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Hydrographical conditions in the Bornholm Basin of importance for oxygenation of the deepwater by pumping down oxygen saturated water from above the halocline

BOX WIN

Technical report no.1

Malin Ödalen &
Anders Stigebrandt

C96
Rapport
Gothenburg 2013

Department of Earth Sciences
University of Gothenburg

GÖTEBORGS UNIVERSITET

UNIVERSITY OF GOTHENBURG
Department of Earth Sciences
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Abstract

The purpose of this report is to present the temperature, salinity and oxygen concentration at different standard depths in the Bornholm Sea. This information is valuable for determination of the depth range of water intakes to water pumps aimed for oxygenation of the Bornholm Basin deepwater. Observations made in the period 1970 – 2010 at the station BY5 located in the Bornholm Sea deep basin were used for the analysis.

The results for the long-term mean values show that salinity increases strongly in the halocline, at depths of 50 – 70 m, and that there is a minimum in mean temperature just above the halocline, which is typical for the Baltic proper. The long-term mean oxygen concentration decreases with depth from the maximum 11.3 – 11.4 g O_2 m^{-3} at 0 – 40 m depth to less than 2 g O_2 m^{-3} at 80m.

The variability is partitioned into three period bands, which include variations shorter than, equal to and longer than one year respectively. We conclude that for temperature the largest variability occurs in the surface layer, due to the annual cycle. Both oxygen and salinity show the largest variability within the halocline, due to many small inflows from the Kattegat. Below the halocline, inter-annual variations are dominant due to long periods of stagnation when there is no water exchange.

For depths below 50 m, there are long-term trends with increasing temperature and decreasing oxygen concentrations. In the depth range 20 – 50 m, annual averages show that higher temperatures have become more common in the late 1980’s and that the vertical salinity gradient has become more pronounced, beginning in the 1990’s.

At a depth of 30 m, oxygen levels are at a maximum and the density is low. Temperature is close to the deepwater temperature and shows relatively low annual variability.

Sammanfattning

Syftet med denna rapport är att presentera temperatur, salthalt och syrgashalt på olika standarddjup. Denna information är användbar för bestämning av lämpligt djupintervall för vattenintag till vattenpumpar med syfte att syresätta Bornholmsbassängens djupvatten. För analysen har vi använt observationer från den hydrografiska stationen BY5 i Bornholmsbassängen under perioden 1970 – 2010.

Analysen visar att salthalten ökar kraftigt i haloklinen, som ligger på djup mellan 50 till 70 m, och att det finns ett minimum för medeltemperaturen strax ovanför haloklinen, vilket är typiskt för Egentliga Östersjön. Medelsyrgashalten avtar med djupet, från maximala 11,3 – 11,4 g O_2 m^{-3} vid 0 – 40 m djup till mindre än 2 g O_2 m^{-3} på 80 m djup.

I en analys delas variabiliteten upp i tre periodband som omfattar variationer kortare än, lika med, samt längre än ett år. Från analysen kan vi dra slutsatsen att den största temperaturvariationen förekommer i ytskiktet och orsakas av årscykeln. Både syrgas och salthalt har sin största variabilitet i haloklinen, vilken orsakas av många små inflöden från Kattegatt. Under haloklinen förekommer långa stagnationsperioder då det inte sker något vattenutbyte och här dominerar därför långa perioder.

För djup under 50 m finns långsiktiga trender med ökande temperatur och minskande syrgaskoncentration. I djupintervallet 20 – 50 m visar serien av årsmedelvärden att högre temperatur har blivit vanligare sedan slutet av 1980-talet och att den vertikala salthaltsgradienten har blivit skarpare, med början under 1990-talet.

På 30 m djup är syrgashalten maximal och densiteten är låg. Temperaturen ligger nära djupvattnets temperatur och har en relativt liten årstidsvariation.

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Preface

Results from the BOX-WIN project will be presented in a series of reports from the Department of Earth Sciences at the University of Gothenburg. A wide range of subjects are covered by BOX-WIN. Technological, environmental, economical and legal facts and circumstances must be considered to develop and locate a full-scale Demonstrator composed of a self-supporting, floating wind mill with a generator producing electric power for deepwater oxygenation by pumping and for delivery to the grid. The Demonstrator will be developed for the Bornholm Basin, which at times has anoxic water in the deepest parts. The projects BOX and PROPPEN have shown that phosphorus leakage from anoxic bottoms may be stopped by oxygenation. The Demonstrator developed by BOX-WIN will hopefully be built and tested in Bornholm Basin. This would be an important step towards installation of a regional system of full-scale floating wind mills with pumps in the Bornholm Basin. An updated list of BOX-WIN reports is given at the end of the report.

The present report “BOX-WIN Technical report no. 1 - Hydrographical conditions in the Bornholm Basin of importance for oxygenation of the deepwater by pumping down oxygen saturated water from above the halocline”, is written by Malin Ödalen and Anders Stigebrandt. The work is funded by the Swedish Agency for Marine and Water Management.

