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The impacts of physical processes on oxygen variations in the North Sea-Baltic Sea transition zone

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Abstract

The bottom water of the North Sea-Baltic Sea transition zone suffers from seasonal hypoxia, usually during late summer and autumn. These hypoxic events are critical for the benthic ecosystems and the concentration of dissolved oxygen is an important measure of the water quality. However, to model the subsurface dissolved oxygen is a major challenge, especially in estuaries and coastal regions. In this study a simple oxygen consumption model is coupled to a 3-D hydrodynamical model in order to analyse oxygen variations in the transition zone. The benthic and pelagic consumption of oxygen is modelled as a function of water temperature and oxygen concentration. A quantitative assessment of the model demonstrates that the model is able to resolve both seasonal and interannual variations in dissolved oxygen. Results from several experimental simulations highlight the importance of physical processes in the regulation of dissolved oxygen. Advective oxygen transport and wind induced mixing are two key processes that control the extent of hypoxia in the transition zone.

1 Introduction

The transition zone between the North Sea and the Baltic Sea is in this study defined to range from the northern Kattegat to Arkona Basin. This area limits the water exchange between these two seas because of a complex topography with several narrow straits and shallow sills. The circulation of this area is characterized by inflowing high saline bottom water from the North Sea and outflowing low saline surface water from the Baltic Sea. This circulation is largely driven by sea level difference between the North Sea and the Arkona Basin which in turn is controlled by wind and river runoff to the Baltic Sea. The water column is stratified with a strong persistent halocline and the stratification is enhanced during summer by the development of a thermocline. The strong stratification in combination with a high productivity leads to an imbalance between the consumption and supply of dissolved oxygen (DO) to the bottom water and

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seasonal hypoxia is a recurring problem. Severe hypoxia, defined as <63 µmol l^{-1}, occurs locally in late summer and autumn and persists until either local DO supply from the surface or advective water exchange re-oxygenates the bottom water.

DO concentration was observed to decline in the 1980th (Andersson and Rydberg, 1988) which has been attributed to the large increase in nutrient input. The nutrient loads from land is believed to have been more than doubled from 1950 to 1980 because of the wide spread usage of fertilizers, increase in population and a growing agriculture industry (Conley et al., 2007). During the last two decades several measures have been taken to decrease the discharge of nitrogen and phosphorus to this region and Carstensen et al. (2006) reported a trend of reduced nutrient concentrations in the water. However, decreasing eutrophication has not yet been accompanied with improved oxygen conditions. The oxygen consumption in the bottom water is related to the nutrient loads through the remineralisation of organic matter that sinks from the productive layer to the bottom water. A reduction in nutrient input could in principle reduce the primary production and thereby the export of organic material. Aerobe remineralisation of organic material is the most important oxygen sink (Xu and Hood, 2006; Oguz et al., 2000) but the DO concentration is also influenced by chemical oxidation of reduced substances from anaerobe remineralisation of organic matter in the sediment and the linkage between nutrient loads and DO is highly nonlinear. In other words, the coupling between primary production, export production and oxygen consumption is far from being resolved (Olesen and Lundsgaard, 1995; Gray et al., 2002).

DO is supplied to the bottom water in the transition zone mainly through horizontal advection of Skagerrak water and vertical mixing of the water column. Both wind and inflows are subjected to a clear annual cycle with lower wind speeds and less inflows in summer than in winter. These physical processes regulate the extent and timing of hypoxia and have a large influence on the interannual oxygen conditions. By using an age traces technique, Bendtsen et al. (2009) examine the distribution of the processes and concluded that advected Skagerrak water is dominating the ventilation in Kattegat whereas vertical mixing is important in Great Belt and western Baltic Sea.

In this study we focus on the importance of physical processes in modulating the seasonal and interannual variation of DO in the transition zone. A hydrodynamical 3-D model coupled with the simplified oxygen consumption model OXYCON (Hansen and Bendtsen, 2009) is established to simulate the DO variations. In this way the physical processes are modelled with a state-of-the-art technique while the more uncertain biogeochemical processes are simplified as mush as possible. The aims of this paper are to assess the capability of the coupled models to simulate the hypoxic events and to evaluate the importance of physical processes in regulating the interannual and seasonal DO variations.

2 Method

2.1 Physical model

The physical model used in this study is BSHcmod (She et al., 2007) which runs operationally at DMI to produce forecast for the Danish and nearby waters. The model is based on Navier-Stokes primitive equations which are spatially discretized with a finite difference method. The discrete equations are closed with a Smagorinsky formulation for the horizontal diffusivity and a two-equation k-ω scheme for the vertical turbulence. The model runs on a two-way nested domain with a course domain (6 nm, 50 vertical layers) covering the North Sea and Baltic Sea and a fine resolution domain (1 nm, 52 vertical layers) in the transition zone (Fig. 1). Climatologies of salinity and temperature are applied along the outer lateral boundaries as well as sea level elevation from a 2-D version of BSHcmod covering the North Atlantic. The model is forced by hourly meteorological data based on the operational weather model DMI-HIRLAM. The meteorological forcing includes wind, air temperature, sea level pressure, surface humidity and cloud cover.

2.2 Oxygen model

The oxygen consumption model (OXYCON) has been developed by Hansen and Bendtsen (2009). In short, the model considers one pelagic oxygen sink and two benthic sinks due to microbial and macrofaunal respiration, and furthermore, it is assumed that the pools of organic carbon available for remineralisation in the sediment and suspended in the water column are almost constant. The temporal variation in remineralisation is determined by the temperature sensitivity of the process and the benthic remineralisation rates also depend on the near bottom DO concentration. This water column model is coupled to the physical model through a time-splitting scheme where first advection and diffusion of DO is calculated and thereafter the biochemical sinks and sources. OXYCON model equations and parameters are presented in Appendix A. A detailed description of the model is presented in Hansen and Bendtsen (2011) where they show that OXYCON is able to simulate DO when coupled to two different physical models.

The oxygen model is highly parameterized for the stratified transition zone which means that DO concentration in the North Sea is not accurately described. Because of this the oxygen model only runs in the fine domain and the Baltic Sea. Oxygen data from a monitoring station in Skagerrak was extracted from the Swedish Meteorological and Hydrological Institute's (SMHI) database SHARK and applied as boundary condition at the northern border of the fine and coarse grid.

