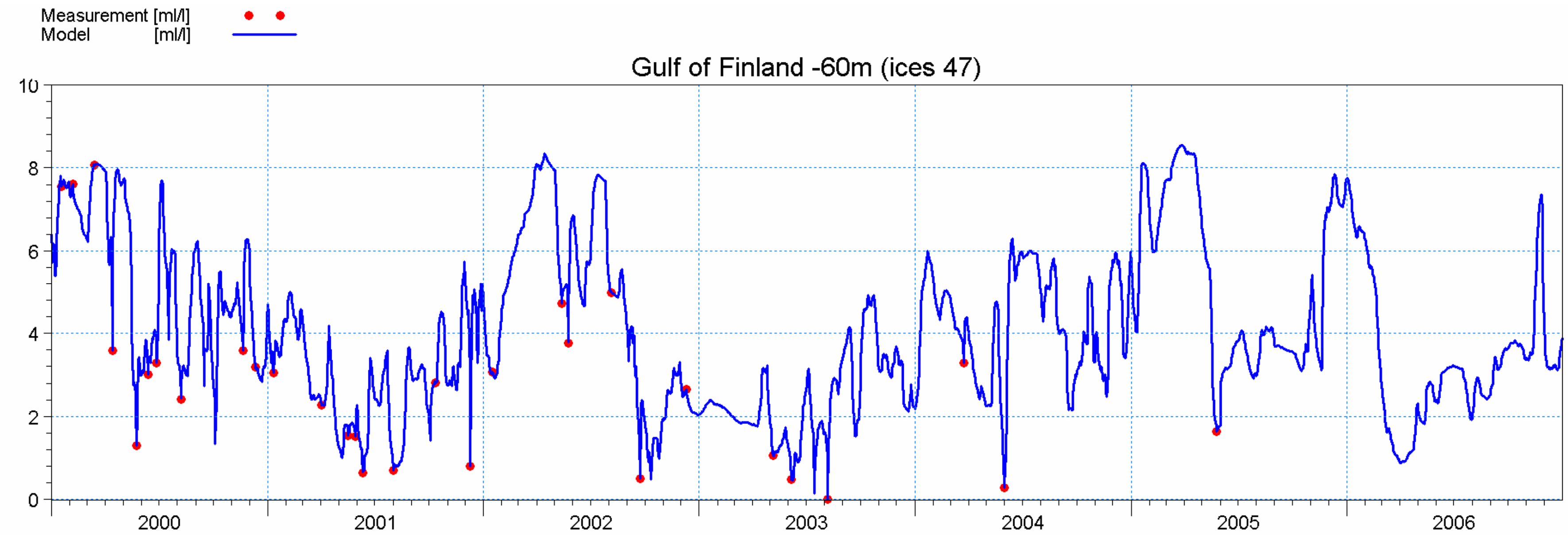
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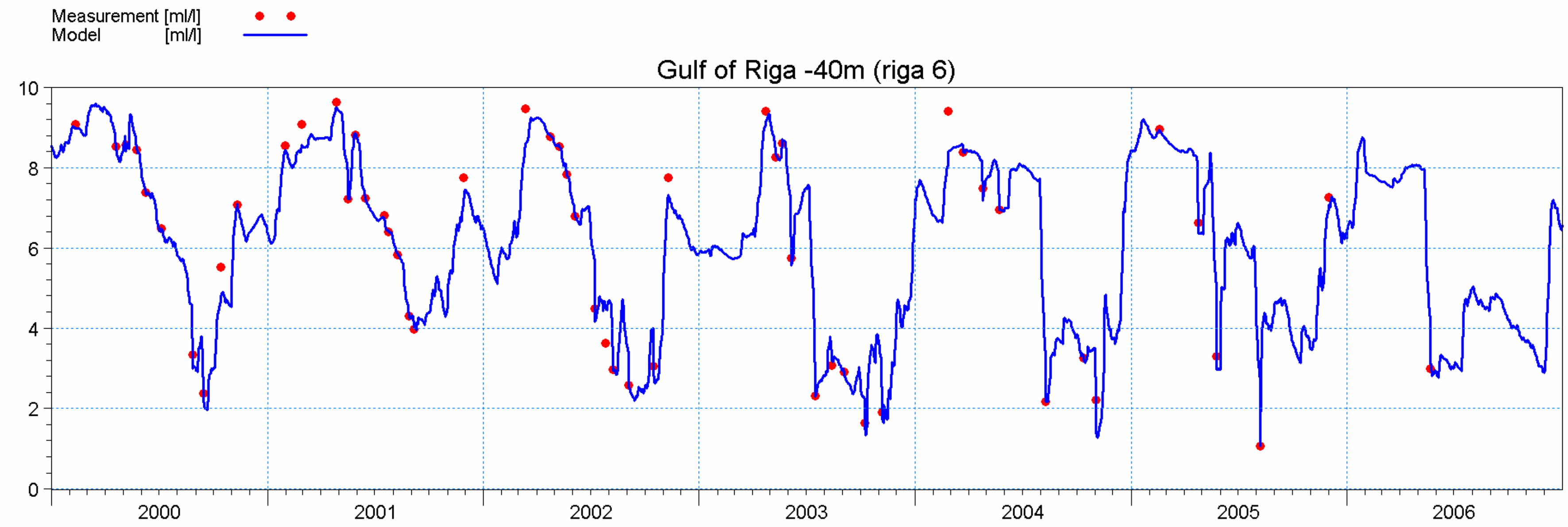
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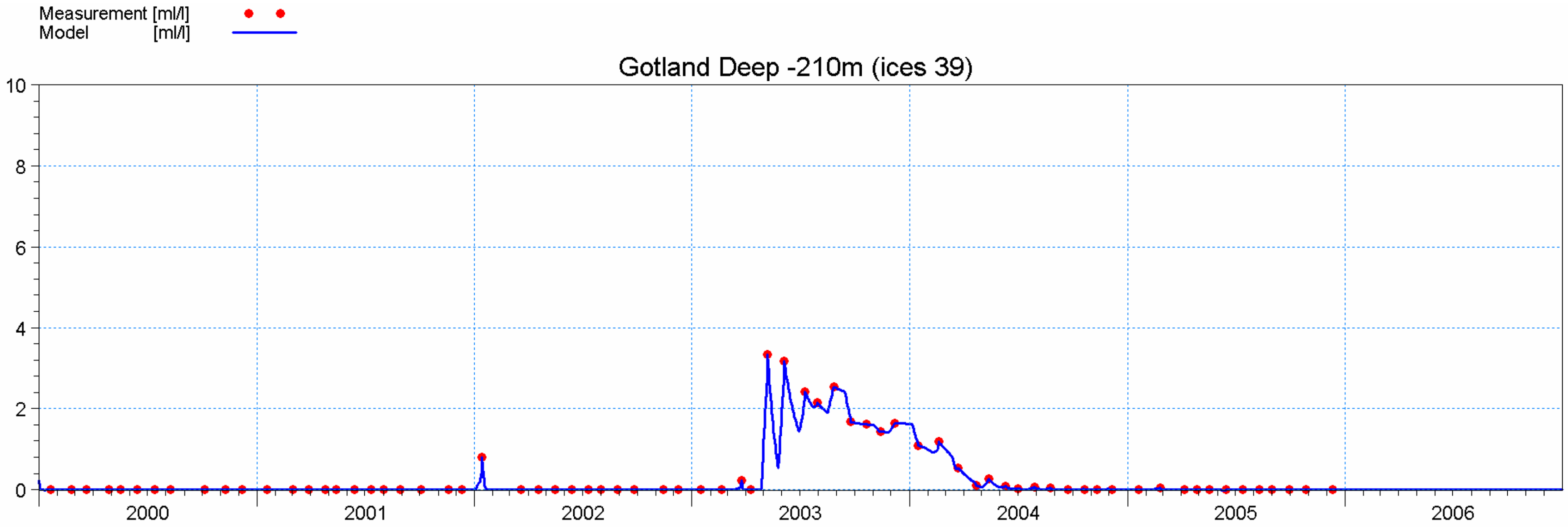
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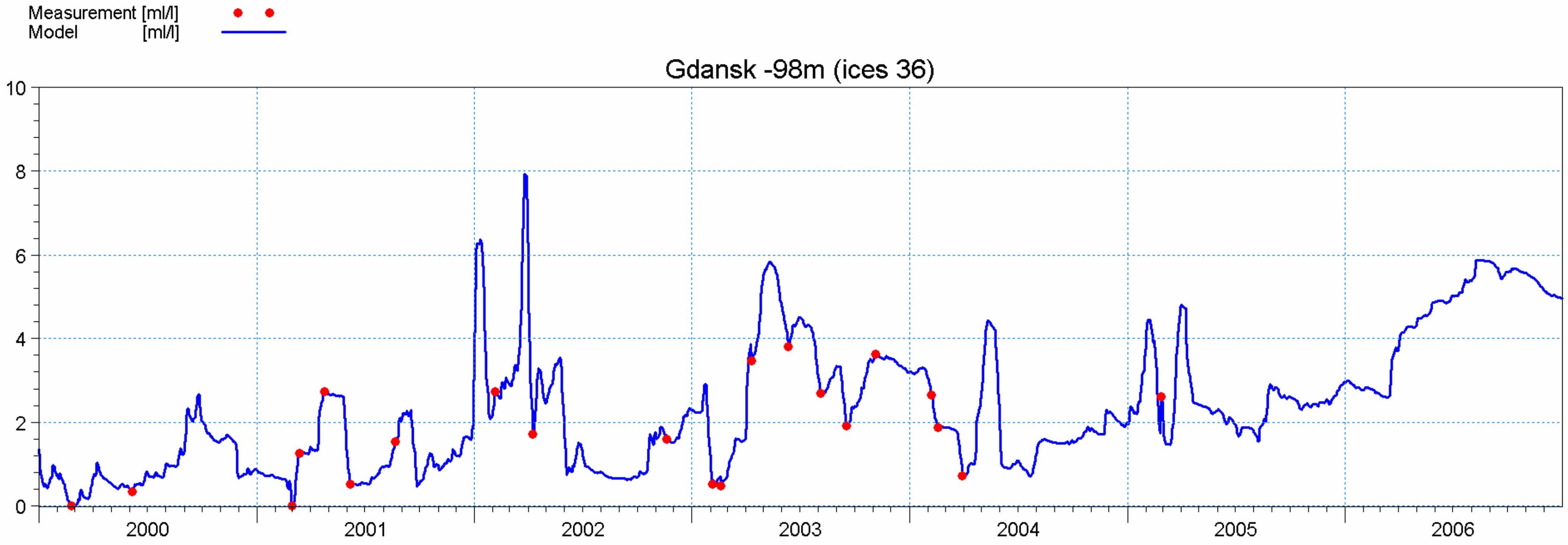
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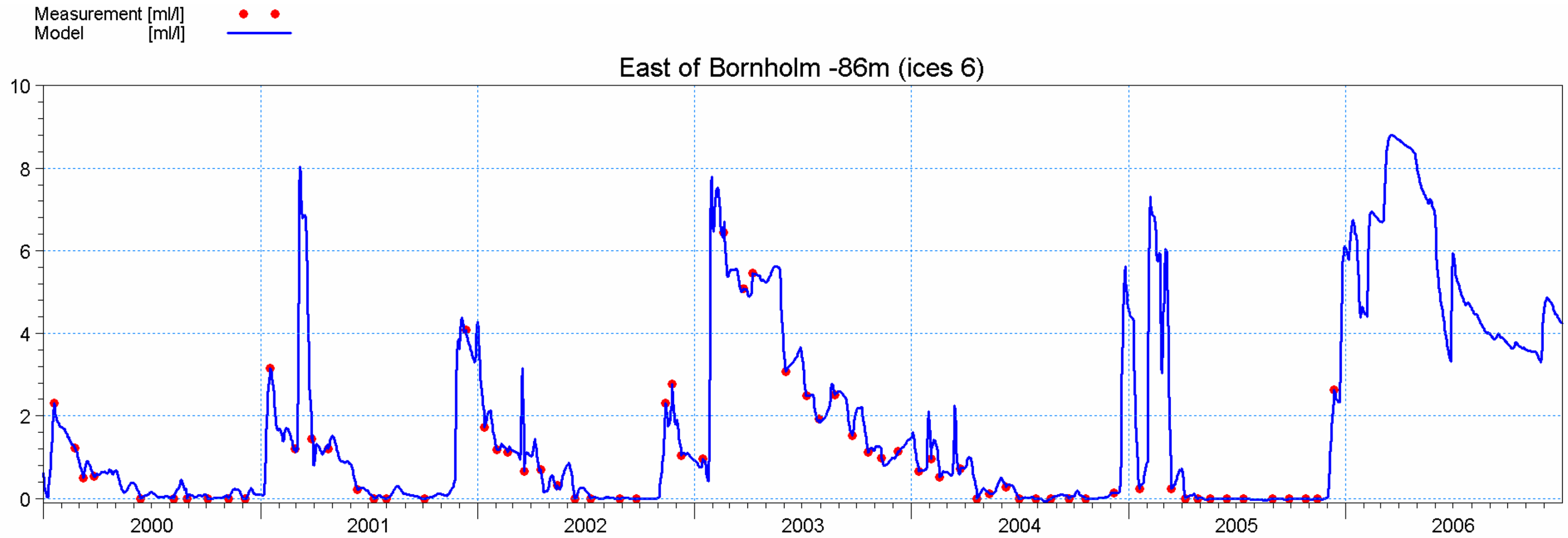
