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The sensitivity of minimum oxygen concentrations in a fjord to changes in biotic and abiotic external forcing

Carina P. Erlandsson, Anders Stigebrandt, and Lars Arneborg
Göteborg University, Box 460, SE-405 30 Göteborg, Sweden

Abstract

We investigated the possible biotic and abiotic causes of the observed long-term decrease of oxygen minimum concentrations in the deep water of Gullmar Fjord. Physical factors explained about 40% of the decreased minimum oxygen concentrations since the 1950s. The North Atlantic Oscillation and more regional climate variations account for an important part of this change. The effect of the climate variations was mainly on the timing of the renewal of the basin water. The consumption rate of oxygen in the basin water has increased by 50% since the 1950s. This biotic effect explained about 60% of the decrease in minimum oxygen concentrations. The likely dominating source of oxygen-consuming matter was (remote) production in the Skagerrak, suggesting that there has been a long-term increase of particulate organic carbon in the Skagerrak water.

Low oxygen concentrations and negative trends in oxygen concentration have been recognized in many coastal waters worldwide (e.g., Barnes and Collias 1958; Justic et al. 1987; Andersson 1996). Decreasing oxygen content might be caused by local and large-scale eutrophication (e.g., Rosenberg 1985; Nixon 1995). Enclosed waterbodies such as fjords and bays are especially sensitive to increased local nutrient input if the residence time of the surface water is large compared with the vertical transport time of particulate organic matter (POM) (Aure and Stigebrandt 1989).

A salient difference between a bay and a fjord is that the latter has a sill. A sill hampers the exchange of basin water (water below the sill level), which leads to longer residence time for the basin water than for the water above sill level. Water renewal is usually the major mechanism of oxygen supply to basin water. Another mechanism is the continuous ongoing vertical diffusion that transports oxygen down from the water above sill level. The exchange of basin water is controlled by the rate of mixing in the basin and occurs when the density of the coastal water at sill level is high enough to replace the resident water (e.g., Gade and Edwards 1980; Aure and Stigebrandt 1990). Long-term variations in the exchange can be caused by long-term variability in the climate.

Important factors for oxygen conditions in basin water are (1) input of organic matter, (2) residence time of the water, and (3) maximum oxygen concentration after a renewal. Large-scale eutrophication leads to increased oxygen consumption in basin water also in fjords with a relatively short surface layer residence time. This would be of minor importance in fjords with short basin water residence time, but of great importance if the residence time is long enough for the oxygen concentration to reach critical values.

The sink of oxygen is connected to consumption of organic matter by animals and bacteria. Possible local and remote sources of particulate organic carbon (POC) to the basin water are (1) POC in the surface layer of the fjord, which will either be flushed offshore by water exchange or sink down into the basin water; (2) POC produced outside the fjord, which has a good chance of ending up in the basin water if it enters just above sill level; (3) POC entering with freshwater. A schematic picture of different sources of POC and oxygen (O_2) entering the basin water is shown in Fig. 1.

In this paper, we explore possible biotic and abiotic reasons for the decline of the minimum oxygen concentration in the basin water of a fjord along the Swedish west coast. We also investigate the different local and remote contributors to the organic matter mineralized in the basin water.

Area description

Different studies suggest a decreasing trend in oxygen content in the basin water of Gullmar Fjord (Fig. 2) from the 1960s up to the beginning of the 1990s (Rosenberg 1990; Kajrup 1996; Nordberg et al. 2000). Negative trends in oxygen concentration (Andersson 1996) and increasing oxygen consumption (Stigebrandt et al. 1996) outside the fjord in the eastern Skagerrak have also been reported.

The fjord is 28 km long and 1–2 km wide with a maximum depth of 120 m. The sill depth is 43 m and the basin water below sill level constitutes about a third of the total volume. Tides are weak in the area with amplitude of 0.15 m, and water exchange mainly takes place by baroclinic processes driven by the slowly varying offshore density field (Arneborg 2004). The fjord is relatively open above sill level. With the rather weak freshwater input of 21 m^{-3} s^{-1}, this means that the waters above sill level are similar to those outside the fjord. The water masses in the fjord are separated vertically into four layers. A thin freshwater layer (~0.5 m) resides on top of the surface layer of Kattegat water (salinity 22–31), which is a mixture of Skagerrak water and water from the Baltic Sea. The third layer, between the Kattegat water and the sill level and the fourth layer (basin water) constitute the Skagerrak water (salinity 31–35).

