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Sensitivity of Baltic Sea deep water salinity and oxygen concentration to variations in physical forcing

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In this study, we investigate the Baltic Sea deep water exchange with focus on oxygen conditions. We assumed that the oxygen removal rate associated with decomposition of organic matter is constant, however, we use different rates for different sub-basins. The results obtained from this study of the deep water oxygen dynamics suggest a gradual increase in removal rate from the eastern Gotland Basin to the Danish Straits. Moreover, it is suggested that a drier climate would result in a reduced ventilation of the halocline region due to strong stratification. A wetter climate on the other hand is found to markedly improve the oxygen conditions in the upper deep water as a consequence of a weakened stratification and a more intense wintertime mixing.

Introduction

The input of salt to the Baltic Sea (Fig. 1) is determined by the dynamics of the inflows of dense water through the Danish straits. Such inflows are important to the brackish water ecosystems not only by being responsible for maintaining suitable salinities, but also by oxygenating the deep water. At times, so-called major inflows (*see* Matthäus and Franck 1992) replace the bottom water of the deeper basins, but a decade may pass without such events. One example is the 1983–1992 stagnation period when no inflow was intense enough to ventilate the deeper parts of the Baltic Proper. Exchange of the water in the deeper pools is normally related to a barotropic transport through the Danish straits, although it has been observed that baroclinic inflows can be large enough to ventilate the bottom waters at times. Two such events, during the summers of 2002 and 2003, have been described by Feistel *et al*. (2006).

The instantaneous barotropic water exchange through the Danish straits is determined by the water level difference between the Kattegat and the Baltic Sea. This depends mainly on the long-period fluctuations (longer than one month) of the sea level in the Kattegat, which is strongly related to the north–south air pressure difference across the North Sea, as shown by Gustafsson and Andersson (2001). The barotropic exchange is to a certain degree altered by the freshwater input to the Baltic Sea (e.g. Stigebrandt 1992). An increased freshwater input results in a decreased barotropic inflow as well as a decreased salinity of the inflowing water. This implies that inflows are less likely to be large and dense enough to replace the bottom water in the deeper basins during wet periods than during dry periods (cf. Stigebrandt 2003). Earlier studies

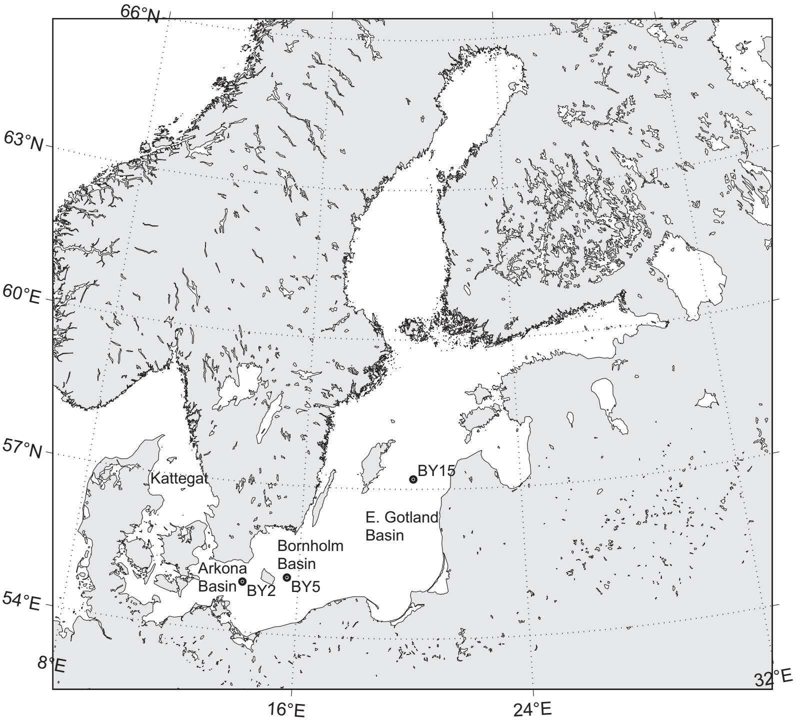

Fig. 1. The Baltic Sea region, including the positions of the hydrographic stations BY2, BY5 and BY15 in the Arkona, Bornholm and eastern Gotland Basins, respectively.

have suggested that the Baltic Sea would turn to a freshwater lake if the freshwater input were increased to a level several times higher than the contemporary value (Meier and Kauker 2003a, Stigebrandt and Gustafsson 2003, Omstedt and Hansson 2006a, 2006b).

Meier and Kauker (2003b) identified two major causes for the variability of the Baltic Sea salinity on a decadal time scale. Except the good correlation between accumulated freshwater input and freshwater storage, which was earlier pointed out by Winsor *et al*. (2001, 2003), they attributed a large part of the variability to low-frequent variations of the large-scale wind field over Scandinavia. It was concluded that an increased sea level in the Baltic Sea caused by anomalously strong westerly winds results in reduced salt transports from the Kattegat.

