Baltic Sea Environment Proceedings
No. 90

Thematic Report

The 2002 Oxygen Depletion Event in the Kattegat, Belt Sea and Western Baltic

Helsinki Commission
Baltic Marine Environment Protection Commission

Baltic Sea Environment Proceedings
No. 90

Thematic Report

The 2002 Oxygen Depletion Event in the Kattegat, Belt Sea and Western Baltic

Gunni Ærtebjerg & Jacob Carstensen
National Environmental Research Institute
Denmark

Philip Axe
Swedish Meteorological and Hydrological Institute
Sweden

Jean-Noël Druon & Adolf Stips
EC Joint Research Centre
Italy

Helsinki Commission
Baltic Marine Environment Protection Commission

2003

(Blank page)

Contents

Preface

The exceptional oxygen depletion events in the Gulf of Finland, the Kattegat - Belt Sea area and the western Baltic in summer and autumn 2002 raised great concern within the HELCOM community. HELCOM MONAS-4 in October 2002 proposed to establish a Working Group to analyse the development and causes of the oxygen depletion as well as the main sources to the nutrient loads to the Baltic Sea area. The HELCOM HOD-10 in November 2002 welcomed the proposal, but decided that the Working Group should be established as part of a Danish initiative concerning eutrophication problems in the Baltic Sea area as preparation for the HELCOM ministerial meeting in June 2003. At the beginning of February 2003 the Working Group on the 2002 Oxygen Depletion chaired by Denmark had its kick-off meeting in Copenhagen. Denmark, Germany, Sweden and the EC Joint Research Centre participated in the Working Group. It soon became clear that it was not possible for the Working Group to include the Gulf of Finland in the analysis, and the work was concentrated on the western Baltic, the Belt Sea, the Sound and the Kattegat. At MONAS-5 this decision was unanimously supported.

The first draft of the Working Group report was presented to the HELCOM MONAS-5 meeting in late April 2003. The second draft was presented and discussed at a scientific seminar in Sønderborg, Denmark, 16-17 June 2003. The second draft was also forwarded to the HELCOM Ministerial Meeting in Bremen 25 June 2003 as a back-ground document. The final report was prepared taking the outcome of the scientific seminar into account.

Roskilde, July 9th 2003

Gunni Ærtebjerg
Project manager

1. Introduction

Late summer and autumn 2002 wide spread and long lasting severe oxygen depletion was observed in the Belt Sea, the Sound and the Kattegat. Especially in the Belt Sea area the depletion was among the worst ever recorded. Hydrogen sulphide was released from the sediments in several areas. Bottom fauna was killed, and in the beginning of October 2002 dead fishes and benthic animals washed ashore along the east coast of Jutland.

The transition area, that is the Belt Sea, the Sound and the Kattegat, between the Baltic Sea and the Skagerrak/North Sea is very sensitive to eutrophication due to a number of inherent natural conditions. The stratification of the water column is very strong due to outflowing brackish water from the Baltic Proper in the surface (salinity about 8) and inflow of saline Skagerrak water in the bottom (salinity 33-35). The salinity stratification is during summer reinforced by temperature stratification with warm surface water and cold bottom water. The primary pycnocline is generally situated in about 13 m depth. The stratification highly reduces the vertical transport of oxygen from the oxygenated surface layer to the bottom layer, and renewal of the oxygen in the bottom water deeper than 15 m largely depends on inflow of new oxygenated water from the Skagerrak. Due to the sills at Gedser-Darss in the southern Belt Sea (max. depth 18 m) and at Drogden in the Sound (max depth 8 m) the inflow of Skagerrak water is restricted and much dependent on wind forces and directions.

The depth of the transition area is relatively low with a maximum depth of 109 m in the north-eastern Kattegat and a mean depth of only 18.9 m. The volume below the pycnocline is small (~250 km^3), and the amount of oxygen stored in the bottom water restricted. Therefore, during spring and summer, when the water exchange and mixing is low, the oxygen concentration in the bottom water inherently decreases to a minimum in late summer and autumn. Increased oxygen consumption caused by eutrophication and/or reduced renewal of the bottom water oxygen due to climatic variations may lead to widespread oxygen depletion.

Disregarding possible effects of climate changes, human activities primarily influence the oxygen consumption rate. The additional supply of anthropogenic nutrients from landbased sources via rivers, direct point sources, the atmosphere and from adjacent sea areas increases the phytoplankton primary production above natural level, which in turn increases the amount of organic matter decomposing using oxygen in the bottom water.

This report analyses the 2002 oxygen depletion event in the Kattegat - Belt Sea area by addressing the different components in the cause - effect chain: nutrient loads, nutrient concentrations, chlorophyll-a concentrations, primary production, wind forces, hydrography and water exchange. The analysis is based on the data and information available spring 2003, which in some cases is only preliminary. The report thus summarises the state of knowledge spring 2003 on the causes of the 2002 oxygen depletion event.

2. Description of the 2002 oxygen depletion

Seasonal development at representative stations

The oxygen deficiency in 2002 is believed to be the worst ever recorded in the Kattegat, the Sound and especially in the Belt Sea over the last three decades. The seasonal development of the deficiency is in this section illustrated with measurements of oxygen concentrations close to the bottom in 2002 at 8 Danish high frequency monitoring stations (figure 2.1) in the western Kattegat, the Sound and the Belt Sea, and compared to data from 2001 and long term monthly means 1990-2001 (figure 2.2).

The bottom water was well reoxygenated during January-February 2002 and reached in March a higher than average concentration in the Sound and Belt Sea. After sedimentation of the phytoplankton spring bloom in March the bottom water oxygen concentration showed a steep decrease in April in the Sound and the Belt Sea, but not at the Kattegat stations. The bottom water oxygen concentration stayed about normal till June/July at all stations.

During July and beginning of August the oxygen concentration decreased to unusually low levels in August-September. During October the oxygen situation became normal in the shallow western Kattegat (Ålborg Bight), due to vertical mixing and easterly wind forcing the oxygen poor bottom water out of the area. In the north-western Belt Sea (Århus Bight and northern Little Belt) shifting wind conditions during October-November forced the oxygen poor bottom water in and out of the area, but generally increased the oxygen level.

At the end of October the oxygen concentration also increased in the north-western Kattegat (Læsø Rende), the Sound and the Great Belt. However, the oxygen concentration stayed unusually low in the south-western Kattegat, the Great Belt and especially in the southern Little Belt also through November-December (figure 2.2).

Seasonal development in area and volume affected

The 2002 oxygen deficiency prompted several new initiatives, one being that high resolution maps in time and space were produced to describe the situation in 2002. In this section the 2002 situation is described by means of such high resolution maps and compared to the year 2001, which is considered to be more of an average year with respect to oxygen deficiency in these waters. First, the method for producing these maps will be described before the results are presented. Weekly maps for the last half of the years 2001 and 2002 are presented in Annex A, and this section will only concentrate on information extracted from these maps. Two threshold concentrations are used to characterise the oxygen depletion:
1) below 4 mg l^{-1} is denoted oxygen deficiency and
2) below 2 mg l^{-1} is denoted severe oxygen deficiency.

Material and methods

Oxygen data were obtained from national and regional authorities in Denmark, Germany and Sweden in the form of a continuous profile from CTD casts and oxygen concentrations from discrete water depth samples measured by Winkler titration. Oxygen data were provided for both 2001 and 2002. There were in total 4454 and 4923 profiles for 2001 and 2002, respectively, with relatively more profiles taken during the late summer and early autumn. Oxygen profiles from SMHI and NERI were provided as discrete depth samples at approximately 5-10 m interval. These profiles were linearly interpolated to produce profiles with a depth resolution of 0.20 m.

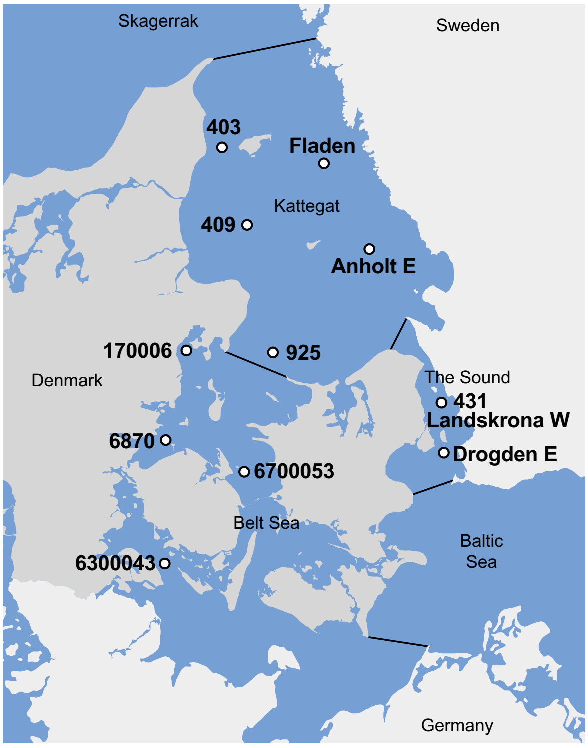


Figure 2.1
High frequency monitoring stations in the open Kattegat – Belt Sea area. Danish stations given with numbers, Swedish with names.

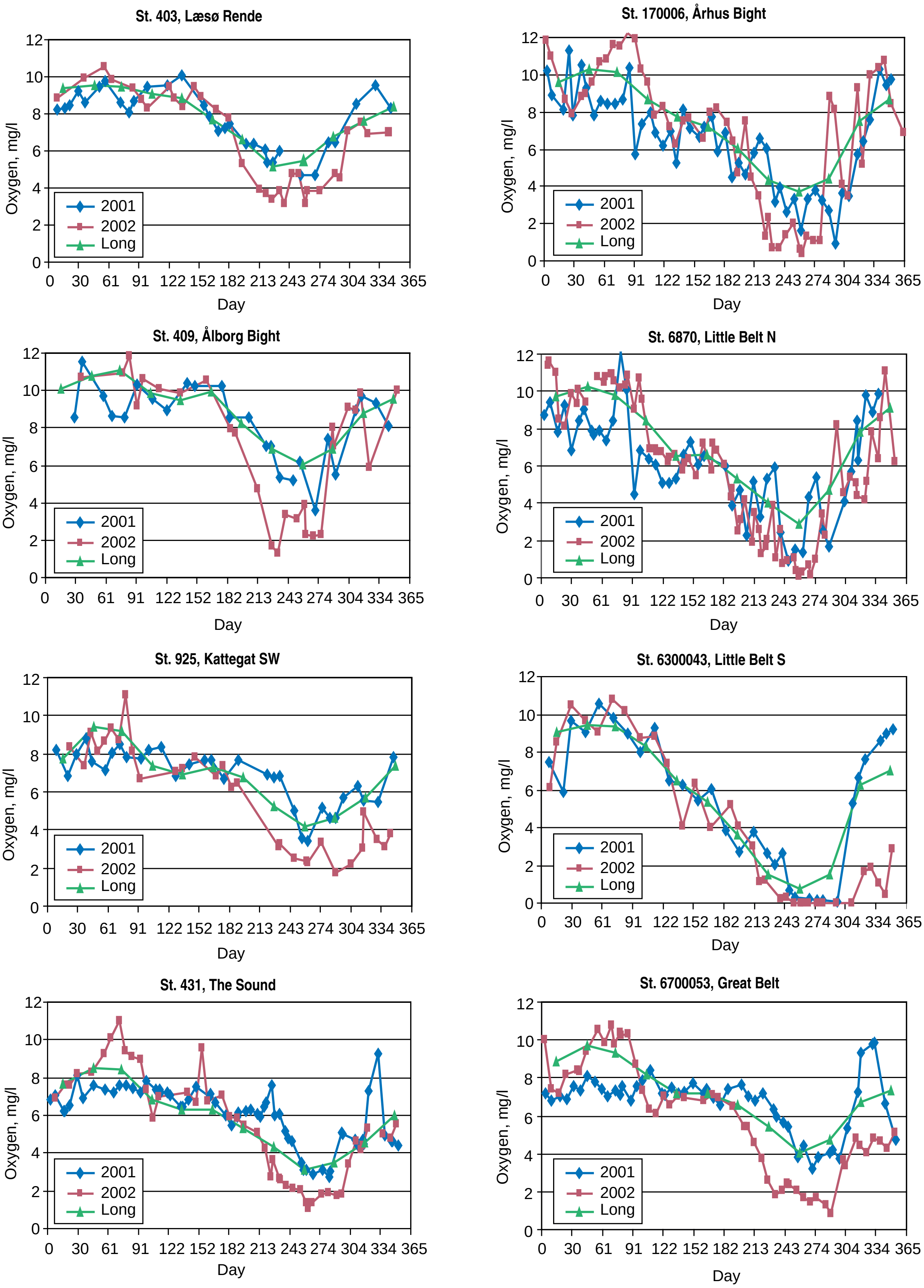


Figure 2.2

Seasonal distribution of bottom near oxygen concentrations in 2002 compared to 2001 and long term monthly means 1990-2001.

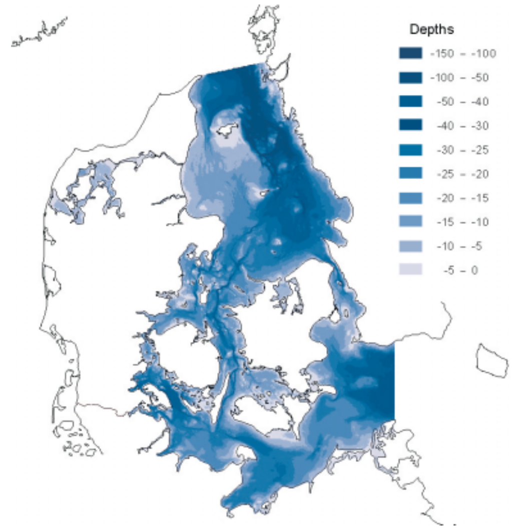


Figure 2.3
Bathymetry of study area. The GIS depth model was obtained by combining depth models from NERI, DHI, LANU and County of Nordjylland. Resolution is 400x400 m.

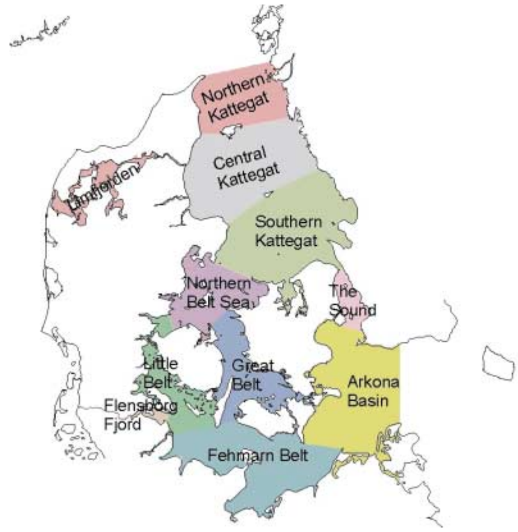


Figure 2.4
The study area partitioned into sub-areas for regional assessment.

For each profile depth limits (in m) for oxygen deficiency and severe oxygen deficiency were determined as:

1. First occurrence of oxygen concentration below 4 mg l^{-1} and 2 mg l^{-1} when examining the oxygen profile down through the water column.
2. If observations from the oxygen profile were not below the thresholds a regression of the deepest 2.5 m data was performed. In case a significant relationship with a negative gradient was obtained the depth limits was determined from the intersection of the regression with 4 mg l^{-1} and 2 mg l^{-1}, i.e. these depth limits are below the bottom depth.
3. The procedure in 2) was repeated for the deepest 10 m of the oxygen profile if depth limits was not found in step 2.
4. The procedure in 2) was repeated for the entire oxygen profile if depth limits were not found in step 2 or 3.
5. Maximum depth limits were set to 1.5*water depth + 10 m for oxygen deficiency and 2*water depth + 10 m for severe oxygen deficiency, where water depth is the station-specific water depth relating to the profile. If depth limits were not obtained by the procedure above (step 1-4) or exceed the maximum depths, then they were set to the maximum depth values.

Applying the algorithm above associates all oxygen profiles with depth limits for oxygen deficiency and severe oxygen deficiency that were either in the water column (obtained in step 1) or between the bottom depth and the maximum depths set in step 5.

The depth limits determined above were first interpolated in temporal domain and subsequently in the spatial domain. The temporal resolution was set to one week and the regular monitoring stations were interpolated linearly in time to produce time series of weeks for both 2001 and 2002. Stations that were not part of a regular monitoring program were interpolated linearly in time provided that depth limits determined from profiles were not more than 2 weeks apart. The linear interpolation resulted in between 100 and 200 depth limits that could be spatially interpolated.

For each week the depth limits determined in step 1-5 above as well as temporally interpolated depth limits were spatially interpolated by means of ordinary kriging (Cressie 1993) using a linear semivariogram model without nugget effect. This approach provided planes for the depth limits for oxygen deficiency and severe oxygen deficiency, respectively. These planes were combined with a GIS bathymetry model for the Kattegat, Belt Sea, the Sound and western part of the Arkona basin (figure 2.3). The planes for depth limits of 4 mg l^{-1} and 2 mg l^{-1} were combined with the GIS depth model to estimate areas impacted by oxygen deficiency and severe oxygen deficiency.

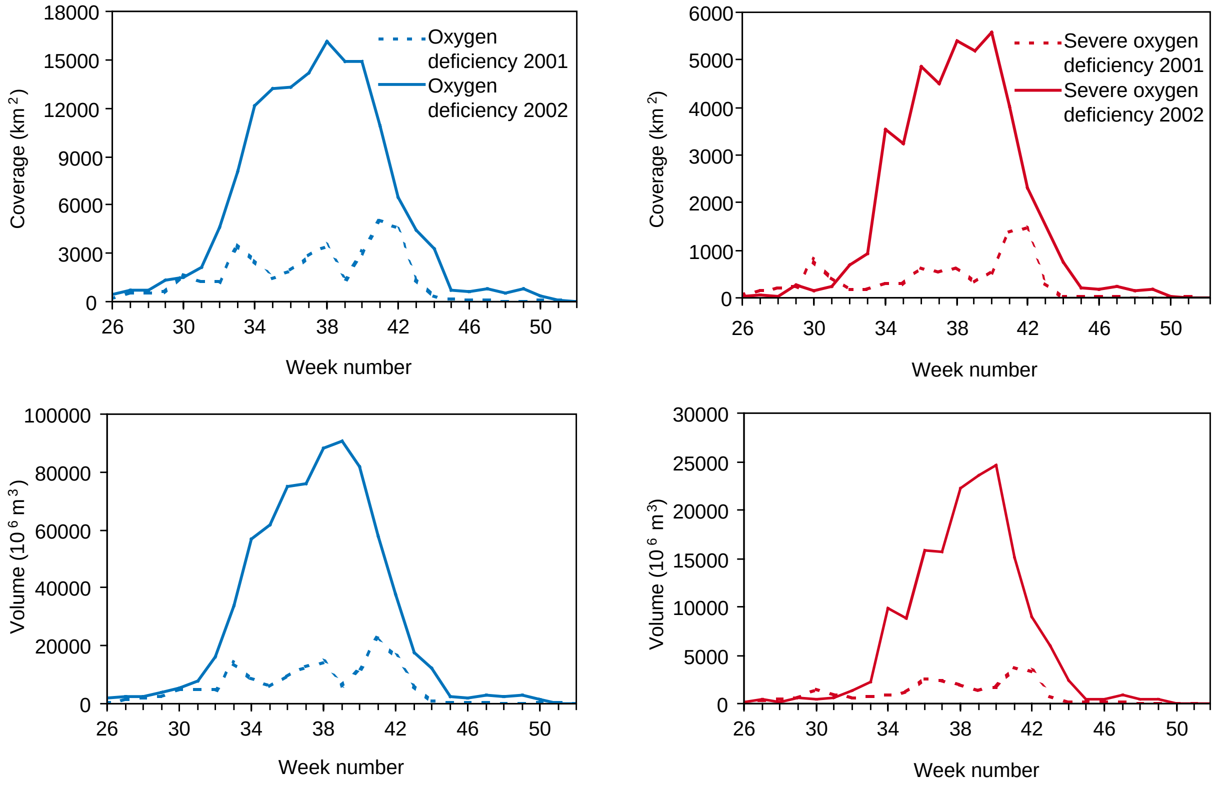


Figure 2.5

Area and volume impacted by oxygen deficiency (left panel) and severe oxygen deficiency (right panel) in 2001 and 2002. Includes the entire study area in Figure 2.4 except for the Arkona basin.

The bathymetry model was partitioned into regions (figure 2.4) to enable regional estimates of oxygen deficiency. The integrated areas with oxygen deficiency and severe oxygen deficiency were calculated for each week in each region for both 2001 and 2002. The volumes of water with oxygen concentrations below the two thresholds were similarly calculated by integration over the specific regions. Estimates of area and volume were also calculated for the entire study area excluding the Arkona basin.

Results

The development and decline of oxygen deficiency is shown for 2001 and 2002 week by week in Annex A. Oxygen deficiency was observed for both years following the spring bloom, but these short-lived events of smaller magnitude are not considered in the following. In both 2001 and 2002 the development of oxygen deficiency started around end of June (week 26). In July (weeks 27-31) the situation developed comparably for the two years with hypoxic conditions in vulnerable areas such as Limfjorden, Little Belt and Mecklenburg Bight. In August 2002 (weeks 31-35) the oxygen deficiency escalated tremendously, whereas a slow steadily development was observed in August 2001. In September (weeks 36-39) the situation remained stable, however, for 2002 at a much higher level with widespread oxygen deficiency in most of the study area except Limfjorden and northern part of the Kattegat. October (weeks 40-44) was characterised by a slow gradual retreat of the oxygen deficiency and there was no substantial oxygen deficiency at the end of October 2001. There was still, however, considerable oxygen deficiency in the southern Kattegat, northern Belt Sea, Little Belt and Mecklenburg Bight at the end of October 2002. There was no substantial oxygen deficiency in November and December 2001, whereas the oxygen deficiency situation in 2002 lasted until mid December in the Little Belt.

