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Millennial changes of the Baltic Sea salinity

Studies of the sensitivity of the salinity to climate change

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Abstract

An important question for safety assessments of nuclear waste repositories is the salinity of the Baltic Sea under different conditions. The salinity affects the potential recipient ecosystems, the water turnover along the coast and the hydrology as well as the groundwater chemistry.

In this report a model that enables computation of the Baltic Sea salinity for different sea level positions and freshwater supplies is presented. The model is used to compute the salinities in Baltic proper, Bothnian Sea and Bothnian Bay for all combinations of global sea level changes from –10 m to 10 m and freshwater supplies from 0 to 60,000 m^3/s. The results are presented in a series of graphs that enables the reader to make an assessment of the impact of a given climatic change. The model is also used to compute the decrease of the salinity in Bothnian Sea and Bothnian Bay during the next few millennia due to the postglacial uplift.

The results show that modest changes in global sea level, say +/– 1 m, give a salinity change of the order of 1 psu in southern Baltic proper. Changing the freshwater supply with about 2000 m^3/s (approximately 10%) gives a similar salinity change. Further, a sea level drop of about 5 m or an increase of the freshwater supply by a factor of 3 is needed to reduce the salinity in southern Baltic proper below 1 psu. In this limit large parts of the Baltic would be limnic. A 50% decrease of the freshwater supply increase the salinity in the southern Baltic proper by a factor of 2 to some 15 psu, but the effect is even more drastic in Bothnian Sea and Bothnian Bay where the salinity increase to 13 and 10 psu, respectively.

A less windy climate might have a significant effect in lowering the Baltic salinity due to a combined effect of lowered mixing in Kattegat and lowered exchange between Kattegat and the Baltic. A windier climate will not have such strong effect since increased mixing does not affect the Baltic as much.

Most probably the shoreline displacement due to isostatic adjustment after the previous glaciation will dominate the salinity variations in the Bothnian Bay during the coming few millennia. The salinity will gradually decrease until 1750–2000 years from now when the Bay becomes a lake.

Sammanfattning

För att kunna utvärdera säkerheten hos kärnavfallsanläggningar är salthalten i Östersjön en viktig faktor. Salthalten påverkar potentiella recipient ekosystem, vattenomsättning i kustbandet samt grundvattenhydrologi och kemi. I denna rapport presenteras en modell för beräkning av salthaltens variation i Östersjön beroende på variationer i globala vattenståndet och färskvattentillförseln till Östersjön. Modellen används för att beräkna salthalterna i egentliga Östersjön, Bottenhavet och Bottenviken för alla kombinationer av förändringar av globalt vattenstånd mellan –10 och +10 m och färskvattentillförslar mellan 0 och 60 000 m^3/s. Resultaten presenteras i en serie grafer som gör det möjligt för läsaren att göra en utvärdering av effekterna från ett givet klimatscenario. Beräkningar av hur salthalten förändras i Bottenhavet och Bottenviken förändras under de kommande tusentalen år på grund av landhöjningen.

Östersjöns salthalt bestäms av utbytet genom de danska sunden. Utbytet beror i sin tur på en rad av faktorer av vilka de viktigaste är de dagliga variationerna i vattenståndet i Kattegatt som driver vatten in och ut från Östersjön, färskvattentillförseln till Östersjön samt blandingen mellan Östersjö och Nordsjövatten i Kattegatt som skapar den mix av vatten som tränger in i Östersjön. Modellen består av två delmodeller. En delmodell beräknar den dagliga vattentransporten genom de danska sunden och beskriver netto effekten av dessa transporter på salttransporten. Nettoeffekten används i den andra delmodellen som beräknar salthalterna. Förutsättningarna för modellresultaten är att vindklimatet inte förändras och att den dagliga variationen i vattenstånd i Kattegat inte förändras. I rapporten diskuteras hur stor betydelse dessa begränsningar har för resultaten.