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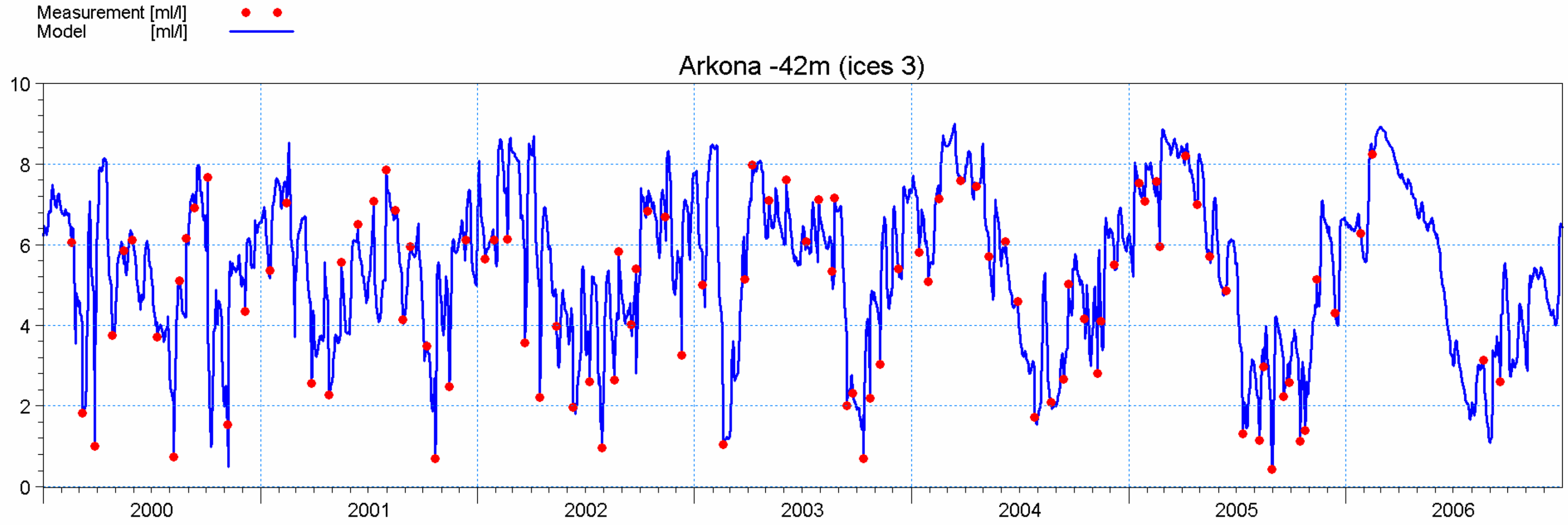
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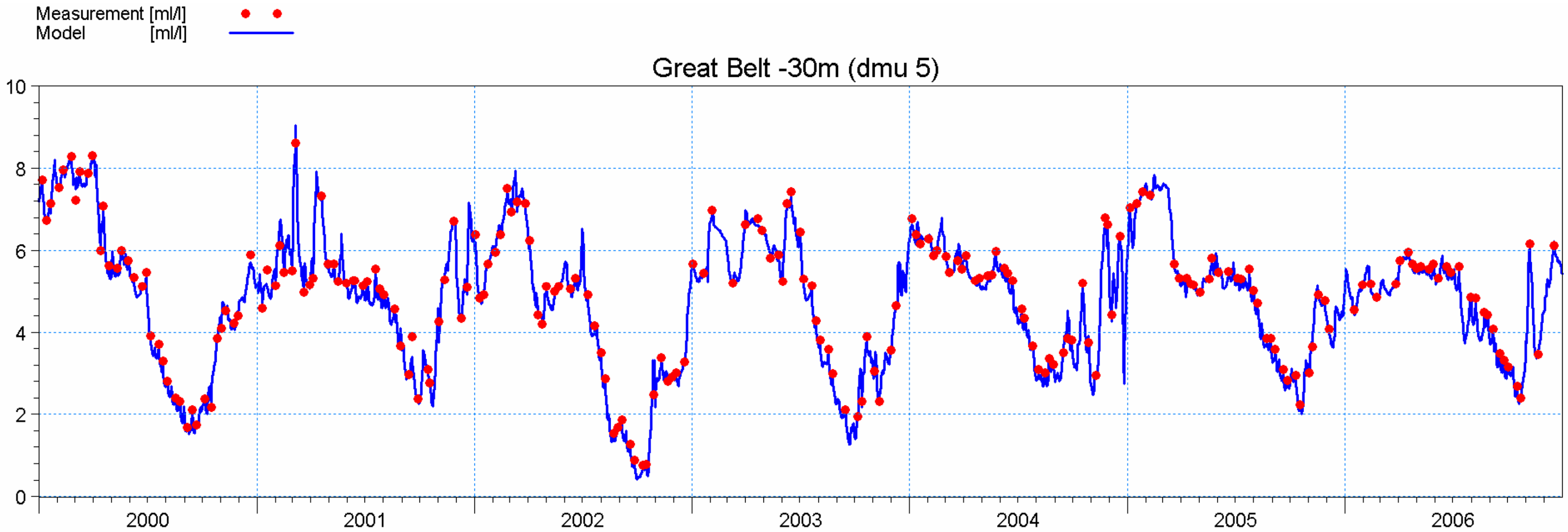
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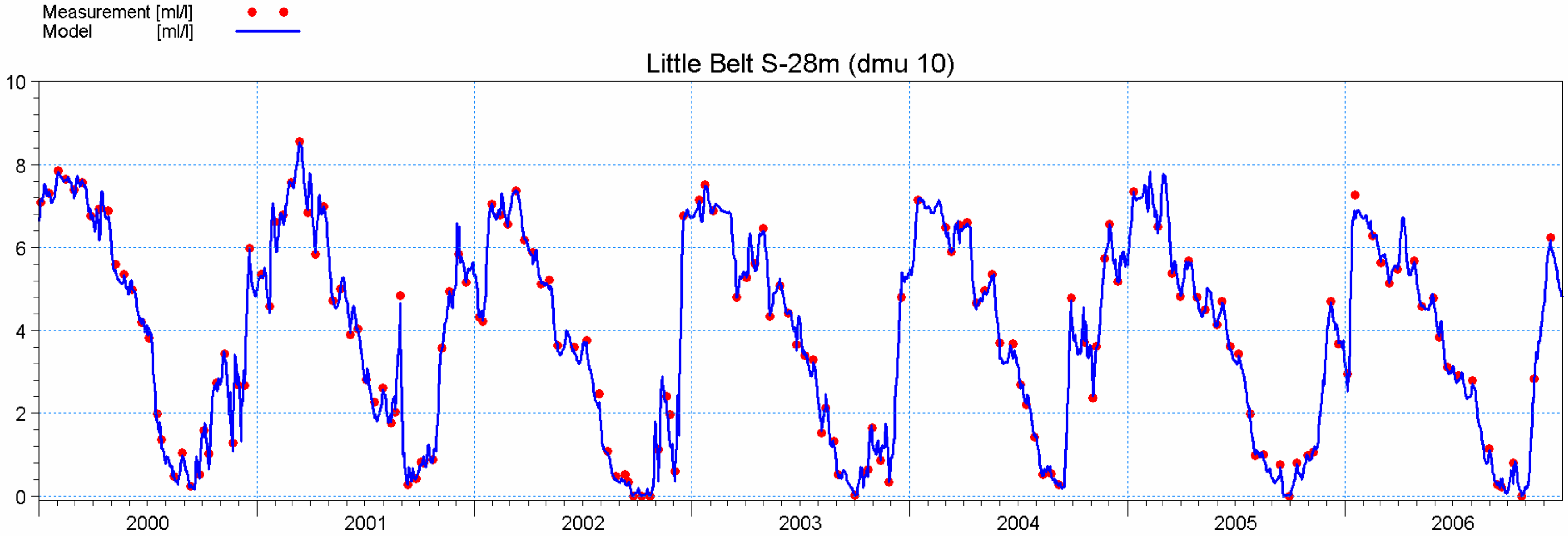
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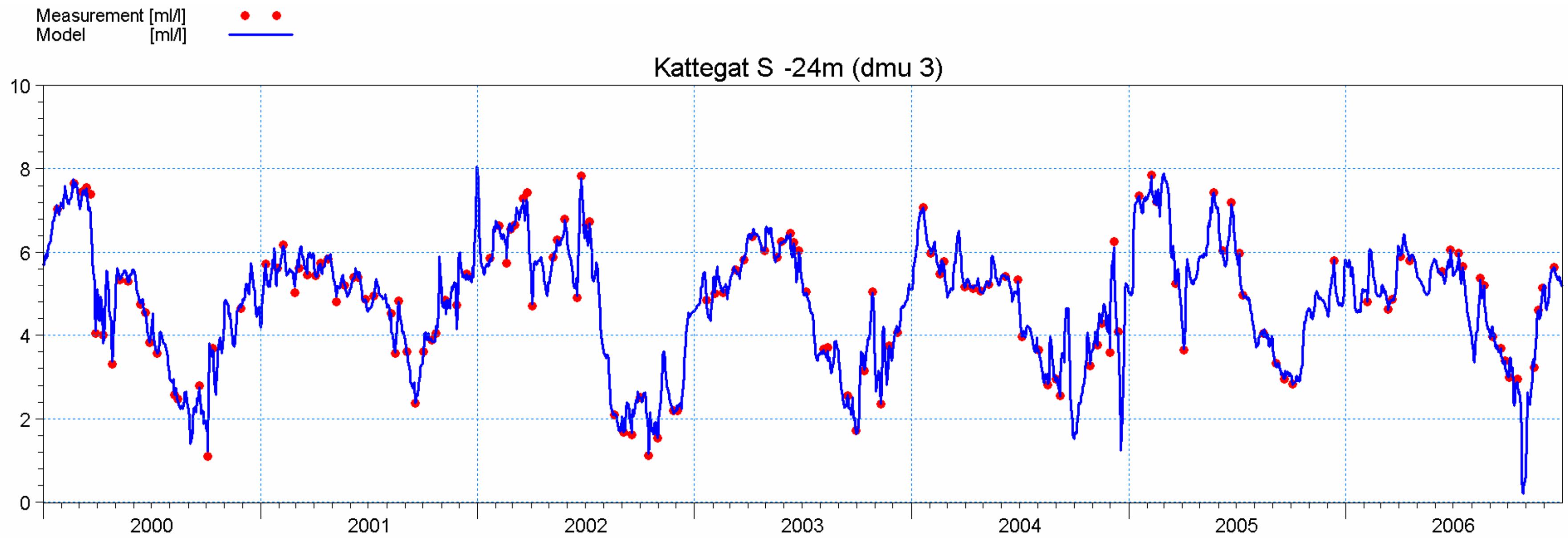