This development and retreat of hypoxia was also reflected in the area and water volume impacted by oxygen deficiency and severe oxygen deficiency (figure 2.5), which showed the rapid strong development in August 2002 and a small increase in September 2002. Regional assessment of area and water volume

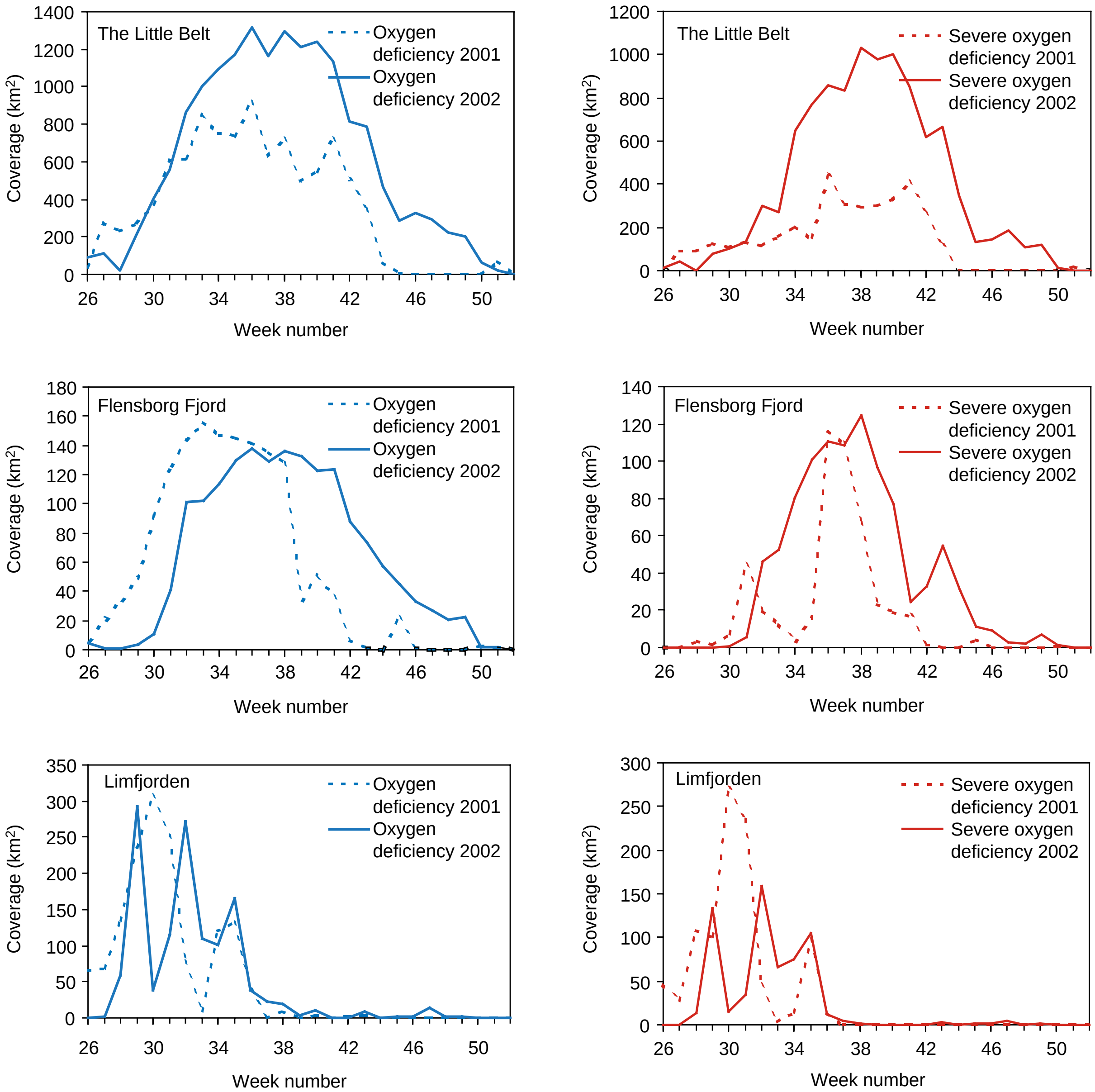


Figure 2.6

Regional assessment of area impacted by oxygen deficiency (left panel) and severe oxygen deficiency (right panel) in 2001 and 2002. Data shown for regions deviating from the overall trends only (figure 2.5).

impacted by oxygen deficiency showed that the overall temporal pattern with 5-10 fold increases relative to 2001 (figure 2.5) was duplicated for the typical open-water regions (the central and southern Kattegat, the Sound, the northern Belt Sea, the Great Belt and the Southern Belt Sea). In the Little Belt these values were approximately doubled from 2001 to 2002, whereas Flensborg Fjord and Limfjorden showed temporal patterns in 2002 similar to those of 2001 (figure 2.6). This suggests that 2002 was exceptional in the sense that the open-water regions were especially severely affected by hypoxia.

The oxygen deficiency in 2002 was, as described previously, prolonged relative to 2001 (figure 2.7). Large areas in the southern Kattegat, northern Belt Sea, Little Belt and Southern Belt Sea were exposed to hypoxia for long periods. Considering the entire period from week 26 to 52 in 2002 oxygen deficiency and severe oxygen deficiency affected approximately 20,500 km^2 and 9,000 km^2 (excluding the Arkona basin), respectively (Table 2.1). These estimates correspond to 47% and 21% of the total area, respectively. The difference between 2001 and 2002 was most pronounced for central and southern Kattegat, the Sound,

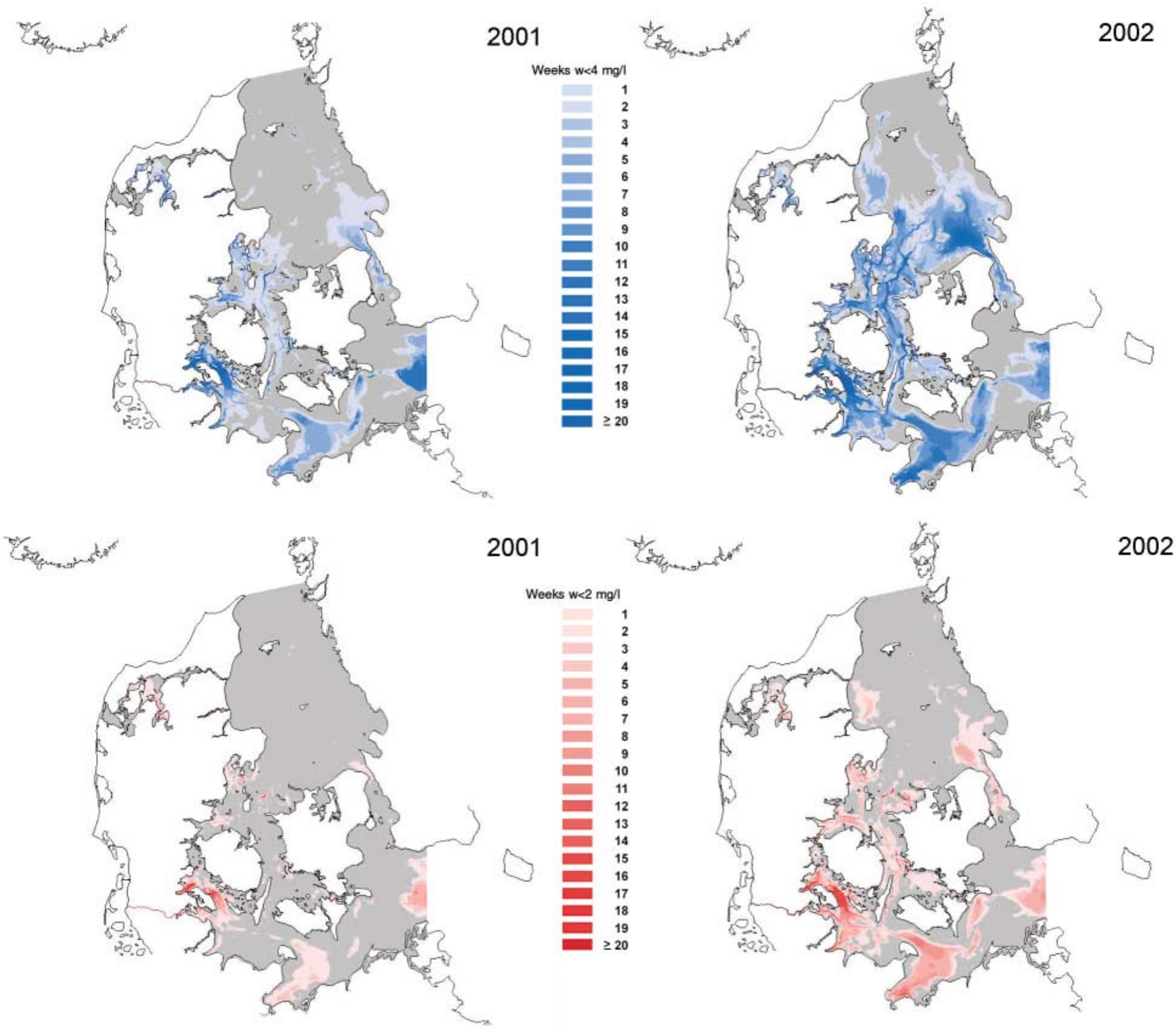


Figure 2.7

The length in week of bottom exposure to oxygen deficiency (upper panel) and severe oxygen deficiency (lower panel). The same colour scale was used for both 2001 and 2002 with intensive colours indicating long exposure to hypoxic conditions.

Region	**Total area (km²)**	**2001**		**2002**	
		<4 mg l^{-1}	**<2 mg l^{-1}**	**<4 mg l^{-1}**	**<2 mg l^{-1}**
Northern Kattegat	4405	2 (0%)	0 (0%)	106 (2%)	0 (0%)
Limfjorden	1522	385 (25%)	329 (22%)	377 (25%)	251 (17%)
Central Kattegat	8491	66 (1%)	8 (0%)	1688 (20%)	524 (6%)
Southern Kattegat	9432	2386 (25%)	93 (1%)	7012 (74%)	1360 (14%)
The Sound	1049	248 (24%)	3 (0%)	443 (42%)	205 (20%)
Northern Belt Sea	4027	1421 (35%)	220 (5%)	2596 (64%)	1208 (30%)
Great Belt	4012	653 (16%)	37 (1%)	1740 (43%)	965 (24%)
Little Belt	3019	1103 (37%)	608 (20%)	1641 (54%)	1281 (42%)
Flensborg Fjord	293	160 (55%)	121 (41%)	162 (55%)	138 (47%)
Southern Belt Sea	7597	2970 (39%)	1491 (20%)	4820 (63%)	3241 (43%)
Entire area	**43847**	**9394 (21%)**	**2909 (7%)**	**20586 (47%)**	**9173 (21%)**

Table 2.1

Total area and proportion affected by hypoxic conditions for each region and entire area (excluding Arkona Basin).

northern Belt Sea, Great Belt and Southern Belt Sea, and to some extent also Little Belt. Particularly, for 2002 in the southern Kattegat 74% of the area was exposed to oxygen deficiency, mainly due to hypoxic bottom water being shifted around over the autumn.

Conclusion

The oxygen deficiency in 2002 was exceptional compared to 2001 reaching a maximum extent at the end of September of about 16,000 km^2 and 5,500 km^2 with oxygen concentrations below 4 mg l^{-1} and 2 mg l^{-1}, respectively. The oxygen deficiency started developing in August and started retreating again beginning of October. In August and September 2002, when oxygen deficiency was most widespread, the area coverage was approximately 5 times that of 2001. It was particularly the open-water area that became affected by oxygen deficiency in 2002 relative to 2001, whereas estuaries and coastal areas having annual reoccurring oxygen deficiency did not deviate substantially from 2001 to 2002. The oxygen deficiency was shifted around in the open-water area, particularly in the southern Kattegat, that resulted in 47% and 21% of the total area being affected by oxygen deficiency and severe oxygen deficiency, respectively, for shorter or longer periods of time.

3. Nutrient loads from surrounding land and atmosphere

Introduction

The availability of limiting nutrients in the water column during the productive season of the phytoplankton (March-October) determines the production of organic matter. Part of the organic matter sinks to the bottom and uses the same amount of oxygen during remineralisation, as was released during the production in the surface water. The supply of limiting nutrients to the photic zone thus largely determines the oxygen consumption in the bottom water, the actual consumption rate being partly determined by the actual temperature. Nitrogen is the most limiting nutrient in the open Kattegat and Belt Sea, while phosphorus only rarely is limiting in these areas. In the estuaries phosphorus is often limiting in the first half of the year, followed by nitrogen limitation late summer and autumn (Granéli 1987, Granéli et al. 1990, Ærtebjerg et al. 2003).

The final total estimates of the seasonal runoff and nutrient loads to the Kattegat-Belt Sea area in 2001 and 2002 were not available. Therefore, it was necessary to produce preliminary estimates in order to evaluate the effects of nutrient load on the 2002 oxygen depletion. For Denmark the 2002 runoff and nutrient loads were estimated from a limited number of runoff stations in the major rivers, and the relation between runoff and nutrient concentrations in the river waters in 1999-2001. For Germany seasonal runoff and nutrient loads in 2001 and 2002 were produced for Schleswig-Holstein from measurements in the rivers. From the ratio between annual runoff and nutrient load in Schleswig-Holstein and Mecklenburg-Vorpommern 2000-2001 estimates were produced for the whole German coast to the Belt Sea. Swedish 2002 annual nutrient loads were estimated from the relation between runoff and nutrient loads during the later years. The seasonal distribution of annual nutrient loads from Sweden were estimated from monthly freshwater runoff data. It has to be kept in mind, that the load estimates for 2002 are preliminary and more uncertain than data covering earlier years.

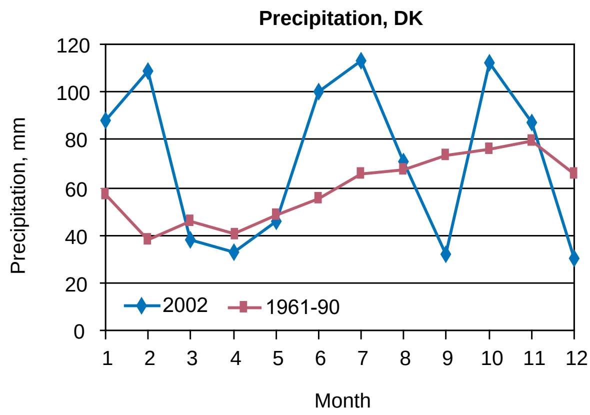


Figure 3.1
Monthly precipitation in Denmark in 2002 compared to monthly means for the period 1961-1990. Based on data from the Danish Meteorological Institute.

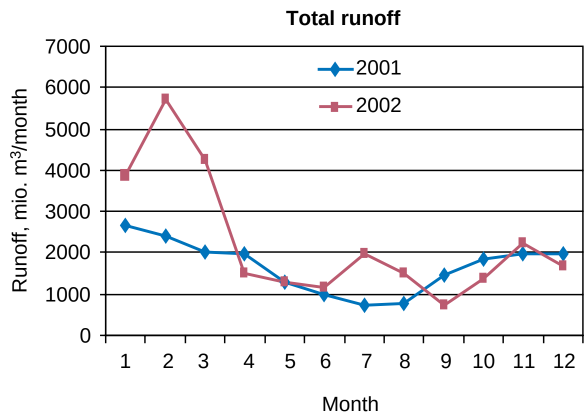


Figure 3.2
Seasonal distribution of estimated total freshwater runoff to the Kattegat - Belt Sea area from Denmark, Germany and Sweden in 2002 compared to 2001.

Runoff and nutrient loads

Precipitation

The precipitation in Denmark was in January-February 2002 more than twice the long term average 1961-90, and in June-July 76% above nornal. The precipitation in March-May and August was about average, but low in September (figure 3.1).

Freshwater runoff in 2001 and 2002

Freshwater runoff is the most important factor affecting the nutrient load from surrounding land and the nutrient concentrations in the Kattegat-Belt Sea area (Ærtebjerg et al. 2003). The amount and seasonal variation of the runoff to the area in 2001 was about average for the period 1989-2001, and the amounts and seasonal variations in runoff and nutrient loads in 2002 is in the following compared with the situation in 2001.

The runoff to the Kattegat – Belt Sea area was in 2002 about 33% higher than in 2001. Especially during January through March the runoff was unusually high, but also in July and August the runoff was about twice as high as in 2001 (figure 3.2).

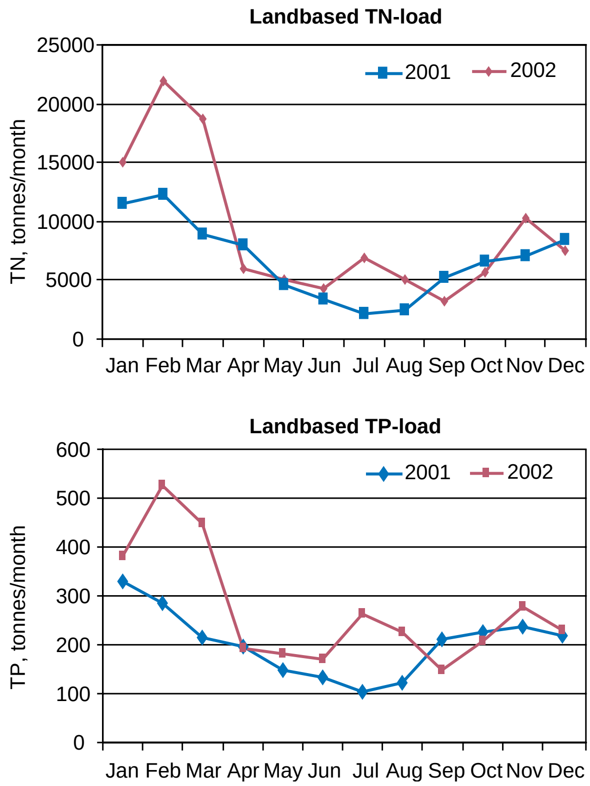


Figure 3.3
Seasonal distribution of estimated total nitrogen load (upper fig.) and phosphorus load (lower fig.) from land to the Kattegat - Belt Sea area from Denmark, Germany and Sweden in 2002 compared to 2001.

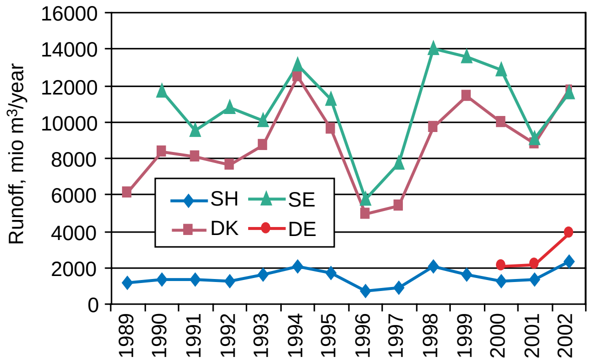


Figure 3.4
Long term variation in annual freshwater runoff from Sweden (SE), Denmark (DK), Schleswig-Holstein (SH) and Germany (DE) to the Kattegat - Belt Sea area 1989-2002.

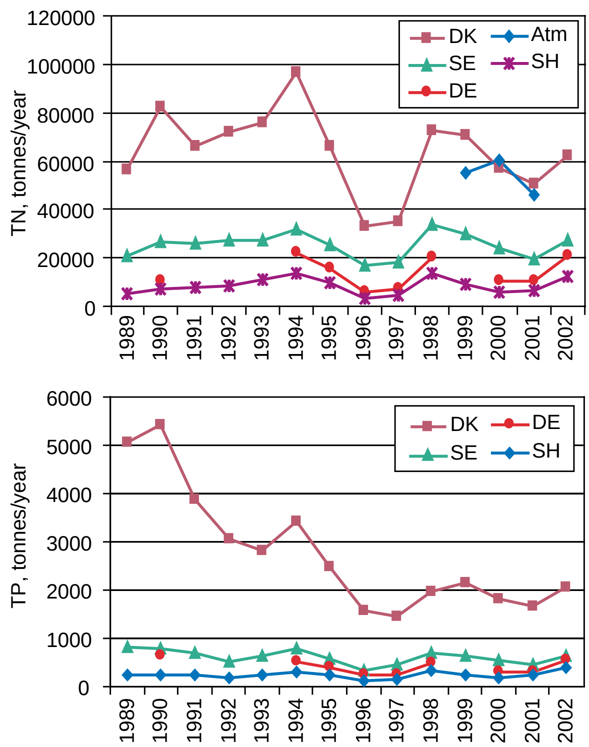


Figure 3.5
Long term development in annual land based nitrogen load (upper fig.) and total phosphorus load (lower fig.) from Sweden (SE), Denmark (DK), atmosphere (Atm), Schleswig-Holstein (SH) and Germany (DE) to the Kattegat - Belt Sea area 1989-2002.

Nutrient loads in 2001 and 2002

The total nitrogen and total phosphorus loads from land were 37% and 34% higher, respectively in 2002 than in 2001. As for the runoff the estimated loads were especially high in February-March and in July-August (figure 3.3).

Long term development in runoff and nutrient load

The annual runoff varies much from year to year due to variations in precipitation. The runoff in 2002 was among the highest seen in the period 1989-2002 and about 20% higher than average 1989-2001. High runoff was also seen in 1994 and 1998-2000, while the years 1996-1997 were extremely dry in the whole area (figure 3.4).

The variation in annual nitrogen load mirrors the runoff, except that the load per runoff has decreased significantly in the later years. Thus the nitrogen load in 2002 was only about 4% higher than average for the period 1989-2001, in spite of the high runoff in 2002 (figure 3.5). The nitrogen load was in the extremely dry years 1996-1997 only 54.5% and 59%, respectively of the average 1989-2001.

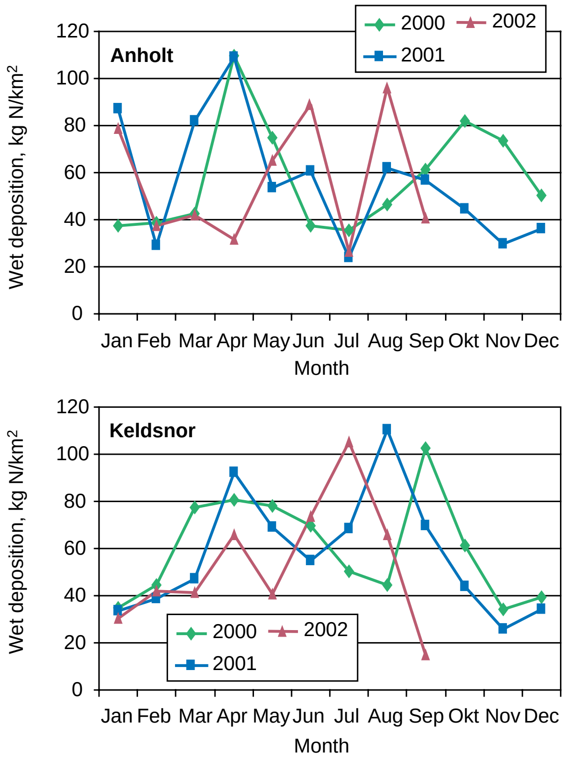


Figure 3.6
Monthly wet deposition of nitrogen nutrients in 2000, 2001 and 2002 measured at Anholt in the middle of Kattegat (upper fig.) and Keldsnor in the southern Belt Sea (lower figure).