2.3 Sensitivity experiments

Four different experimental simulations were performed and compared to a reference simulation during the period 2002–2004. In each simulation the flow across two sections below 15 m depth is measured (Fig. 2). The inflow of Skagerrak water is measured in the northern Kattegat section (S1) and the flow through Great Belt at the centre of the strait (S2).

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The first two experiments are similar and can be seen as a sensitivity analysis of the seasonality of DO. In the first experiments (simulation 1) the seasonality of the three respiratory sinks are removed by setting each respiration rate to its respective annual mean. The second sensitivity experiment (simulation 2) concerns the effect of the oxygen solubility. In the latter scenario the concentration of DO in the surface water is kept constant as opposed to the real situation where the oxygen solubility is determined by temperature, salinity and to a minor degree pressure.

It is well known that the wind speed during the autumn months has a pronounce effect on the DO conditions in the transition zone, especially in estuaries and coastal areas (Møhlenberg, 1999; HELCOM, 2003). High wind speeds will weaken the stratification and bring DO rich surface water across the pycnocline. The wind also influences the circulation and Skyum et al. (1994) described how vertical movement of the pycnocline in Kattegat influenced the DO concentrations at the Danish coasts. Many previous studies focus on data from a specific fjord or estuary (Møhlenberg, 1999) but equipped with this 3-D model it is possible to quantitatively describe the impact of wind driven mixing not only at monitoring stations but in the whole model domain. The hypoxia in 2002 was one of the most severe events ever recorded and the hypoxic area was up to 9200 km^2 (HELCOM, 2003) while two years after, in 2004, the oxygen condition was better than normal. A comparison of the wind in August and September for these two years revealed that the average wind in 2004 was 15 % and 27 % higher than in 2002, respectively. In order to investigate the relationship between hypoxia and wind speed the difference in monthly mean wind speed in September is eliminated by increasing the September wind 27 % in 2002 (simulation 3) and decreasing the wind speed in 2004 to the level in 2002 (simulation 4).

3 Model assessment

To produce a confident and qualitative assessment of a model it is important to first identify the purpose of the model (Rykiel, 1996). This is a crucial step of the

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assessment process which must not be foreseen. However, in many cases this is not a trivial task but without having stated the model requirements the model can not be validated nor invalidated. The purpose of this model is to simulate the hypoxic events in the transition zone and in order to produce ecological relevant predictions the model error should be less than 63 µmol l^{-1} which is also the definition of hypoxia. Furthermore, as hypoxic events occur in the bottom water and usually in the autumn months the model should ideally be assessed during this season and in the bottom water layer. Another important consideration is what kind of statistical measures to use. Here we use a combination of several metrics calculated as follows: the centred root mean square difference (cRMSD) in Eq. (1) is the unbiased root mean square difference (RMSD) and can be seen as the combined effect of misfits in amplitude and the correlation. The model efficiency (MEF) in Eq. (2) was introduced by Nash and Sutcliffe (1970) and produces a model skill score which can be easily compared to other models. It compares the model-observation miss-match with the variability of the observations and the performance is usually categorized as seen in Table 1 (Vichi and Masina, 2009; Lewis and Allen, 2009). Also used in the assessment are the absolute average error (AAE) and the model-observation bias.

$$\mathrm{cRMSD} = \sqrt{\mathrm{RMSD}^2 - \mathrm{bias}^2} \tag{1}$$

$$\mathrm{MEF} = 1 - \frac{\mathrm{RMSD}^2}{\sigma_o^2} \tag{2}$$

The physical model has been assessed in earlier studies (She et al., 2007; Larsen et al., 2007) and in this context the performance of the model will only be documented by comparison of modelled and observed salinity and temperature for station GB (Fig. 2). The oxygen model will be thoroughly assessed by the usual time series analysis, where model and observations are compared at the four stations seen in Fig. 2. The observations are gathered from SHARK and the National Environmental Research Institute's (NERI) database MADS. With time series analysis it is easy to visualise and follow the

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model-observation miss-match in time but a major disadvantage is that we do not get any information of the spatial error distribution. To account for this, all available observations in the autumn months of 2002 to 2007 are collected from the International Council for the Exploration of the Sea's (ICES) database and model-observations pairs below 15 m are gathered into a grid in which the statistical measures are calculated.

3.1 Physical model

One of the most important aspects for oxygen modelling is a well resolved stratification, both in strength and position in depth because the stratification acts as a barrier for the bottom water ventilation. In Fig. 3 model output of salinity and temperature are shown together with observations for Great Belt. The depth of the halocline is 15 m in both model and observations and the salinity profile is well described. The timing of modelled collapses of the halocline agrees with observations and it can for example be seen during the storm Gudrun in the beginning of 2005. Modelled variations in temperature are also consistent with the observations with a development of a thermocline at 15 m depth in summer. Since the surface temperature is more or less determined from the atmospheric forcing the model performance should rather be assessed from the resolution of the bottom temperature. The model succeeds in simulating the downward convection of warm surface water and cold winter water which is a good indication of a sound turbulence scheme. Based on previous studies and visual inspection the conclusion is that the model is able to simulate the main features of this area.

3.2 Oxygen model

In Arkona Basin the absolute average error (AAE) exceeds 50 μmol l^{-1} but for the remaining stations the AAE range between 22–40 μmol l^{-1} (Fig. 4). The three stations in Kattegat and Great Belt all show a negative bias and the DO concentration seems to be underestimated during winter and spring, however the minimum oxygen in autumn is well described. The negative bias is likely caused by insufficient mixing, too high

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respiration rate during winter or that the model does not consider mixing and advection of oxygen oversaturated water during the spring bloom. Both model and observations at Station 413 show a nearly linear decrease of DO during spring and summer while the variability is larger further to the south, probably because of a weaker stratification, a stronger influence from vertical mixing or influence from coastal water masses. Not shown in Fig. 4 is the model efficiency, this value range from 0.4–0.5 and the performance can be categorized as “good” (Table 1). It is not surprising that the error is largest in Arkona Basin because the model is parameterized for the Kattegat and the Belt Seas. Furthermore the ecosystem structure in Arkona Basin differs from that of Kattegat and the Belt Seas and the water column is characterised by a three-layered structure in the summer due to a seasonal thermocline which also influences the DO dynamics.