- Resultaten visar att relativt blygsamma förändringar i globala vattenståndet, t ex en ökning (minskning) av vattenståndet med 1 m, ger en förändring på 0,8 psu (–1,5 psu) i södra Östersjön. Salthaltsförändringen är alltså ungefär dubbelt så stor för sänking av vattenståndet som för höjning. En förändring av färskvattentillförseln med 2000 m^3/s (motsvarar ca 10 %) ger en motsvarande effekt. Detta kan vi betrakta som det intervall av förändringar som inte ger drastiska förändringar i Östersjön jämfört med de variationer i salthalt som observerats under de senaste 100 åren.

- Modellen visar att en global vattenståndssänkning med ca 5 m eller en ökning av färskvattentillförseln med en faktor 3 är nödvändig för att sänka salthalten i södra Östersjön till under 1 psu. Vid denna gräns blir stora delar av Östersjön i det närmaste limniska.

- En halvering av färskvattentillförseln ökar salthalten i södra Östersjön med en faktor 2 till 15 psu, men effekten blir ännu större i Bottenhavet och Bottenviken där salthalterna ökar till 13 respektive 10 psu.

- Vid ett mindre blåsigt klimat minskar både blandingen i Kattegat och vattenutbytet mellan Kattegat och Östersjön, vilket kan ge en relativt stor effekt i form av reducerad salthalt i Östersjön. Blåsigare klimat förväntas inte ge riktigt så stor effekt eftersom ökad blanding i Kattegat inte har så stor effekt som minskad blandning.

- Relativt stor höjning av globala vattenståndet behövs för att ge stora effekter på salthalten. En höjning med 10 m behövs för att öka salthalten i södra Östersjön till 15 psu.
- Troligtvis kommer landhöjningen att dominera salthaltsutvecklingen i Bottenviken under de 1750–2000 åren det tar innan innanhavet förvandlas till en sjö.

Contents

1 Introduction

1.1 Project background and objective

An important question for safety assessments of nuclear waste repositories is the salinity of the Baltic Sea under different conditions. The salinity affects the potential recipient ecosystems, the water turnover along the coast and the hydrology as well as the groundwater chemistry. This report describes computations of salinity in the Baltic Sea that can be used to complement scenarios of future fate and effects of radionuclide exposures.

This project is a continuation of an investigation of the salinity variations in the Baltic during the past 8500 years /Gustafsson and Westman, 2002; Westman et al, 1999/. In that study, proxy data for salinity was compared with computations using a simple hydrodynamic model. One of the experiences was that the hydrodynamic model was quite suitable for analyzing changes in Baltic Sea salinity on these time–scales and it was found natural to continue the development of this tool.

The objective of this project was primarily to give an indication of extreme values of the Baltic Sea salinity that might occur during the time–span before next glaciation.

Specific scenarios of the approach to the next glaciation is available /Morén and Påsse, 2001/ but they are not detailed enough to provide magnitudes of the governing driving forces of the Baltic Sea salt exchange. This is especially so for freshwater supply to the Baltic. Instead, we explore circulation and equilibrium salinity during periods of drastically different climatic conditions and sea level positions. Therefore, we believe that our results can be useful when discussing effects from different scenarios. An exception is that the changes in salinity due to postglacial uplift on the Bothnian Sea and Bothnian Bay are computed as time-series. The reason to do this computation is that postglacial uplift clearly is a large, maybe even dominating, effect in at least Bothnian Bay.

1.2 Oceanography of the Baltic Sea

The exchange between the Baltic Sea and the Ocean is limited due to the shallow sills and a large transitional area. The present freshwater surplus is about 16,000 m^3/s. The combined effect of limited exchange and high freshwater supply makes the present salinity rather low, ranging from about 12 in the deepwater of Baltic proper to about 3 in the surface waters of Bothnian Bay. Further, due to the same reasons the Baltic is permanently salt stratified. The intermittency and variability inflows of saline water in combination with limited diffusive vertical exchange make regularly the deep-water of Baltic proper stagnant, with oxygen depletion as a consequence.