This latter result confirms the findings in a statistical analysis performed by Zorita and Laine (2000). Furthermore, Zorita and Laine (2000) found a negative correlation between salinity and oxygen concentration on longer time scales. Stigebrandt and Gustafsson (2007) reported an increased oxygen concentration in the water between 60 and 125 metres during the period 1991–1997. This was described as a result of increased inflows at this depth interval due to a weakened stratification. As a result of this, the area of anoxic bottoms was actually much smaller at the end of the 1983–1993 stagnation period than at the beginning (Conley *et al*. 2002). The negative correlation between salinity and oxygen can thus probably be explained by the increased inflow activity within and just below the halocline region during low saline phases, probably in combination with a tendency to stronger winds and increased mixing during the same periods.

Salinity observations at the hydrographic station BY15 in the eastern Gotland Basin are available for more than a century, with the two world wars excepted (Fig. 2). As reported by Winsor *et al*. (2001, 2003), there is no long-term trend in the Baltic Sea salinity during the 20th century, although decadal trends are visible, and most prominently in the deep water (Fig. 2). Stagnation periods are characterised by a density reduction in the deep water as a result of vertical diffusion. In the tideless Baltic Sea, the deep water diffusivity is probably determined by wind strength and stratification (Stigebrandt 2003).

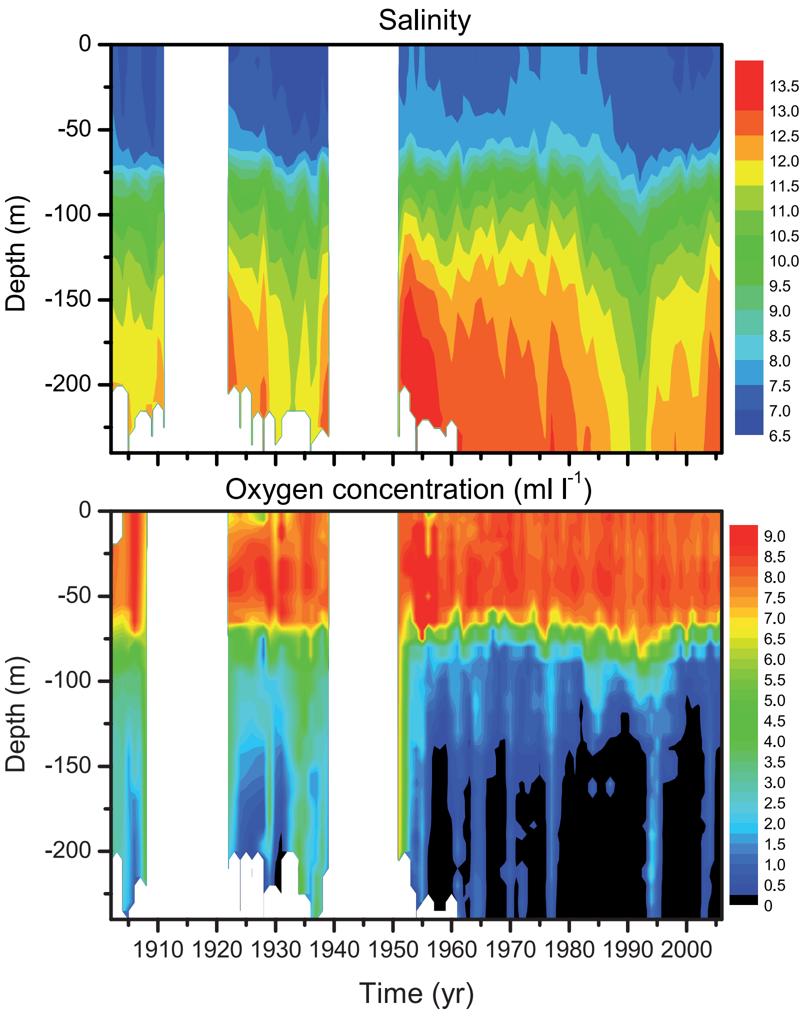

Fig. 2. Observed salinity and oxygen concentration (ml l^{-1}) at the hydrographic station BY15 in the eastern Gotland Basin, using data from the Baltic Environmental Database (BED) and the Swedish Ocean Archive (SHARK).

Axell (1998) showed a seasonal variability in the Baltic Sea deep water diffusivity, with increased values during the generally windier winter seasons. A long term mean of the deep water density reduction in the Baltic Proper during stagnation periods is about –0.13 kg m^{-3} yr^{-1}, which corresponds to a salinity reduction of approximately –0.16 psu yr^{-1} (Stigebrandt 2003).

It must be stressed that a stagnation period is depth dependent. During periods lacking major inflows, the upper deep water may still be well ventilated by numerous inflows of lower intensity. This can for example be seen in a study by Meier (2005), in which he modelled the depth-dependent age of Baltic water masses. According to his experiments, the maximum age of the eastern Gotland Basin deep water for the period 1903–1998 amounts to almost ten years. He identified three stagnation periods when the deep water age exceeded eight years. Two of these (1920s/1930s and 1980s/1990s) were related to a high freshwater input (Fig. 3) and stronger than normal zonal wind velocity. The third one (1950s/1960s) was speculated to be a consequence of the very strong 1951 inflow (*see* Fig. 2), which may have been too saline to allow new deep water inflows until the density was sufficiently reduced several years later.