More than 3000 observation are collected and used in the spatial validation and the overall metric estimates are presented in Table 2. It shows a negative bias and an average error of 38 $\mu mol\,l^{-1}$ which is well below the limit for hypoxia (<63 $\mu mol\,l^{-1}$). Further more, the model efficiency index is 0.48 which by using the categorization in Table 1 places the model in the upper limit of “good”. The spatial error distribution reveals a distinct gradient from north to south with errors increasing southward (Fig. 5). This is most probably because of a decreasing impact from the northern boundary condition. The bias distribution shows that the model underestimates the DO concentrations in southern Kattegat and Arkona Basin and overestimates it in Mecklenburg Bight. It should also be mentioned that the error in Arkona Basin might be underestimated because the halocline is deeper than 15 m and some surface water is included in the calculations. All in all, only two boxes show errors larger than 63 $\mu mol\,l^{-1}$ and we conclude that the model is able to simulate the spatial distribution of DO and oxygen depletion events.

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4 Results

4.1 Seasonal variations

The results from simulation 1 and 2 can be seen in Fig. 6 together with the reference simulation. Averaged over the three years, the mean bottom water DO concentration varies between 330 µmol l^{-1} in March and a 150 µmol l^{-1} in September/October. Arkona basin is excluded in the calculation of the mean DO concentration because the halocline is much deeper than 15 m. As expected the DO concentration is lower in winter and higher in summer in both the experimental simulations. However, compared to the reference case, the decrease in seasonality in the two simulations is relatively small. The amplitude of the seasonal variation is decreased only 13 % and 24 % in simulation 1 and 2, respectively. However, even though the change in mean bottom DO concentration is small, it should be mentioned that the average value cover a large geographic range in transition zone from the northernmost well oxygenated areas to the southern parts close to the Baltic Sea which are frequently subjected to hypoxia. The seasonal variation in respiration rate becomes increasingly significant the further south in the area where the water has been affected by oxygen consumption for a longer time. Hence, oxygen conditions may locally be very sensitive to such changes and the extent of hypoxia is less in both simulations, especially in shallow areas (spatial pattern not shown).

The average wind speed over 2002–2004 (Fig. 7a) show no spatial variation in the domain and was 6.4 and 8.0 m s^{-1} during summer (May–August) and winter (November–February), respectively. The maximum wind speed also shows a clear annual cycle with stronger winds during winter season. The accumulated flow through the bottom water of northern Kattegat section (S1) and Great Belt section (S2) can be seen in Fig. 7b. Positive values indicate a flow from Skagerrak to Kattegat for S1 and from Kattegat through the Great Belt for S2. The inflow from Skagerrak to the bottom water of Kattegat varies seasonally with a stagnant period in summer. The flow rate though Great Belt is much more stable throughout the year. By comparing

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the accumulated flow through the two sections it is obvious that only a fraction of the volume passing S1 continuous through Great Belt.

During the three years, a volume of 2300 km^3 flows from Skagerrak into the bottom water of Kattegat but only 300 km^3 continues through the Great Belt. This means that a major part of the inflowing Skagerrak water is entrained into the surface water in Kattegat and moves northward in the anti-cyclonic circulation described by Nielsen (2005) before reaching the Great Belt.

The correlation between Skagerrak inflows and DO concentration at stations 413 appears when the mean flow is subtracted from the accumulated flow at S1 (Fig. 8). The seasonal variation in bottom DO concentrations mimics the variations in volumetric flow rate. The stagnant period during spring and summer coincides with a decrease in DO concentrations and larger inflows rapidly oxygenate the bottom water.

4.2 Interannual variations

The interannual variation of the hypoxic condition is clearly seen when comparing the monthly mean DO concentration in September 2002 and 2004. In 2002 large areas of hypoxic waters can be seen at Mecklenburg Bight and Little Belt, comprising an area of 3180 km^2, and oxygen deficiency (<126 $\mu mol\,l^{-1}$) covers large parts of western Kattegat and Great Belt (Fig. 9a). In 2004 only smaller patches of hypoxic water are visible (706 km^2) and an even larger decrease is seen in the extent of oxygen deficiency (Fig. 9c). In the calculation of the mean hypoxic area Arkona Basin has been excluded because of two reasons; (1) in order to ease the comparisons with other studies which usually do not include the basin, e.g. HELCOM (2003). (2) Arkona basin can be seen as a part of Baltic Sea and differs significantly from other parts of the region in for instance total depth, stratification strength, productivity and trophodynamics (Fennel, 1999).

The monthly mean wind speed in 2002 and 2004 was 5.9 $m\,s^{-1}$ and 7.5 $m\,s^{-1}$. In 2004 11 % of the recorded wind speeds were above 14 $m\,s^{-1}$ with directions predominant from the west while in 2002 the maximum wind speed was 12.5 $m\,s^{-1}$ with a more varying direction (Fig. 10). In both simulation 3 and 4 the largest change in DO concentration is seen in shallow regions such as the southwest Kattegat and the southern Belt Seas (Fig. 9b and d). In 2002 the monthly mean hypoxia in September is decreased to 1900 km^2 and in 2004 the area is increased to 1890 km^2. It should be mentioned that in the end of August there was no significant difference in oxygen condition between the two years, actually, mid August in 2004 had a larger extent of hypoxia than in 2002. This shows the importance of wind induced mixing in regulating hypoxia but also that the wind speed itself could not account for the extreme event in 2002. In order to explain the remaining variations the accumulated flow through S1 is compared to the area of hypoxic water (Fig. 11).

The development of hypoxia from July to the beginning of September is almost identical in 2002 and 2004. But in September the two years differ significantly (Fig. 11a, c). In 2004 the bottom waters are ventilated concomitant with a larger inflow through S1 while in 2002 there is almost no flow through S1 and the hypoxia increases throughout September. The flow through the cross sections show no significant modifications by reducing or increasing the wind speed (Fig. 11b, d). Since the wind is only modified in the CMOD domain (Fig. 1) this indicates the water transport through the Danish Straits is mainly regulated by the barotropic signal outside the modelled domain.