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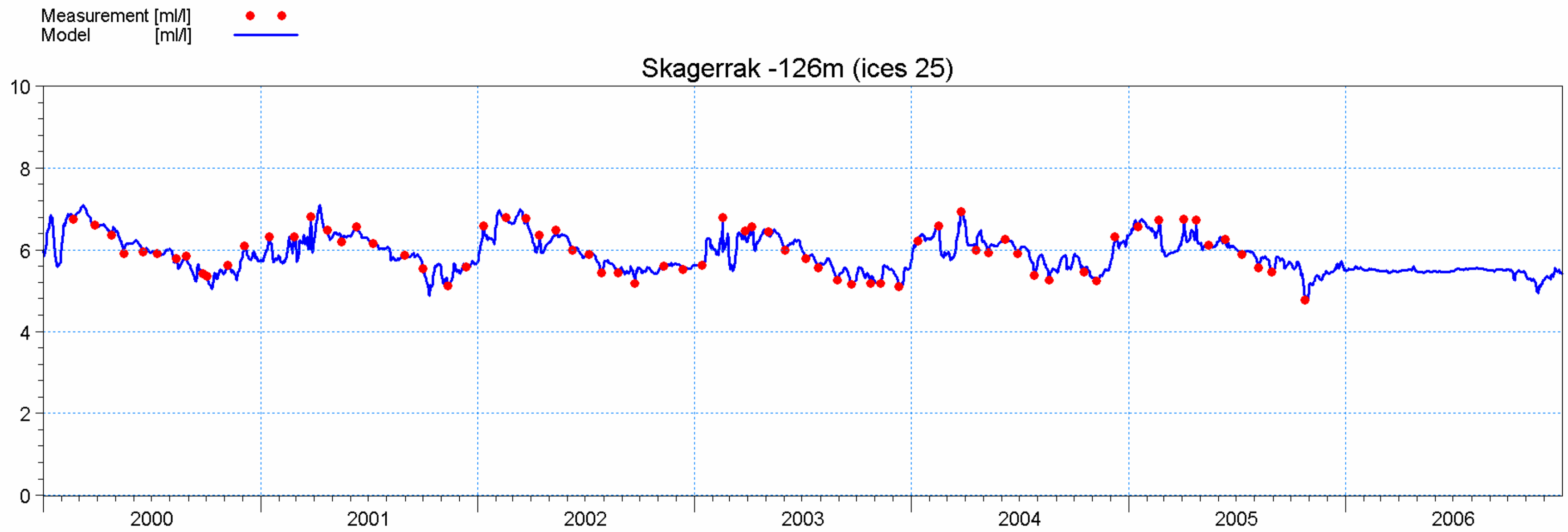
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About the BALANCE project

This report is a product of the BSR INTERREG IIIB project "BALANCE".

The BALANCE project aims to provide a transnational marine management template based on zoning, which can assist stakeholders in planning and implementing effective management solutions for sustainable use and