Periods lacking an exchange of the deeper deep water, stagnation periods, are naturally occurring in the Baltic Sea as a result of the restricted water exchange and the stratified water column. However, measurements of oxygen concentrations since the early 1900s at BY15 reveal

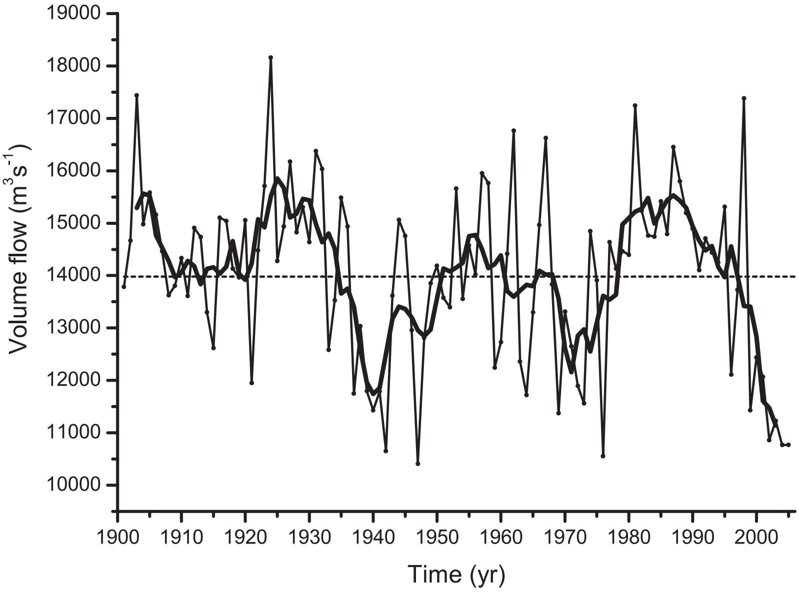

Fig. 3. Total river runoff to the Baltic Sea (not including the Kattegat). Annual mean (dots), total mean (dashed line) and four year running mean (thick line). For a detailed description of the data sources, *see* Material and methods.

a generally deteriorated oxygen situation in the deep water during the second half of the 20th century as compared with that during the first half (Fig. 2). Although the vertical diffusion results in an oxygen transport to the Baltic Sea deep water, the rate of the oxygen consumption associated with the decomposition of biological material is by far high enough to reduce the oxygen concentration in stagnant water. In the eastern Gotland Basin, the deep water oxygen is often completely depleted, resulting in the occurrence of hydrogen sulphide (H_2S). It is important to be aware of the fact that despite the visual appearance of oxygen contour plots (Fig. 2), oxygen deficiency is often restricted to relatively small volumes of water and thus small bottom areas, as a result of the area/depth distribution. The mean depth of the eastern Gotland Basin is approximately 75 metres, and the water column down to 105 metres amounts to about 90% of the total volume. Even during severe oxygen conditions, hydrogen sulphide is usually present only at depths greater than ~130 metres in the eastern Gotland Basin, which corresponds to less than 5% of the total water volume.

In barotropic inflows across the shallow Drogden and Darss sills (8 and 18 metres deep respectively), the water can be assumed to be oxygenated by exchange with the atmosphere. This would suggest that the oxygen concentration in the inflowing water is mainly determined by the water temperature and to some extent the salinity (Weiss 1970), but not to so much affected by the history of oxygen consumption in the Kattegat, Öresund and Belt Sea basins. Entering the bottom pool of the Arkona basin, the inflowing water masses become more isolated from the atmosphere (the well mixed surface layer) due to the density stratification. An exception is severe storm events, which at times may mix the entire Arkona Sea, as reported by Liljebladh and Stigebrandt (1996). The decomposition process begins to consume the oxygen in the bottom pool of Arkona. As the bottom pool subsequently is filled up by inflowing water, the water spills over to the Bornholm Basin bottom pool, where oxygen consumption continues. The outflow from these dense bottom pools has by several authors been assumed to be in baroclinic geostrophic balance, and thus controlled by the pool stratification and sill depth (cf. Omstedt and Kõuts 1993, Liljebladh and Stigebrandt 1996, Stigebrandt 2001). Detailed field investigations however illustrate that large temporal and spatial variations exist with intermittent overflows in the form of baroclinic eddies, fronts and internal waves (e.g. Piechura and Beszczynska-Möller 2004).

Entering the eastern Gotland basin through the Stolpe Channel, the flow dynamics as a first approximation takes the form of a gravity current (cf. Stigebrandt 1987), which by the act of entrainment is mixed with the surrounding waters of depth dependent salinities, temperatures and oxygen concentrations. Consequently, the inflowing bottom current will obtain different properties depending on (1) the initial salinity, temperature and oxygen concentration, (2) the thickness of the surface layer, and (3) the properties of the surrounding deep water, which are determined by the eastern Gotland Basin diffusivity and oxygen consumption rate together with the time elapsed since the last exchange of the deep water.