5 Discussion

5.1 Seasonal variations in DO concentration

The DO variation in the bottom water of the North Sea-Baltic Sea transition zone follows an annual cycle with highest concentration in early spring and lowest in autumn. When the entire transition area is considered as a whole the annual variation is dominated by hydrodynamics, as the results show that the seasonality of the respiration only accounts for 13 % of the DO annual variation and the effect of the temperature and salinity dependent oxygen solubility contributes 24 %. Moreover, the effect of keeping the

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boundary condition constant was found to be negligible (not presented). This means that variations of local DO supply from the upper layer by mixing and horizontal advection must explain the major part of the bottom water variation. Local supply of DO to the bottom water is important in shallow regions where the halocline is easily weaken or collapses but in the relatively deep eastern Kattegat a persistent stratification prevents the ventilation and advective transport of DO plays the major role (Bendtsen et al., 2009).

In Fig. 12 the net DO transport across the two transects is compared against the respiratory sink. The advection at S1 is compared to the volume integrated respiration in the Kattegat bottom water east of the island Læsø. Since the flow through S1 almost exclusively occurs on the east side of Læsø (Andersson and Rydberg, 1993) it is assumed that all water crossing S1 enters the volume. The net advection through S2 is compared to the respiration in a volume covering the bottom water from the entrance of Great Belt to Darss sill.

The results show that the seasonal variation in the total respiratory oxygen consumption in the bottom water in the Kattegat, as parameterised in OXYCON, is much smaller than the seasonality in the amount of DO advected from Skagerrak (Fig. 12a). In winter the advective process is much larger than the respiration but because of a drastic decrease in the input of DO the two processes are more or less equal in summer. Approximately 250 000 t O_2/month are advected to Kattegat in summer (June–August), 450 000 t O_2/month in autumn (August–October) and 830 000 O_2/month in winter (November–February). These figures are in agreement with Andersson and Rydberg (1993), although they estimated a larger winter transport. As also assumed in OXYCON, this documents that the variation of DO respiration is of minor importance to the seasonality of bottom DO in the Kattegat as a whole.

The water flux through the Great Belt (S2) is considerable smaller and at the same time the bottom water DO content has been reduced during the passage of the Kattegat, thereby amplifying the seasonal variation in the southward transport of DO. Here the variation in the DO transport is of the same magnitude as the variation in the

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respiration and the total advective DO supply is much less than the respiratory oxygen requirements in the areas south of the Great Belt. This is also the region where hypoxia is a reoccurring phenomenon during the late summer and autumn concomitant with the period where the respiratory oxygen demand consistently exceeds the DO transport through the Great Belt (e.g. Fig. 12b). Wind mixing plays a more prominent role in this area and, as shown in the simulation with increased wind, the deficit in advected DO can be compensated by increasing wind mixing. Nevertheless, the DO transport across S2 is a very important factor in the regulation of DO in the western Baltic Sea and better estimates of DO transport could potentially improve forecasts of hypoxia.

5.2 Interannual variations of hypoxia

The model nicely reproduces the interannual variation of hypoxia, especially the model predicts the extreme extent of hypoxia in 2002. The simulated respiration was assumed to be almost constant from year to year and the modelled interannual variation is mainly caused by the physical processes. The serious hypoxia in 2002 was likely caused by a combination of low vertical mixing and stagnant inflow from Skagerrak. The main difference in 2002 to other more normal years (referred to as 2004) is that the low wind speed did not ventilate the shallow areas in western Kattegat and southern Belt Seas. The fact that shallow areas are more affected by wind conditions is a consequence of three things: (1) the volume of the bottom water is less and gets easier ventilated by vertical mixing, (2) the salinity pool in the bottom water is less and the stratification is much easier broken down or weakened and (3) shallow areas develop hypoxia much faster than deeper areas because of the relatively larger contribution from benthic oxygen uptake from the shallower water column. However, the difference in wind speed did not completely explain the large differences between 2002 and 2004. In 2002 the stagnant bottom water prolonged the event and the deeper parts of Kattegat and Great Belt were not oxygenated until a larger inflow from Skagerrak occurred in the beginning of October. The inflowing Skagerrak water brings large amount of DO to the bottom

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water of Kattegat. Since bottom Kattegat water moves southward, mainly through the Great Belt, the inflow events will also affect the oxygen conditions further south. Another indirect effect of the inflowing water is that increased velocity shear may produce vertical turbulence and enhance the local supply of DO from the upper layer. This is specifically important in the narrow straits where the horizontal velocities can be rather large. Because of this mechanism Bendtsen et al. (2009) considered the Great Belt as a “breathing hole”. The present study also emphasis the critical water flux through the bottom transect in the Great Belt for the ventilations of the western Baltic Sea.

6 Conclusions

DO in the transition zone of the North Sea and Baltic Sea is simulated using a 3-D circulation model together with a simple parameterization of the respiratory sinks. The complex biogeochemical process controlling the oxygen consumption is simplified with a temperature dependent function for three processes: pelagic respiration, benthic respiration and diffusive sediment oxygen uptake. A quantitative assessment using more than 3000 observations shows that the model is able to simulate the DO in this region. The fact that this simplified treatment of the biogeochemical processes yields such realistic results highlights the importance of physical processes in controlling the spatiotemporal variation of DO in open waters. There is a large difference in timescales between the physical and biogeochemical processes. A storm or an inflow event can supply large amount of DO to the bottom water within a couple of hours while the remineralisation of organic material continuously consumes oxygen during the summer, but at a much slower rate. A long term increase in export production because of e.g. eutrophication will lead to a larger consumption of oxygen and hypoxia may occur more frequent. In short term circulation and meteorological conditions are likely the dominating factors controlling DO and the extension of hypoxic areas. The general and long term oxygen conditions depend on the respiration rate and on the amount of oxygen imported to the transition zone across the northern boarder.

Appendix A

Model equations and parameters

At each time step the coupled model solves the prognostic Eq. (A1)

$$\frac{dO_2}{dt} = \text{adv} + \text{diff} + O_2^{\text{flux}} - R_\text{p} - R_\text{b} - R_\text{s}, \tag{A1}$$

where "adv" and "diff" is advection and diffusion of DO and O_2^{flux} is oxygen flux through the sea surface. R_p, R_b and R_s is the three different respiratory sinks described below.