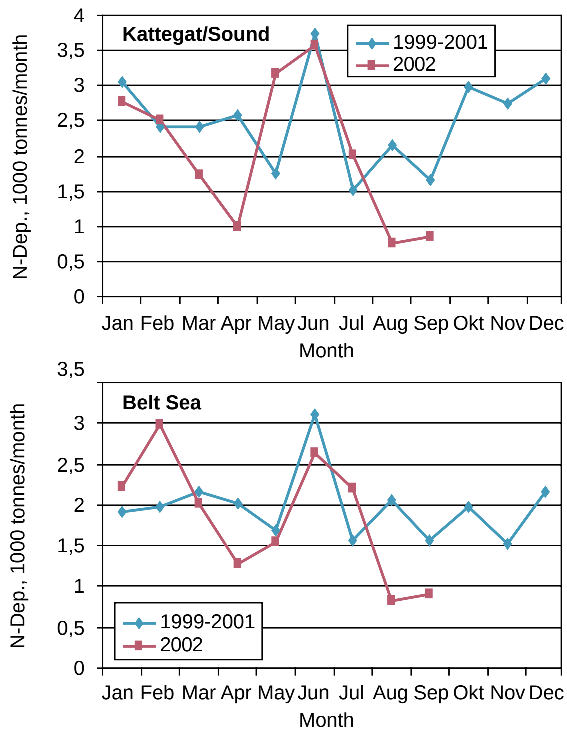


Figure 3.7
Model calculated monthly nitrogen deposition in the first 3 quarters of 2002 compared to means 1999-2001 at the Kattegat -Sound area (upper fig.) and the Belt Sea area (lower figure).

The phosphorus load has decreased significantly from the late 1980s through the first half of the 1990s, mainly due to point source reductions in Denmark, but also in Germany and Sweden. Since mid 1990s the phosphorus load follows the runoff, and the phosphorus load in 2002 was therefore higher than in the previous two years, but less than half of the load in 1990 (figure 3.5).

Atmospheric deposition

Atmospheric nitrogen deposition

The atmospheric deposition of inorganic nitrogen nutrients to the sea surface is an important nutrient contribution in open sea areas. In the Kattegat - Belt Sea area the atmospheric deposition constitutes about 1/3 of the directly supplied nitrogen from land and atmosphere to the area. The atmospheric nitrogen deposition is in the phytoplankton growing season March-October directly available for the primary production, as it is supplied to the surface water in inorganic form, and the primary production most often is nitrogen limited.

The atmospheric nitrogen wet deposition is measured at Anholt in the middle of Kattegat and at Keldsnor in the southern Belt Sea. At Anholt the deposition in 2002 was relatively high in January, June and August, while at Keldsnor the deposition was relatively high in July. However, the wet deposition during the first 9 months of 2002 did not show significant deviations from the two previous years, neither in seasonal distribution or in total amount (figure 3.6).

Model calculations of the total N-deposition on the Kattegat and the Belt Sea, respectively, revealed relatively high depositions on the Kattegat in January-February and May-June 2002, and on the Belt Sea in January-March and June-July 2002. Contrary, the deposition was low in both areas in April and August-September 2002 (figure 3.7). However, the seasonal distribution and the amounts deposited were not unusual.

Direct nitrogen loads to the Kattegat - Belt Sea area

The seasonal variation in the estimated total nitrogen load from surrounding land and atmosphere in 2002 is shown in figure 3.8 compared to the load in 2001.

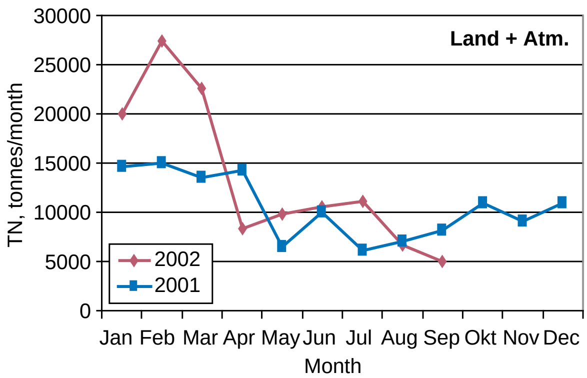


Figure 3.8

Total monthly nitrogen supply form surrounding land and atmosphere to the Kattegat - Belt Sea area in 2001 and first 3 quarters of 2002.

The high nitrogen load during January-March was supplied to the surface waters of the Kattegat-Belt Sea area just prior to and at the time of the phytoplankton spring bloom in March, and much of it was probably trapped by the bloom. The produced organic matter was transferred to the bottom with the diatoms sinking out of the water column after the bloom, and determining the oxygen consumption in the following months.

The relatively high nitrogen loads in May-July took place in a period when the phytoplankton production usually is strongly nutrient limited. The nitrogen was used up by the primary production, and thereby added to the oxygen consumption in the bottom layer.

Nutrient sources

Land based nutrient sources

Source apportionment of land based nutrient loads in 2000 from Denmark, Germany and Sweden to the Kattegat - Belt Sea area has been made using slightly different methods in the three countries (table 3.1). The Danish loads include discharges to the Kattegat, the Sound and the Belt Sea. The German loads include discharges to the southern Belt Sea. The Swedish loads include discharges to the Sound and the Kattegat, but excluding the Göte River, which discharges in the north-easternmost Kattegat and mainly is transported to the Skagerrak. Therefore the Göta River is not included in Swedish load data presented in this report. Loads from all countries include discharges to open coasts as well as bights and associated estuaries.

Agriculture (in Sweden agriculture plus forestry) is the main source of nitrogen nutrient loads. In Sweden and Denmark 65% and 80%, respectively, of the nitrogen load to fresh and marine surface waters came from this source, while in Germany it made up to 58%. Point sources to fresh and marine surface waters accounted for 8-10% of the nitrogen load to surface waters in Denmark and Sweden, and in Germany for 16%.

Also for the phosphorus loads agriculture is an important factor. In Denmark, Germany and Sweden 45%, 50% and 55%, respectively, of the phosphorus load to fresh and marine surface waters came from this source. Point sources to fresh and marine surface waters accounted for 16-18% of the phosphorus load in Sweden and Germany, and in Denmark for 36%.

In Sweden and Denmark direct point sources to marine waters accounted for 4-5% of the total nitrogen load to fresh and marine surface waters, and for 10% and 17%, respectively of the phosphorus load.

Atmospheric nitrogen sources

From 15% to 31% of the nitrogen deposition on different sub-areas of the Kattegat - Belt Sea area came in 2001 from Danish sources. The Danish contribution was lowest in the southern Belt Sea and highest in the northern Belt Sea and the Kattegat. From 10% to 50% of the nitrogen deposition on different sub-areas of the Kattegat – Belt Sea area came from German sources.

The German contribution was highest in the southern Belt Sea and lowest in the Kattegat. The Swedish contribution to the deposition on the area is only a few percent. More than half of the total deposition on the Kattegat-Belt Sea area came from sources in other European countries.

In the Kattegat 54% of the 2001 deposition was in the form of oxidised nitrogen compounds, the rest in reduced form. Nearly all the oxidised nitrogen stems from combustion of fossil fuels (e.g. traffic, power supply, industry, house warming, shipping etc.),

Sources	Nitrogen in %			Phosphorus in %		
	DE	DK	SE	DE	DK	SE
Riverine inputs:						
A Diffuse load						
• Background	18.4	9.2	21.3	16.6	11.2	18.3
• Agriculture and forestry	57.6	79.9	64.5	49.8	44.5	55.0
• Deposition	5.5		4.2	3.2		0
• Small Settlements without connection		1.1	2.0		8.5	10.7
B Point sources to freshwater						
• Sewage plants	15.6	2.7	2.6	18.1	9.7	2.4
• Industry	0.1	-	0.2	0.3	0.2	0.6
• Rainwater overflows	2.8	0.6	0.5	12.0	5.8	3.6
• Freshwater aquaculture	-	2.6		-	3.5	
C Retention in freshwater	-28.6	-9.6	-17.9	-58.8	-1.4	-23.7
• **Total riverine load**	**71.4**	**86.5**	**77.5**	**41.2**	**82.0**	**66.9**
D Direct point sources:						
• Sewage plants	-	2.4	3.5		11.4	4.7
• Industry	-	0.9	1.0		2.1	3.6
• Rainwater overflows	-	0.2	0.2		1.7	1.2
• Mariculture	-	0.4	0	-	1.4	0
Total direct load		**3.8**	**4.7**	**-**	**16.6**	**9.5**
Total load to marine waters	**71.4**	**90.4**	**82.1**	**41.2**	**98.6**	**76.3**

Table 3.1

Source apportionment of nutrient loads in 2000 from Germany, Denmark and Sweden to the Kattegat - Belt Sea area given as percentage of discharges to both fresh and marine surface waters. Different methods have been used in the analysis in the different countries. For Germany the discharges from direct point sources are included in the riverine loads, and German figures for »rainwater overflows« represent both discharges from separate sewers, combined sewer overflows, sewers without treatment plants and households without connection to sewer systems.

while nearly all the reduced nitrogen stems from ammonia evaporation from agricultural husbandry. The oxidised nitrogen compounds have a longer spreading range before deposition than the reduced ones. Therefore the Danish contribution of reduced nitrogen to the Kattegat is about three times higher than the Danish contribution of oxidised nitrogen (Ellermann et al. 2002).

Conclusion

The main sources to the direct nitrogen load to the Kattegat-Belt Sea area are runoff from agriculture and forestry in the surrounding countries and deposition from the atmosphere. Also for the phosphorus load the agriculture is a major source (45%, 55% and 65% in Denmark, Sweden and Germany). Phosphorus point sources to fresh and marine surface waters accounted in 2000 for 36% in Denmark, 29% in Germany and 16% in Sweden.

Neither the total direct land based nutrient load nor the total atmospheric nitrogen deposition to the Kattegat - Belt Sea area in 2002 deviated significantly from preceding years. But the seasonal distribution of the loads reinforced the oxygen consumption in the bottom waters during spring and summer. However, high nutrient loads during winter and summer have occurred earlier within the last 20 years, accomplishing less severe oxygen depletion. Thus the nutrient loads are not the only responsible for the severity of the 2002 oxygen depletion in the Kattegat - Belt Sea area. Other factors significantly influenced the situation.

4. Nutrients, chlorophyll-*a* and primary production

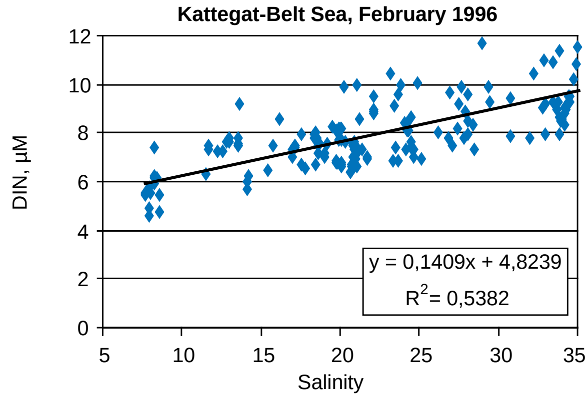
Nutrient concentrations

The water masses in the Kattegat – Belt Sea area (including the Sound) are essentially mixtures of Baltic Sea surface water (salinity 8) relatively low in dissolved inorganic nitrogen (DIN) and saline Skagerrak water (salinity 33-35) with higher nitrogen nutrient concentrations. The local freshwater runoff to the Kattegat - Belt Sea areas is low (21.5 km^3 yr^{-1}, average 1990-2001) compared to the outflow of low saline Baltic water (gross average 950 km^3 yr^{-1}) and has only small influence on the salinity outside estuaries and near coastal waters. In winter, a simple mixture of Baltic and Skagerrak waters would result in a linear relationship between DIN and salinity. However, the winter DIN concentrations in the Kattegat – Belt Sea area in February 2002 showed a strong positive deviation from the linear relationship in the salinity interval 10-25, due to local supplies of DIN from land, atmosphere and internal remineralisation. In 1996, which was an extremely dry year with low DIN runoff from land, the deviation was much smaller or absent (figure 4.1).

From measurements at intensive stations with high sampling frequency (see map figure 2.1) it is seen (figure 4.2), that the 2002 winter surface DIN concentrations in the western Kattegat and Århus Bight did not deviate significantly from the year 2001 or from the 1990-2001 long term means. In the Sound, the southwestern Kattegat and the Belt Sea, higher DIN concentrations were observed in February and first half of March than in the same period during 2001. These lasted until the onset of the phytoplankton spring bloom about mid March. However, in February the DIN concentrations did not significantly exceed the long term means 1990-2001.

In 2002, the winter surface concentrations of dissolved phosphate (DIP) were lower than or equal to the concentrations observed in 2001 or the long term averages from 1990-2001, with the exception of high winter DIP concentrations in the southern Little Belt in 2002 (figure 4.3).

The long lasting severe oxygen depletion caused an accumulation of inorganic nutrients in the bottom water in the autumn of 2002. The DIN pool (mainly ammonium) and the phosphate pool peaked in October and decreased during November-December as the water exchange and mixing increased (figure 4.4).



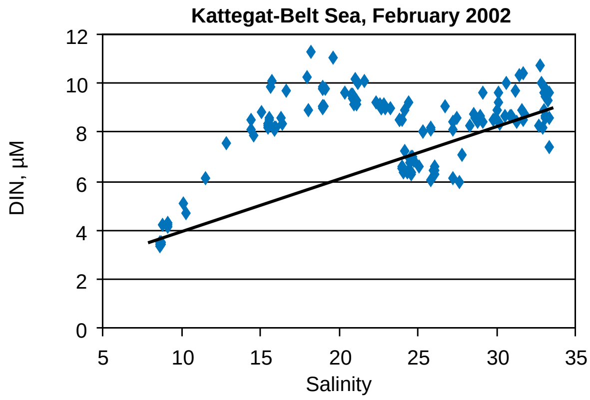


Figure 4.1
Relationship of DIN to salinity in the Kattegat - Belt Sea area in February 1996 and 2002. The line in the 1996 plot is a linear regression line, while the line in the 2002 plot is a theoretical mixing line for mixtures of Baltic and Skagerrak waters.

Chlorophyll-*a* concentrations

Chlorophyll-*a* is an indicator of the phytoplankton biomass. In 2002 in the western Kattegat and Århus Bight, the chlorophyll-a concentrations in the uppermost 15 m (main photic zone) showed an intense spring bloom in March. These values exceeded those observed in 2001 and the long-term means (figure 4.5). In the Sound and Belt Sea the chlorophyll concentration peaked in the second half of March, but the concentrations were not significantly different from 2001 or long term seasonal averages. During the rest of 2002 no obvious significantly higher chlorophyll concentrations were observed until autumn, when high concentrations of chlorophyll were observed in most areas. This followed vertical water mixing which brought nutrients from the bottom waters to the surface.

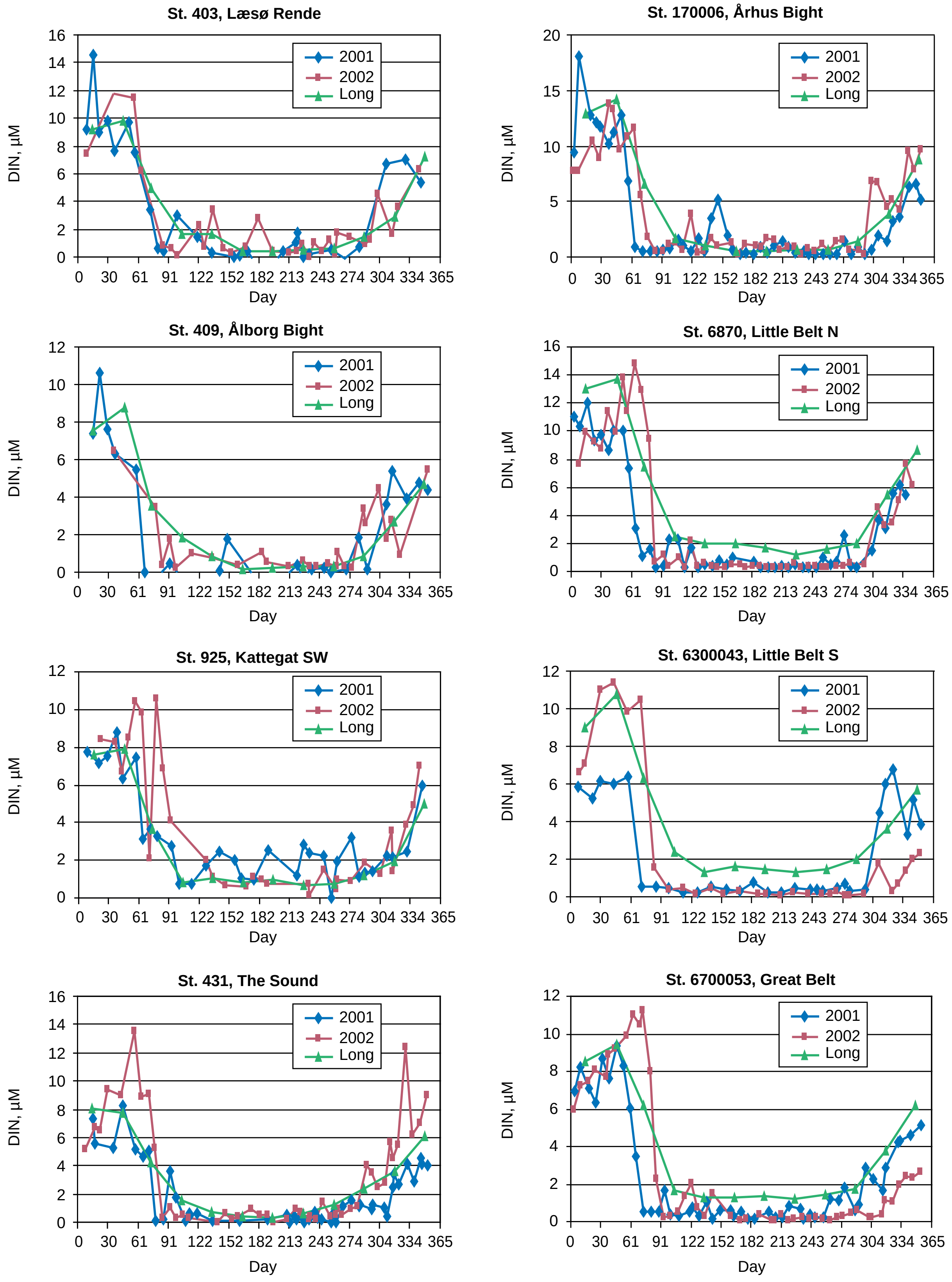


Figure 4.2

Seasonal distribution of surface concentrations (0-10 m) of disolved inorganic nitrogen (DIN) in 2002 compared to 2001 and long term monthly means 1990-2001.

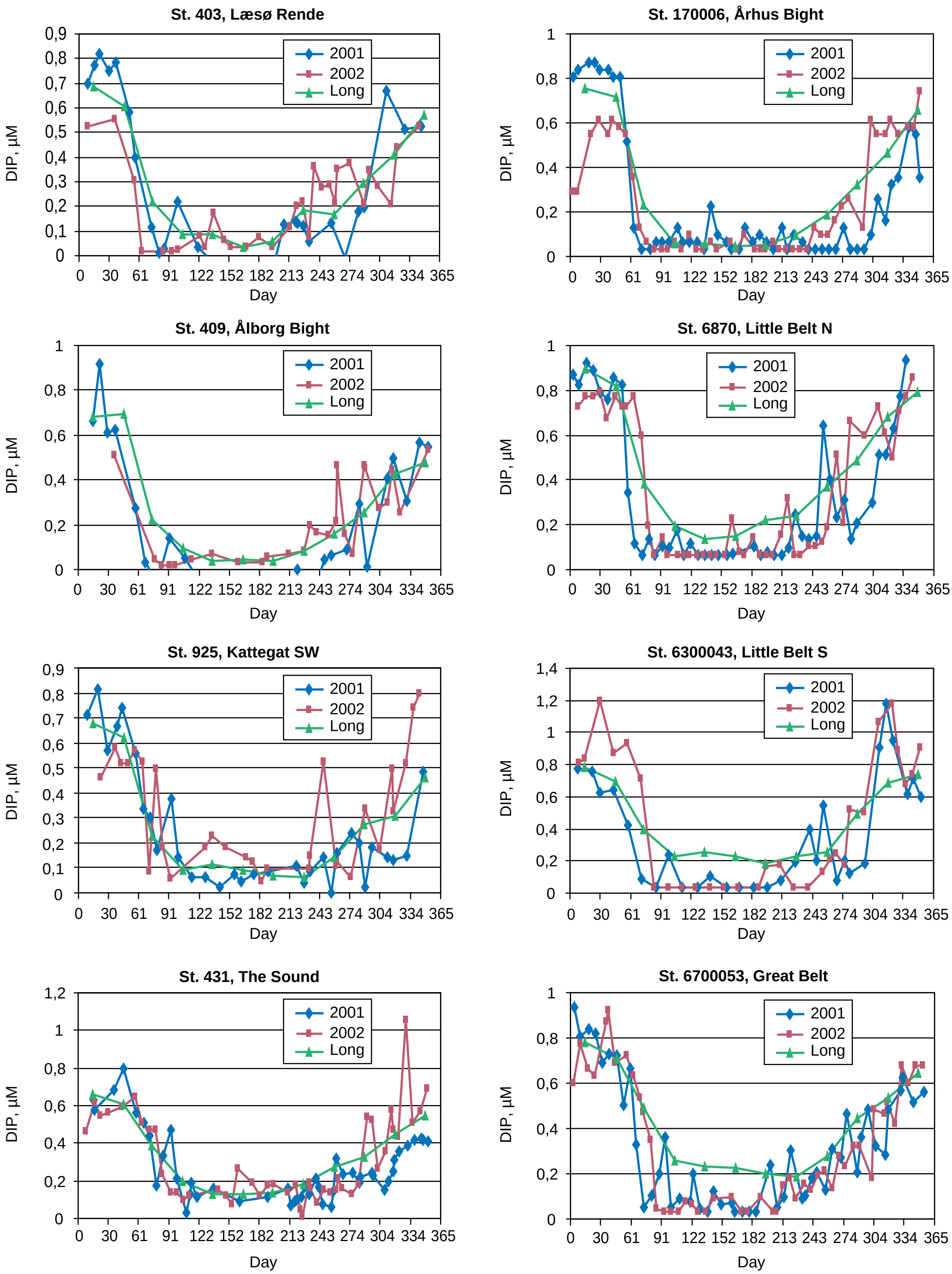


Figure 4.3

Seasonal distribution of surface concentrations (0-10 m) of disolved phosphate (DIP) in 2002 compared to 2001 and long term monthly means 1990-2001.