Eutrophication is most likely largely responsible for the change to the worse concerning the deep water oxygen concentrations. It is well known that the loading of nutrients to the Baltic Sea has increased several times beyond the natural level, as a result of for example changes in the agriculture and increased sewage emissions. Reviews on the subject are given by Grimvall and Stålnacke (2001) and Boesch *et al*. (2006). The relative importance of variations in the physical forcing of the system in comparison to the increased eutrophication is however not yet quantified. The main purpose of this study is to examine the sensitivity of the Baltic Proper salinity and oxygen concentration to changes in the physical forcing, i.e. the water level in the Kattegat, the magnitude of the river runoff and the strength of the wind. The effects of a considerably lower oxygen removal rate (which would correspond to a reduced eutrophication) will be examined as well.

Material and methods

The calculations were performed using the PROBE-Baltic model (for description *see* Omstedt and Axell (2003). In short, the PROBE-Baltic model is a process-oriented, time-dependent, coupled-basin model. The rather complex Baltic Sea topography is modelled as thirteen horizontally homogenous basins with high vertical resolution; from the Kattegat in the southwest to the Gulf of Bothnia in the north. Each of the coupled basins is forced by monthly mean river runoff and net precipitation as well as geostrophic wind components, air temperature, cloudiness and relative humidity every third hours. Daily mean sea level observations for the Kattegat are used. In this study, forcing fields for the period 1 November 1958 to 31 December 2006 were used.

The meteorological forcing files are based on data from the European Centre for Medium-Range Weather Forecasts (ECMWF, ERA40 data set) for the period 1 November 1958 to 31 December 2001 and the Swedish Meteorological and Hydrological Institute (SMHI, 1° × 1° data set) for the period 1 January 2002 to 31 December 2006 (cf. Omstedt *et al*. 2005). The freshwater input data was collected from several sources. For the period 1901–1920: Cyberski and Wróblewski (2000) and for the period 1921–1949: Mikulski (1986). For the period 1950–2006 data from the BALTEX hydrological data centre is used, where the period 1950–1998 was based on observations and the period 1999–2006 based on model results. To validate the model runs, observational data of salinity, temperature and oxygen were extracted from the Baltic Environmental Database (BED) for the period 1900–1998 and from the Swedish Ocean Archive (SHARK) for the period 1958–2006.

To estimate the response of the Baltic Sea to changes in the physical forcing of the system, we examine the model sensitivity. There are earlier sensitivity studies on the Baltic Sea in which one or several parameters at a time (e.g. freshwater input, wind speed, etc.) have been changed (e.g. Stigebrandt 1983, Meier and Kauker 2003a, Gustafsson 2004). In this study, we take a different approach; the "true" forcing files are used for a certain ten-year period; i.e., the freshwater input, the Kattegat water level and the additional meteorological parameters (wind speed, air temperature, relative humidity and cloudiness) are all kept unaltered for a ten-year period of special interest. As mentioned above, there are several studies regarding the response of the Baltic Sea to large changes in the freshwater input. In the same tradition, we pick one wet and one dry period in this study after examination of the freshwater input for the last 50 years (Fig. 3). The wet/dry period is then used over and over again (12 times) to create 120-year-long time series. The reason for creating such long time series is that the system requires several decades to spin up and become independent from initial conditions regarding salinity (cf. Omstedt and Hansson 2006a, 2006b). What we expect to obtain in this study is a realistic response for the modelled Baltic Sea region if the climate were to be shifted either towards wetter or drier conditions on longer time scales.

Oxygen modelling

In the PROBE-Baltic model, the oxygen equation is written as follows

$$\frac{\partial O_2}{\partial t} + w\frac{\partial O_2}{\partial z} = \frac{\partial}{\partial z}\left[\frac{\mu_{\text{eff}}}{\rho}\frac{\partial O_2}{\partial z}\right] + S_{O_2}. \quad (1)$$

Here, O_2 is the concentration of oxygen, μ_{eff} the effective dynamical turbulent viscosity and ϱ density. S_{O_2} represents the sources and sinks due to photosynthesis, respiration and the biochemical oxygen demand. The vertical velocity w at a depth z is expressed as

$$w(z) = \frac{\left[Q_{\text{in}}(z) - Q_{\text{out}}(z)\right]}{\text{Area}(z)} \quad (2)$$

where Q_{in} (Q_{out}) is the inflow (outflow) at depth z. The boundary condition for the air–water interface is given by

$$\frac{\mu_{\text{eff}}}{\rho}\frac{\partial O_2}{\partial z} = V_{O_2}\left[O_2 - O_{2\text{sur}}\left(1 + c_{\text{bu}}\right)\right]. \quad (3)$$

Here, $O_{2\text{sur}}$ is the saturation oxygen concentration at the surface, which depends on temperature and salinity (Weiss 1970). Stigebrandt (1991) introduced the factor c_{bu} in order to take into account the effects of air bubbles in the surface water. He estimated the value of the "bubble factor" to be $c_{\text{bu}} = 0.025$. V_{O_2} is an exchange velocity dependent on wind speed and can be written

$$V_{O_2} = \frac{5.9}{\sqrt{\text{Sc}}}\left(aW + b\right). \quad (4)$$

Here, Sc is a temperature dependent Schmidt number for oxygen, W is the wind speed, and a and b are empirical constants depending on wind speed (*see* Stigebrandt (1991) and references there therein).