Gothenburg 11 January 2013

Anders Stigebrandt

1. Introduction

The Bornholm Sea has an isolated basin below the 59 m deep sill in Stolpe Channel (Figure 1). The water below the sill, the basin water, is exchanged only when sufficiently dense new deepwater arrives from Kattegat and the Belt Sea via Arkona Sea. Less dense new deepwater is interleaved in the halocline that is centered at about the sill depth. The residence time of basin water varies but can be as long as several years. Oxygen is consumed at a rate determined by the rate of supply of organic matter from the productive layers near the sea surface. In periods when the residence time is long, the deeper part of the basin water may be exhausted from oxygen.

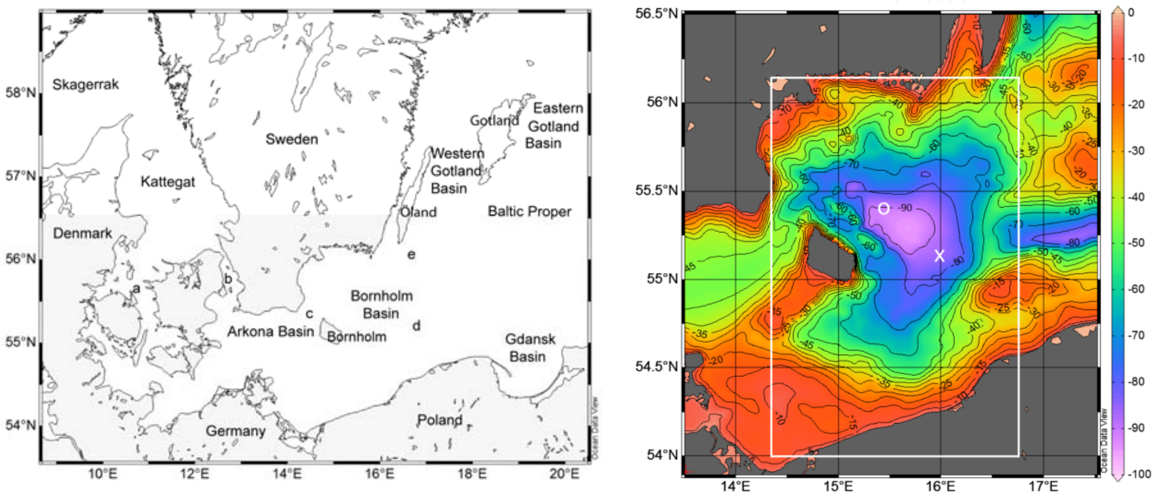

Figure 1. Left panel: Map of the Baltic Sea. Some important topographic features of the Baltic Sea are marked; a- The Great Belt; b – Öresund; c – Bornholm Channel; d – Stolpe Channel; e – Öland Channel. Right panel: a close-up showing the bathymetry of the Bornholm Basin, using the spherical grid topography of the Baltic Sea by Seifert et al. (2001.) The locations of the monitoring stations BY4 and BY5 are indicated by the white circle and cross, respectively. In this report, only data from BY5 are used. (from Stigebrandt & Kalén, 2012)

By pumping less dense, oxygen saturated water from above the halocline down into the basin water of the Bornholm Sea one achieves two effects. One is that the basin water is oxygenated and the other is that the basin water becomes less dense. The latter effect will increase the frequency of inflows of new oxygen rich deepwater and thereby increase the oxygen minimum in the basin water. Thus, due to the rapid rate of density decrease due to pumping new deepwater that otherwise would be interleaved in the halocline may instead penetrate deep into the basin. Oxygenation of the Baltic Proper by pumping well oxygenated water down to the deepwater was suggested by Stigebrandt & Gustafsson (2007).

In this report we describe long-term mean and variability of salinity, temperature and oxygen concentration at different standard depths in the Bornholm Sea. This information may be used to determine the optional depth range of water intakes to pumps.

2. Data

Data used in this report are from the hydrographical station BY5 (N 55° 15.0'; E 15° 59.0') in the Bornholm Sea (Figure 1). These data were retrieved from the database SHARK (Svenskt HavsARKiv) provided by SMHI (the Swedish Meteorological and Hydrological Institute). Data have been developed by SEPA (the Swedish Environmental Protection Agency) within the Swedish coordinated environmental monitoring.

In Table 1a –1c we show the number of observations of temperature, salinity and oxygen made per month and in total at the standard depths in the data series from BY5, between the years 1970 – 2010. These observations are used for calculation of monthly and long-term mean values respectively. Observational data are also plotted.

Table 1a. Number of observations at BY5 of temperature per month and in total per standard depth, 1970 –2010.