The oxygen flux through the sea surface is given in Eq. (A2) and applied at surface grid points. In line with Stigebrandt (1991) the surface water is assumed to be 2.5 % over saturated because of the supply of oxygen from bubbles. Here, α is the piston velocity and β is a scaling constant for the bubble effect and O_2^{sat} is the oxygen saturation.

$$O_2^{\text{flux}} = \alpha (O_2^{\text{sat}} \cdot \beta - O_2) \tag{A2}$$

The pelagic and benthic respiration is given by Eq. (A3). The pelagic respiration is applied at all water points while the benthic respiration is only applied at the bottom grid points.

$$R_i = \mu_i Q_{10}^{\frac{T - T_\text{ref}}{10}} \frac{O_2}{O_2 + k_i}, \tag{A3}$$

the index "i" should be interchange with benthic (b) and pelagic (p). Q_{10} the exponential temperature dependence, T and T_ref the water temperature and the reference temperature and k is the oxygen half saturation.

The sediment oxygen uptake is given by a similar expression but is limited by the diffusive transport of oxygen into the sediment which is described by the saturation level. The formulation for this process is given in Eq. (A4) and it is applied at bottom grid points.

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$$R_s = \mu_s Q_{10}^{\frac{T-T_{ref}}{10}} \frac{O_2}{{O_2}^{sat}} \tag{A4}$$

Parameter values can be found in Table A1 below.

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Table 1. MEF performance levels.

> 0.65	Excellent
0.5–0.65	Very good
0.2–0.5	Good
0–0.2	Poor
< 0	Worse than observation mean

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Table 2. Calculated assessment indices for the oxygen model.

Number of observations	3149
Bias	$-8.7\,\mu mol\,l^{-1}$
AAE	$38.4\,\mu mol\,l^{-1}$
RMSD	$52.6\,\mu mol\,l^{-1}$
MEF	0.48

Table A1. Parameters.

Symbol	Meaning	Value
β	Bubble effect	1.025
α	Piston velocity	$5.2 \times 10^{-5}\,\mathrm{m\,s^{-1}}$
μ_p	Pelagic respiration constant	$6.952 \times 10^{-6}\,\mu\mathrm{mol\,O_2\,l^{-1}\,s^{-1}}$
μ_b	Benthic respiration constant	$0.0464\,\mu\mathrm{mol\,O_2\,m^{-2}\,s^{-1}}$
μ_s	Constant for sediment uptake	$0.0338\,\mu\mathrm{mol\,O_2\,m^{-2}\,s^{-1}}$
k_p	Pelagic half saturation	$5.0\,\mu\mathrm{mol\,O_2\,l^{-1}}$
k_b	Benthic half saturation	$60.0\,\mu\mathrm{mol\,O_2\,l^{-1}}$
Q_{10}	Respiratory temperature effect	3.0
T_{ref}	Reference temperature	4.0 °C

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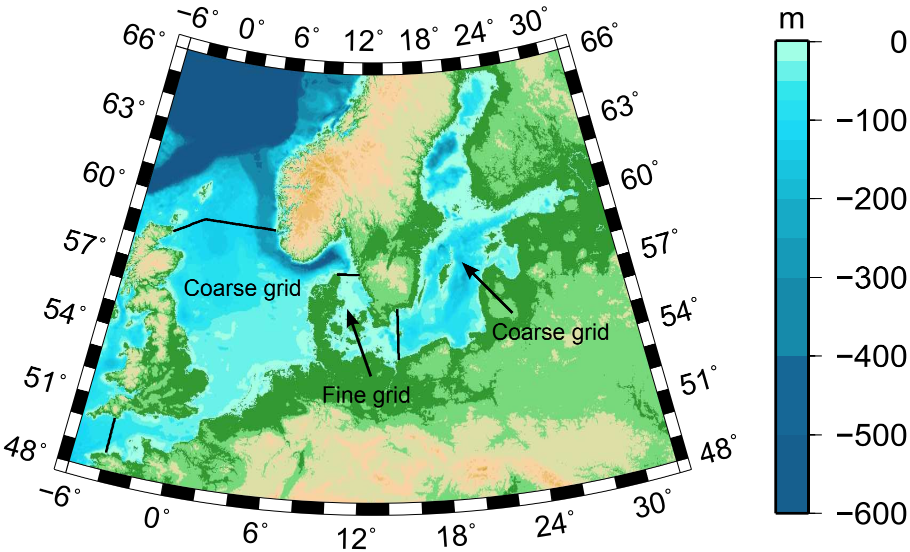

Fig. 1. The two-way nested domain for the physical model.

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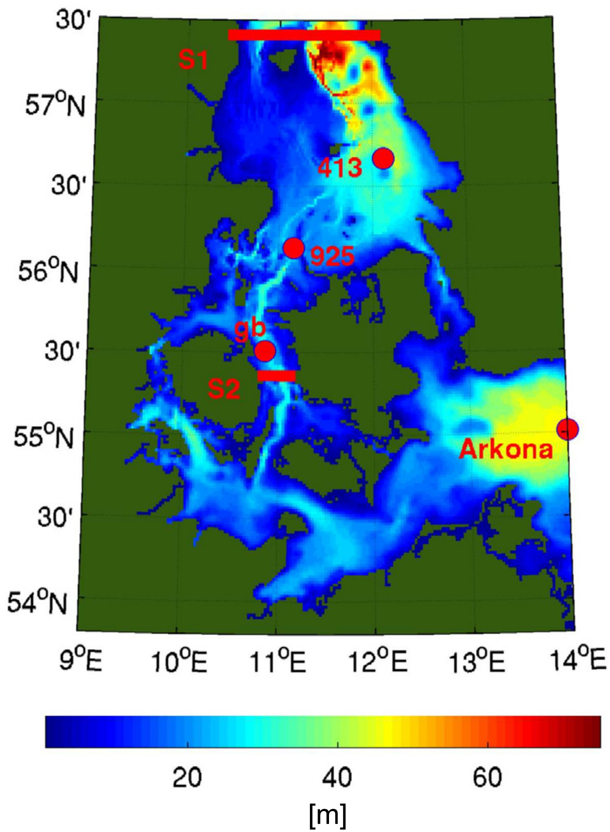

Fig. 2. The North Sea-Baltic Sea transition zone with model bathymetry. Monitoring stations used in the model assessment are indicated with red dots and the two cross sections with red lines.