In this simple experiment, we did not include a plankton model. This means that the oxygen source associated with primary production was not accounted for. As mentioned above, the input of nutrients to the different basins in the Baltic Sea has varied during the period for the model experiments. In spite of this, we used constant oxygen removal rates for the different basins throughout the experiment period. The decomposition of biological material was furthermore assumed to take place below the thermocline only and to continue at a constant rate regardless temperature and oxygen concentration; i.e., the oxygen source/sink term S_{O_2} (Eq. 1) has a constant value.

We did, however, use different rates for different basins (Table 1). In the eastern Gotland Basin, the current oxygen removal rate during stagnant periods seems to be of the order of 2–2.5 ml O_2 l^{-1} yr^{-1} (e.g. Pers and Rahm 2000). In the Öresund Basin, the rate was earlier estimated to be about 10 ml O_2 l^{-1} yr^{-1} (Mattsson and Stigebrandt 1993). In this study, we assumed that this rate applies to the Belt Sea as well. In order to fit model results to observations, the Arkona and Bornholm Basin oxygen removal rates were trimmed to 10 and 4.5 ml O_2 l^{-1} yr^{-1}, respectively (earlier, the rate for the Bornholm Basin was estimated to be 3.5 ml O_2 l^{-1} yr^{-1} for the period 1968–1977, *see* Pers and Rahm (2000) for reference). If the oxygen is totally depleted, another regime is entered. The hydrogen sulphide found during anoxic conditions was converted into "negative oxygen" by assuming that two molecules of oxygen are needed to oxidise one molecule of hydrogen sulphide. We assumed that the decomposition rate during anoxic conditions corresponds to an oxygen removal rate of 1.5 ml O_2 l^{-1} yr^{-1}. Gustafsson and Stigebrandt (2007) found that in the deep water in the eastern Gotland Basin (deeper than 150 metres), the rate of decomposition of organic material tends

Table 1. Modelled oxygen removal rates (ml O_2 l^{-1} yr^{-1}) in some sub-basins during oxic conditions.

Sub-basin	Mineralisation rate (ml O_2 l^{-1} yr^{-1})
Öresund	10
Belt Sea	10
Arkona Basin	10
Bornholm Basin	4.5
Eastern Gotland Basin	2

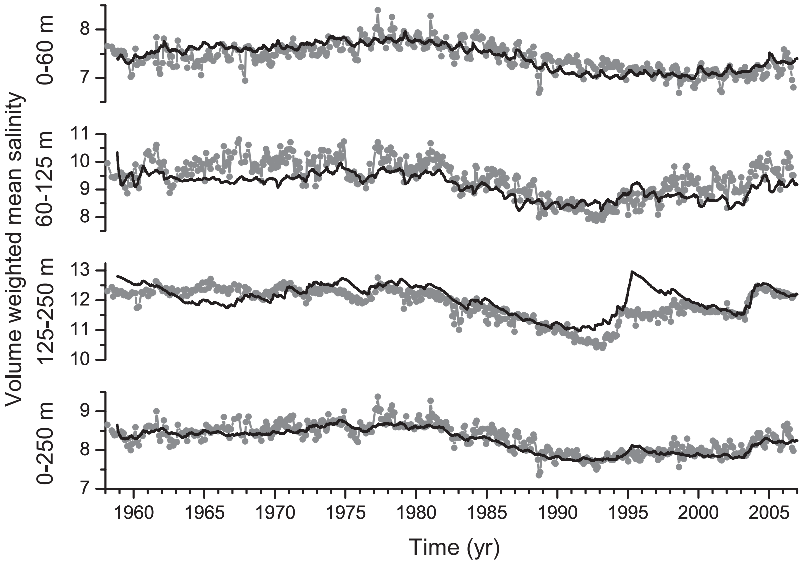

Fig. 4. Volume weighted mean salinity in the eastern Gotland Basin for the experiment period 1958–2006. Gray dots are monthly averaged observed values and the fully drawn lines are the model results. The upper panel is the surface layer (0–60 m), followed by the upper deep water (60–125 m), the deeper deep water (125–250 m) and finally the total volume weighted mean salinity for the eastern Gotland Basin (0–250 m). Sources to the observational data are the Baltic Environmental Database (BED) and the Swedish Ocean Archive (SHARK).

to increase with increased oxygen concentrations during oxic stagnation periods. No similar relation was however found for decomposition during anoxic conditions.

Results

Model validation

To better see the variations in different properties at different depths, as well as allowing a more detailed comparison between observations and model results, we defined three water layers for the eastern Gotland Basin. The upper limit for the permanent halocline is typically at about 60 metres depth. The first layer was thus chosen to consist of the upper 60 metres of the water column (~65% of the total volume). Stigebrandt and Gustafsson (2007) observed that during the first half of the 1990s, the water occupying the depths between 60 and 125 metres in the Baltic proper was for reasons discussed above unusually well oxygenated (in relation to the "normal" situation for the last 50 years). In line with this, we define the second layer as the water between 60 and 125 meters (~30% of the total volume). Finally, we chose the third layer as the water body below 125 meters (~5% of the total volume). Adopting the terminology from Stigebrandt (2003), the second and third layers are henceforth referred to as the upper and deeper deep water, respectively. For each layer, we calculated the volume weighted mean values for salinities, temperatures and oxygen concentrations. Here we assumed that the measurements at BY15 (Fig. 1) are representative for the entire eastern Gotland Basin.