Several investigations have quantified the sensitivity of the salinity to changes in freshwater supply and oceanic exchange /Gustafsson, 1997a; Gustafsson, 1997b; Gustafsson, 2000b; Gustafsson and Westman, 2002; Omstedt et al, 2000; Stigebrandt, 1983; Westman et al, 1999/. However, all these investigations dealt with relatively small changes in environmental conditions. /Rodhe and Winsor, 2002/ and /Stigebrandt and Gustafsson, 2003/ have exploited how large the freshwater supply needs to be to force the Baltic Sea to become a freshwater lake. These two investigations gave quite diverging results where /Rodhe and Winsor, 2002/ found that the salinity would become negligible already for a 25% increase of the supply, while /Stigebrandt and Gustafsson, 2003/ found that the supply needs to increase by a factor of 4. The latter figure has also been confirmed recently by /Meier and Kauker, 2003/.

In the long-term perspective, the Baltic Sea undergoes a continuous gradual change due to postglacial uplift and sea level change. About 8500 years ago the present Baltic estuary was formed when the Danish straits opened and seawater could intrude the Baltic basin. During this time span the Baltic Sea salinity has varied substantially, increasing from zero to 10–15 around 6000–5000 years ago and there after reduced to 8–10 by 3000 years ago. During the past 1500 years or so the salinity seems to have been about the same as now. /Gustafsson and Westman, 2002/ showed that the salinity variations are not only caused by postglacial uplift and sea level variations, but also variations in freshwater supply has contributed especially to the salinity maximum 5–6000 years ago.

The present day surface salinity is only 7 to 8 psu in the Baltic proper and even less in Bothnian Sea, Bothnian Bay and Gulf of Riga. The halocline of the Baltic proper is located at 60–80 m depth and below this the salinity increases to 11–13 psu, see e.g. /Samuelsson and Stigebrandt, 1996/ for a discussion on the salinity variations during the last 40 years. Inflows of salty water through the Danish Sounds are the source of salt for the Baltic Sea and since the halocline is much deeper than the sill depth there is no possibility for the Baltic deep water to return directly through the Danish Sounds. Thus, the water exchange through the Danish Sounds is very important for the hydrographic conditions in the Baltic Sea. Instantaneous flows across the sills are an order of magnitude greater than the average. The variability of the flows is of crucial importance for the effective salt transport across the sills. The Belt Sea and Öresund are both usually strongly salt stratified because of the fluxes of low saline water from the Baltic Sea and of high saline water from the Kattegat to the lower layers.

The hydrography of Kattegat is characterized by a quite sharp halocline at about 15 m depth dividing the surface mixed layer with a salinity of 15 to 25 psu from the deep water with salinity 32 to 35 psu /Svansson, 1975/. The deep-water layers are filled from the north with Skagerrak water and are successively emptied by wind-forced vertical entrainment into the surface layer. The Kattegat-Skagerrak front puts a clear marking line between the seas. The position of the front is somewhat variable, but it appears that the most common position for it is to take off at Skagen and heading to the northeast /Gustafsson and Stigebrandt, 1996/. In general, frontal dynamics force the outflow from the surface layer of the Kattegat to enter the Skagerrak along the Swedish coast.

There is however large spatial variations in salinity throughout the Baltic Sea and changes in the horizontal salinity distribution can be expected if the distribution of freshwater supply changes and when the topography changes due to postglacial uplift. /Stigebrandt and Gustafsson, 2003/ analysed how the salinity in the three main basins Bothnian Bay, Bothnian Sea and Baltic proper change in response to varying freshwater supply.

Changes in the vertical stratification, and consequently changes in stagnation periods etc, can also be anticipated primarily due to changes in freshwater supply and winds. /Stigebrandt, 2003/ have recently discussed the mechanisms regulating the ventilation of the deep-water of Baltic proper. Following this work and the work by /Gustafsson and Andersson, 2001/ that describe the forcing mechanisms of major inflows there are ongoing research attempting to model how the deep-water reacts to climate change. Promising preliminary results were recently presented /Gustafsson and Stigebrandt, 2003/, but further research is necessary before reliable results can be published.