protection of our valuable marine landscapes and unique natural heritage. The template will be based on data sharing, mapping of marine landscapes and habitats, development of the blue corridor concept, information on key stakeholder interests and development of a cross-sectoral and transnational Baltic zoning approach. BALANCE thus provides a transnational solution to a transnational problem.

The BALANCE partnership is composed of the following institutions based in 10 countries: The Danish Forest and Nature Agency (Lead), The Geological Survey of Denmark and Greenland, The National Environmental Research Institute/University of Aarhus, The Danish Institute for Fisheries Research, WWF Denmark, WWF Germany, Institute of Aquatic Ecology at University of Latvia, Estonian Marine Institute at University of Tartu, Coastal Research and Planning Institute at Klaipeda University, Metsähallitus Natural Heritage Service, The Finnish Environment Institute, The Geological Survey of Finland, WWF Finland, The Swedish Environmental Protection Agency, The National Board of Fisheries – Department of Research and Development, The Geological Survey of Sweden, County Administrative Board of Stockholm, Department of Marine Ecology at Gothenburg University and WWF Sweden.

The following institutes contribute as consultants to the partnership: The Geological Survey of Norway, Norwegian Institute for Water Research, DHI Water & Environment, The Leibniz Institute of Marine Sciences, The Sea Fisheries Institute, The Finnish Game and Fisheries Research Institute, Metria Miljöanalys and The Nature Conservancy.

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