The modelled and observed volume weighted mean salinities for each layer agree well, although too much salt is transported to the modelled deepest layer after the long stagnation period 1983–1992 (Fig. 4). In the surface layer and the upper deep water, the modelled temperatures follow observations closely, whereas there are some discrepancies in the deeper deep water (Fig. 5). Obviously, the dynamics of the oxygen variations in the different layers cannot be expected to be fully captured, as the oxygen removal rates in the different basins were set to constant values (Table 1). Nevertheless, the model calculations result in oxygen concentrations reasonably close to observations, although too low values are found in both the surface layer and the upper deepwater (Fig. 6). This is of course partly linked to the lack of a proper plankton model.

Sensitivity study

To investigate how the salinities and oxygen

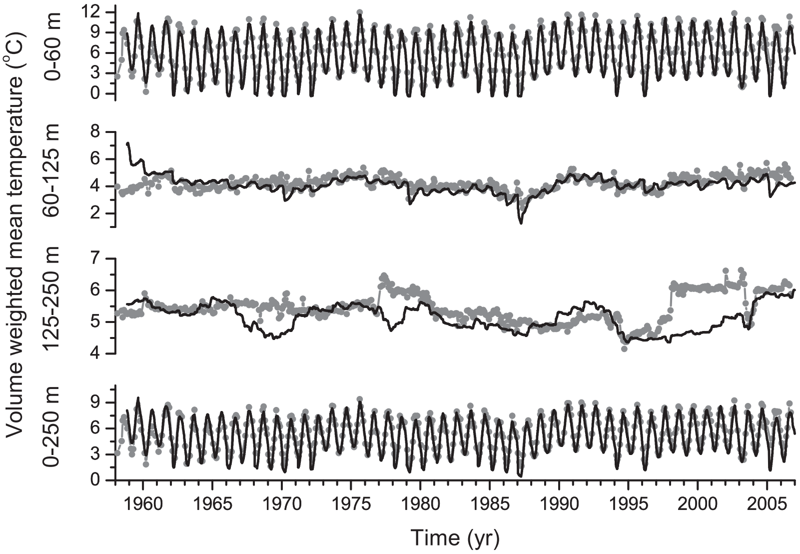

Fig. 5. Same as Fig. 4, but for temperature (°C).

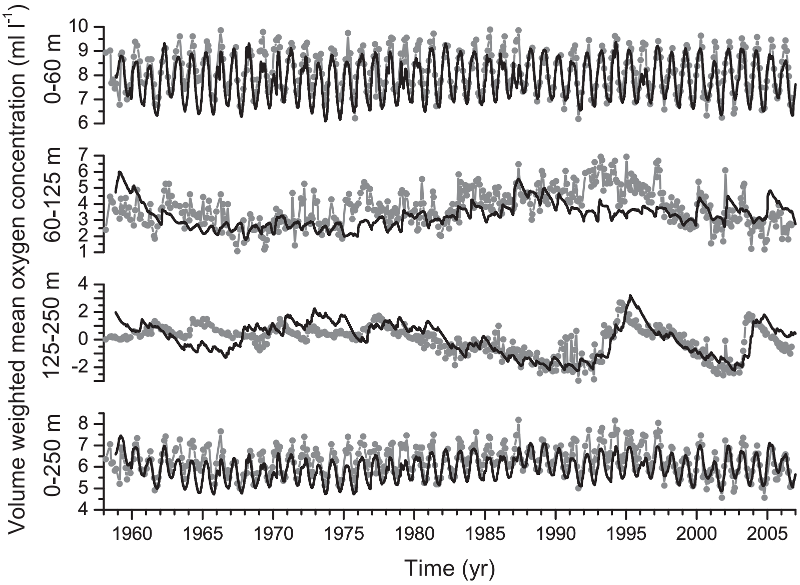

Fig. 6. Same as Fig. 4, but for oxygen concentration (ml l^{-1}).

concentrations in the deep water respond to changes in the physical forcing, we performed three different experiments and compared the results with a reference period. The reference period consists of mean values in each layer during the 30-year-long period 1961–1990. We constructed mean values for both observations and true forcing model results (cf. Figs. 4 and 6). The properties of the three experiments are outlined below.

Firstly, we simulated a drier climate. As the 1970s was a period of relatively low river runoff (*see* Fig. 3), the ten years of 1970–1979 were used for the first experiment. The reason for choosing a ten-year period was to achieve a reasonable climatic scale on the variations in the forcing. In this study, a period of about 70 years was necessary to spin up the system regarding salinities. Thus, we used the meteorological forcing, the river runoff and the Kattegat water level from 1970 to 1979 over and over again during a period of 120 years. The last 30 years of the experiment (when the system is approximately spun up) were used to form mean values and then to compare them with the results from the true forcing model run during the reference period.