2 Sensitivity of the overall Baltic Sea salinity to changes in mean sea level and freshwater supply

As mentioned in the introduction, the overall salinity the Baltic Sea is sensitive to changes in the freshwater supply as well as to changes in the exchange with the ocean. The exchanges between the Baltic basins can be coupled with a model of the exchange with the North Sea. Thereby the response of the horizontal salinity distribution to changing freshwater supply and mean sea level can be computed. /Stigebrandt and Gustafsson, 2003/ presented such computations. They used a somewhat simpler model of the salinity in Kattegat compared to the one presented here and the response to changing sea levels were not analysed.

Any long-term forecast will be utterly uncertain since information is lacking on the climate development. Therefore, we present a sensitivity analysis that gives the equilibrium Baltic Sea salinity for wide ranges of freshwater supply and mean sea level change.

2.1 Model description

The model for the salinity of the Baltic Sea is a modification of the model presented in /Gustafsson, 1997b; Gustafsson and Westman, 2002; Westman et al, 1999/. All parameter values are given in Table 2-1.

2.1.1 The barotropic water exchange

In order to analyse how topographic changes in the Danish Sounds, primarily in the Öresund, affect Baltic Sea salinity it is necessary to calculate the changes of the oscillating flow. In this Section we review some basics of channel flow and discuss the influence of topographic changes.

The flow of homogeneous water through a channel is primarily forced by the pressure gradient caused by a sea-level difference between the adjacent basins. During steady-flow conditions, the pressure gradient force is balanced by frictional forces against the walls and bottom of the channel and by large-scale topographic drag due to acceleration in contractions /Stigebrandt, 1980; Stigebrandt, 1992/. The latter actually causes turbulence downstream of the contraction. In the case of a stratified channel there might be an additional pressure gradient due to differences in density between the connected basins /Mattsson, 1996/ and additional resisting forces due to transfer of energy to internal waves /Stigebrandt, 1999/. These effects of stratification are detectable but still quite small and in the present investigation uncertainties about the stratification are so large that the inclusion of the effects of stratification on the water flow through the Danish Straits seems superficial.

Following, e.g. /Stigebrandt, 1992/, the current speed through a channel reads,

$$u|u| = \frac{g\Delta\eta}{\frac{1}{2} + C_d L \frac{W+2H}{WH}}. \tag{2-1}$$

Here g is the acceleration of gravity, $\Delta\eta$ the sea-level difference between the basins, C_d a drag coefficient, L the length of the channel, W the width of the channel, and H the depth of the channel. The flow, Q, is easily found by multiplying with the cross-sectional area as the equation is already averaged across the channel.

$$Q = C_T \frac{\Delta h}{\sqrt{\Delta h}} \tag{2-2}$$

Where the transmission coefficient is given by

$$C_T = WH \sqrt{\frac{g}{\frac{1}{2} + C_d L \frac{W+2H}{WH}}}. \tag{2-3}$$

In the case of present-day flow across the Darss and Drogden Sills, the transmission coefficients have been found by tuning Equation (2) towards observations /Carlsson, 1998; Jakobsen et al, 1997; Jakobsen and Ottavi, 1997; Jakobsen and Trebuchet, 2000; Mattsson, 1995; Mattsson, 1996; Stigebrandt, 1992/. The most recent values are

$$C_T = \begin{cases} 0.63 \cdot 10^5 \; m^{5/2} s^{-1} & \textit{Öresund} \\ 1.67 \cdot 10^5 \; m^{5/2} s^{-1} & \textit{Belt Sea} \end{cases}. \tag{2-4}$$