Typically, the fjord has a diatom spring bloom, with krill as important zooplankton and cod as top predator. In sum-

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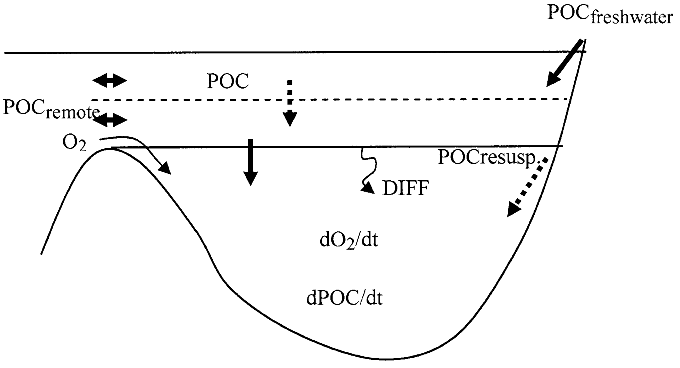

Fig. 1. A schematic picture of different sources of basin water POC and O_2. dO_2/dt is the rate of oxygen depletion, and $d\mathrm{POC}/dt$ is the rate of consumption of POC.

mer, flagellates, cladocerans, and jellyfish are important. The mean value of the gross annual primary production in the outer part of the fjord for 1985–1996 was 241 g C m^{-2} (Lindahl et al. 1998).

Climate change and long-term variability (e.g., the North Atlantic Oscillation [NAO]) influence the ecosystems and the timing and frequency of basin water renewals in the fjords along the Swedish west coast (Josefson and Widbom 1988; Belgrano et al. 1999; Nordberg et al. 2000). During winter, when winds between north and east predominate over Skagerrak (negative NAO index), dense water will come closer to the sea surface in the inner parts of Skagerrak and increase the likelihood of basin water exchange in the fjords along the coast. During winter, when winds between south and west predominate (positive NAO index), freshwater will be retained in Skagerrak and mixed down in the water column (i.e., the water in inner Skagerrak will be less dense). Therefore, one could expect that periods with increasing NAO index will lead to weak or absent renewals, whereas periods with decreasing NAO index will lead to efficient flushing of basin water in the fjords. The last two decades have been dominated by an unusually long period with a positive NAO index, and this period happened to coincide with a period of decrease in the minimum oxygen concentrations in the deeper part of Gullmar Fjord.

The major source of oxygen supply to the basin water of the fjord is relatively oxygen-rich deep water from the Skagerrak. This water originates from levels below the sill level (43 m) and down to about 100 m with salinities of 34–35 (Björk and Nordberg 2003). The basin water in Gullmar Fjord is characterized by a period of inflow during winter followed by a longer stagnation period of typically 9 months, which ends with a new deep-water inflow. This gives a sawtooth appearance of the time series of oxygen concentration in the basin water (Fig. 3). It is seen that low oxygen concentrations in the deep basin of the fjord is not a new phenomenon. The lower panel (Fig. 3) shows a change in the minimum oxygen concentration from about 2 mL L^{-1} to 1 mL L^{-1} in the beginning of the 1970s. A deep-water renewal event in the fjord was described in detail by Arneborg et al. (2004).

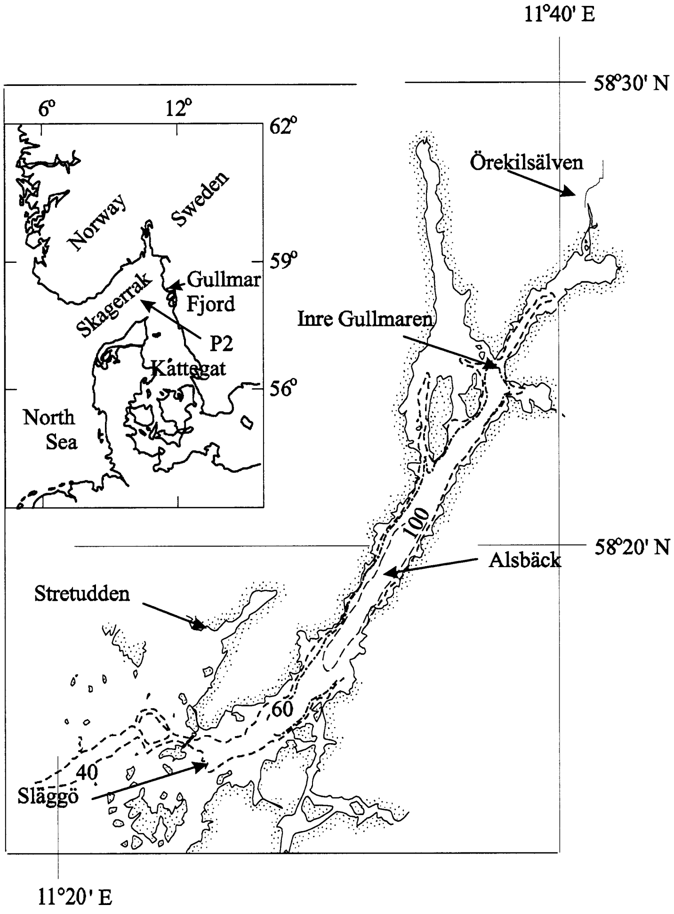

Fig. 2. Map of the Gullmar Fjord.