As the years 1983 to 1992 constituted an unusually wet period and a period without major inflows, these ten years were thought to be interesting to use in a second experiment. Again, this means that the forcing for the years 1983–1992 was reused throughout the 120-year-long experiment period. Eilola (1998) estimated that the vertical flux of organic matter to the Baltic proper deep water during the late 1930s was about 55% of the contemporary rate. We performed a third experiment with true forcing, but with the oxygen consumption halved in each basin. This final experiment would thus roughly correspond to the rate of oxygen removal during the first half of the 20th century, i.e. a rate not so much affected by human activities. The long spin-up time associated with salinity does not apply to oxygen concentrations, which allows us to use mean oxygen concentrations for the period 1961–1990 when comparing the results from the final experiment with observations. The much shorter spin-up time for oxygen is partly explained by the rapid exchange between the atmosphere and the surface layer. The dominating part of the total water volume is ventilated each winter due to mixing down to the permanent halocline. Thus, the very long model runs needed to make the salinity stratification independent from initial conditions are not necessary when dealing with oxygen concentrations.

Table 2. Volume weighted mean salinities in the different layers obtained from observations as well as the true forcing model run during the period 1961–1990. The mean values for the last 30 years of dry and wet climate experiments respectively are then compared to the true forcing model run.

Depth interval (m)	Observations	True forcing	Climat	
			Dry	Wet
0–60	7.6	7.6	+0.5	–1.6
60–125	9.7	9.3	+0.6	–1.8
125–250	12.0	12.1	+0.7	–1.9
0–250	8.5	8.4	+0.5	–1.7

The results are presented in the form of volume weighted mean values of salinities obtained from both observations and the model run using true forcing in the different layers for the period 1 January 1961 to 31 December 1990. The mean values of the last 30 years of the dry and wet climate experiments respectively are then compared to the results from the true forcing model run (Table 2). This is performed for oxygen concentrations as well (Table 3). Additionally, changes in mean oxygen concentrations (for the period 1961–1990) resulting from a halved oxygen removal rate is shown (Table 3).

Except a somewhat too low salinity in the modelled upper deep water, only small differences are found between the mean values of the observed salinities and the model experiment using true forcing. As expected, the dry (wet) climate experiments result in higher (lower) salinities throughout the water column (Table 2). Using true forcing, the modelled oxygen concentrations are a bit too low in the surface layer and the upper deep water. When comparing the experiments with the true forcing model run, it is evident that the dry climate experiment results in an increased oxygen level in the deeper deep water, but otherwise decreased concentrations. The results from the wet climate experiment shows generally increased oxygen levels, and most prominently in the upper deep water. In the experiment with a decreased oxygen removal

Table 3. Same as Table 2, but for mean oxygen concentrations (ml l^{-1}). In addition, the last column contains the difference between the true forcing oxygen concentrations and the values resulting from the model run with a halved oxygen removal rate in each sub-basin.

Depth interval (m)	Observations	True forcing	Climate		Oxygen removal 50%
			Dry	Wet	
0–60	8.2	7.8	–0.3	+0.3	+0.4
60–125	3.6	3.1	–0.5	+1.1	+2.7
125–250	0.1	0.1	+0.7	+0.3	+3.7
0–250	6.3	5.9	–0.3	+0.6	+1.3

rate, much higher oxygen concentrations are as expected found in both the upper and deeper deep water (Table 3).

Discussion

Seemingly, this very simple treatment of the oxygen dynamics in the Baltic Sea deep water yields rather realistic results (Fig. 6 and Table 3). The trimmed values of oxygen removal in the different basins suggest that the rate increases from the eastern Gotland basin towards the Danish sounds (cf. Table 1). The model does not take into account possible changes in the oxygen dynamics during the investigated period. Nevertheless, constant oxygen removal rates result in model values close to observations.

We used a ten-year period over and over again to simulate a drier or wetter climate. It is obvious that the sporadic behaviour of the Kattegat water level, largely determining the inflow volumes, will have a great impact on the resulting salinities and oxygen concentrations in the different layers. The consequence of reusing a certain period is that identical inflow volumes will enter the Baltic Sea every ten years (during identical meteorological conditions). The salinities, temperatures and oxygen concentrations in the inflowing water will drift slightly until the system has spun up completely — in which case each ten year period looks exactly the same.

Neither the dry nor the wet climate experiments resulted in such extended periods of severe oxygen conditions as both the observations and the true forcing model run revealed (Fig. 6). This is a consequence of the fact that the forcing is "reset" every ten years in the experiments. In reality, the oscillating behaviour of e.g. the river runoff (Fig. 3) and thus the salinities of inflows may naturally result in extended stagnation periods. Assume for example that a high saline inflow ventilates the deeper deep water during the later part of a drier period. Then inflows during a following wetter period may not be sufficiently large and saline to reach the deepest layer for several years. The length of the stagnation period will of course to a certain degree depend on the strength of the vertical diffusivity, i.e. the rate of the deep water density reduction.

The salinity stratification in the Baltic proper is determined by the salt water exchange with the open sea outside the Baltic Sea entrance area. The properties of inflows and outflows through the Danish straits depend on freshwater input, mixing wind and Kattegat water level (*see* e.g. Stigebrandt 2003). The strength of the stratification has a large impact on where intruding water is interleaved. During drier periods in the Baltic Sea region, inflows from the Kattegat are more likely to be dense and large enough to penetrate into the deepest layers than during wetter periods. However, long periods of low freshwater input will subsequently result in generally higher salinities throughout the water column, which means that the inflows will have do become denser to be able to reach into the deepest layer. It is apparent from this investigation that throughout the experiment period, the dry climate experiment gives higher oxygen concentrations in the deepest layer than the wet climate experiment (Table 3). This should be explained by an increased number of inflows dense and large enough to reach the deeper deep water during high saline phases.