In order to explain the empirical value in Equation (2-4) for the Straits and the value obtained by inserting the dimensions of the channel into Equation (2-3) one finds, first, that the frictional force is an order of magnitude larger than the resistance due to contraction and second, that the friction must be of a considerable magnitude over the whole length of the Straits, not only at the sill. Further, as the width of the Straits is much larger than the depth and the frictional forces are dominant, Equation (2-3) can be approximated with good accuracy by the following,

$$C_T = WH \sqrt{\frac{gH}{C_d L}}. \tag{2-5}$$

By assuming the channel length and the drag coefficient to be constant, variations of the oscillating barotropic flow can be calculated from Equation (2-2) and (2-5) based on time-series of topographic changes. For simplicity a time-varying topographic factor can be defined so that

$$C_T = \alpha C_{T0}, \tag{2-6}$$

where C_{T0} is the present flow resistance, as in Equation (2-4), and the topographic factor α is defined as

$$\alpha = \frac{WH^{3/2}}{W_0 H_0^{3/2}}, \tag{2-7}$$

or

$$\alpha = \frac{A_C \sqrt{H}}{A_{C0}\sqrt{H_0}} \tag{2-8}$$

where A_C is the cross-section area and H mean depth. Zero in subscript denotes present conditions.

From a new digital topographic chart with approximately 1 km resolution /Seifert et al, 2001/, the changes of the topography due to sea level change has been computed. The effect on the barotropic flow is computed similarly as in /Gustafsson and Westman, 2002/, that is the momentary flow is given by

$$Q = (\alpha_S C_{TS} + \alpha_B C_{TB}) \frac{\eta_K - \eta_B}{\sqrt{|\eta_K - \eta_B|}} \tag{2-9}$$

where η_B and η_K are the sea levels in the Baltic Sea and the Kattegat, respectively. C_{TS} and C_{TB} are transmission coefficients for the Öresund and Belt Sea for present topography and α_S and α_B are topographic factors that change with sea level position according to Equation (2-8). Thus, Equation (2-9) enables separation of the flows through Öresund and Belt Sea, respectively.

A complication is that a change of the flow resistance in one of the straits will be somewhat compensated for by flows through the other. Therefore, it is necessary to evaluate the net change in magnitude of the oscillating flow by using a simple time-dependent model of the Baltic sea level. Following /Stigebrandt, 1992/, the Baltic sea level is given by

$$A_B \frac{d\eta_B}{dt} = Q + Q_F \tag{2-10}$$

Here A_B is the surface area of the Baltic Sea, η_B the sea level of the Baltic and Q_F the freshwater supply to the Baltic. Equation (2-9) gives the flow across the two sills.

When computing the exchange, the variations of the surface area of the Baltic Sea need also to be taken into account. For sea level changes less than +/– 10 m, a simple linear relation can approximate the surface area (cf also Figure 1).

$$A_B = \begin{cases} A_{B0}(1 + 0.013 \times z) & z < 0 \\ A_{B0}(1 + 0.01 \times z) & z > 0 \end{cases} \tag{2-11}$$

Here A_{B0} is the surface area of present Baltic Sea and z is the variation in mean sea level.

The sea-level model defined by Equations (2-10) and (2-9) is forced by observed sea-level variations in the Kattegat for a length of time sufficient to give accurate statistics of the flow variability. Note that the results do also vary with freshwater supply via

Equation (2-10), so computations need to be repeated for each combination of sea level and freshwater supply change.

2.1.2 The steady-state salinity model

The salinity model computes the salinities in the Baltic Sea and the upper layer salinity and depth in Kattegat. A schematic of the model with notation indicated is drawn in Figure 2. This description starts with describing how the salinity in the southern Baltic proper is computed, thereafter how the salinities in Bothnian Sea and Bothnian Bay are computed. Notable is that the salinity in southern Baltic proper is not dependent of the latter computations, nor should it be sensitive to changes in these seas.

As pointed out by /Stigebrandt and Gustafsson, 2003/, the model presented in /Gustafsson, 1997b; Gustafsson and Westman, 2002; Westman et al, 1999/ does not take into account the feedback on the oscillating exchange that arises when the freshwater supply is changed drastically. Instead of using a separate oscillating flow, we do now directly compute average inflows and outflows through the Danish straits, so that the salt balance may be written

$$S_0 = S_{IN} \frac{Q_{IN}}{Q_{OUT}} \qquad (2\text{-}12)$$

Daily flows are computed using the channel model described above and then averages of Q_{IN} and Q_{OUT} computed. The volume that enters the Baltic during a specific inflow event, V_i, can be integrated from the volume flow

$$V_i = \int_{\tau_i} Q dt \qquad (2\text{-}13)$$

If V_i is larger than a given volume V_F, that represents frontal excursions that prohibits efficient salt exchange, then salt is transported into the Baltic. So Q_{IN} is computed from

$$Q_{IN} = \frac{1}{T} \sum_i \max\left[V_i - V_F, 0\right] \qquad (2\text{-}14)$$

A similar expression for Q_{OUT} is easily derived.