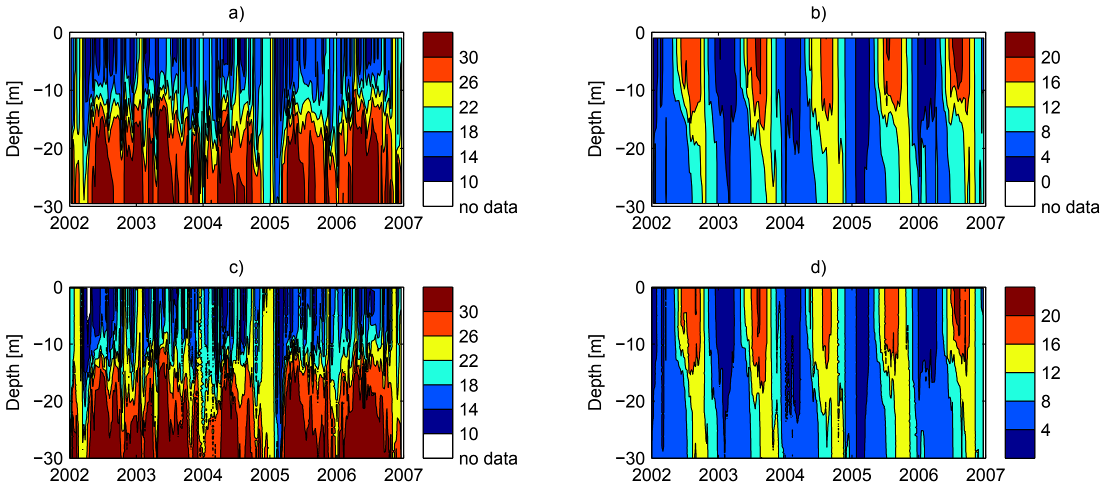

Fig. 3. Simulated and observed salinity and temperature for station GB in Great Belt: **(a)** modelled salinity, **(b)** modelled temperature, **(c)** observed salinity, **(d)** observed temperature.

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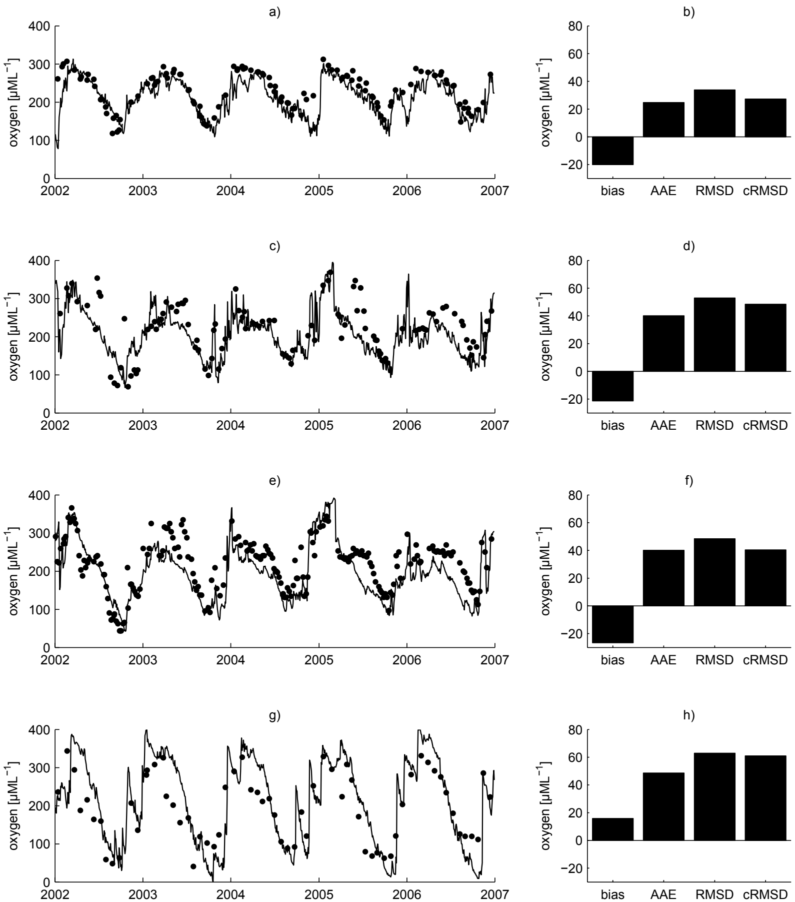

Fig. 4. Simulated (black line) and observed (black dots) DO concentrations together with statistical measures (right panels) for the bottom layer of the model at station **(a, b)** 413, **(c, d)** 925, **(e, f)** GB and **(g, h)** Arkona Basin.

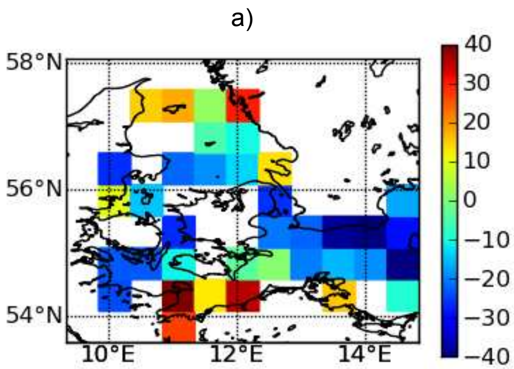

Fig. 5. Average spatial variation of the **(a)** oxygen bias and **(b)** average error during autumn for the years 2002–2006 (units in µmol l^{-1}).

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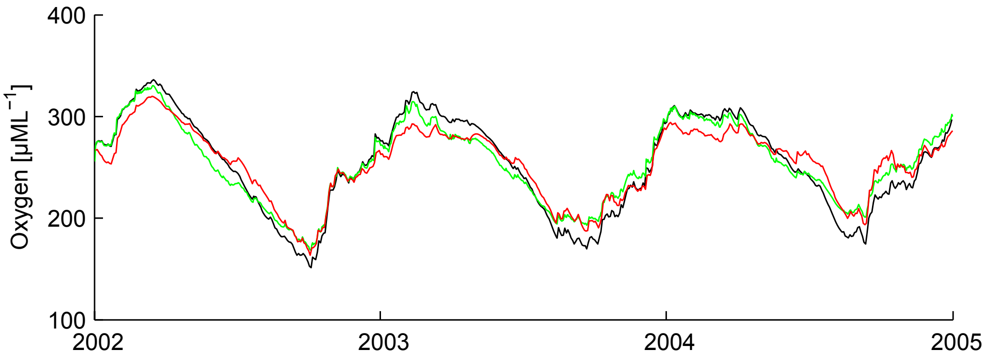

Fig. 6. Simulated mean oxygen concentration for the bottom water in the oxygen model domain (Arkona basin excluded). The black line indicates the reference simulation, green line simulation 1 with constant respiration rates and red line simulation 2 with constant oxygen saturation at the surface.