Depth	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
0	37	17	36	22	31	41	24	40	31	22	42	19	362
10	38	17	36	22	31	38	24	40	29	22	42	19	358
20	38	16	37	22	30	39	23	40	29	22	41	19	356
30	38	17	37	22	31	39	24	40	29	22	42	19	360
40	38	17	37	20	31	39	22	40	29	22	42	19	356
50	38	17	38	22	31	40	24	40	29	21	41	19	360
60	38	17	38	22	30	41	23	39	29	21	42	19	359
70	38	16	38	22	29	41	24	40	29	22	42	19	360
80	37	17	38	22	31	40	24	40	29	22	41	19	360

Table 1b. Number of observations at BY5 of salinity per month and in total per standard depth, 1970 – 2010.

Depth	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
0	38	16	36	22	31	41	23	41	31	22	42	19	362
10	38	17	37	22	31	38	24	41	29	22	42	19	360
20	38	17	36	22	31	38	22	40	29	22	41	18	354
30	38	17	37	22	31	39	24	41	29	22	41	19	360
40	38	17	37	22	31	39	24	41	29	22	41	19	360
50	38	17	38	22	31	41	24	41	29	22	41	19	363
60	38	17	38	22	31	41	24	41	29	22	42	19	364
70	38	17	38	22	30	41	24	40	29	22	42	19	362
80	37	17	38	22	31	40	24	41	30	22	39	19	360

Table 1c. Number of observations at BY5 of oxygen per month and in total per standard depth, 1970 – 2010.

Depth	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
0	34	15	36	21	31	39	23	37	31	21	40	18	346
10	37	17	37	21	31	36	24	39	29	21	41	19	352
20	36	17	37	21	31	37	23	40	29	20	40	18	349
30	37	16	36	20	31	37	24	39	29	20	39	18	346
40	38	17	37	22	30	38	24	39	29	20	41	19	354
50	38	17	37	22	31	40	24	40	29	20	41	19	358
60	38	17	37	22	31	40	24	40	29	20	41	19	358
70	37	17	37	21	29	41	24	40	29	20	41	19	355
80	38	17	37	22	30	41	23	39	29	20	39	19	354

3. Analyses

From observation for the period 1970 – 2010, we first display the time series to make visible long-term, annual and monthly variations of temperature, salinity and oxygen concentrations for standard depths that range from 0 to 80 m with a 10 m interval. Then we make a formal partition of the total variability into the three period bands considered.

The long-term variance of the time series at each standard depth, *Var(tot)*, can be analyzed by a partition into three period bands (Stigebrandt, 2012); one for the part caused by variations with periods shorter than one year, *Var(< 1)*, one for variations with the period one year (the annual cycle), *Var(=1)*, and one for the part caused by variations with periods longer than one year, *Var(> 1)*. Thus,

$$Var(tot) = Var(<1) + Var(=1) + Var(>1) \qquad (1)$$

The analysis follows the same scheme as in Stigebrandt (2012). Thus, we begun by computing the total variance, *Var(tot),* for each depth using all data from the observation period 1970 – 2010. The monthly averages describe the mean annual cycle. The variance of these monthly averages is *Var(=1).* In the next step, the monthly mean values were subtracted from the original time series. This step aims to obtain a series that is free from influence from the annual cycle. From this time series a series of annual averages was computed. The variance of this series of averages represents the inter-annual variability and is denoted *Var(>1).* Finally, by a few simple algebraic operations, Equation (1) is used to compute the remaining term, *Var(< 1),* which describes short-term variability. It should be noted that due to the low sampling rate, the variability of shorter periods is present in the observations but cannot be quantified. This variability is spread over the three period bands in an unknown way. This problem, called aliasing, is further discussed in e.g. Stigebrandt (2012).

The water density for each standard depth was computed from the observations of temperature and salinity using a standard routine.

4. Results

Long-term means and standard deviations have been calculated using all measurements between 1970 and 2010 at standard depths (Table 2).

4.1 Long-term means

Salinity increases slowly from 7.5 in the upper 20 m to 7.8 at 40 m (Table 2). At 50 m it reaches 8.9 and then it increases strongly in the halocline, in the depth interval 50 – 70 m, which is centered on about the sill depth (59 m) of the outlet through Stolpe Channel. The temperature long-term mean first decreases with depth. It reaches a minimum of 5°C at 40 – 50 m depth and then increases again in and below the halocline (between 6 – 7°C). The results for the long-term mean temperature are typical of the Baltic proper with a minimum just above the halocline. The long-term mean oxygen concentration is very similar, 11.3 – 11.4 g O_2 m^{-3}, from 0 to 40 m depth. At 50 m it has dropped to 9.8 g O_2 m^{-3}. The concentration then decreases continuously with depth and is less than 2 g O_2 m^{-3} at 80 m.

Table 2. Long-term mean values and standard deviations between 1970 and 2010 of temperature (°C), salinity and oxygen (g O_2 m^{-3}) at selected standard observational depths.