The salinity of inflowing water is given by the similar parameterisations as in /Gustafsson, 1997b; Gustafsson and Westman, 2002/. In the model, the upper layer of the Kattegat and Belt Sea is treated as a single water mass (box), while the lower layer is treated as a dynamically passive source of water and salt. A principal sketch of the model is shown in Figure 2. In steady state the volume and salt conservation of the box yield,

$$-Q_G + Q_E + Q_F = 0 \qquad (2\text{-}15)$$

$$-SQ_G + S_D Q_E + S_0 Q_{OUT} - S_{IN} Q_{IN} = 0 \qquad (2\text{-}16)$$

Equation (2-15) expresses volume conservation of the Kattegat/Belt Sea box, where Q_G is the geostrophic outflow to the Skagerrak, Q_E is the entrainment flow from the lower layer and Q_F ($=Q_{f1}+Q_{f2}+Q_{f3}$)is the net supply from the Baltic Sea (freshwater input). Equation (2-16) expresses the conservation of salt in the upper layer of salinity *S*, where S_D is the salinity of the lower layer, S_0 is the salinity of the Baltic, and Q_{IN} and Q_{OUT} are the effective fluctuating flows across the sills. Conservation of salt in the Baltic Sea is also required, as shown in Equation (2-12).

The geostrophic flow and the entrainment velocity, w_E, are calculated from

$$Q_G = \frac{g\beta(S_D - S)h^2}{2f} \tag{2-17}$$

$$w_E = \frac{2m_0 u_*^3}{g\beta(S_D - S)h} \tag{2-18}$$

where *h* is the depth to the pycnocline in the Kattegat-Belt Sea, *f* the Coriolis parameter, *g* the constant of gravity, β the contraction coefficient of seawater due to addition of salt, m_0 the efficiency of turbulent mixing with respect to work against the buoyancy forces and u_* the friction velocity.

The hypsographic function of the Kattegat-Belt Sea shows that the horizontal area *A(h)* decreases approximately linearly with depth and at a depth of about 15.5 m the area is 50% of the area at the sea surface. However, we need to adjust the hypsographic function of the Kattegat/Belt Sea as mean sea level is changed. The hypsography shows that a linear relationship between area and sea level is valid within the range of sea level changes we consider here. This means that the entrainment flow in Kattegat/Belt Sea can increase when sea level rises since the horizontal area of the halocline increase.

Using Equations (2-15) to (2-18) and the hypsographic function one can deduce analytical expressions for salinity and halocline depth in the Kattegat/Belt Sea. These are

$$h = \frac{C_M(2h_m + z) + FQ_F}{C_M + Q_F} \tag{2-19}$$

$$S = S_D\left[1 - \frac{F}{h}\right] \tag{2-20}$$

F is the freshwater height given by

$$F = \sqrt{\frac{2fQ_F}{g\beta S_D}} \tag{2-21}$$

and C_M a parameter defined by

$$C_M = \frac{m_0 u_*^3 A_0}{g\beta S_D h_m}. \tag{2-22}$$

Here A_0 is the surface area of the Kattegat.