Methods

The analysis of oxygen consumption from 1903–2002 data at Alsbäck in the deepest part of the fjord was made

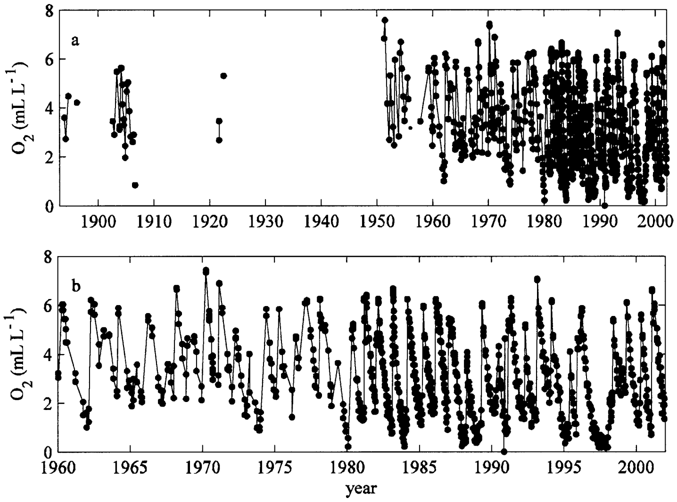

Fig. 3. (a) Oxygen concentration at Alsbäck at 110 m depth from 1893 to 2002. (b) Close-up of the oxygen concentration series between 1960 and 2002.

for stagnation periods, thus excluding periods in which inflows of new basin water were identified by temperature, salinity, and oxygen data.

At low concentration levels, the consumption rate is influenced by factors other than the supply of organic matter because the benthic fauna is seriously affected by oxygen deficiency (e.g., Baden et al. 1990). For this reason, we excluded time periods with oxygen concentrations <1.9 mL L^{-1}. The consumption rate was expressed as a mean rate per month but could not be estimated for every month because of a lack of data. The Winkler method (Winkler 1888) was used to determine the oxygen concentrations and because the systematic error of the Winkler method is smaller than 5% (Golterman 1983), we judged the data to be reliable and included data from the beginning of the previous century in the analyses as well.

The mean consumption of oxygen (CONS) at a certain depth is determined by the temporal change in oxygen (DEPL) shown in measurements, but also by vertical diffusion of oxygen (DIFF) from higher to lower concentration and can be expressed as Eq. 1.

$$\mathrm{CONS}(z) = \mathrm{DEPL}(z) + \mathrm{DIFF}(z) \quad \text{where} \tag{1}$$

$$\mathrm{DEPL}(z) = -\frac{\partial O_2}{\partial t} \quad \text{and} \tag{2}$$

$$\mathrm{DIFF}(z) = \frac{1}{A}\left\{\frac{\partial}{\partial z}\left[A(z)\kappa\frac{\partial O_2}{\partial z}\right]\right\} \tag{3}$$

Here, $A(z)$ is the area of the fjord at depth z, and the vertical coefficient of diffusion, κ, can be parameterized as Eq. 4.

$$\kappa = -\alpha\sqrt{\frac{\rho}{g}\frac{1}{\frac{\partial \rho}{\partial z}}} \tag{4}$$

Here, α is an empirical constant, g is gravity, and ρ is the density. This method to estimate oxygen consumption was discussed in Aure and Stigebrandt (1989). The empirical constant, α, (1.3×10^{-7} m^2s^{-2}) has been estimated from density changes during periods of stagnation in Gullmar Fjord.

A mean vertical profile of oxygen consumption was constructed from all (17) profiles with no missing values, and was used to complete vertical profiles with missing values. When applied, the mean profile was normalized against the observed oxygen consumption at the greatest depth available because the variance of the mean profile decreased with increasing depth, and the resulting relative consumption was adopted to calculate missing values.

Error caused by the filling-in procedure was estimated with the standard deviation of the normalized mean profile, and the resulting error bars are given in Fig. 4. Early data with a relatively long time between observations also has possibilities for errors because of undetected minor inflows. This type of error would lead to an underestimate of oxygen consumption but is not included here.