Depth (m)	Temp (°C)	± StD T	Salinity	± StD S	Oxygen (g m^{-3})	± StD O_2
0	9.6	5.6	7.5	0.3	11.4	1.5
10	9.2	5.4	7.5	0.3	11.4	1.5
20	8.2	4.6	7.5	0.3	11.3	1.5
30	6.4	3.4	7.6	0.3	11.4	1.4
40	5.0	2.2	7.8	0.4	11.3	1.3
50	5.0	2.0	8.9	1.3	9.8	2.1
60	6.4	2.4	12.1	1.7	6.7	2.3
70	6.8	1.8	14.7	1.1	3.6	2.2
80	6.9	1.7	16.0	0.9	1.9	2.4

4.2 Long-term variability

The largest variability of temperature (see Table 2) occurs in the surface layer due to the annual heating-cooling cycle. The largest variability of salinity and oxygen occurs below the sill depth. It is due to the long periods of stagnation between water exchanges during which salinity decreases steadily due to vertical diffusion and oxygen decreases due to biological consumption although vertical diffusion delays the response. Below we discuss the variability of salinity, temperature and oxygen concentration that is due to the seasonal cycle and inter-annual variability.

4.3 Inter-annual variability

The tables in section 2 show that the number of observations in different years varies. To get a reasonable picture of inter-annual variations in the upper 50 m, we have added to the data series the long-term monthly mean for months when observations are lacking at one or all standard depths. In Figure 2 we show the in this way completed time series of annual means from 1970 to 2010 between 20 and 50 m depth. This depth range was chosen because pump intakes will be somewhere within this interval, above the halocline but below the productive surface layer.

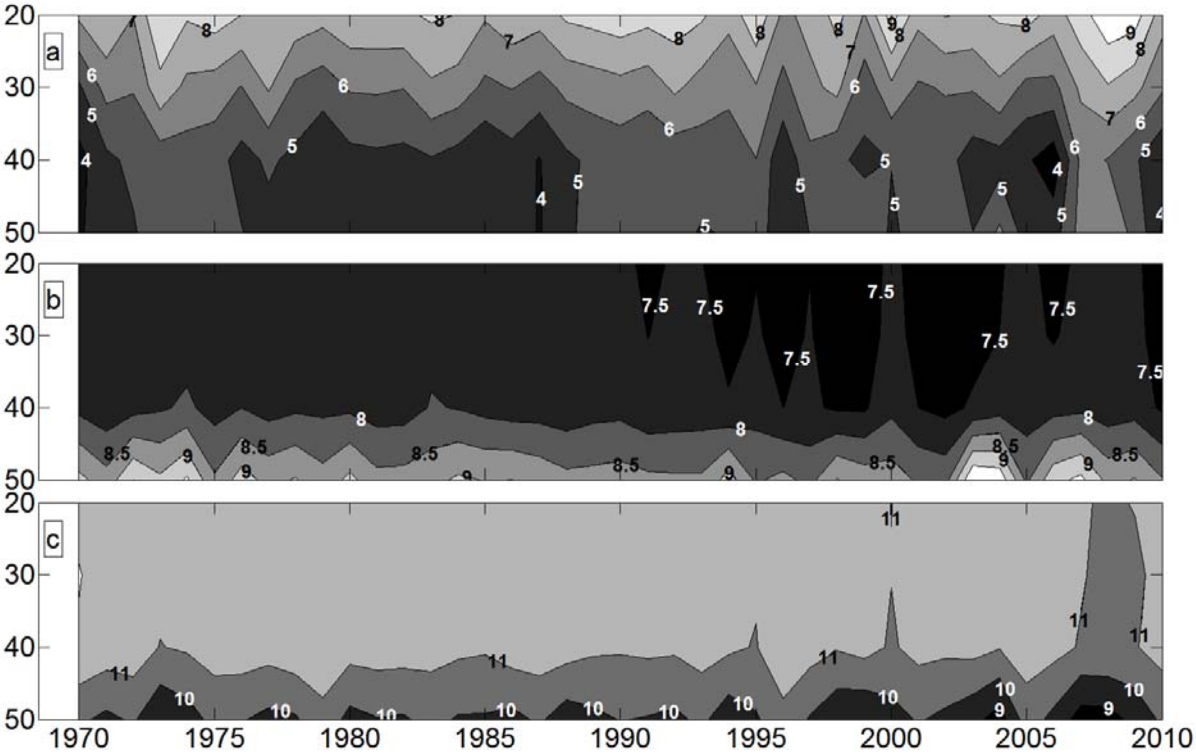

Figure 2. Time series of annual means of a) temperature (°C), b) salinity, and c) oxygen (g O_2 m^{-3}) between 20 and 50 m depth, from 1970 to 2010.