The inflowing salinity, S_{IN}, is in reality a complex function of the dynamics of the straits and Kattegat. /Gustafsson and Andersson, 2001/ devised semi-empirical relationships that demonstrated that much of the variance is due to frontal movements. However, those relationships were rather complex and also heavily tuned to present climate. Therefore they are not really applicable in this investigation. There are also dynamic models available that could be used, e.g. /Gustafsson, 2000a; Gustafsson, 2000b; Omstedt and Axell, 1998/, but these models need much more complex forcing data to be run which makes them not so suitable to demonstrate the main features of the system. Knowing that we need a better parameterisation we will here only assume that

$$S_{IN} = \gamma S + (1-\gamma) S_0 \tag{2-23}$$

were γ is a constant that we choose based on present day conditions. Thus, we have two unknown empirical parameters, γ and V_F, that in reality most probably are functions of both mean sea level position and freshwater supply. Further investigations are needed to elucidate how these mechanisms can be parameterised well. However, we discuss below the sensitivity of the results to changes in these parameters. Tuning the model with present day sea level and freshwater supply we find that $\gamma = 0.5$ and $V_F = 10\times10^9$ m^3 give results consistent with observations.

The salinity difference between the surface waters in neighbouring basins is due to the dynamics of the strait connecting the basins. The dynamics of the straits connecting sub-seas within the Baltic Sea are simpler than the dynamics of the Danish Straits and therefore salinity differences between sub-basins are easier to predict.

The flow from the Bothnian Sea to the Baltic proper is baroclinic and in geostrophic balance. This is similar to the flow from the Kattegat to Skagerrak, i.e. Equation (2-17), but since the halocline in Bothnian Sea is located deeper than the sill the flow is controlled by sill depth rather than halocline depth. Thus, the flow is computed from

$$Q_{s1} = \frac{g\beta (S_{n1} - S_1)(h_{SK} + z)^2}{2f} \tag{2-24}$$

where S_{n1} is the salinity flowing in from northern Baltic proper, S_1 is Bothnian Sea salinity and h_{SK} is a representative depth of the Southern Kvark. Using conservation equations similar to Equations (2-15) and (2-16) one finds that the salinity of the Bothnian Sea is given by

$$S_1 = S_{n1} - \sqrt{\frac{2fS_{n1}\left(Q_{f1} + Q_{f2}\right)}{g\beta\left(h_{SK} + z\right)^2}} \tag{2-25}$$

where Q_{f1} and Q_{f2} are the freshwater supplies to Bothnian Sea and Bay, respectively. The salinity in northern Baltic proper, S_{n1}, is substantially lower than the salinity in the south, S_0, computed above. Here we assume that northern Baltic proper water comprises of an equal mix of southern Baltic proper water and Bothnian Sea water, that is $S_{n1} = \frac{1}{2}(S_1 + S_0)$.

In straits where the width is smaller than the internal radius of deformation the effect of the earth rotation becomes small. This is the case in the Northern Kvark and here the exchange will be limited by baroclinic hydraulic control /Stommel and Farmer, 1953/. This concept implies that there exist a so-called critical section in the strait where

$$\frac{u_1^2}{g\beta(S_1-S_2)h_1}+\frac{u_2^2}{g\beta(S_1-S_2)h_2}=1. \qquad (2\text{-}26)$$

Here $u_{1(2)}$ is the velocity and $h_{1(2)}$ is the thickness of the upper (lower) layer. The conservation of volume and salt in the Bothnian Bay is given by

$$\begin{aligned} Q_{s2} &= Q_{n2}+Q_{f2} \\ S_1Q_{n2} &= S_2Q_{s2} \end{aligned} \qquad (2\text{-}27)$$

Combining Equation (2-26) with the conservation laws one can obtain the following equation /Stigebrandt, 1975; Stigebrandt, 1981/:

$$P^3\left(1+\frac{\eta^3}{(1-\eta)^3}\right)-2P^2+P=\frac{\eta^3}{F_e^2} \qquad (2\text{-}28)$$

Here, $P = Q_{s2}/Q_{f2}$, where $Q_{s2} = u_1h_1W$ is the outflow from the Bothnian Bay, $\eta = h_1/(h_{NK} + z)$, $h_{NK} + z = h_1+h_2$, W is the width of the strait and the estuarine Froude number F_e is defined by

$$F_e^2=\frac{Q_{f2}^2}{g\beta S_1\left(h_{NK}+z\right)^3W^2}. \qquad (2\text{-}29)$$