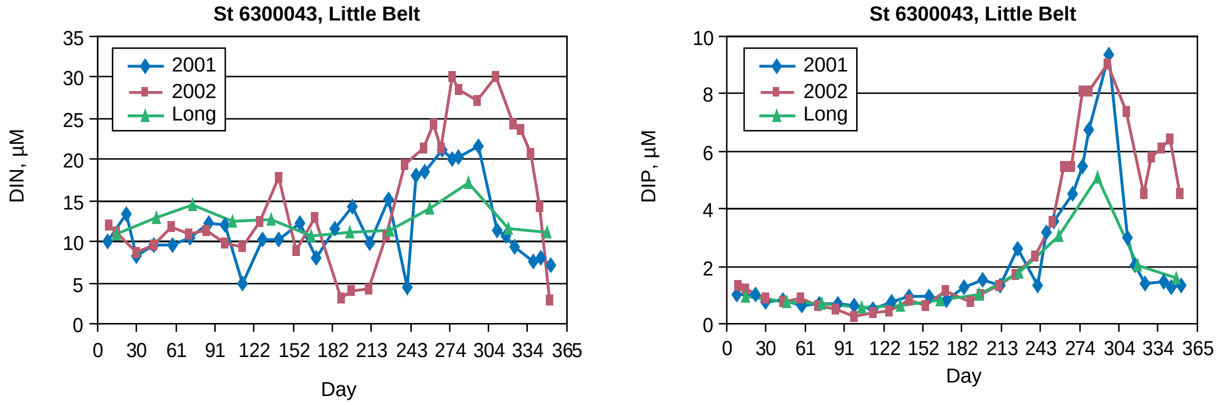


Figure 4.4
Seasonal distribution of bottom water concentrations of disolved inorganic nitrogen (DIN) and disolved phosphate (DIP) in 2002 compared to 2001 and long term monthly means 1990-2001 in the southern Little Belt

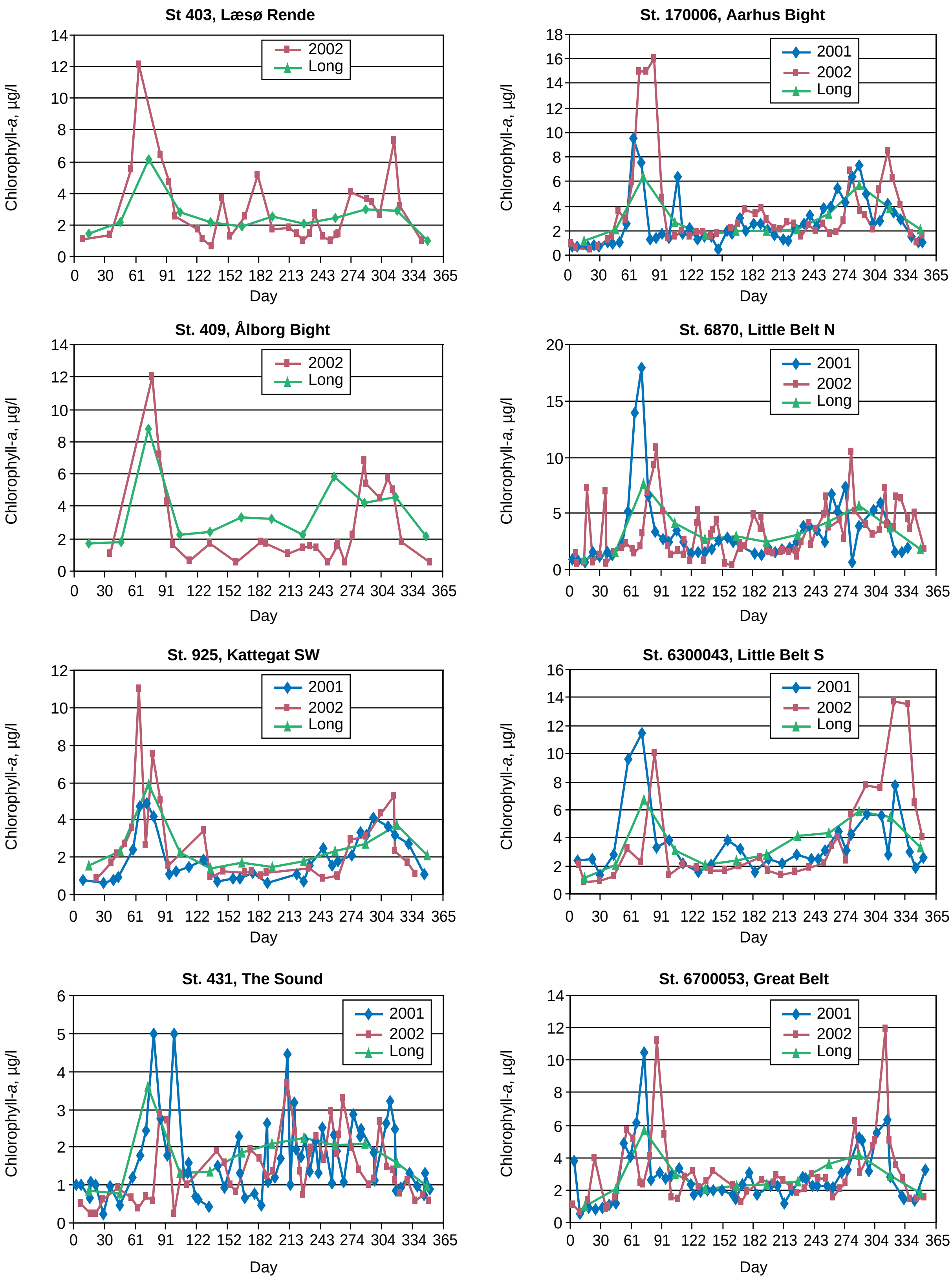


Figure 4.5

Seasonal distribution of surface concentrations (0-15 m) of chlorophyll-*a* in 2002 compared to 2001 and long term monthly means 1990-2001.

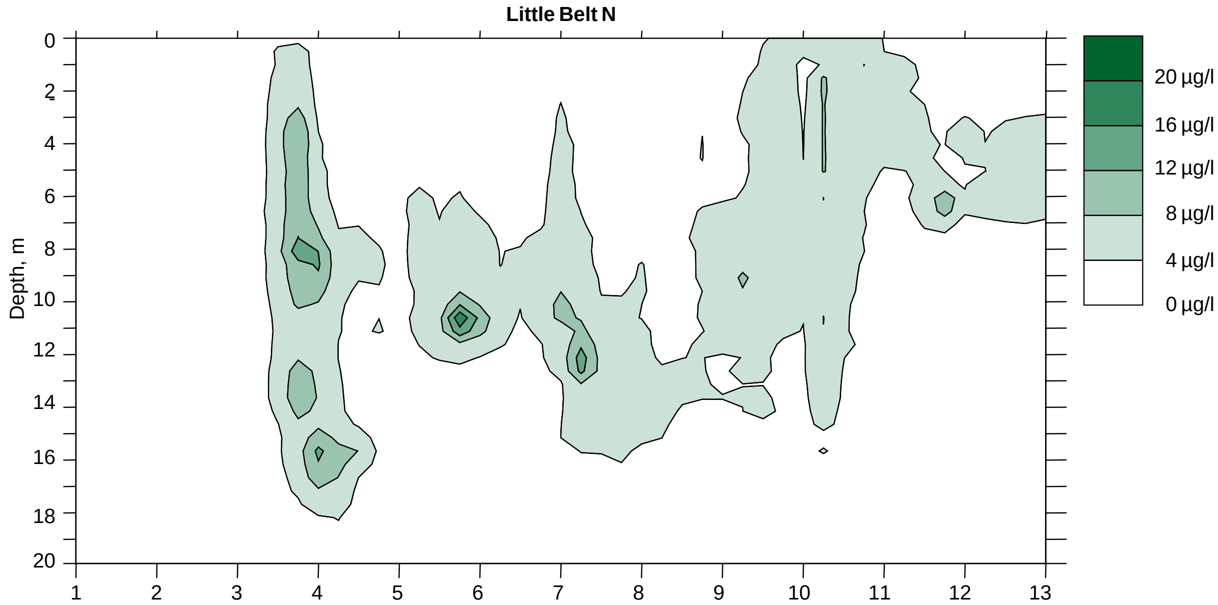


Figure 4.6

Distribution of chlorophyll-*a* in the water column in the northern Little Belt through 2002. Note the pronounced sub-surface maximum from May to September. Figure from the County of Vejle.

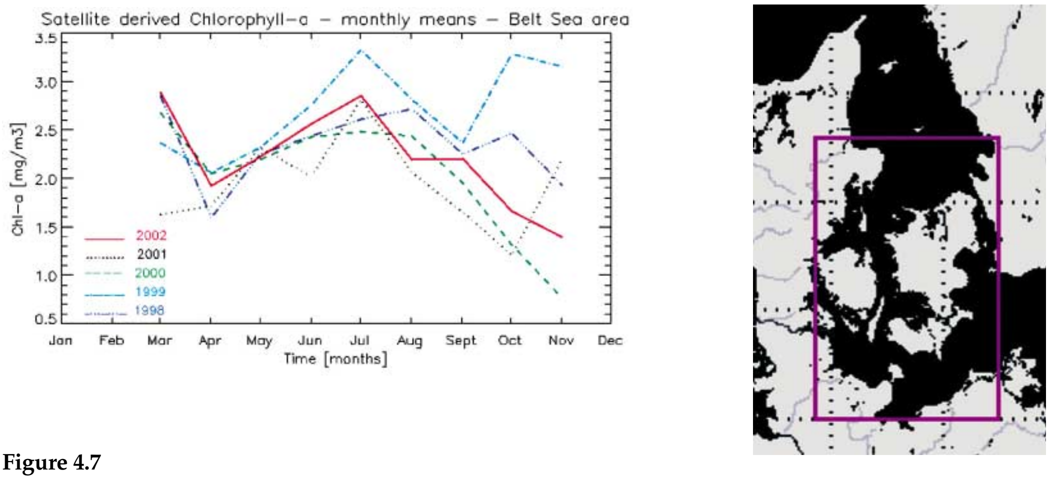


Figure 4.7

Monthly mean chlorophyll-*a* derived from the SeaWiFS satellite sensor averaged on the Belt Sea area (54-56.6ºN; 9.7-13ºE, see map) between 1998 and 2002 (January, February and December excluded due to low satellite cover). JRC data.

After the spring bloom in March and depletion of the nutrients in the surface layer a pronounced sub-surface chlorophyll maximum was established around the pycnocline in May to September (figure 4.6).

Monthly means of surface chlorophyll-*a* content were computed from SeaWiFS satellite data (launched in September 1997) using the atmospheric correction scheme developed at the JRC-IMW (Sturm & Zibordi 2002) and the standard NASA-OC4v4 chlorophyll algorithm. A direct comparison between satellite-derived chlorophyll values (figure 4.7) and in situ measurements (figure 4.5) is difficult as the satellite data are averaged in space and time and the values are largely smoothed compared to punctual measurements. However, the general trend can be compared. In agreement with most of the in situ data presented, the monthly means of the Belt Sea area (1998-2002) show the seasonal cycle with a high spring bloom in March and another peak of biomass in July (figure 4.7). It must be emphasised that summer chlorophyll level in 2002 is slightly higher than the 1998-2002 mean but substantially lower than 1999.

The close to mean chlorophyll levels for 2002 (figure 4.5) cannot explain the oxygen depletion event alone although the primary production is an important factor, being the source of oxygen demand at the sea bed. The water exchange section of this report (chapter 7) provides complementary information to explain why the 2002 oxygen event was more intense than 1999 despite the 2002 surface biomass being lower than in 1999.

It must be noticed that the surface biomass estimate from remote sensing can differ from the biomass integrated on the water column using field measurements due to the occurrence of the sub-surface chlorophyll maximum, which is generally not seen by the sensor. This deeper biomass can lead to a significant bias in summer, particularly in the Kattegat-Belt Sea region where it is persistent (figure 4.6). Surface satellite- derived chlorophyll does however provide a synoptic assessment of the surfacebiomass and its variability at seasonal and interannualtime scales.

Phytoplankton primary production

The few phytoplankton primary production data available revealed an unusually high spring bloom in March 2002 in the western Kattegat and the Belt Sea, and relatively high production rates during summer and autumn compared to 2001 and long term monthly means 1990-2001 (figure 4.8).

Conclusion

The winter surface concentration of dissolved inorganic nitrogen (DIN) in February 2002 showed a strong influence from local sources but, in the western Kattegat, did not deviate significantly from 2001values or from long term means. In the Sound and Belt Sea, high DIN concentrations were observed in March 2002. The winter surface phosphate concentrations in 2002 were lower than or equal to the concentrations in 2001 or the long term averages 1990-2001. Chlorophyll concentrations show that there was a strong spring bloom in the western Kattegat in March 2002, but in the Sound and the Belt Sea the spring chlorophyll peak

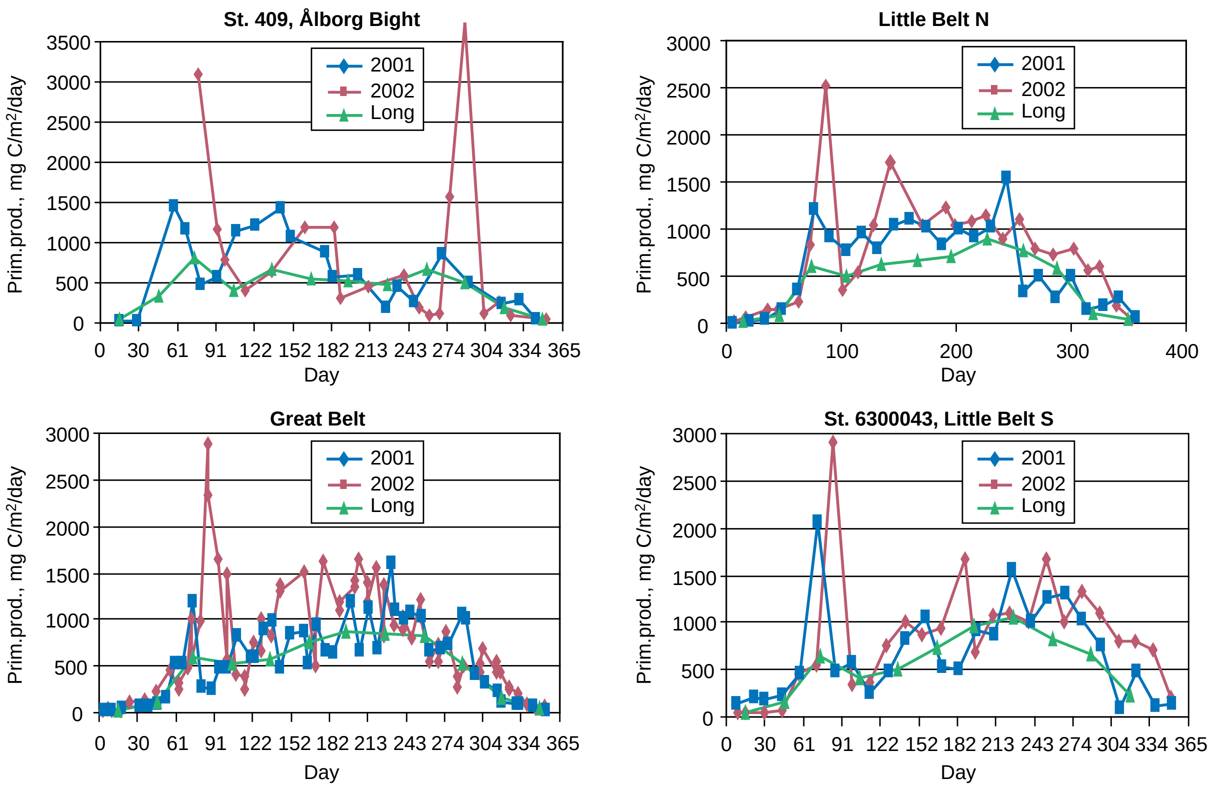


Figure 4.8

Seasonal distribution of daily phytoplankton primary production in 2002 compared to 2001 and long term monthly means 1990-2001.

did not significantly differ from 2001 or from long term means. A pronounced sub-surface chlorophyll maximum was observed in the Belt Sea from May to September. Satellite-derived chlorophyll averaged over the Belt Sea area show slightly higher chlorophyll concentrations during spring and summer 2002 than average 1998-2002 but substantially lower chlorophyll levels during summer 2002 compared to 1999. Primary production data shows an unusually strong spring bloom in March and relatively high production rates during summer and autumn 2002, suggesting that there was an enhanced oxygen consumption rate during 2002.

5. Atmospheric forcing

Introduction

Sea level pressure data, from the NCEP 5° x 5° 12 hourly gridded data set, were used to compare the mean atmospheric pressure at sea level in 2002 with the mean from 1992-2002.

Offshore wind parameters have been measured at Nidingen (57.3°N, 11.9°E), in the northern Kattegat, since 1969. These data are considered to be representative of offshore wind conditions over the Kattegat as a whole. To describe wind forcing during the summer of 2002, data from 1992 onwards were analysed for wind speed exceedence for eight direction sectors, and compared with the results from 2002. Results for the months June-November, from 1992-2002 (inclusive) are presented in figure 5.3. Figure 5.4 shows the equivalent plots for the 2002 data alone.

Results

Figure 5.1 shows the monthly mean atmospheric pressure at sea level, between 1992 and 2002, and also in 2002. These data come from the 55°N, 10°E grid point of the NCEP gridded data product, and were obtained from NCAR – the National Center for Atmospheric Research: http://www.ucar.edu/ucar/. From May to August, mean pressure was within one standard deviation of the average (though slightly above average in August). In September average pressure was 6 hPa above average. In addition, the variance in the signal in August and September 2002 is less than that observed in the data from the previous ten years. The higher atmospheric pressures suggests light, variable winds, while the reduction in variance suggests that fewer depressions passed through the area, also indicating reduced wind activity in 2002 compared to an average year.

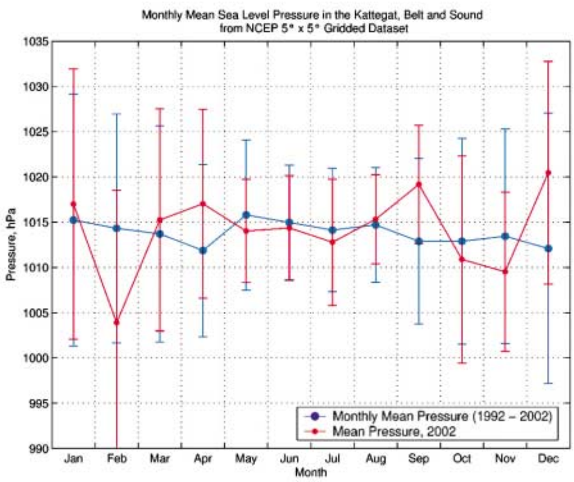


Figure 5.1

Monthly mean sea level pressure (in hPa) calculated from twice daily values between 1992 and 2002 (blue data) and in 2002 (red data). Error bars indicate one standard deviation. Data originate from the NCEP (and US Navy for pre 1994 data) gridded dataset, and were extracted for the grid cell 55°N, 10°E.

Tables 5.1 and 5.2 show the percentage of time the wind speed at Nidingen exceeds certain values each month during summer and autumn. Table 5.1 is based on data from 1992-2002, while table 5.2 shows data from 2002 only. June and July 2002 were close to average. In June, winds stronger than 8.5 m/s occurred more often than usual.

August and September 2002 were much calmer than average, with winds over 8.5 m/s for only 8% and 17% of the time respectively, compared with 25% and 30% in an average year. In August 2002, the dominant wind direction was easterly (for 25% of the time). During average August conditions, the dominant direction is westerly or south-westerly.

October and November were also calmer than usual (lower frequency of winds greater than 11.5 m/s). In 2002, the dominant direction was easterly (52% of the time from the east or north east in October, compared with 22% in an average year, and 82% of wind from between north easterly and southerly in November 2002, compared with 60% in an average year).

That the observations from Nidingen can be regarded as representative for the whole Kattegat - Belt Sea area is supported by the observed frequency of wind forces over 10.8 m/s (gale force) measured at Danish meteorological stations (figure 5.2). However, in 1997 the wind activity was also unusually low from May to the first week of September (weeks 18-36), and especially in July-August (weeks 27-35), generally dominated by wind from easterly directions. In spite of the low wind activity unusually little oxygen depletion was observed in August 1997. This might be a consequence of the low nitrogen load from land based sources, which in both 1996 and 1997 was less than 60% of the average 1990-2001.

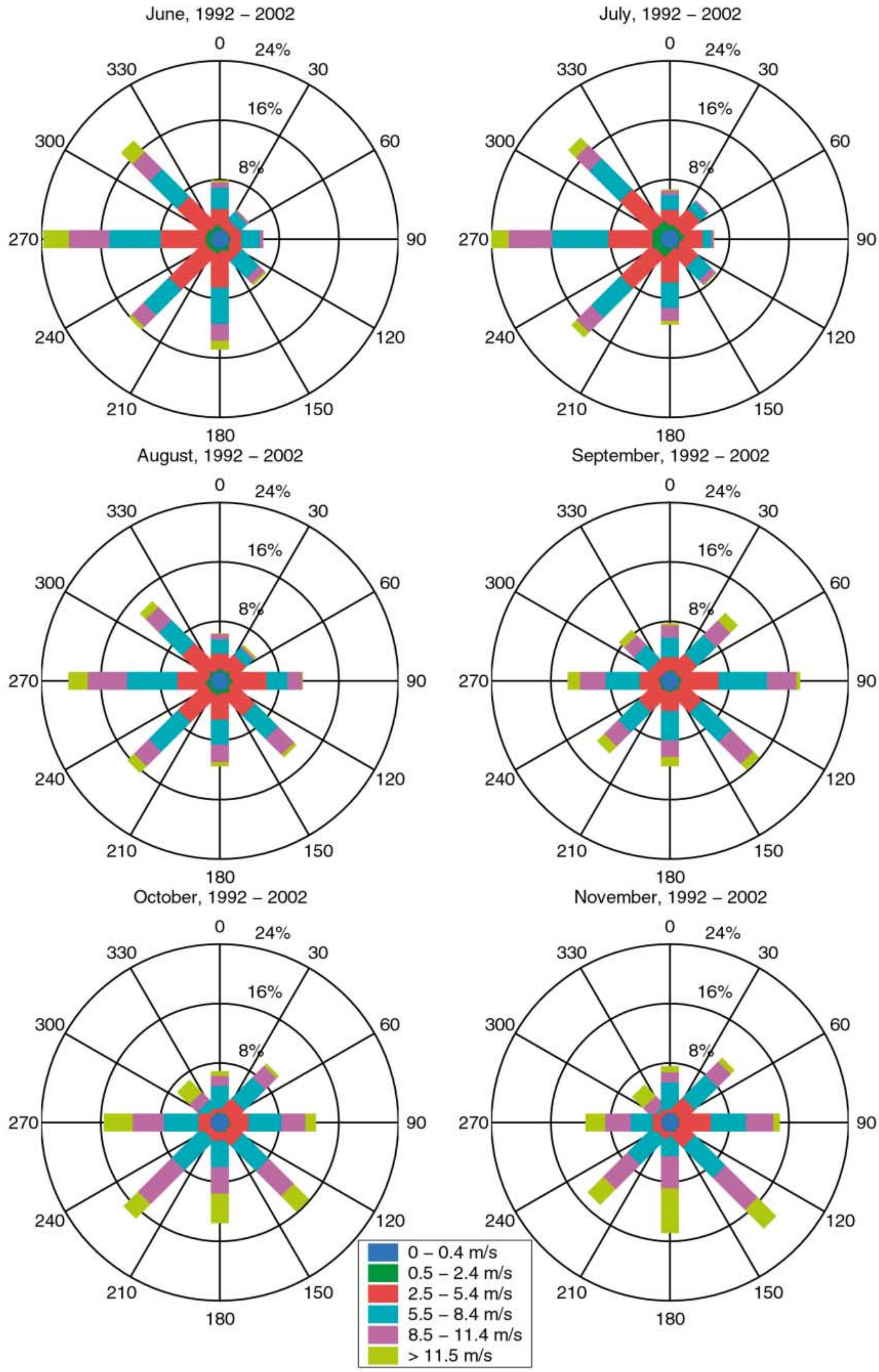


Figure 5.3

Wind roses showing frequency of occurrence of different wind speed/direction combinations at Nidingen, based on data from 1992 - 2002.