The time series in Figure 2 indicates that, within the depth range 20 – 50 m, higher temperatures have become more common since the late 1980's, with annual averages reaching 9°C at 20 m and 6°C at 50 m. This can be compared to the long-term means in Table 2, which are 8.2 and 5.0°C respectively. After 1990, the water at 20 – 30 m has become fresher with annual average salinities commonly below 7.5 and during the 2000s the water at 40 – 50 m has become saltier, occasionally reaching annual average salinities above 9.5. The oxygen levels have been relatively stable until the year 2000. During the 2000s, oxygen levels dropped slightly throughout the depth interval. This is most likely due to the higher temperatures at which the oxygen saturation is lower.

In Figure 3 we show the time series of observations in the depth interval 50 – 80 m between 1970 – 2010. Since the time scale of this part of the basin is longer than one year we have not replaced missing values by monthly means. One may see that the lower part of the basin show little seasonal variability. Instead the variability is inter-annual. There is no evident trend in salinity but the temperature has increased and oxygen concentrations have decreased in later times.

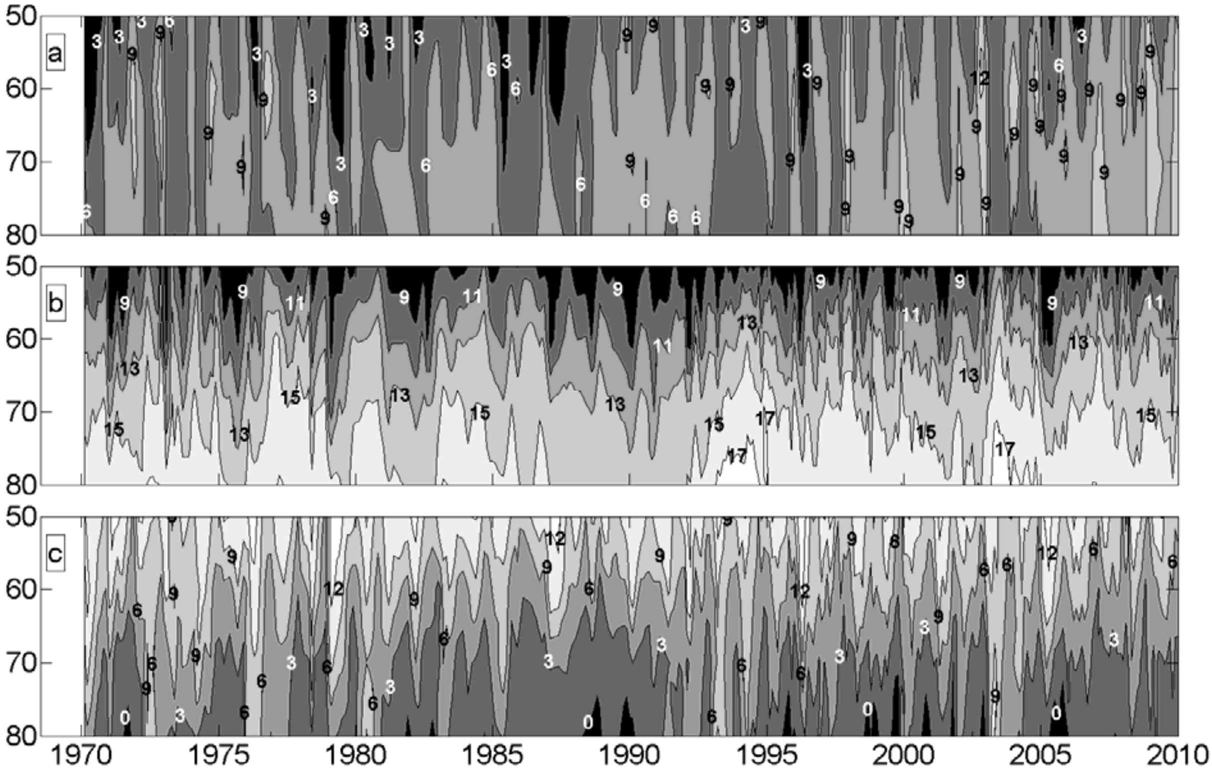

Figure 3. Time series of observations of temperature (°C), b) salinity, and c) oxygen (g O_2 m^{-3}) between 50 and 80 m depth, from 1970 to 2010.

4.4 Seasonal variability

In Figure 4 we show the seasonal cycles based on monthly means from 0 to 50 m depth for all observations made between 1970 and 2010. The surface layer shows effects of annual cycles in heating/cooling, precipitation/runoff and algal bloom/decomposition.

Oxygen saturation levels, calculated from salinity and temperature monthly means, are shown in the bottom panel of Figure 4. Comparing mean oxygen values in panel c) with the saturation levels in panel d), we see that the surface waters are supersaturated with oxygen in spring, whereas they are under-saturated during the autumn. At 40 – 50 m depth the water is in general under-saturated with oxygen.