There is a very clear difference concerning oxygen concentrations in the upper deep water when comparing the dry and wet experiments. As discussed above, the explanation to the improved oxygen situation during the wet climate experiment can probably be found partly in a weakened stratification, which should result in an increased number of not so dense inflows penetrating into the halocline region (i.e. the depth interval 60–125 m). In addition, a more effective mixing in the surface layer is expected especially during the latter part of this period. This can be seen when examining the strength of the geostrophic wind over the eastern Gotland basin during the 1983 to 1992 winter seasons (Fig. 7). During the winter, the temperature stratification breaks down and the mixing wind is allowed to erode the permanent halocline and thus deepen the well mixed layer. In line with this, the decrease in oxygen in the surface layer and the upper deep water during a drier period should be explained firstly by a stronger stratification preventing low-saline inflows from reaching below the surface layer. Secondly, as opposed to the wet period, the 1970s were characterised by comparably weak winds during the winter seasons (Fig. 7).

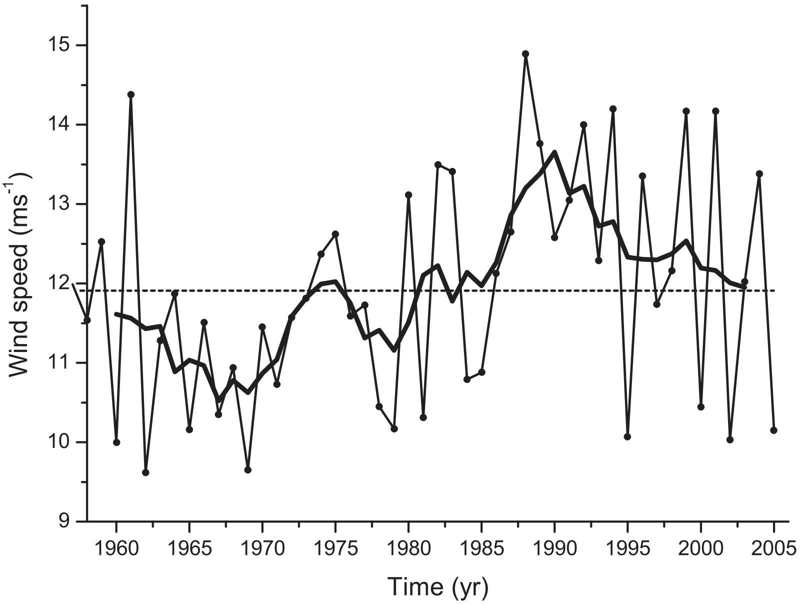

Fig. 7. Winter (December, January and February) mean geostrophic wind over the eastern Gotland Basin, using data from ECMWF, ERA40 data set and SMHI, 1° × 1° data set (*see* Material and methods for details). Mean wind strength for each winter (dots), total mean (dashed line) and four year running mean (thick line).

Conclusions

In this study, we modelled the salinities, temperatures and oxygen concentrations for some Baltic Sea sub-basins for the period 1 November 1958 to 31 December 2006. We assumed that the removal of oxygen associated with decomposition of biological material progress at a constant rate below the thermocline. Hence, factors that may influence the rate of decomposition, such as temperature and oxygen concentration, were disregarded. We did, however, apply different rates applied to different sub-basins of the Baltic Sea and the decomposition rates were furthermore given different values during oxic and anoxic conditions respectively.

Modelled salinities and temperatures were found to agree well with observations within the different layers of the Baltic Sea water column. The same is true for the oxygen concentrations, which suggests that as a first approximation, the oxygen removal rates in the different basins may be set to constant values. It is however apparent that the oxygen dynamics in the surface layer and upper deep water would probably be better reproduced if a proper plankton model were used. In a few sub-basins, we used oxygen removal rates reported in earlier studies (*see* Pers and Rahm 2000). In other cases, we trimmed the removal rates in different basins to fit observations. The results suggest an increase in oxygen removal rate from the eastern Gotland Basin to the Arkona Basin just inside the Danish Straits. The decomposition rate in the Arkona Basin was found to be more than twice the rate in the Bornholm Basin, which in turn is about twice the rate in the eastern Gotland Basin (Table 1).

Moreover, we investigated the resulting salinities and oxygen concentrations from drier and wetter climate experiments and compared them to values obtained from a model run where true physical forcing was used. A conclusion that emerges is that periods with a weakened stratification due to high freshwater input and strong winds are periods when larger volumes than usual become rather well oxygenated. This has as mentioned already been discussed by Stigebrandt and Gustafsson (2007). Furthermore, a negative correlation between salinities and oxygen concentrations was revealed in the statistical analysis by Zorita and Laine (2000). During drier periods, it seems that a strengthened stratification would prevent less dense inflows from reaching below the surface layer, thus causing a rather poor ventilation of the upper deep water.

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