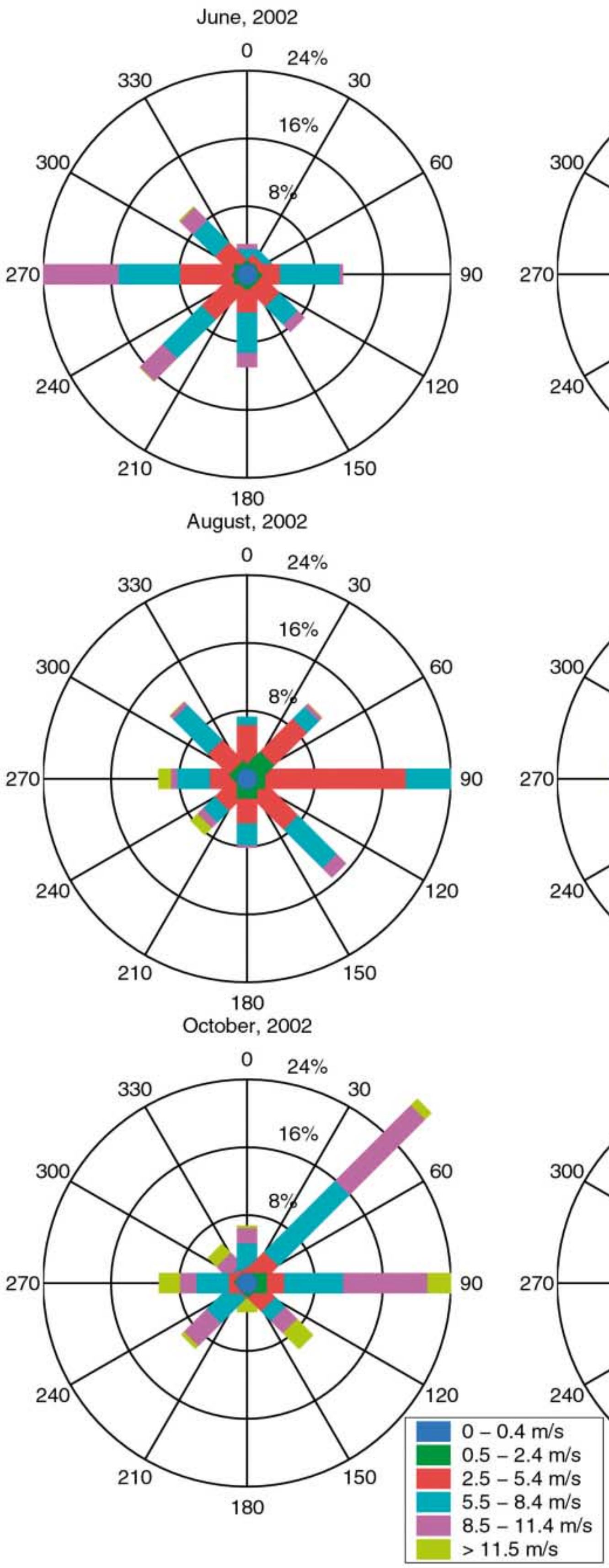


Figure 5.4

Monthly wind roses showing frequency of occurrence of different wind speed/direction combinations at Nidingen, based on data from 2002 only.

Wind speed range	Month					
	June	July	August	September	October	November
< 0.4 m/s	1.06	1.09	0.89	0.50	0.73	0.31
0.5 – 2.4 m/s	10.54	13.52	10.50	7.33	5.23	3.87
2.5 – 5.4 m/s	32.69	34.82	32.54	27.42	16.52	17.62
5.5 – 8.4 m/s	31.74	29.16	30.35	33.22	31.69	30.53
8.5 – 11.4 m/s	15.78	14.97	18.93	22.65	27.24	27.65
> 11.5 m/s	8.18	6.44	6.78	8.88	18.59	20.03

Table 5.1

Wind speed exceedence, as a percentage of time, for each month (June to November), from Nidingen data from 1992 - 2002.

Wind speed range	Month					
	June	July	August	September	October	November
< 0.4 m/s	0.00	0.40	0.81	0.00	0.00	0.00
0.5 – 2.4 m/s	9.11	10.09	14.53	11.66	6.90	4.46
2.5 – 5.4 m/s	25.41	34.24	45.60	37.48	12.53	22.36
5.5 – 8.4 m/s	34.44	31.87	30.67	33.74	32.56	36.48
8.5 – 11.4 m/s	25.41	17.73	5.17	16.28	33.80	26.97
> 11.5 m/s	5.63	5.67	3.23	0.83	14.21	9.73

Table 5.2

Wind speed exceedence, as a percentage of time, from Nidingen data, summer and autumn 2002.

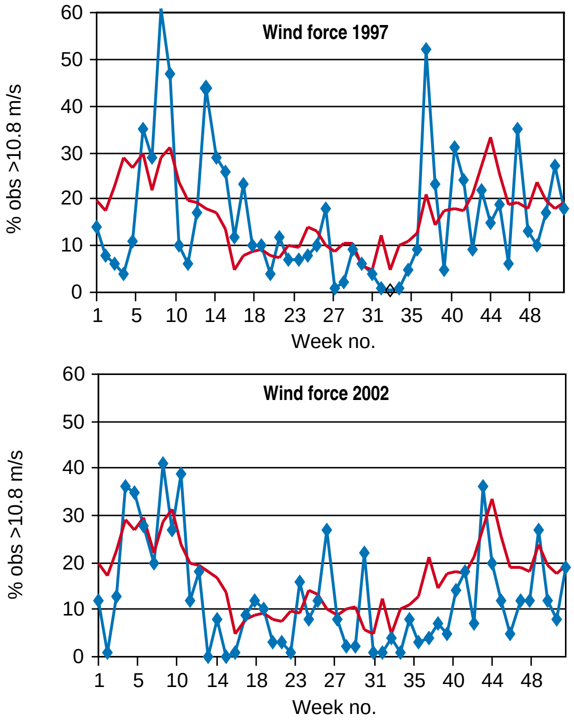


Figure 5.2

The weekly frequency of wind forces over 10.8 m/s (gale force) at Danish meteorological stations in 1997 and 2002 (diamonts) compared with weekly means 1994-2002 (thin lines). Based on data from the Danish Meteorological Institute.

Conclusions

1. Atmospheric pressure data indicate that August and September 2002 experienced higher pressure than normal.

2. The low variance in the pressure data also suggests that atmospheric conditions were calm, and winds would be expected to be light.

3. Wind data recorded at Nidingen indicate that winds were much weaker than normal in August and September 2002.

4. Winds were predominantly from the east in August. This would limit the fetch available for wave growth - particularly in the Sound and the Belt Sea.

5. The calm atmospheric conditions, and resulting reduced wave activity, reduce vertical mixing. This is particularly significant in shallow waters.

6. Hydrography

Introduction

The shallow water hypoxia and anoxia, experienced in the Kattegat, the Belt Sea and the Sound in the late summer and autumn 2002 may have been caused, or exacerbated, by calm atmospheric conditions, leading to increased heating of the surface water, a strengthening of the vertical stratification and a stagnation of the bottom water. An increase in the strength of stratification can prevent the mixing of oxygen from the surface water to deeper layers, and the calm weather with dominating easterly and southerly wind may have prevented inflow to the bottom layer of oxygen rich water from the Skagerrak. This chapter examines hydrographic data collected in the Kattegat, the Belt Sea and the Sound to see if there was evidence to support the hypothesis on increased stratification. The next chapter will focus on the horizontal water exchange.

SMHI has four high frequency (> 12 times per year) sampling stations in the affected area. These are Fladen, Anholt East, West Landskrona and Drogden East. Drogden East has only been sampled since 2001. High quality CTD data for the other stations exists from 1995. The sampling station locations are shown in Chapter 2, figure 2.1. In addition, data from four very high frequency stations sampled by Danish counties, in the Kattegat, the Sound, the Great Belt and the Little Belt were studied (see map figure 2.1).

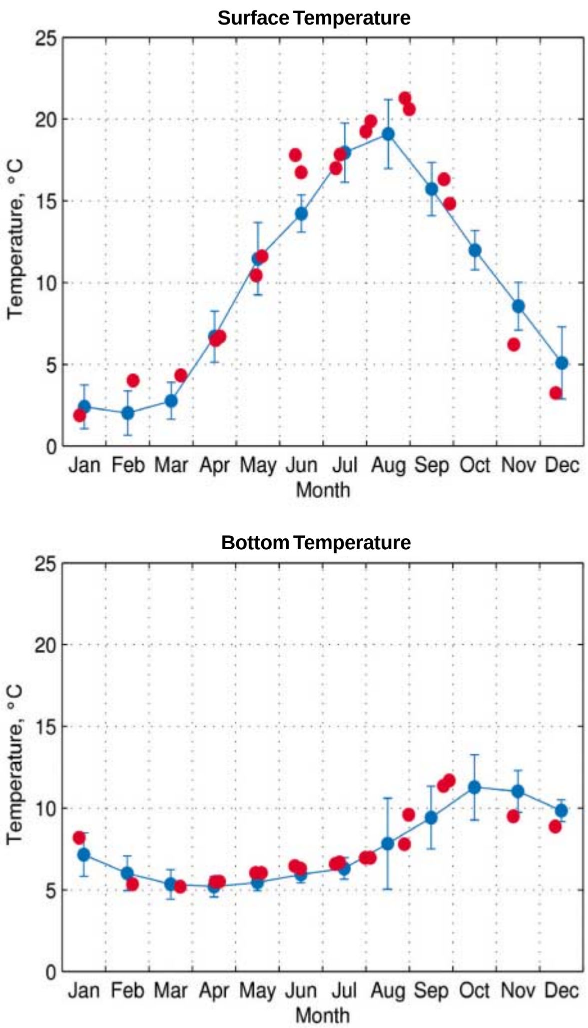


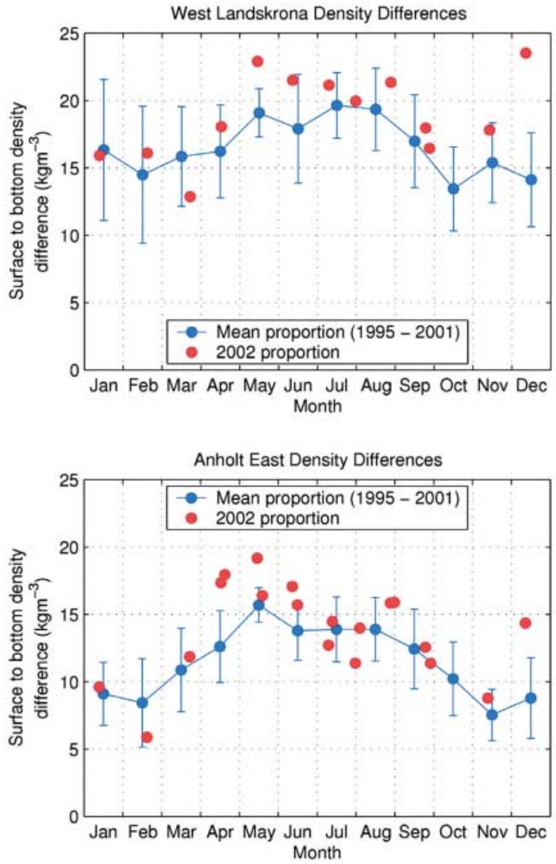
Figure 6.1

Surface and bottom water temperatures, measured at Anholt East. Blue points with error bars represent the monthly mean temperatures, based on data collected from 1995 - 2001, +/- 1 standard deviation. Red points show data collected in 2002.

Data from these stations were analysed to show whether hydrographic conditions in 2002 differed from 'normal', and to discover if the strength of stratification in 2002 was greater than in previous years. Stratification strength was assessed by looking at the difference in water density, due to temperature and salinity, between the surface and deep water, and also by studying the 'buoyancy frequency' N^2. This takes into account differences in both temperature and salinity to give a measure of the variation in stratification throughout the water column. A high value of the maximum buoyancy frequency indicates strong stratification. Additionally, the proportion of the water column that was strongly stratified was calculated, and compared with previous years.

Results

Surface temperatures at Fladen were slightly higher than average for the time of year in late July and September, before cooling to below average in November and December. With the exception of February, June and November, surface temperatures were within one standard deviation of the mean. At West Landskrona, surface temperatures were also above average in June and from the end of July to the start of October - and with the exception of mid June - were within one standard deviation of the mean. At Drogden East, the August surface temperature was 3°C warmer than in 2001, while at Anholt East, surface temperatures in June, August and September were up to 5°C warmer than usual. Temperatures in July were close to normal. Again with the exception of June, all temperatures between April and November were within one standard deviation of the monthly mean.



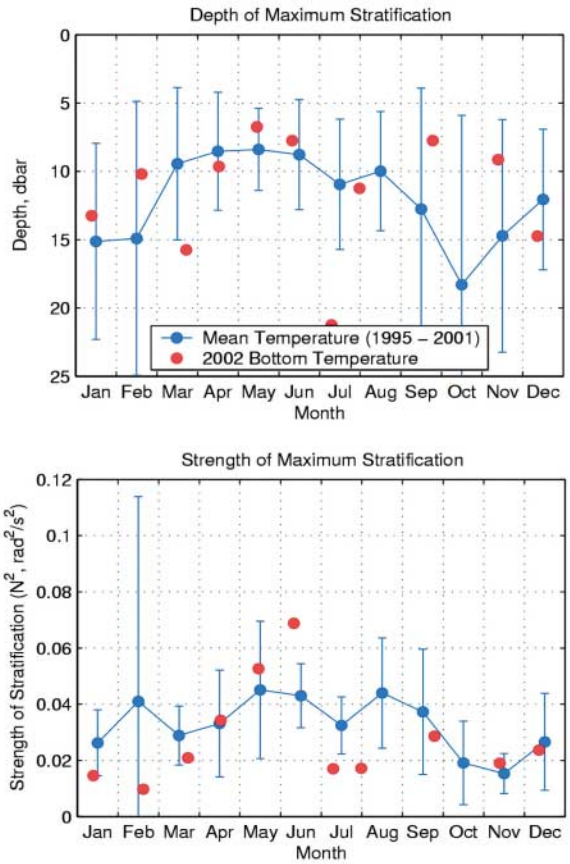


Figure 6.2

Density differences (bottom - surface) at West Landskrona and Anholt East, in 2002 (red dots) compared with mean values from 1995 - 2001 (blue dots). Error bars indicate +/- 1 standard deviation.

Figure 6.3

Depth (upper fig.) and strength of maximum stratification at Fladen in 2002 (red dots) compared with monthly mean values based on data collected from 1995 - 2001. Error bars indicate +/- 1 standard deviation.

At the Danish stations (figure 6.5, left hand column) a positive temperature anomaly in the surface in June reached the bottom water in August increasing the temperature 1–2°C above the long term mean 1990–2001. The August-September surface temperature anomaly raised the bottom water temperature 1–2°C above mean in October (figure 6.5). Surface temperatures were greater than average between at least day 213 (August 1st) and day 274 (October 1st).

At the Danish stations, bottom temperatures were close to average throughout the year, only deviating from normal (1990–2001 mean values) in August and October (figure 6.5). At Fladen, bottom temperatures (at about 80 m depth) have a small annual cycle – varying between 5 and 10°C between March and November, respectively. In 2002, bottom water temperatures were higher than average between March and the end of September – being close to one standard deviation greater than average until August. At West Landskrona (50 m depth) the annual cycle is stronger – from 5°C in March – May, rising to 12°C in October. In 2002, spring temperatures were cooler than average in March and April, but warmer between May and November. Drogden East is a very shallow station (around 12 m deep) and bottom temperatures were very similar to surface temperatures – that is, 2002 temperatures heigher than 2001 in August and September. At Anholt East (60 m depth), bottom temperatures were about one standard deviation above average between April and July, and increased more quickly during August and September, before cooling rapidly to be below average in November and December (figure 6.1).

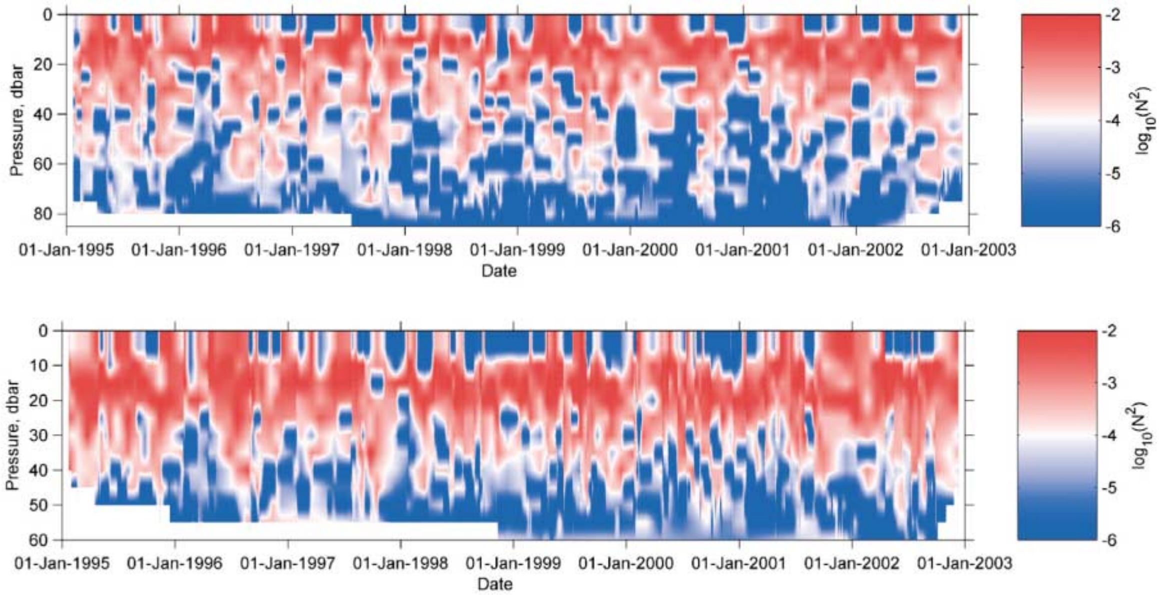


Figure 6.4

Gridded buoyancy frequency at Fladen (upper) and Anholt East (lower). Red areas show strong stratification, while blue areas are well mixed.

The salinity of the surface waters (0-5 m depth) in the Sound and Belt Sea area was in 2002 generally high in February–March, low in April–June, normal in July and again low in August–September (figure 6.5). In the bottom water the salinity was in 2002 generally low in March–April, and generally normal to high during the last half of the year. Low surface salinity indicates outflow from the Baltic Sea. High bottom water salinity indicates inflow from the Skagerrak and/or low vertical mixing in the water column.

Calculating the strength of stratification in terms of the buoyancy frequency indicated that the stratification at Fladen was weaker than average between July and September (figure 6.3). With the exception of early July, the depth of the greatest stratification was close to normal throughout the year. At Anholt East stratification was stronger than average when the site was visited in May, June and late August, but weaker than average in July. At West Landskrona, the peak stratification was close to normal.

Buoyancy frequency calculations show a higher proportion of the water column was stratified in 2002 at Anholt East and Fladen than in the period 1997–2001 (figure 6.4). Data were plotted against the monthly mean proportion of the water column that was strongly stratified. At Anholt, between August and the end of October, six profiles were more stratified than usual, one was close to normal, and one less than normal. Of those profiles that showed more stratification, two were more than one standard deviation from the expected values. At Fladen, all four profiles taken after the beginning of August show more stratification than normal – though three of the points are within one standard deviation of the mean. At West Landskrona, all four profiles from the end of August to the end of November show greater stratification. Two profiles are less than one standard deviation from the mean.

Discussion

The slightly raised bottom water temperature in the Sound, south-western Kattegat and Great Belt in August may have increased the oxygen consumption rate in the bottom water, but not enough to explain the widespread oxygen depletion already developed in August 2002.

The larger than normal temperature difference between surface and bottom, combined with the lower than usual surface salinity indicates that the water column was more stable than usual in the summer and autumn of 2002. This implies that the stratification was stronger, and it would therefore be more difficult to mix oxygen from the surface to the deeper waters.