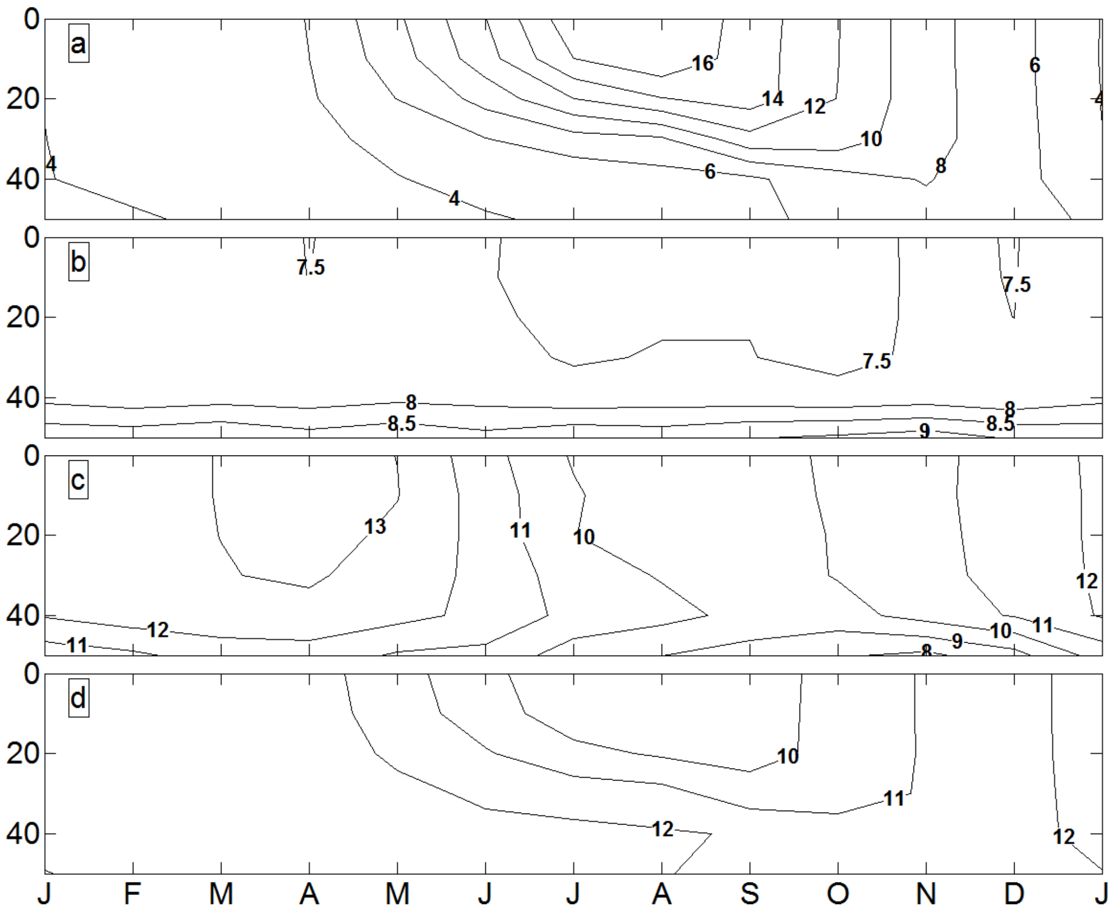

Figure 4. Mean seasonal cycles of a) temperature (°C), b) salinity, c) oxygen (g O_2 m^{-3}) and d) oxygen saturation (g O_2 m^{-3}) between 0 to 50 m depth.

4.5 Variability in summary

In order to get an overview of the variability of water properties in the Bornholm Basin and its causes, the variance analysis described in section 2 was performed. The results are seen in Figure 5 where the square root of the variance, the standard deviation, of each property at different depths and for different period bands is presented.

The subdivision of the total variance into period bands reveals that above and within the halocline, the temperature variations are mainly due to the annual cycle (Figure 5a). Salinity (Figure 5b), on the contrary, shows small variability on shorter time scales above the halocline and is mostly affected by long-term variations. Within the halocline, salinity variations are more rapid due to frequent inflows of new water from the Kattegat. However, these inflows are rarely dense enough to reach all the way down into the deep basin water. Thus, below the halocline, scarce inflows and slow diffusion being the main causes for variability, time scales longer than a year are once again dominating.

Density variations (seen in Figure 5c) are governed by the variations in temperature and salinity. Above the halocline, where temperature varies strongly with the annual cycle while salinity is more stable, density shows similar variability as temperature. In consequence, most density variations above the halocline occur on an annual basis. Within the halocline, salinity variability is large both on short and longer time scales and density varies according to the same pattern. From 70 m depth, temperature varies only little in all three bands while salinity variations are dominated by periods longer than one year which is hence also the case for density variability.