To find out whether the minimum oxygen concentrations from 1950 to 2002 (Fig. 3) would have decreased without an increase in oxygen consumption, we used a simple model of the minimum oxygen concentration in the basin water. The starting and ending dates of the stagnation period were determined from Fig. 3. We also made an attempt to couple changes in the NAO index and a more regional index (Andersson 2002) to the changes in oxygen conditions in the basin water. To study different sources of organic matter, POC data at 5 and 20 m depths at Brofjorden-Stretudden (hereafter referred to as Stretudden) and Inre Gullmaren from 1990 to 1995 were used. Stretudden is situated about 5 km north of the fjord mouth and was considered representative for the state of coastal water outside the fjord. Monthly measurements of freshwater runoff and nutrients from the Örekilsälven river were used to investigate the importance of local input. Trend analyses of nutrient transports from the Örekilsälven were made with the Kendall test (Kendall and Ord 1990).

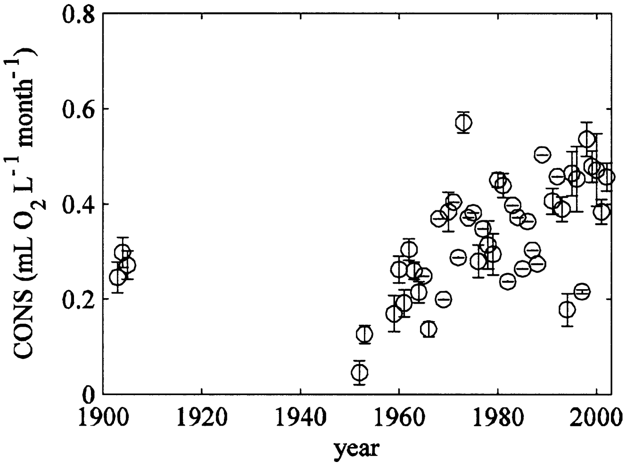

Fig. 4. The integrated oxygen consumption from 50 to 100 m during summer at Alsbäck from 1900 to 2002. The error bars account for errors because of missing data from one or more depths.

Results

Oxygen consumption—The integrated oxygen consumption rate in the basin water from 50 to 100 m was calculated (Fig. 4) according to the method described in *Methods.* Because June and August were the most well represented months during stagnation periods, these months were used for the calculations, but valid data from other months were used if no data from June or August were available. This should be acceptable because we found no pronounced annual variation in the consumption of oxygen (data not shown). Figure 4 shows that the mean integrated consumption of oxygen seems to have increased from about 0.21 mL O_2 L^{-1} $month^{-1}$ in the period 1950–1970 to about 0.35 mL O_2 L^{-1} $month^{-1}$ during the 1970s and the early 1980s and to about 0.41 mL O_2 L^{-1} $month^{-1}$ from 1989 onward. The standard errors for the two earlier periods were about one tenth of the increase in the mean value between periods. This was also the case when comparing statistical values for the increase in oxygen consumption between the last two periods when discarding the two outliers during the 1990s (~0.2

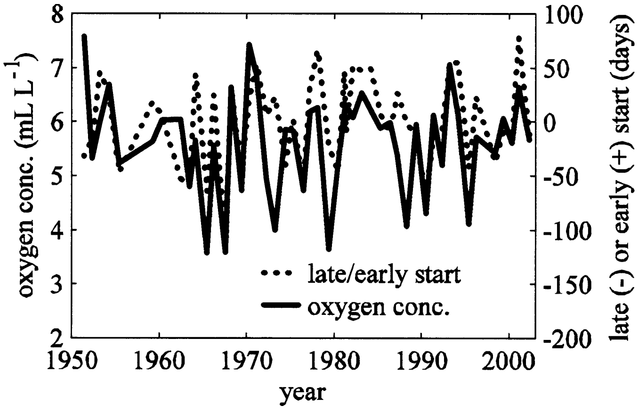

Fig. 5. Maximum oxygen concentrations for each year at 110 m depth (solid line). The dotted line shows how many days later (negative) or earlier (positive) than the mean starting date (26 April) the stagnation period started each year; 1997 is excluded.

mL O_2 L^{-1} $month^{-1}$). We therefore concluded that the increase was significant. The contribution of diffusion (Eq. 3) to oxygen consumption (Eq. 1) varies. In our calculation for shorter periods (months), and close to the bottom (110 m), the mean diffusive flux was about 10% of the consumption during 1986–2002. This is similar to figures reported by Aure and Stigebrandt (1989) for Norwegian fjords.