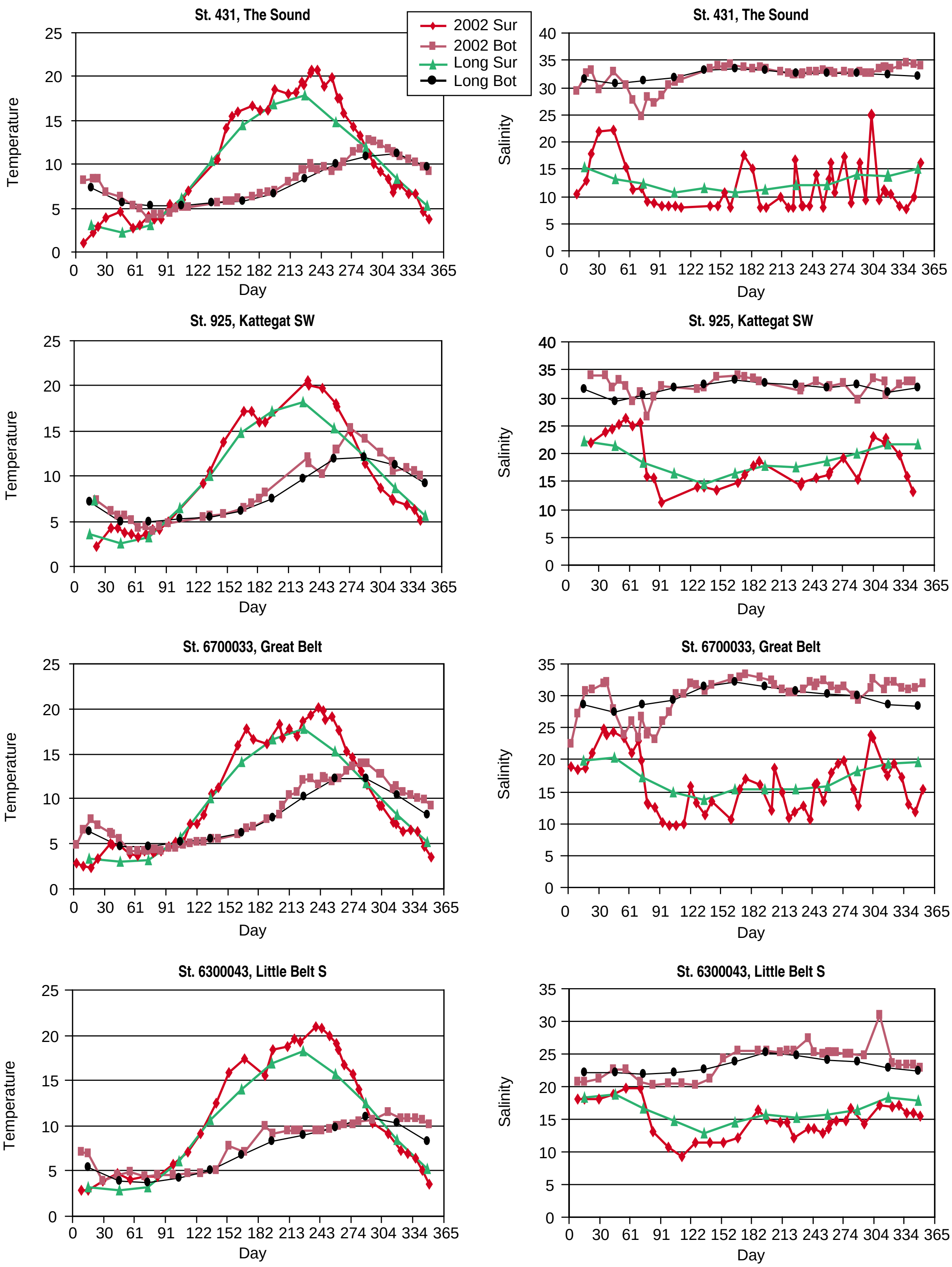


Figure 6.5

Seasonal distribution of temperature and salinity in the surface (Sur) and close to the bottom (Bot) in 2002 compared to long term monthly means 1990-2001.

Calculations based on the buoyancy frequency give a less emphatic result. The peak buoyancy frequency was close to normal, indicating that the maximum change of density with depth was close to normal. The change in buoyancy frequency through the water column (figure 6.4) suggested however that while the maximum stratification was close to normal, the pycnocline extended through a greater proportion of the water column than in the years from 1997 to 2001. The extent of the pycnocline appeared similar in 1995 and 1996.

When the density difference from surface to bottom is great, the water column is stable, and more energy is needed to mix oxygenated surface water to the bottom. Where the pycnocline is strong, due to a large density gradient, or where the pycnocline is broad, turbulence – the mixing mechanism that allows oxygen, heat and tracers to be transported – is damped out. Turbulent eddies are suppressed in the stratified area, and cannot mix oxygen (or heat) downwards – or additional nutrients upwards. This can be attributed both to the increased stratification, brought about by the warm, calm conditions, and also due to the absence of stirring, due to the lack of strong wind events.

Whether the increased stratification was sufficient to cause the observed anoxia is not clear from these data. The area is permanently stratified, so the vertical supply of oxygen to the bottom water is limited to events where the pycnocline depth is deepened due to wind mixing. Rasmussen (1997) estimates the influence of wind mixing to be limited to the upper 10 metres in the southern Kattegat. This suggests that the oxygenation of the deeper layers at water depths larger than about 10-15 m is dependent more on the horizontal advection of oxygen rich water, than on the vertical mixing.

Conclusions

1. Surface water temperatures in the summer and autumn of 2002 were higher than normal – while bottom water temperatures were similar to, or lower than, normal, except in the Belt Sea in August and October.

2. The bottom to surface density difference was greater in the summer of 2002 than in earlier years, leading to a more stable water column.

3. The maximum strength of the pycnocline was not greater than normal, but the width of the pycnocline was, which has the same effect of inhibiting the mixing of surface and deep water.

4. The prolonged period of warm, calm weather in the summer and autumn of 2002 prevented the vertical exchange of oxygen (and heat) and contributed to the oxygen deficiency observed in the Kattegat, the Sound and the Belt Sea, especially in shallow areas with bottom depths less than 15 m.

5. The literature suggests that oxygenation of the deep water is dependent more on the horizontal advection of oxygen rich water, and the stratification, though stronger than normal in 2002, is normally too strong to allow the vertical transport of oxygen to the bottom layers deeper than about 15 m.

7. Water exchange and residence times

Introduction

Anoxia in summer 2002 affected the bottom water in the Belt Sea, the Sound and the Kattegat. Exchanges through the Belt Sea and the Sound were calculated with three different 3D hydrodynamic models:

1. The Danish Hydraulics Institute (DHI) model covers the North Sea and the Baltic Sea with a resolution of 3 nm in Danish waters and 9 nm elsewhere with a 2 m vertical resolution.

2. The Swedish Meteorological and Hydrological Institute (SMHI) operational model HIROMB (Hi–Resolution Model of the Baltic) covers the Baltic Sea and the north–eastern North Sea with 3 nm resolution. This produces output of temperature, salinity, and current velocities at up to 16 depth levels. In the shallow water of the Belt Sea, four-hourly data, covering the period 1998–2002, were available at 4, 8, 12, 18 and 24 metres.

3. The European Commission Joint Research Centre (JRC) model covers the North Sea and the Baltic Sea with a resolution of 3 nm and 25 depth levels in the entire area.

All three models have suitable characteristics for calculating flows in the Belt Sea area.

Output from the JRC model was compared with that from the SMHI and DHI models for validation purposes and to show the depth-integrated picture of exchanges through these seas. The SMHI and JRC models allowed the contributions from different levels to be examined in detail. To investigate the impact of horizontal water exchange involving the more oxygen-rich bottom water of the Kattegat on the oxygen deficiency in the Belt Sea area, HIROMB accumulated flow from the 18–24 metre layer was calculated and used to assess the residence time of this water, on the assumption that vertical exchanges were negligible. For the same purposes, the absolute flow of the bottom layer (layer between the stratification and the sea bed) derived from the JRC model was investigated based on monthly mean values.

Results

Figure 7.1 shows the accumulated water flow through the Great Belt (Nyborg section) in 2002, based on model output from DHI. The model shows the accumulated outflow of around 370 km^3 during the year towards the Kattegat. Figure 7.2 shows outflow through the Hasenøre-Gniben section (the border between the Kattegat and the Belt Sea) for the same period, calculated by SMHI's operational model HIROMB, for each depth layer (0–4 m, 4–8 m, 8–12 m, 12–18 m and 18–24 m), as well as the total outflow

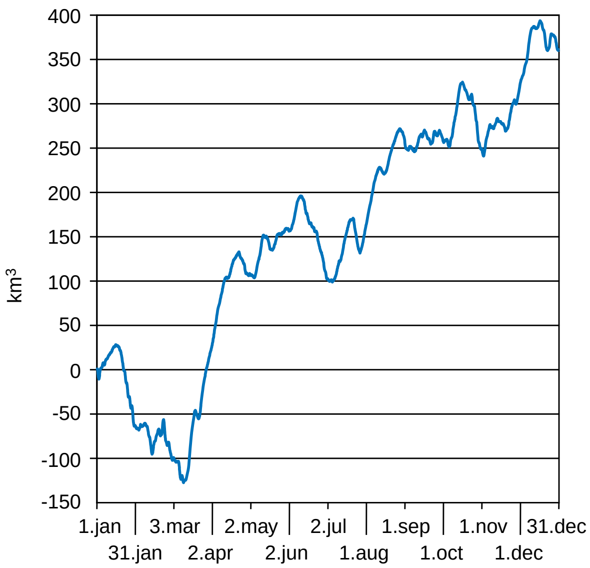


Figure 7.1
Accumulated flow in 2002 through the Great Belt, Nyborg section, from the DHI model.

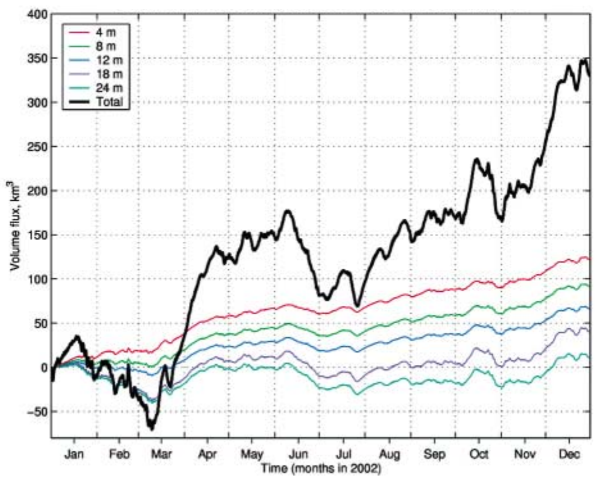


Figure 7.2
Accumulated flow in 2002 through Hasenøre – Gniben section (border between the Kattegat and the Belt Sea), at 5 depth levels and total, from the SMHI HIROMB model. The depth levels are: 0-4 m, 4-8 m, 8-12 m, 12-18 m and 18-24 m.

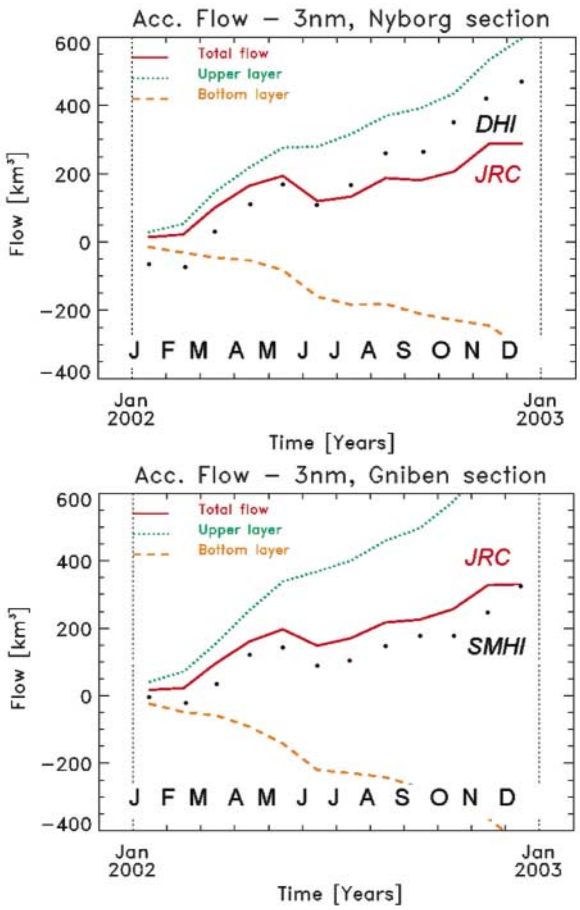


Figure 7.3
Accumulated flow through the Great Belt (Nyborg section) and the Hasenøre – Gniben section for 2002 estimated by the JRC model (monthly mean values of the upper layer, bottom layer and total accumulated flow). For comparison purposes, values of total flow (black dots) of the DHI (upper graph) and SMHI (lower graph) models are represented.

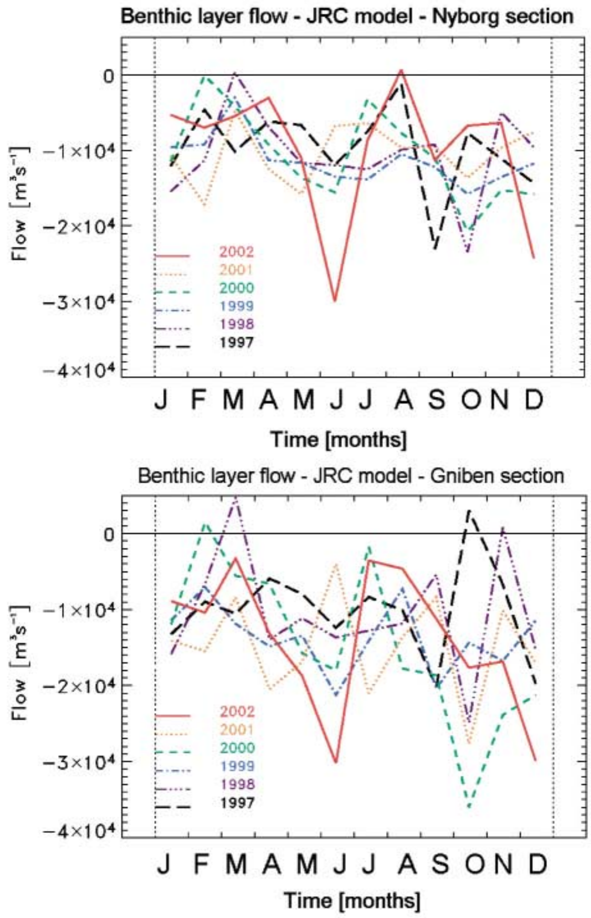


Figure 7.5
Benthic layer flow for the Nyborg section (Great Belt) and Hasenøre–Gniben section calculated by the JRC model from 1997 to 2002. Negative values indicate a flow southward from the Kattegat to the Belt Sea area.

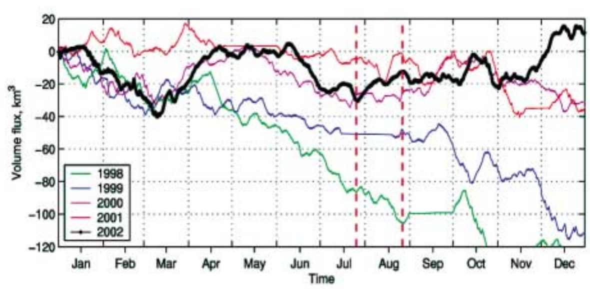


Figure 7.4
Comparison of cumulative volume flows (1998–2002) in the bottom layer (18–24 m), for the Hasenore – Gniben section. Vertical dashed lines indicate water outflow during summer 2002. HIROMB model.

volume. Figure 7.3 presents the accumulated flow derived from the JRC model for the upper layer, bottom layer and entire water column for both sections in order to compare with the other two models.

There is a slight inconsistency between the DHI model and the other two regarding the total flow in the Nyborg section. This flow cannot exceed the flow through the Hasenøre–Gniben section, as the latter also includes the flow through the Little Belt. However, the three models agree reasonably, especially for the major flow variations. Differences may be due to differences in forcing data, fx. the water level in the Baltic Sea at the start of the modelled period and the runoff to the Baltic Sea during the year, as well as differences in the respective models' performance and/or implementation.

All models show that the total outflow was interrupted by periods of inflow from the Kattegat. The largest of these flow reversals occurred from the middle of January to the middle of March. Further, smaller flow reversals occurred at the end of April (~30 km^3), during June (~100 km^3) and at the end of October (~80 km^3). The periods immediately after these inflow events appear to have greater than average outflow.

The HIROMB data shows that the main outflow takes place in the upper 12 metres. The 18 metre layer (12–18 m) shows inflow and outflow to be balanced until the end of October. In the bottom layer, at 24 metres (18–-24 m), inflow occurred from January to about March 10th, in the second half of June, and the second half of October. The first inflow was succeeded by outflow until the middle of April, followed by a calm period until the beginning of June. Only small volume changes occurred during the period from the end of July, until the beginning of October.

Figure 7.4 shows the outflow in the deepest layer (18–24 m, negative values indicate inflow from the Kattegat to the Belt Sea) for the years 1998 to 2002. With the exception of 2001, there was about 40 km^3 inflow to the Baltic in the first three months of each year. All years show that the inflow pauses or reverses in the second half of March to the beginning of April. In 1998 and 1999, the inflow continued throughout the year – although data are missing for July – August 1998, and September 1999. In 2000 and 2001, the inflow appears weaker (though data are missing for May and late November 2001), and the overall signal looks more like the data from 2002. Data from 2001 show less water movement than 2002 in June and July, but in August - September 2001 there was an inflow, then outflow, then further inflow of 20 km^3. During the same period in 2002, the model indicates maybe 20 km^3 moving into the area from the Baltic, followed by very small fluctuations (< 7 km^3) during September and early October. Of interest also is the result from 2000, which shows similar, small flows between July and the middle of September.

Figure 7.5 presents the absolute flow of the benthic layer for both sections calculated by the JRC model from 1997 to 2002. Negative values indicate a southward flow from the Kattegat to the Belt Sea area. In agreement with the SMHI model, the JRC model (Gniben section) shows maxima of inflow to the Belt Sea for 2002 in February, June and December. Minima for 2002 are in March, July and August. Compared to other years, 2002 is mainly characterised by exceptional inflow in June and December and, above all, an inflow minimum that lasted for an exceptionally long time during July-August in the Gniben section, with stagnation during August in the Nyborg section.

This minimum of water exchange during summer months meant that there was poor oxygen supply to the bottom waters of the Belt Sea area, while July 2002 corresponded to a peak of phytoplankton biomass (figures 4.5 and 4.7). It must be noticed that 1999 was characterised by higher inflow during summer compared to 2002 while the surface phytoplankton biomass was substantially higher (figure 4.7). This explains why the 1999 oxygen depletion event was important, but significantly lower than in 2002. Summer water exchange in 1997 has similarities to 2002, although the inflow as a whole was substantially higher.

Residence times were calculated for the deepest model layer, using the water volume flowing into the Belt Sea from the Kattegat, using the flow out of the Belt Sea, and also using the residual flows. Fluxes were smoothed using a 30 day running average. Layer volume was calculated as 33 km^3, using Seifert et al's

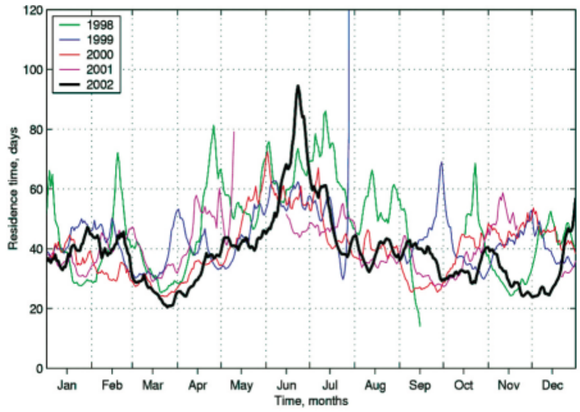


Figure 7.6

Residence time in the bottom layer of the Belt Sea, based on Kattegat inflows. HIROMB model.

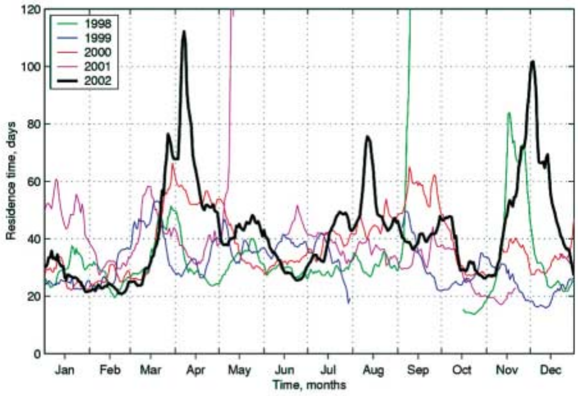


Figure 7.7

Residence times, as for Figure 7.6, but based on outflow from the Belt Sea to the Kattegat. HIROMB model.

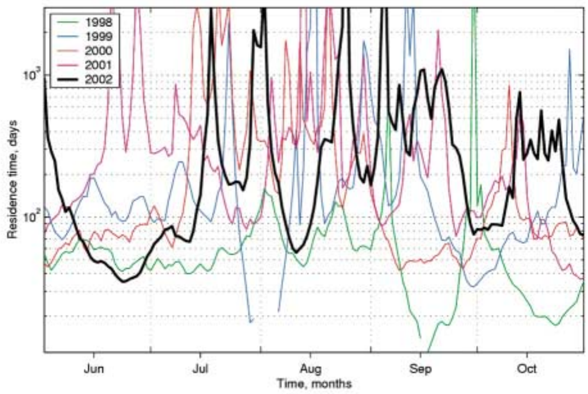


Figure 7.8

Summer residence times, based on residual flows, in the bottom layer of the Belt Sea, modelled by HIROMB.

(2001) bathymetry, with the HIROMB deepest layer extending from 18 to 24 metres. This underestimates the volume of the deepest part of the Belt Sea – and also therefore the residence times.

Figure 7.6 shows the calculated residence times based on modelled inflows (only) from the Kattegat, for 1998–2002. Low values indicate strong saline inflows to the area. Higher values indicate weaker inflows, stagnation, or outflows of bottom water to the Kattegat. All years show maximum residence times between May and August, as deep water flows, forced by wind action in the Kattegat, reach a minimum. Residence time minima occur around March and in the autumn, where wind forcing is strongest. In summer 2002, the residence time peaked in June, at more than 90 days, decreasing to about 40 days in late July. It stayed around this value until late in September. Data from 2000 and 2001 also show values around 40 days in July and August. In 1999, the values are similar for this period (the spike at the end of July is due to lack of data). In July and August 1998, residence times were greater than in 2002. With the exception of 1999 and 2002, all years show a reduction in estimated residence time at the start of September.

Figure 7.7 shows residence times calculated from fluxes out of the deep model layer towards the Kattegat. Low values in this figure represent relatively strong flows out of the region – possibly due to the inflow of Baltic water in the southern Belt Sea. High values indicate weak currents out of the region, due either to stagnation, or due to inflow of Kattegat water. In July and most of August 2002, these residence times were greater than had been observed in three of the previous four years (data from 1999 was unavailable), suggesting either inflow of Kattegat water, or stagnation in this area. The values remained relatively high throughout September (though lower than in 2000) and only fell in October.

Figure 7.8 shows summer (June - October) residence times based on residual flows in the deep layer. Residual flows are small, so the residence times are sensitive to small changes. From around the 10th August until the middle of September, residence time estimates were greater than 200 days. These values were higher than seen in 1998. In 1999, similarly high values were observed, but were short-lived compared to the 2002 event. In 2000, there was a similar pattern, where the residence time had fallen to ~30 days by the 10th September. In 2001, there were similar high values as 2002 - with high values in late August and September. These periods were more short-lived however than were seen in 2002 – with a period of about a week in early September 2001 where the residence time fell to about 90 days – approximately half the 'low' value for a similar period in 2002.