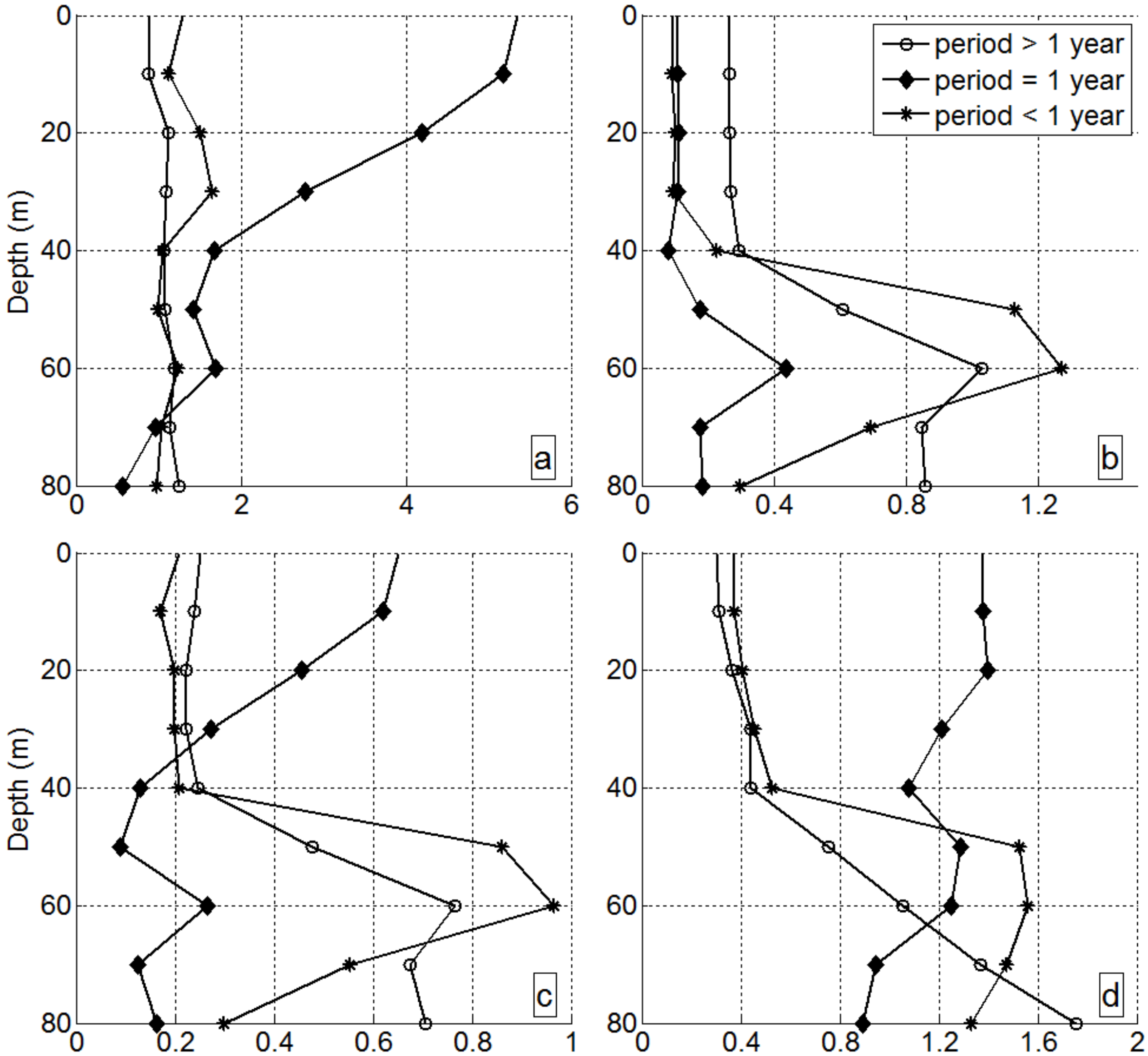

Figure 5. Standard deviation of a) temperature (°C), b) salinity, c) density (kg m^{-3}) and d) oxygen (g O_2 m^{-3}) partitioned into three period bands including periods longer than one year, the period equal to one year and periods shorter than one year respectively, c.f. Equation (1).

Variations in oxygen concentration (Figure 5d) above the halocline mainly follow an annual cycle. This is connected to the solubility of oxygen which changes with temperature and to oxygen production by algal blooms. Within the halocline, frequent smaller inflows from the Kattegat, which are not dense enough to replace the deep basin water, often bring new oxygen. Hence, short time scales are dominating the variations in the depth range 50 – 60 m. The influence of long period variations increases with depth and, as for density, the variability below the halocline occurs mostly on longer time scales. Inflows replenishing oxygen reserves at these depths are rare and, between these inflow events, slow processes of diffusion and oxygen consumption are governing the variability.