A simple model of the oxygen minimum in basin water—We used a simple model to find out whether minimum oxygen concentrations decreased without an increase in the oxygen consumption discussed previously. Assuming a constant oxygen removal rate, DEPL (Eq. 2), the minimum oxygen concentration in the deep water of the fjord can be calculated from the variation of physical factors only for each stagnation period. The minimum oxygen concentrations, $O_{2\text{min}}$, then depend on the concentration, $O_{2\text{start}}$, measured at the starting date (Fig. 5), and the length of the stagnation period, T_{stag}, which can be calculated from Fig. 3.

$$O_{2\text{min}} = O_{2\text{start}} - T_{\text{stag}}\text{DEPL} \qquad (5)$$

In this case, we used DEPL instead of CONS because we compare with observed minimum oxygen concentration.

Two different model results, one with constant oxygen depletion (0.29 mL L^{-1} month $^{-1}$) and the other with a tuned oxygen depletion (increasing stepwise from 0.29 to 0.43 mL L^{-1} $month^{-1}$) are shown in Fig. 6, together with observed minimum oxygen data from 110 m depth.

Abiotic effects: In our analyses of the oxygen conditions in the fjord, the year 1973 was chosen to mark the shift from better to worse oxygen condition in the basin water. The shift can be seen in Fig. 3 but is further emphasized in Fig. 7, showing the cumulative frequency of oxygen observations before and after 1973. The frequency of observations of <1 mL O_2 L^{-1} increased from 4% before 1973 to 25% in 1973 and later. The corresponding figures for observations of <2 mL O_2 L^{-1} were 18% and 48%, respectively (Fig. 7). The integrated oxygen consumption shown in Fig. 4 also indicates a change at the beginning of the 1970s compared with the 1960s and earlier.

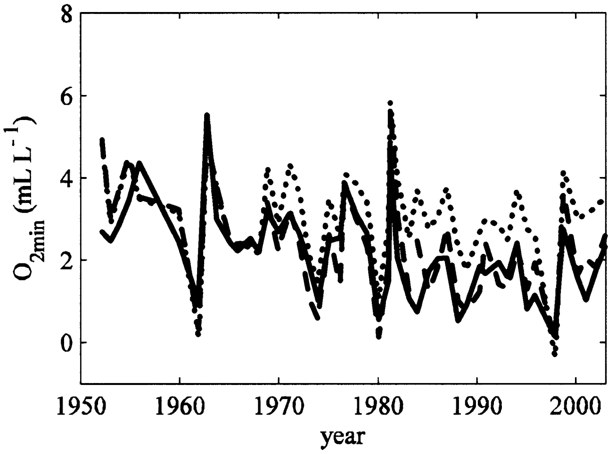

Fig. 6. Calculated oxygen minimum with stepwise increasing oxygen depletion (dashed line), with constant oxygen depletion (dotted line), and with observed oxygen minimum concentration at 110 m (solid line).

The correlation between the calculated oxygen minimum with a constant oxygen consumption and the measured oxygen minimum for 1900–2003 was 0.74, indicating that physical factors are important. However, an increase in the correlation coefficient to 0.84, including a variable consumption rate, suggests that biotic factors must also be considered. All correlation coefficients given are significant at the 0.1% level. The mean values of minimum oxygen concentrations from observations before and after 1973 show that the long-term change was 1 mL L^{-1}. The difference between the mean values of observed and calculated minimum oxygen concentration with a constant consumption rate before and after 1973 was 0.42 mL L^{-1} (dotted line in Fig. 6). The model with constant oxygen depletion thus explained about 40% of the long-term decrease since the 1950s, which suggests that abiotic effects might explain 40% of the observed change in the oxygen minimum.

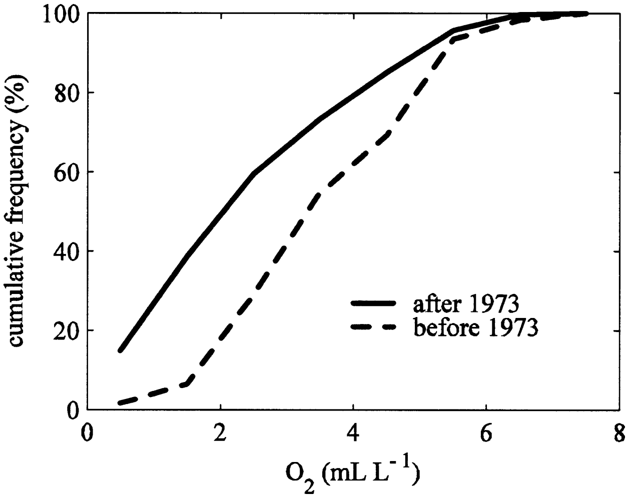

Fig. 7. The cumulative frequency distribution of oxygen observations at 110 m depth from before and after 1973 at Alsbäck. The area between a curve and the horizontal axis is a measure of the "oxygen deficit" during the period.