Conclusions

1. Three independent models show good agreement describing the total outflow through the Belt Sea and the major flow variations in 2002.

2. There were saline inflows to the Belt Sea and the Sound during June 2002, followed by increased brackish water outflow from the Baltic in July and especially in August, followed by a period of stagnation until the end of September.

3. Absolute inflow of the benthic layer estimated by the JRC model suggests an exceptional inflow from the Kattegat in June 2002, which led to normal oxygen conditions near the bottom. The start of the oxygen deficiency in July suggests that the necessary time for reversing the bottom oxygen conditions is only of few weeks.

4. The June inflow was followed by an inflow minimum in July-August through the Great Belt that lasted for two months, with stagnation in August in the Gniben section. There were lower inflows in July, October and November compared to other years. It is exceptional that these inflow minima and stagnation events were sustained for so long.

5. The seasonal cycle of inflows from the Kattegat to the Belt Sea has a minimum (maximum residence time) during the summer.

6. From August until the middle of September 2002, residence time calculations based on modelled currents flowing into the Belt Sea from the Kattegat, in deep water (18-24 m) suggest a long period of weak currents.

7. Residence times based on outflow from the Belt Sea also suggest a period of weak currents, which extended from July until October.

8. Residual currents suggest stagnation occurred in the first half of August and for most of September.

9. Stagnation events in 2002 appeared to be of a longer duration than observed in the previous four years of model data.

10. Summer 1997 also had a relatively long stagnation period, but the nutrient load was low in 1996-1997, and oxygen depletion limited. Summer 1999 had much higher surface phytoplankton biomass (figure 4.7) than 2002, but larger bottom water exchange. The oxygen depletion was widespread, but substantially lower than 2002. This shows that the dynamic balance between the chemical/biological and physical activity controls the major part of the extent and duration of the oxygen depletion.

8. Assessment

The oxygen conditions in the Kattegat, the Sound, the Belt Sea and associated estuaries were about normal during the first half of 2002. However, wide spread oxygen depletion developed in August and culminated in the last half of September. At that time about 16,000 km^2 had less than 4 mg O_2 l^{-1} close to the bottom and 5,500 km^2 had less than 2 mg O_2 l^{-1}. The corresponding water volumes were ca. 90 km^3 and 24 km^3 bottom water, respectively. During the depletion period 20,500 km^2 experienced less than 4 mg O_2 l^{-1} and 9,170 km^2 less than 2 mg O_2 l^{-1}, corresponding to 47% and 21% of the entire area (excluding the Arkona Basin). The corresponding percentages in 2001 were 21% and 7%, respectively.

The actual oxygen concentration in the bottom water is the result of the oxygen consumption rate, the amount of available oxygen stored in the bottom water volume and the supply of new oxygen from the surface layer and the Skagerrak. The oxygen consumption rate is, in short term, dependent on the temperature, and in longer terms, the supply of organic matter from the phytoplankton primary production in the surface photic zone. This in turn is dependent on the supply of nutrients from land, atmosphere, bottom water and neighbouring seas. The volume of the bottom water depends on the depths of the pycnocline, which, similar to the supply of new oxygen, is generally determined by wind conditions and the strength of the outflow of brackish surface water from the Baltic Sea.

The amount and seasonal distribution of land based nutrient loads to the area is much dependent on the precipitation and freshwater runoff. In 2002 the runoff was unusually high, especially in February–March and July–August bringing high amounts of nitrogen and phosphorus nutrients to the sea during these periods. However, the nutrient load per runoff from surrounding land has decreased significantly during the later years due to measures taken. Therefore, the total annual nutrient load in 2002 did not deviate significantly from previous years, the nitrogen load being on the average of the last 14 years despite the high runoff, and the phosphorus load only about half of the load in 1990.

The dominating nitrogen source is loss from agriculture and in Sweden also forestry. These sources contributed in 2000 73.5% of the nitrogen load to fresh and marine surface waters. Phosphorus discharge from agriculture is also a major source (47.5%). Point source discharges to fresh and marine surface waters accounted in 2000 for 38.5% of the phosphorus load, the remaining fraction deriving from natural sources.

Atmospheric nitrogen deposition to the area was in 2002 relatively high in January–February and May/June–July, but low in April and August-September. However, the seasonal distribution and the amounts deposited were not unusual. High nutrient loads from land and atmosphere during winter and summer have occurred earlier within the latest 20 years, accomplishing less severe oxygen depletion. Thus, the exceptional 2002 oxygen depletion in the Kattegat - Belt Sea area cannot entirely be attributed to the nitrogen load.

The winter surface concentration (February 2002) of dissolved inorganic nitrogen (DIN) showed a strong influence from local sources, and particularly high DIN concentrations were observed in March 2002 in the Sound and the Belt Sea. The winter surface phosphate concentrations were in 2002 at the same level as in 2001 or alternatively the long-term average from 1990-2001.

Chlorophyll concentrations showed a high spring peak in the western Kattegat in March 2002, but in the Sound and Belt Sea the spring chlorophyll peak did not differ significantly from 2001 or long term means. A pronounced sub-surface chlorophyll maximum was observed in the Belt Sea from May to September. Satellite derived chlorophyll estimates showed chlorophyll concentrations during spring and summer 2002 above the average for 1998-2002, but lower than during summer 1999.

Primary production data showed an unusually high spring bloom in the western Kattegat and the Belt Sea in March and relatively high production rates during summer and autumn 2002. Thus the high winter and summer nutrient loads seemingly were incorporated in organic matter by the phytoplankton, enhancing the oxygen consumption in the bottom water.

The wind activity, that is the wind force and direction, is the most important meteorological factor determining the supply of new oxygen to the bottom water through vertical mixing of the water column and horizontal water exchange. The atmospheric pressure was in August–September 2002 higher and more stable than normal resulting in much weaker winds than normal, in August predominantly from east, in September from changing directions. Also October and November were calmer than usual, in October from easterly and north–easterly directions and in November from north–easterly to southerly directions. This resulted in much lower water mixing and exchange than normal, especially in August–September, when the supply of new oxygen to the bottom water was seemingly highly reduced compared to normal.

The surface water temperature in summer and autumn of 2002 was generally higher than normal reaching 20-22°C at the end of August. The bottom water temperature was in the eastern Kattegat similar to, or lower than normal, but in the Sound and Belt Sea higher than normal in August and October. The bottom to surface density difference was greater in the summer of 2002 than in earlier years, leading to a more stable water column with a broad pycnocline inhibiting the mixing of surface and deeper water. The prolonged period of calm, warm weather in the late summer and autumn of 2002 prevented the vertical exchange of oxygen and contributed to the oxygen deficiency observed, especially in shallow areas with water depths less than 15 m, where occasional wind activity normally at intervals will mix the water column to the bottom.

The high surface temperature in June, which raised the bottom water temperature 1–2°C above normal in August, did probably increase the oxygen consumption rate in the bottom water some, but can not explain the widespread oxygen depletion already developed in August 2002. The relatively high bottom water temperature in October might partly have delayed the oxygenation of the bottom water.

Model calculations of the water exchange through the Belt Sea in 2002 with 3 independent 3D models show an inflow towards the Baltic Sea from mid January to beginning of March, followed by a strong outflow from the Baltic Sea until mid April, levelling off to a generally low outflow until mid June. In the last half of June a new inflow from the Skagerrak occurred. July and August were dominated by outflow from the Baltic, while the water exchange during September was negligible. October started with an outflow from the Baltic, followed by an inflow, which in November to mid December again was substituted by an outflow. Model calculations of the exchange and residence time of the bottom water in the Belt Sea showed that the bottom water generally stagnated from July to the end of October, and especially in August–September. The high outflow from the Baltic Sea and the generally normal to high bottom water salinity during the last half of 2002 increased the stratification of the water column, reinforced by the high surface temperature during August–September.

New oxygen was supplied to the bottom water during February through inflow from the Skagerrak and vertical mixing of the water column, and the oxygen concentration in the bottom waters reached normal winter levels. Another supply from the Skagerrak took place in June. Apparently, from July to the end of October no major supplies of oxygen to the bottom water in the Kattegat – Belt Sea area took place, neither from inflow from the Skagerrak or vertical mixing, mainly due to unusually low wind activity from dominating easterly and southerly directions. Therefore the oxygen depletion, enhanced by the high nutrient loads during winter and summer, could develop into the most severe, widespread and long lasting observed.

9. Conclusions

The widespread, severe and long lasting oxygen depletion summer and autumn 2002 in the Kattegat, the Sound and the Belt Sea area resulted from a nutrient surplus caused by anthropogenic inputs in combination with several natural factors during the year:

1. High nutrient loads in February-March and July-August due to high precipitation and freshwater runoff accomplished a high phytoplankton spring bloom in March and relatively high production during summer and autumn, enhancing the oxygen consumption in the bottom waters. However, nutrient loads of such magnitude and seasonal distribution have occurred in some years within the last 20 years resulting in less severe oxygen depletion.

2. The wind activity was in August-September 2002 much weaker than normal and the supply of new oxygen to the bottom water through vertical mixing and horizontal water exchange was reduced. Also October-November was calmer than normal, which prolonged the oxygen depletion period.

3. The surface water temperature in summer and autumn 2002 was higher than normal. This, together with high outflow of brackish surface water from the Baltic Sea during the second half of 2002, increased the stratification and the stability of the water column, thus reducing the vertical oxygen transport to deeper water layers.

4. The bottom water temperature in the Belt Sea was higher than normal in August and October 2002, which can have increased the oxygen consumption rate during these months. However, this may have contributed to the persistence of the oxygen deficiency in September and October, but it cannot account for the strong development in August.

5. No major inflows of oxygen rich water from the Skagerrak to the bottom water of the Kattegat - Belt Sea area took place in the period from July to mid October 2002, due to the low wind activity and wind directions mainly from east and south.

In summary the 2002 oxygen depletion event in the Kattegat - Belt Sea area resulted from a combination of relatively high nutrient loads during winter and summer enhancing the oxygen consumption, and low transport of new oxygen to the bottom water during late summer and autumn due to unusual climatic factors.

Reduction of nutrient inputs is the key to lowering the likelihood of severe oxygen depletion events in terms of geographical coverage and duration. Climatic variations that made the 2002 event exceptional, are stochastic of nature and cannot be managed. However, it is important to increase return periods of such severe events.

The main direct nitrogen sources are losses from agriculture and forestry in the bordering countries, and deposition from the atmosphere. Phosphorus load from agriculture and point sources are approximately equally important.

10. References

Cressie NAC 1993. Statistics for spatial data. Revised edition. – Wiley.

Ellermann, T., Hertel, O., Kemp, K. & Monies, C. 2002. Atmosfærisk deposition 2001. NOVA-2003. Danmarks Miljøundersøgelser. – Faglig rapport fra DMU nr. 418. http://faglige-rapporter.dmu.dk (In danish with an English summary).

Granéli, E. 1987. Nutrient limitation of phytoplankton biomass in a brackish water bay highly influenced by river discharge. – Estuarine, Coastal and Shelf Science 25: 555-565.

Granéli, E., Wallström, K., Larsson, U., Granéli, W. & Elmgren, R. 1990. Nutrient limitation of primary production in the Baltic Sea. – Ambio 19:142–151.

Rasmussen, B. 1997. The near-surface Buoyancy flux in a highly stratified region, Kattegat. – Estuarine, Coastal and Shelf Sciences 45: 405:414

Sturm, B. & Zibordi, G. 2002. SeaWiFS atmospheric correction by an approximate model and vicarious calibration. – Int. J. Remote Sensing 23: 489–501.

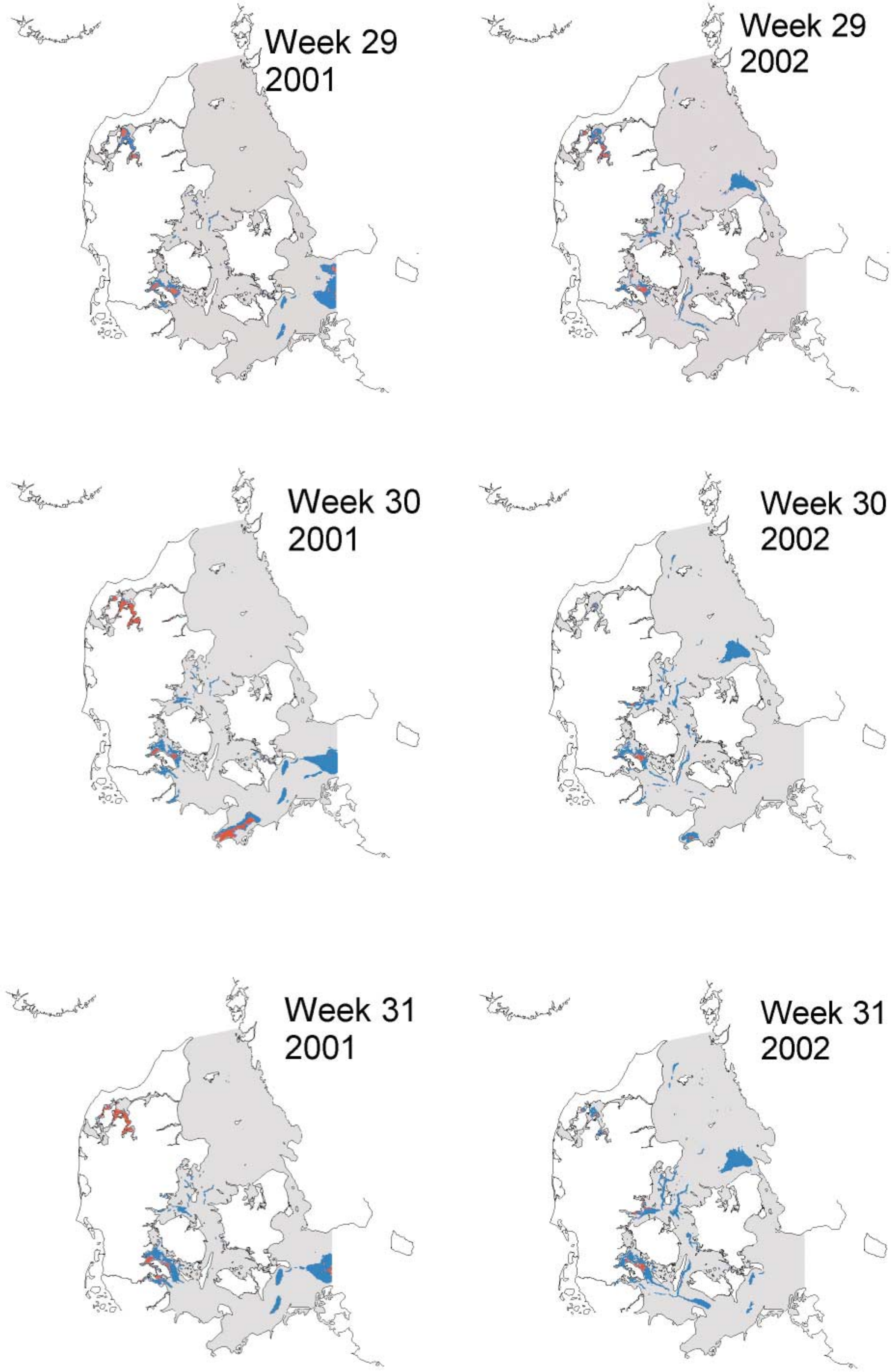
Seifert, T., Tauber, F. & Kayser, B. 2001. A high resolution spherical grid topography of the Baltic Sea – revised edition. - Proceedings of the Baltic Sea Science Congress, Stockholm 25-29. November 2001 (to be published).

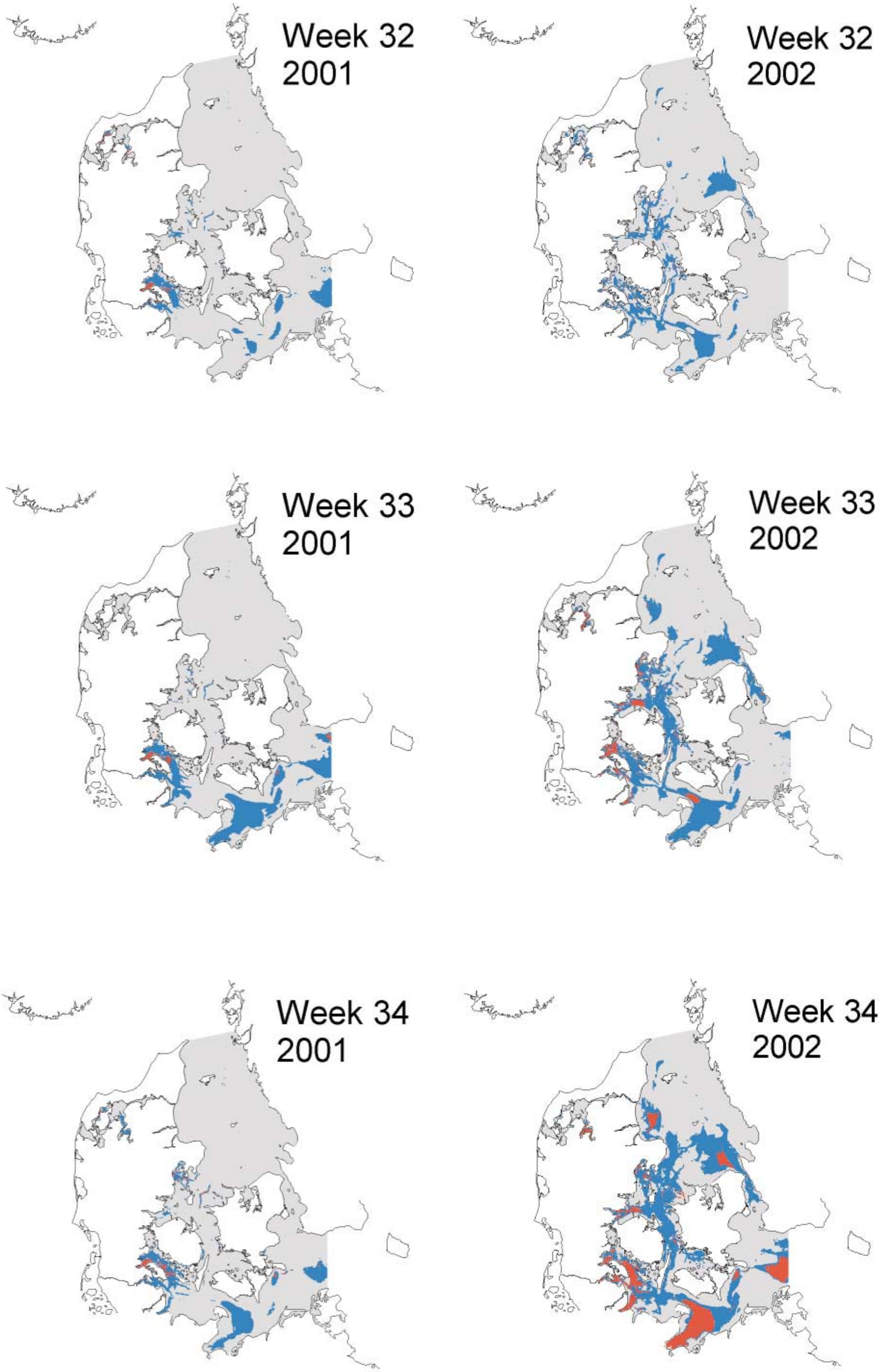
Ærtebjerg, G., Andersen, J.H. & Hansen, O.S. (Eds) 2003. Nutrients and eutrophication in Danish marine waters. A challenge for science and management. –National Environmental Research Institute, Denmark. 126 pp.