5. Considerations regarding the construction of intakes and exits of water pumps

It has been suggested that one may oxygenate the deepwater of the Baltic Proper using a system of pumps. A pump prototype (demonstrator) and a test system for the Bornholm Basin are under construction in BOX-WIN. Stigebrandt and Kalén (2012) showed that the deepwater in this basin may be kept oxygenated by pumping about 800 $m^3\ s^{-1}$ of oxygen saturated winter water to the largest depth of the basin, where the pumped water is forced to mix with the surrounding water. So far we have pumping experience from the pilot experiment in the By Fjord (the BOX-project – see www.marsys.se) where we pump 2 $m^3\ s^{-1}$ of surface water into the deepwater.

A key question is if there is a practical upper limit of the size of a single pump. It is important that the intake of the pump may withdraw selectively water from only a specified layer with optimal properties. The intake has to be designed so that the pumping meets this requirement. It is also important that the pumped fluid can mix efficiently with the ambient fluid at the exit depth, which in the Bornholm Basin is greater than 90 m. The flux of ambient basin water towards the mixing zone at the exit of the pump must not limit the mixing. The aim of the present chapter is just to recall that these questions must be regarded in the pump design.

5.1 Selective withdrawal of winter water

It is well known that selective withdrawal of a specified water layer in a stratified fluid requires that the flow speed at the intake is low relative to the speed of relevant internal waves of higher vertical modes. If this is the case, baroclinic dynamics may arrange flow from a limited depth interval towards the intake. The thickness of the flow towards an intake as a function of the stratification, measured by the local buoyancy frequency N, and the flow speed at the intake, can be computed using the theory for 3-dimensional selective withdrawal presented in Steen and Stigebrandt (1980). For the discussion of the present case we may simplify the problem and require that the horizontal velocity through the intake should be maximum U_{max} m s^{-1}. For a pumped flow Q this means that vertical cross-sectional area A of the intake should be

$$A = Q/U_{max} \qquad (2)$$

Example: $Q = 33$ m^3 s^{-1} and $U_{max} = 0.2$ m s^{-1} gives $A = 165$ m^2. NB! The actual value of U_{max} is determined by the actual speed of higher modes of internal waves, which has to be determined from stratification data.

5.2 Mixing by outlet jets

If the required total initial mixing by the jets at the outlet equals a factor of 10, the inflow along the sea bed towards the pump must be 1100 m^3 s^{-1} if the pumped flow equals 100 m^{3}s^{-1}. Assume that the initial mixing occurs in a virtual vertical cylinder of height H and radius R centered on the pump. The vertical cross-sectional area of the mixing zone is then $2 \cdot \pi \cdot R \cdot H$. The speed of the flow towards the mixing zone cannot be greater than the speed of higher modes of internal waves in the bottom layer. If this is 0.1 m s^{-1} and $H = 10$ m, the radius R of the mixing zone should then be at least 160 m. Thus, local internal wave dynamics determines R. The actual values of the speed of higher modes of internal waves have to be estimated from stratification data. With $R = 160$ m one has to use pipes to arrange so that the mixing occurs sufficiently far away from the pumping device.

6. Discussion and conclusions

When pumping water from above the halocline into the deepwater with the objective to oxygenate this water, it is desirable that the oxygen level in the pumped water is as high as possible. The long-term mean values (Table 2) indicate that this requirement will be met if the intakes to the pumps are placed in the depth interval 20 to 40 m. In this interval, annual averages as well as long-term mean values are above 11 g O_2 m^{-3}. It is also desirable that the density of the pumped water is low in order to get a rapid decrease of density of the basin water. This requirement is fulfilled for all depths down to 40 m.

Concerns have been raised that pumping might cause a mean increase in deepwater temperature. However, the long-term mean temperature of the deepwater is higher than the temperature in the depth interval 30 to 50 m. Thus, if pump intakes are placed somewhere within this depth range, pumping should instead lead to a cooling of the deepwater.

If pump intakes are located above 25 m depth, the seasonal variations seen in Figure 4 may temporarily heat the deepwater during autumn, but this will be compensated by cooling in the winter and spring months.

It is finally concluded that an interval centered on 30 m might be ultimate for pump intakes. Here, oxygen levels are at a maximum, the density is relatively low and the long-term mean temperature is somewhat lower but still close to the deepwater temperature and the annual variation in temperature is small. If the pumped flow equals 1000 m^3s^{-1}, the pumped volume under one year equals about 30 km^3. This corresponds to an about 1.4 m thick layer since the area of the Bornholm Sea at 30 m depth equals 22 450 km^2 (Seifert et.al., 2001). There is thus enough of water of the preferred quality.

7. Acknowledgements

This work was funded by the Swedish Agency for Marine and Water Management. SMHI and SEPA are acknowledged for providing the necessary data for this study.

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BOX-WIN Technical Report Series

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