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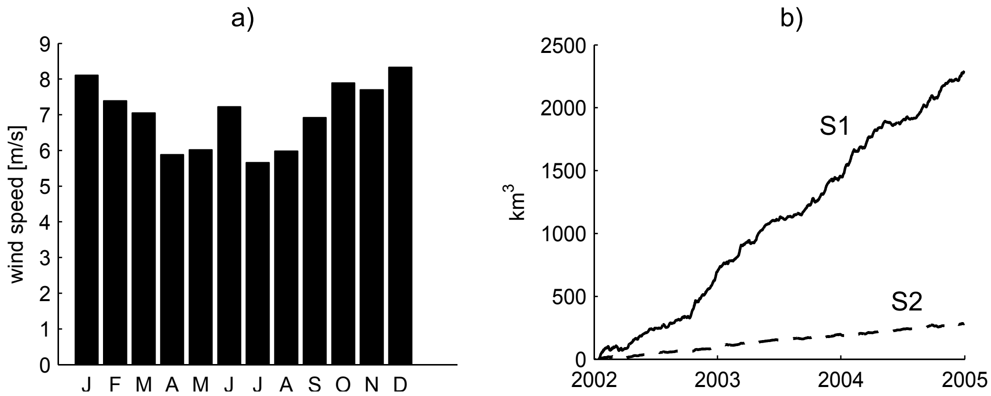

Fig. 7. (a) Monthly mean wind speed during the three years 2002–2004. **(b)** Integrated southward water flux below 15 m through the two sections S1 and S2.

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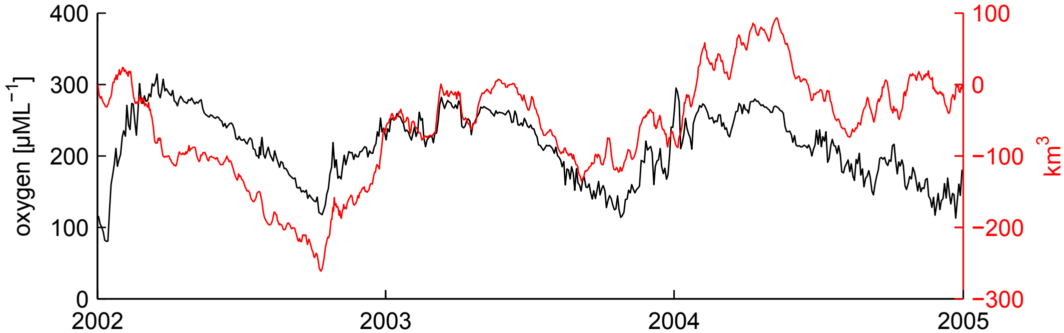

Fig. 8. Simulated DO concentration at station 413 (black line) and the deviations in the accumulated flow from the mean flow through S1 (red line). A negative (positive) gradient of the red line implies a lower (higher) volumetric flow rate then the mean.

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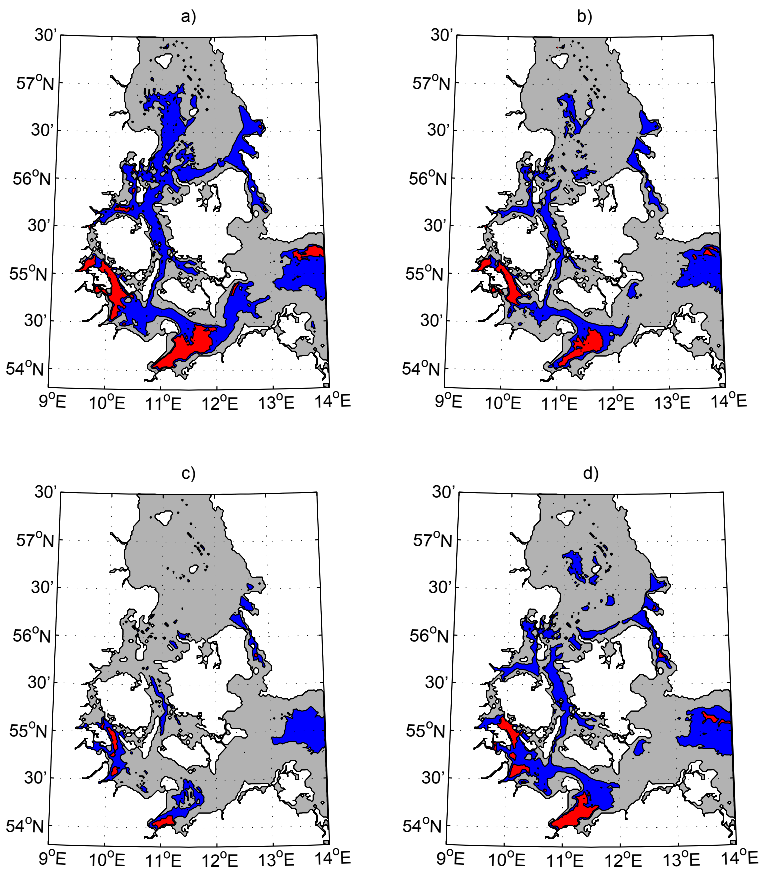

Fig. 9. Monthly averaged bottom DO concentration for **(a)** September 2002 and **(b)** September 2002 with increased wind and **(c)** September 2004 and **(d)** September 2004 with decreased wind. Red and blue patches indicate areas with hypoxia (<63 µmol l^{-1}) and oxygen deficiency (<126 µmol l^{-1}), respectively.