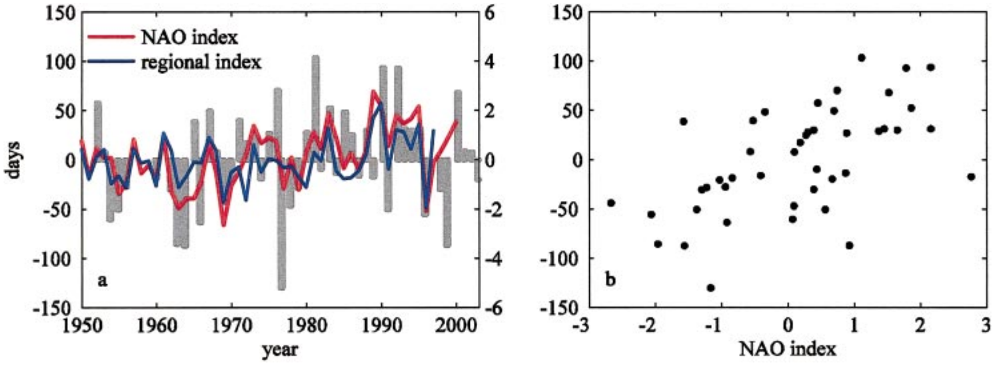

Fig. 8. (a) Later (positive bar) and earlier (negative bar) ending dates of the stagnation period than the mean date (2 January). Also shown are the NAO index (red line) and the regional index (blue line) (Andersson 2002). (b) Later and earlier ending dates of the stagnation period than the mean date (2 January) versus NAO index.

Weak positive correlations (0.24 and 0.28, respectively) were seen between the length of the stagnation period and changes in the NAO index and a regional (North Sea area) index for long-term climate variations (Andersson 2002). The indices are described by the red and blue line in Fig 8a. A stronger pattern related to climate indices was revealed when we analyzed the variations in the starting and ending (Fig. 8a,b) dates of the stagnation period. The mean starting date of the stagnation periods was 26 April, and the mean ending date was 2 January. A later ending date, prolonging the stagnation period, is shown as positive bars in Fig. 8a. The effect of changes in the NAO index on the starting date was not obvious (not shown), but a clear response in the ending date was seen (Fig. 8b), with correlation factors of 0.58 and 0.62 to the NAO index and the regional index, respectively. The calculated mean values for the periods before and after 1973 show that the mean ending date occurred 22.3 days later during the second period. This delayed ending date of about 22 days results at 110 m depth in extra oxygen consumption of 0.38 mL L^{-1}, which is about 40% of the long-term decrease and thus in agreement with our estimate from the model. An early starting date results in a prolonged stagnation period, but it also means more available oxygen to consume because the oxygen content in the Skagerrak water is high, and thereby also the maximum oxygen content in the fjord (Fig. 5). A late starting date, on the other hand, results in a shorter stagnation period but less available oxygen. Therefore, a change in the starting date does not affect the minimum oxygen concentration at the end of a stagnation period as much as a change in the ending date does. Our analyses of the stagnation periods suggest that the major physical effect of changes in the NAO concerns the changes in the ending date of the stagnation periods.

Biotic effects: The model result above suggests that the biotic factors should account for the residual 60%, approximately, of the observed decrease in the oxygen minimum concentration. By including stepwise-increasing oxygen consumption in the model, the correlation coefficient between calculated and observed minimum oxygen concentrations increased to 0.84. To fit the observed data series (solid line in Fig. 6) the model was tuned with an increasing consumption rate (dashed line in Fig. 6). The consumption rates, including the effect of the mean diffusion (10%), were tuned to 0.32 mL L^{-1} $month^{-1}$ in the period 1959–1965, 0.46 mL L^{-1} $month^{-1}$ in 1966–1977, and 0.48 mL L^{-1} $month^{-1}$ from 1978. This means that the oxygen consumption in the model had to be increased by 50% to fit observed data (i.e., a 50% increase in consumption is needed to support the biotic change [60%] of the minimum oxygen concentration).

The estimated integrated consumption on the basis of oxygen observations (Fig. 4) shows an increase of about 65% during the last century, which is in the same range as the model result of about 50%.