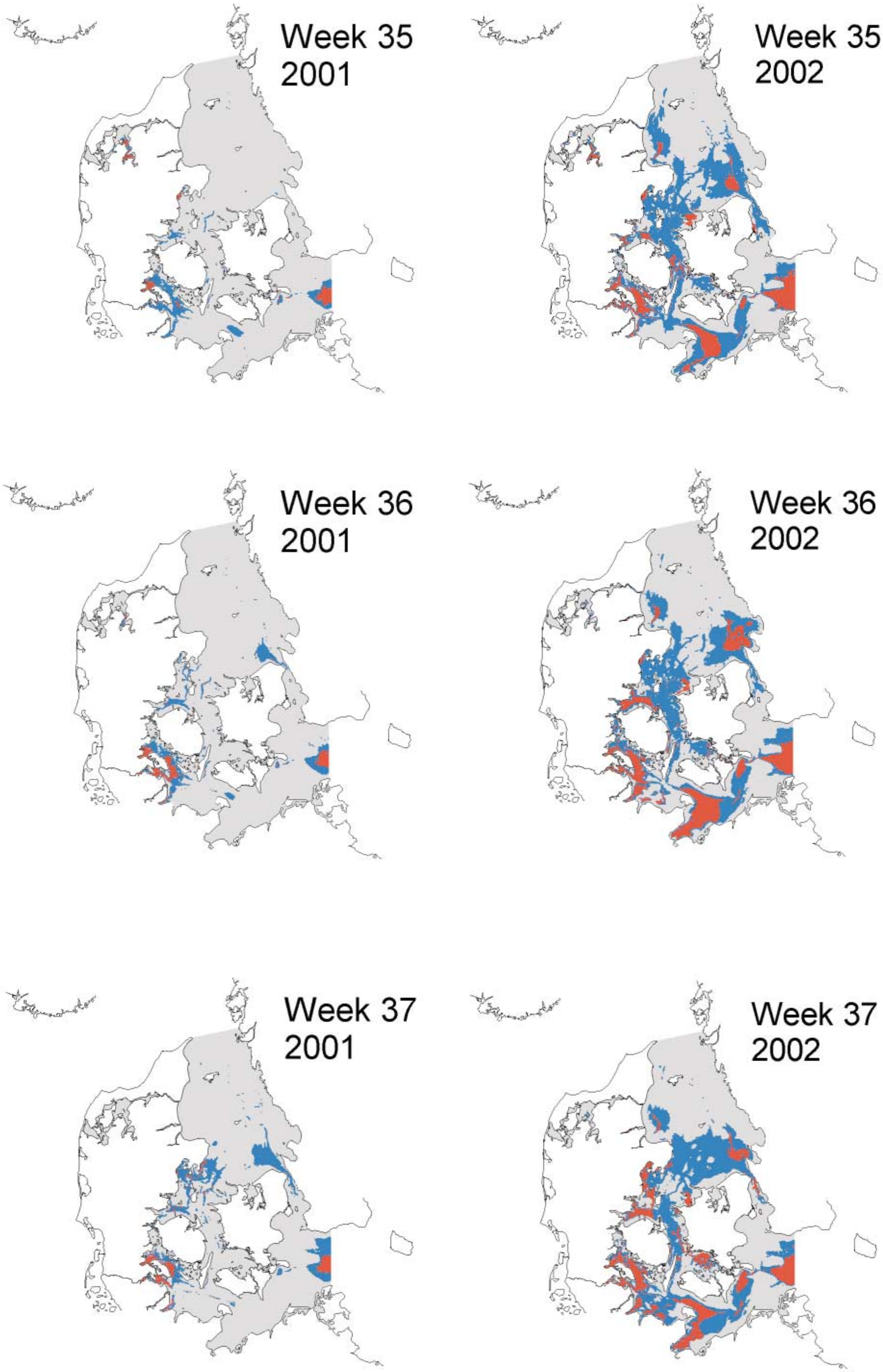
Annex A:

The development and decline of hypoxia in 2001 and 2002

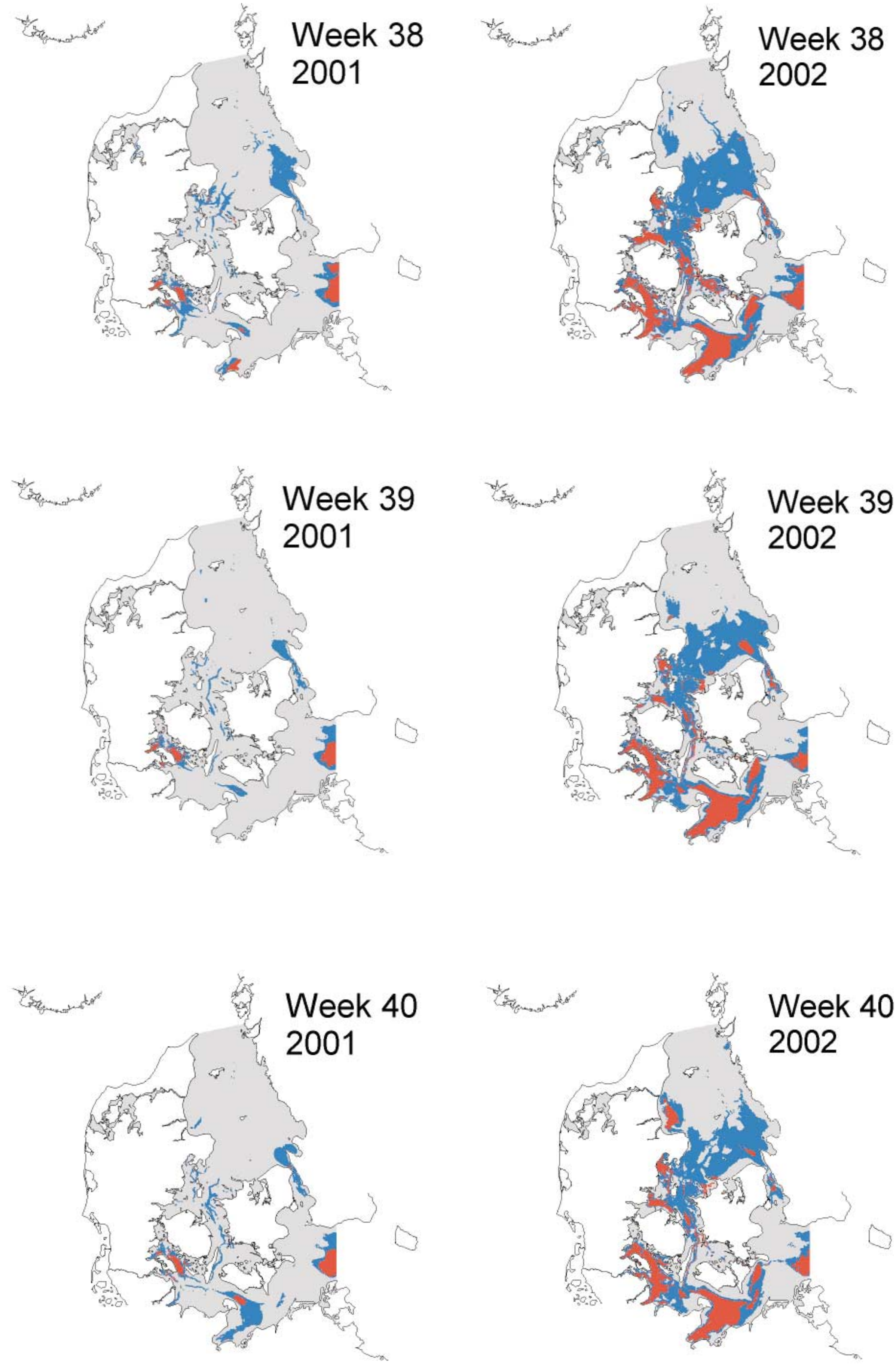
Below are shown maps with weekly estimates of bottom area extent with oxygen concentrations below 4 mg l^{-1} (blue) and below 2 mg l^{-1} (red). The areas covered by hypoxic conditions have been calculated according to the description in Chapter 2 for the Kattegat, the Belt Sea, the Sound, and the western Arkona Basin (marked by grey colour).

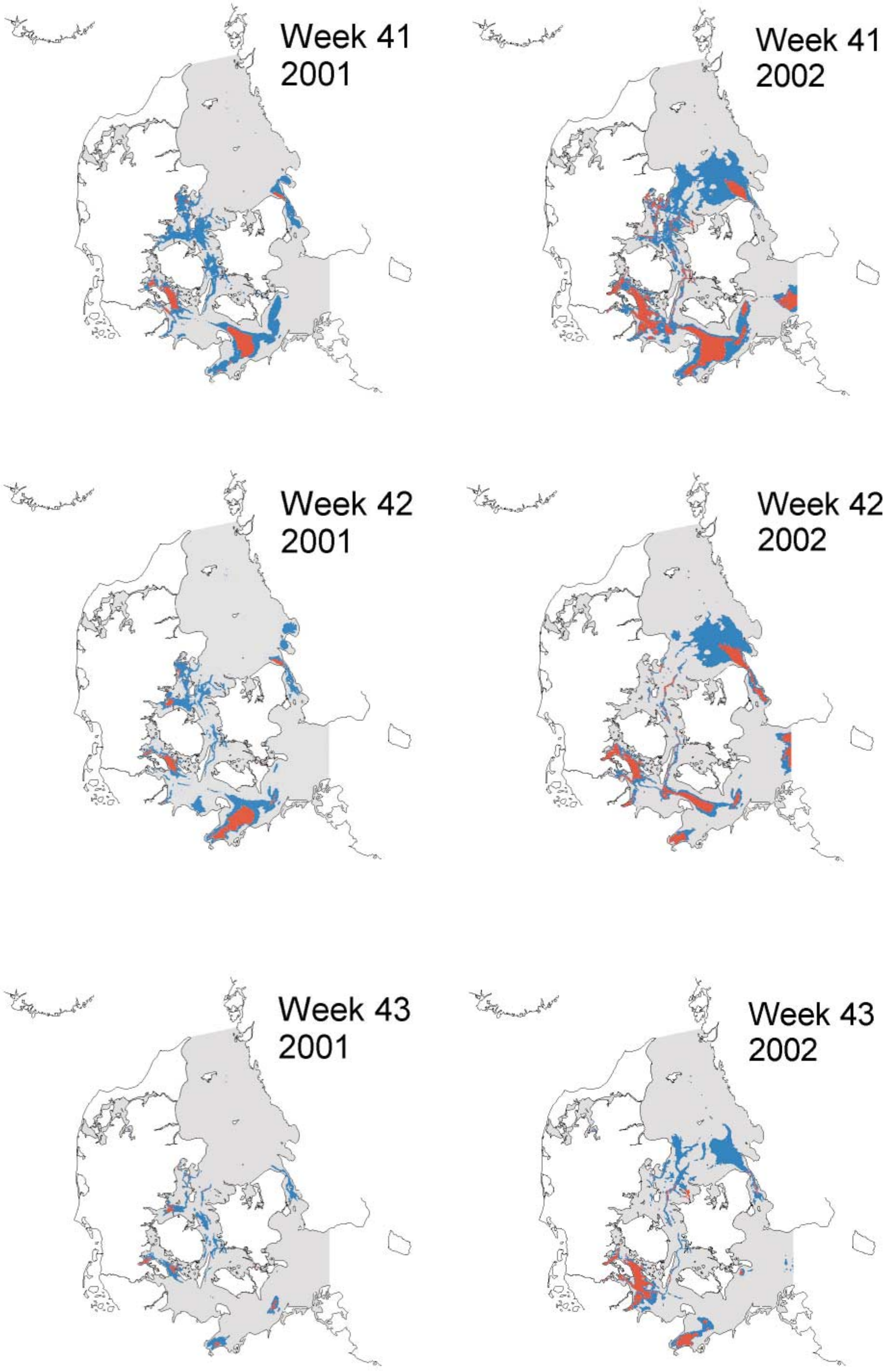

Week 29
2001
Week 29
2002
Week 30
2001
Week 30
2002
Week 31
2001
Week 31
2002

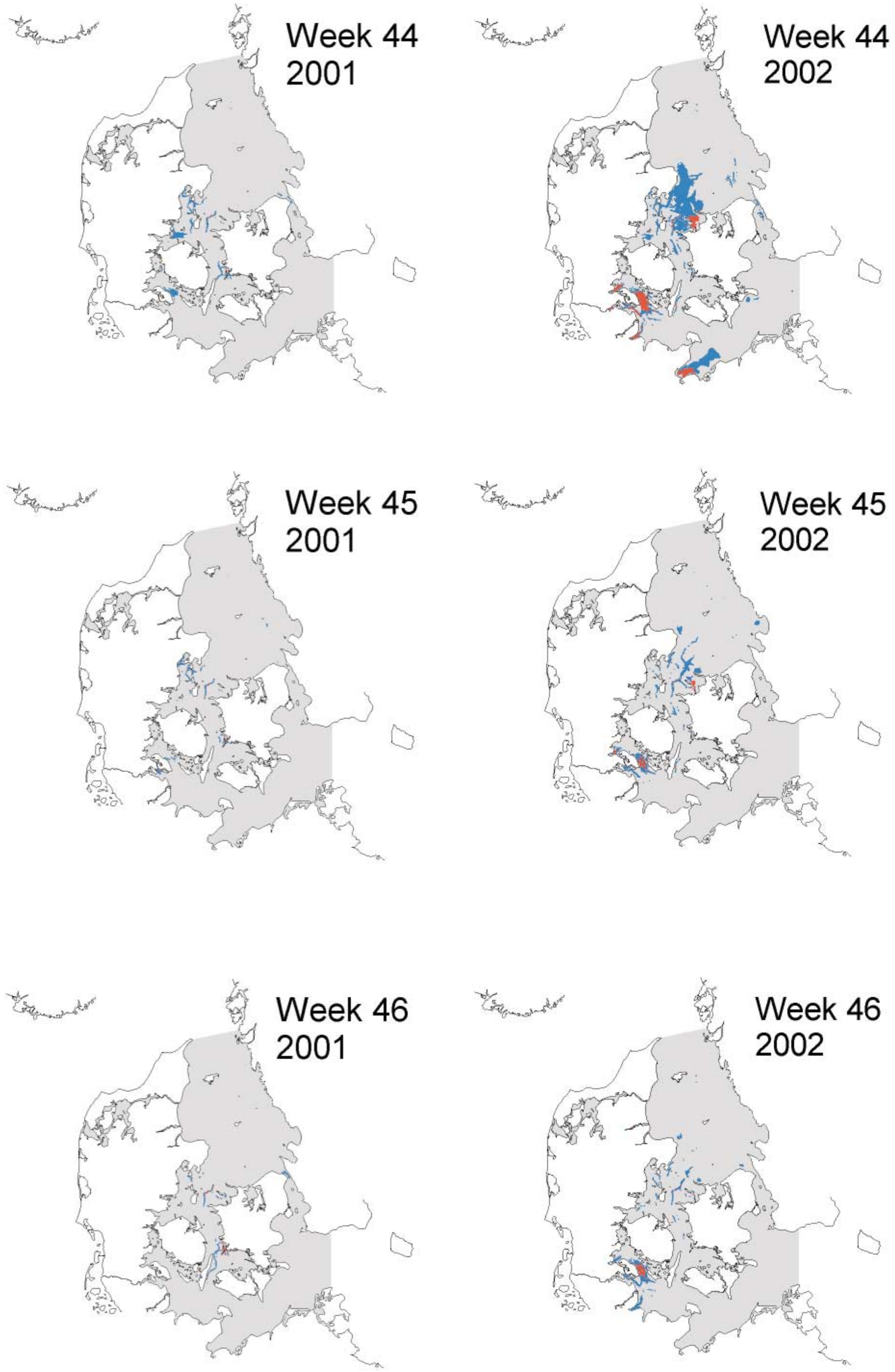

Week 32
2001
Week 32
2002
Week 33
2001
Week 33
2002
Week 34
2001
Week 34
2002

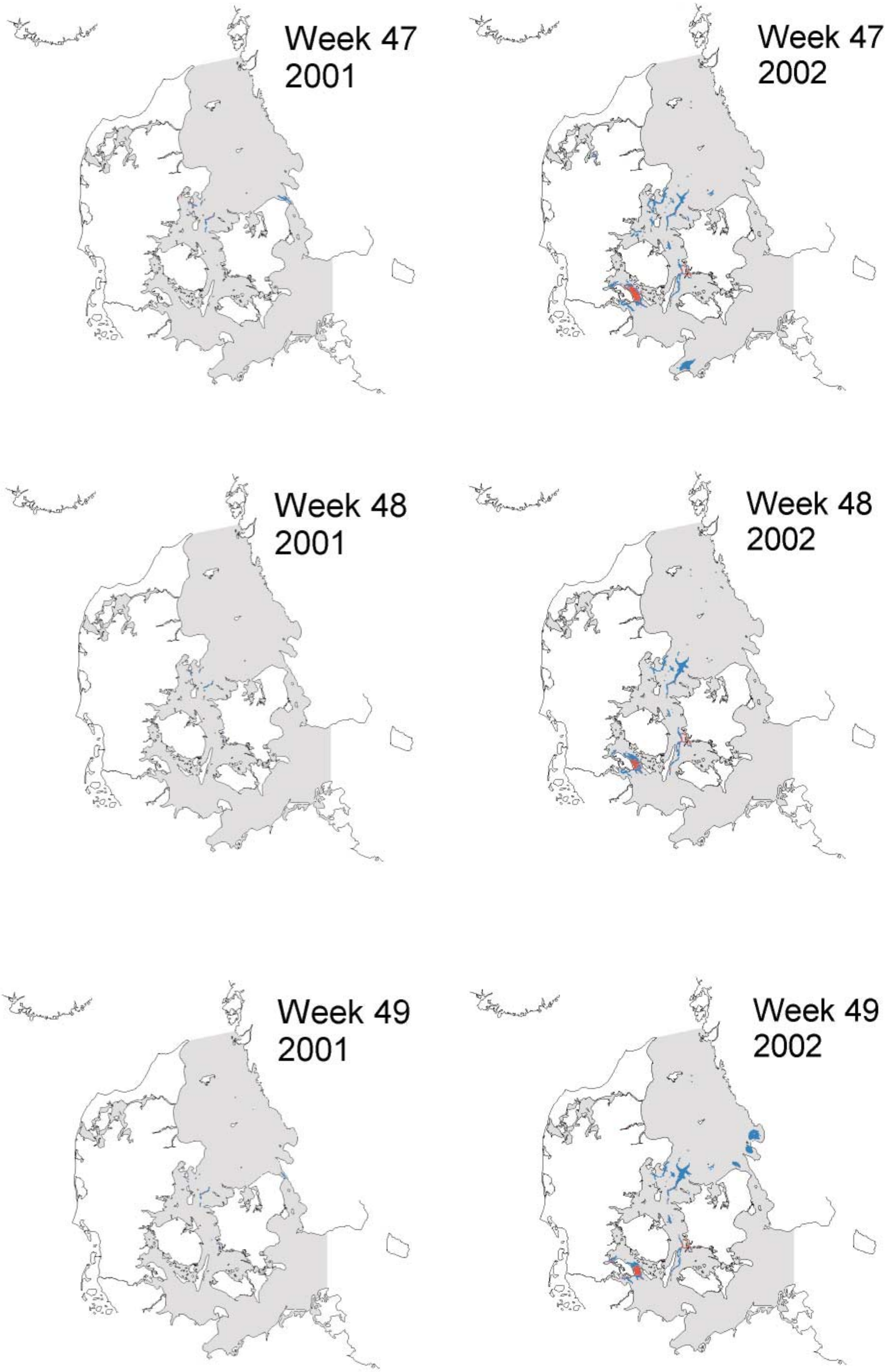


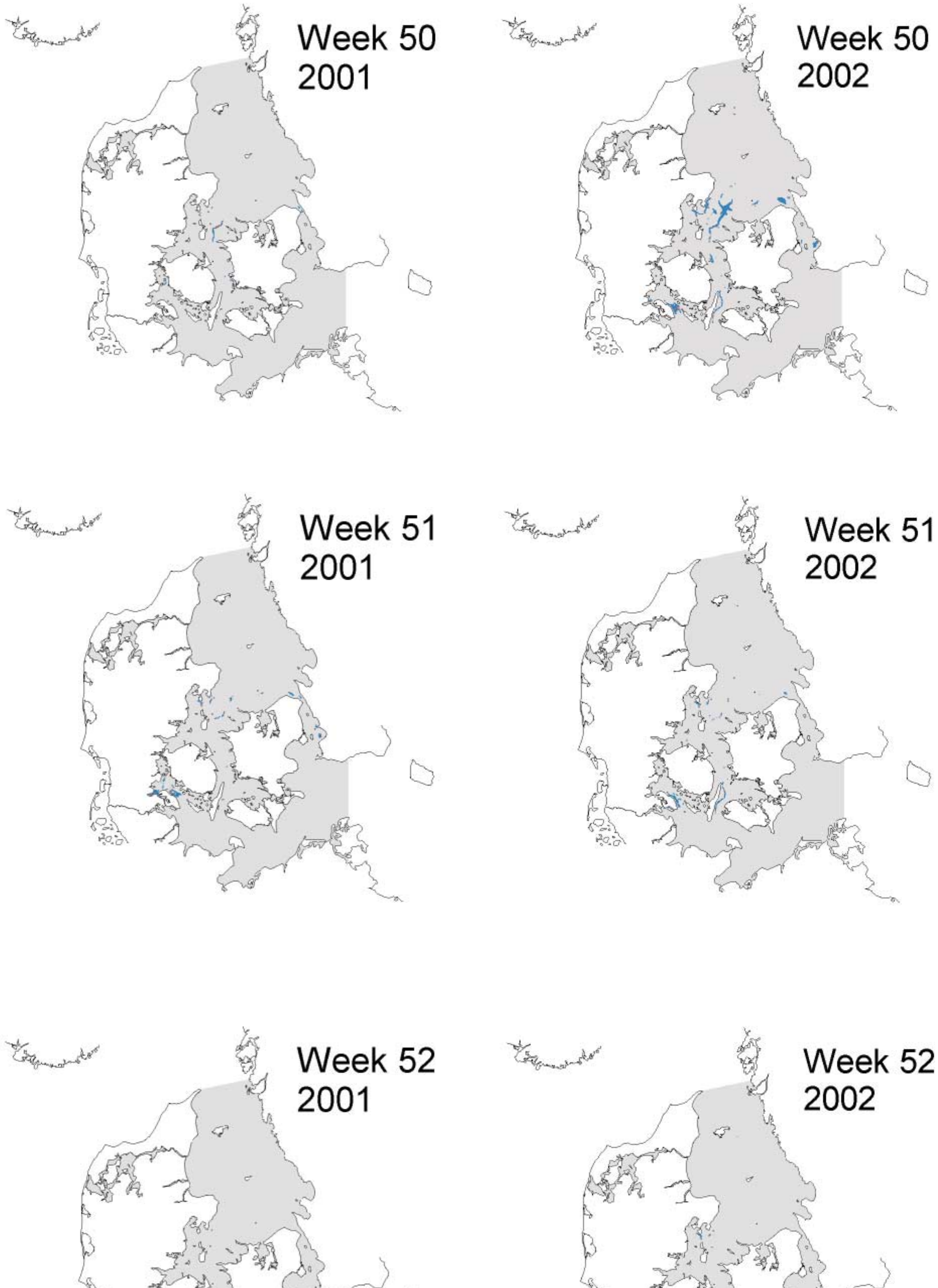
Week 35
2001
Week 35
2002
Week 36
2001
Week 36
2002
Week 37
2001
Week 37
2002


Week 38
2001
Week 38
2002
Week 39
2001
Week 39
2002
Week 40
2001
Week 40
2002


Week 41
2001
Week 41
2002
Week 42
2001
Week 42
2002
Week 43
2001
Week 43
2002


Week 44
2001
Week 44
2002
Week 45
2001
Week 45
2002
Week 46
2001
Week 46
2002


Week 47
2001
Week 47
2002
Week 48
2001
Week 48
2002
Week 49
2001
Week 49
2002


Week 50
2001
Week 50
2002
Week 51
2001
Week 51
2002
Week 52
2001
Week 52
2002

Acknowledgements

The authors wish to express their sincere thanks to the members of the working group, and to the different institutions in Denmark, Germany and Sweden for their readiness to participate in the work and to deliver the necessary data. Likewise, we wish to thank the participants in the scientific seminar 16–17 June 2003 for the valuable discussions of the draft report. We are also much obliged to Britta Munter and Ole S. Hansen for their skilful work with the layout. Finally we wish to thank the Danish EPA for establishing the financial support for the work, the seminar and the printing of the report.

Notes

Data Sheet

Published by:
Helsinki Commission
Katajanokanlaituri 6 B
FIN-00160 Helsinki, Finland
E-mail : Helcom@helcom.fi
Internet: http://www.helcom.fi

Authors:
Gunni Ærtebjerg & Jacob Carstensen
National Environmental Research Institute, Denmark.

Philip Axe
Swedish Meteorological and Hydrological Institute, Sweden.

Jean-Noël Druon & Adolf Stips
EC Joint Research Centre, Italy.

Cover photo:
Dead fish killed by oxygen deficiency washed ashore in Aalborg Bight.
Photo: Christen Jensen, The County of North Jutland.

Layout:
Britta Munter and Ole S. Hansen, National Environmental Research Institute, Denmark.

Number of pages: 64

Printing:
Schultz Grafisk A/S, Certified under ISO 14001 and ISO 9002

Number printed: 1.000

For bibliographic purposes this document should be cited as:
HELCOM, 2003
The 2002 oxygen depletion event in the Kattegat, Belt Sea and Western Baltic
Balt. Sea Environ. Proc. No. 90

ISSN: 0357-2994

HELSINKI COMMISSION
Baltic Marine Environment Protection Commission

Katajanokanlaituri 6 B
FIN-00160 Helsinki
Finland

ISSN 0357-2994