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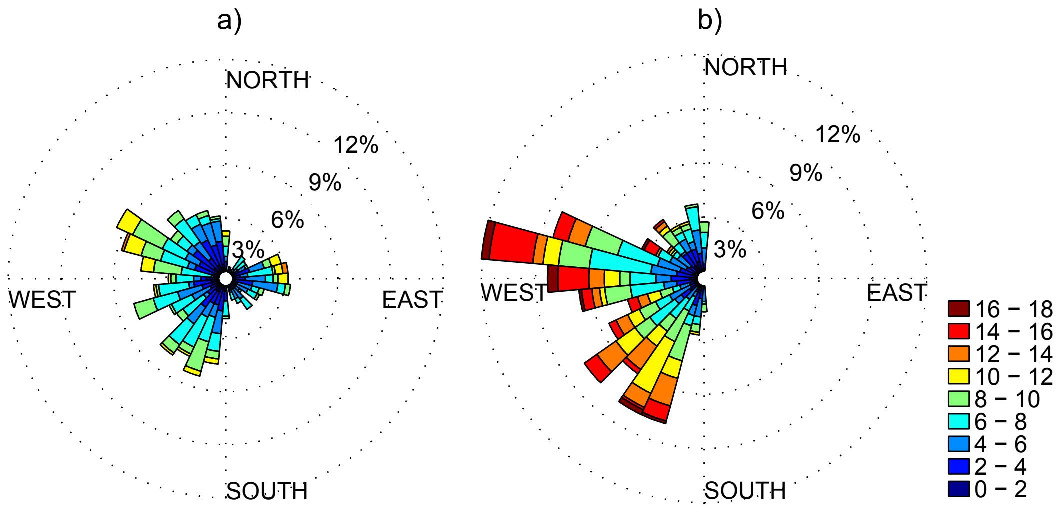

Fig. 10. Wind roses for **(a)** September 2002 and **(b)** September 2004.

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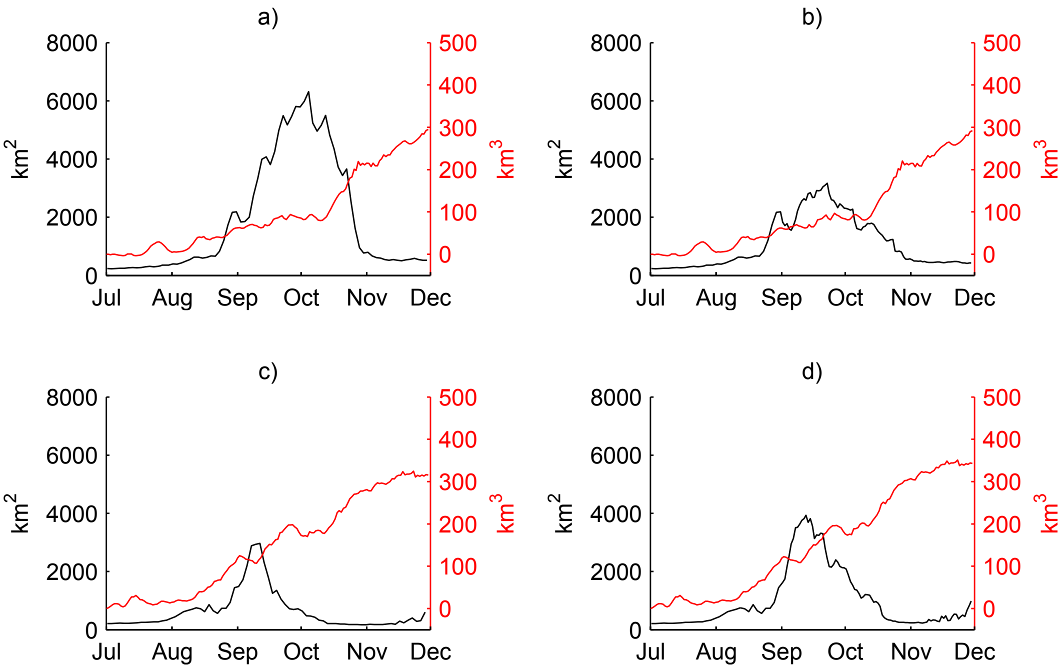

Fig. 11. The black line indicates time evaluation of hypoxic area in the domain (Arkona basin excluded) and the red line the integrated flow from 1 July for **(a)** 2002, **(b)** 2002 with increased September wind, **(c)** 2004 and **(d)** 2004 with decreased September wind.

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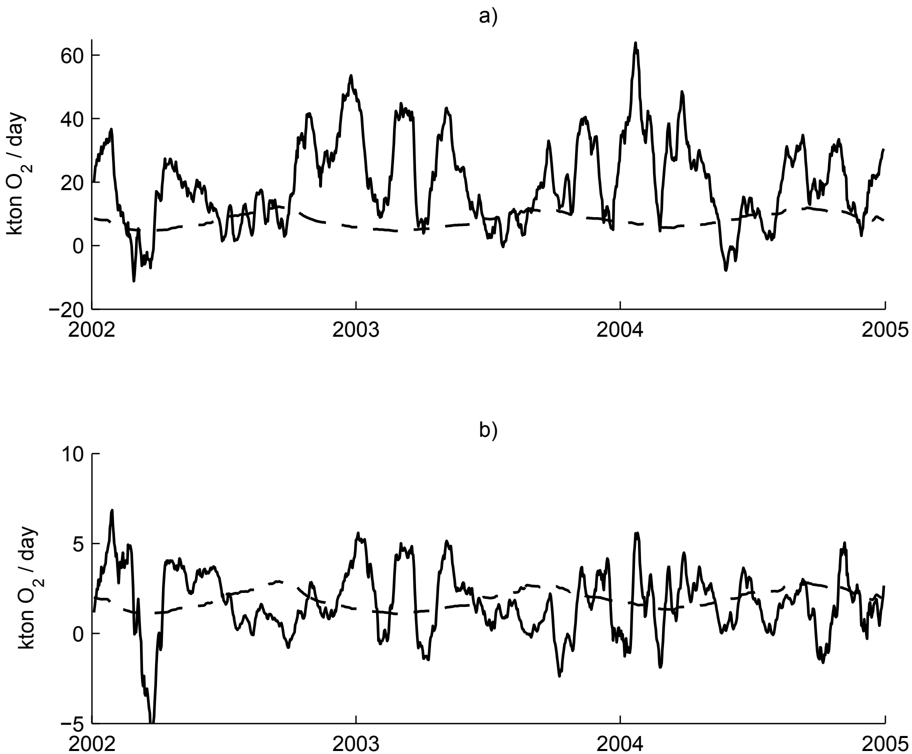

Fig. 12. **(a)** Comparison between the advective DO input (solid line) and the respiratory sink (dotted line) for the bottom water of **(a)** eastern Kattegat and **(b)** the Belt Seas. The DO flux is presented as one month running mean.

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