Supply of organic matter—The local nutrient input varies with freshwater discharge, leading to large input during spring and autumn and small input during summer. An increased input of nutrients during the productive season could explain a part of the increased oxygen consumption shown in Fig. 4, but applying the Kendall test on the transport of total N and total P from Örekilsälven during the productive season (March–September) for 1972–2004 showed no long-term trend during this period. The concentration of POC in the surface water (5 m) at both Stretudden and Inre Gullmaren followed the annual pattern of production of organic matter, with winter values <0.2 g C m^{-3} and summer values >0.3 g C m^{-3} (Fig. 9a). Little if any seasonal variation was seen below the halocline (20 m; Table 1). The halocline moves up and down between approximately 5 and 20 m depths; to avoid surface water in the analysis of water below the halocline, only water with salinities >30 were used. The small annual variation of POC below the halocline at Inre Gullmaren suggests that most of the POC produced locally stayed in the surface layer, probably because of low sinking velocity and rapid water exchange. Most POC below the halocline in the fjord should then originate from coastal waters. The concentrations showed higher variability and a higher mean value at Stretudden than at Inre Gullmaren (Table 1; Fig. 9b). A rough estimate of the contribution of organic matter to basin water from coastal water can be calculated with the difference between annual mean concentrations of POC (ΔPOC) below the pycnocline at

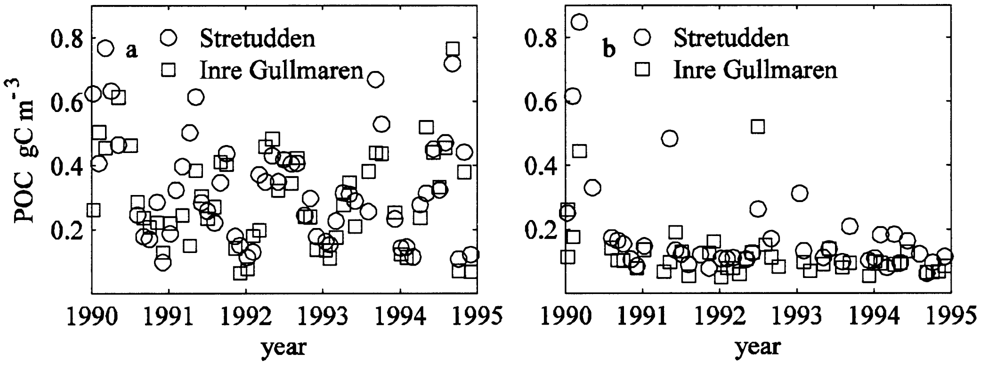

Fig. 9. (a) Concentrations of POC at 5 m depth at Stretudden and Inre Gullmaren. (b) Concentrations of POC at 20 m depth at Stretudden and Inre Gullmaren.

Stretudden and at Inre Gullmaren and the number of exchanges per year (N) and the volume (V) of the intermediate water.

$$\frac{N\ V\ \Delta\mathrm{POC}_{\mathrm{mean}}}{A_{\mathrm{basin}}} \Rightarrow \text{export of POC to basin water} \qquad (6)$$

Here, the horizontal surface area at sill depth is $A_{\mathrm{basin}} = 21 \times 10^6$ m^2 and ΔPOC $= 0.067$ g C m^{-3} (Table 1). On the basis of residence time for water in the third layer (Arneborg 2004), $N \approx 10$. The estimated amount of POC entering the basin water was 23 g C m^{-2} yr^{-1}, which accounts for about 33% of the C needed to sustain oxygen consumption in the basin water (70 g C m^{-2} yr^{-1}). The maximum potential supply from the Skagerrak was 72 g C m^{-2} yr^{-1} and was obtained by replacing ΔPOC in Eq. 6 with the annual mean value of POC at Stretudden (Table 1). The potential supply was thus great enough to cause 100% of the oxygen consumption in the basin water, assuming that the entire amount is biodegradable. For the entire quantity to reach the basin water before it is flushed out again, the sinking velocity should be at least 0.75 m d^{-1} because the residence time of the water below the halocline is about 40 days. The contribution estimated previously of 33% is to be seen as a minimum, and one could argue that the fraction exported to the basin water might be twice as large (66%) because the water has only traveled half the fjord loop at Inre Gullmaren. Assuming that all of the POC is biodegradable is not realistic because it should depend on the composition of the material, but the analysis certainly shows that the Skagerrak water has the potential to be the dominating source of POC.

Table 1. Mean values of POC below the pycnocline (20 m) at station Stretudden and at Inre Gullmaren for 1990–2003. Summer months are March–September and winter months are November–February.

Station	Summer mean (g C m^{-3})	Winter mean (g C m^{-3})	Annual mean (g C m^{-3})
Brofjorden-Stretudden	0.1816	0.1739	0.1789
Inre Gullmaren	0.1282	0.1106	0.1219

Discussion

Abiotic and biotic effects on minimum oxygen concentration—Data from 1893 onward show that concentrations of oxygen <2 mL L^{-1} and even 1 mL L^{-1} is not a new phenomenon in the basin water of Gullmar Fjord (Fig. 3). Even so, the frequency of such low concentrations has increased, in particular during the last three decades (Fig. 7). The decrease in the minimum oxygen concentrations in the basin water between the 1960s and 1990s shown by others (Rosenberg 1990; Kajrup 1996; Nordberg et al. 2000) can partly be explained by an increase in the rate of oxygen consumption and partly by prolonged periods of stagnation, as shown in this paper. The qualitative influence of climate change and long-term variability on the ecosystems and the oxygen conditions in fjords have been discussed by, for example, Nordberg et al. (2000), Ottersen et al. (2001), and Harzallah and Chapelle (2002). However, to the authors' knowledge, no quantitative estimates or estimates of the relative importance of biotic and abiotic factors have previously been presented.

The increase in the integrated consumption rate since the 1950s shown in Fig. 4 was estimated as 100%, but the three values <0.15 mL L^{-1} month^{-1} during the 1950s and the 1960s have a dramatic influence on that estimate. These low values might be a result of minor inflows that were not detected because of a low frequency of observations. A higher consumption than in reality can only be achieved by a mistake during chemical analysis. By including the values for 1903–1905 in the analysis, an increase of 65% is more reasonable. The low frequency of observations during the 1950s and in the beginning of the 1960s might also result in errors in the estimated starting and ending dates of the stagnation periods.

The delay between the increase in oxygen consumption and the decrease in minimum oxygen concentrations in the 1970s was probably due to shorter stagnation periods during those years, demonstrating that physical factors are substantially influencing the minimum oxygen concentration. Our analyses of the stagnation periods suggest that the most important effect of long-term climate variation (e.g., the NAO) on oxygen concentrations in basin water was not as one might perhaps expect for the length of the stagnation period but, mainly, for when the stagnation period in the basin water ended. The mean ending date was 2 January, whereas the mean starting date was 26 April. The closer coupling between NAO and the ending date is probably because the NAO is most noticeable during winter and the index is based on values from November–March. Earlier periods with a positive NAO index should also have led to delayed exchange of the basin water and therefore lower oxygen concentrations, but with lower consumption rates the oxygen conditions were most probably better than today. This is also supported by the findings of Filipsson and Nordberg (2004) that the foraminiferal fauna at the Alsbäck deep did not change to a more opportunistic fauna during a previous positive NAO period during the early 1900s.

Supply of organic matter—Organic matter produced in fjords like the Gullmar Fjord, with a short residence time of water in the surface layer, generally has a small chance to reach the basin water, as shown by Aure and Stigebrandt (1989). They identified import of POM from outside fjords as the usually most important source of oxygen-consuming matter in the basin water. Tiselius and Kuylenstierna (1996) showed that local primary production in Gullmar Fjord can be an important source during bloom situations when coagulation might increase the settling velocity dramatically. Attempts have been made to find trends in primary production in the fjord, but from the results shown in Lindahl et al. (2003), we find that a long-term trend is not evident on the basis of the relatively short observational time series. The contribution from the surface layer is hard to quantify, but it cannot be neglected as a possibly important contributor to the transport of organic matter to basin water. The rather high consumption during winter months found in this paper (not shown) suggests a possible great stock of organic matter in the system, making the consumption insensitive to short-term variations in the supply of organic matter.

The difference in POC concentrations between the second and third layer discussed previously supports the statement that is is difficult for local production to reach the basin water, but the low frequency of data probably misses some bloom occasions. The lower POC concentrations at Inre Gullmaren compared with Stretudden further indicates that the fjord acts as a sink for POC transported into the fjord with the Skagerrak water, which was identified as the most plausible dominating source of organic matter contributing to the oxygen consumption in the basin water. This and the result that the oxygen consumption has increased suggest a possible increase of POC in the Skagerrak water since the 1960s.

The picture that emerges from this discussion is not totally clear and factors other than the increase of nutrients should also be considered. One factor could be that overfishing of the seas affects the ecosystem and possibly leads to reduction of pelagic mineralization in the system, leading to a larger vertical flux of organic matter. However, further research is needed to describe and quantify such effects.

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