Equation (2-28) has (two) real roots only when $F_e \le 1$. The baroclinic flow is maximal when the two roots become equal. This does not necessarily happen depending on the rate of mixing in the estuary and the topography of the strait, but if it happens the estuary is defined as overmixed /Stommel and Farmer, 1953/. A baroclinic control of this kind may be superseded by strong barotropic flows. This is the case in, for example, southern Öresund. /Stigebrandt, 2001/ showed that the exchange of Bothnian Bay through the Northern Kvark can be explained if the Bothnian Bay is regarded as an overmixed estuary. Here we use Equation (2-28) to compute the flow Q_{s2} and then the salinity S_2 is computed using

$$S_2=S_1\frac{Q_{s2}-Q_{f2}}{Q_{s2}}. \qquad (2\text{-}30)$$

Parameter name	Symbol	Value
Acceleration of gravity	g	9.8 m/s^2
Contraction coefficient of salt	β	$8 \cdot 10^{-4}$
Salinity in deep Kattegat	S_D	33.5 psu
Coriolis parameter	f	$1.2 \cdot 10^{-4}$ s^{-1}
Mixing efficiency	m_0	0.6
Mean depth of Kattegat	h_m	15.5 m
Friction velocity in Kattegat	u_*	0.013 m/s
Surface area of Kattegat	A_0	43,300 km^2
Frontal volume	V_F	10 km^3
Mixing ratio in Kattegat	γ	0.5
Freshwater supply to Baltic proper	Q_{f0}	9280 m^3/s (58%)
Freshwater supply to Bothnian Sea	Q_{f1}	3200 m^3/s (20%)
Freshwater supply to Bothnian Bay	Q_{f2}	3520 m^3/s (22%)
Sill depth in Southern Kvark	h_{SK}	40 m
Sill depth in Northern Kvark	h_{NK}	20 m
Sill width in Northern Kvark	W	3300 m
Surface area of Baltic Sea	A_{B0}	370,000 km^2

Table 2-1: Parameters used in the model in the standard configuration.

2.2 Results

The change in topography of the straits due to sea level change is computed in several cross-sections. The locations are shown in Figure 3. The cross-section areas, mean depths and strait widths are computed from the digitised topography for different mean sea levels and the results are drawn in Figures 4 and 5. These changes result in changes in the frictional resistance according to Equation (2-8). α for each cross-section is drawn in Figure 6. The different cross-sections in the Belt Sea give similar values on α, thus a single α representative for the overall flow resistance is easily defined here. In the Öresund α is clearly smaller for negative mean sea level changes in the Drogden cross-section, while for increased sea levels the minimal α is found at the other sections.

Using the minimal α found for each strait and sea level change, Q_{IN} and Q_{OUT} is readily computed using present day external sea level forcing. Computations where made for varying freshwater supply between 0 and 60,000 m^3/s and the result is presented in Figure 7 in form of the ratio between Q_{IN} and Q_{OUT}. As indicated by Equation (2-12), this ratio determines the difference between inflowing and outflowing salinity. In extremes, with low sea level and high freshwater supply the flow becomes nearly unidirectional and the exchange becomes the Baltic becomes a lake with outlets through the straits. There is an asymmetry where for a given freshwater supply the change in ratio is larger for decreased sea level than for increased sea level. This is due to the effect of the shallow and wide cross-sections in the Öresund and Belt Sea limiting the flow for decreased sea levels while for increased sea levels these cross-sections become less limiting than deeper and narrower cross-sections, see Figure 6.

The computed southern Baltic salinity, S_0, as function of sea level change and freshwater supply is drawn in Figure 8. The salinity change is larger for a sinking than for rising sea level as would be expected from the flow ratio shown above. With present day freshwater supply (16,000 m^3/s) a rise of the sea level with one meter would cause the salinity to increase by 0.8 psu while a lowering of the sea level with one meter would cause a decrease in salinity of 1.5 psu. Further, a sea level drop of about 5 m would reduce the salinity of the Baltic to below 1 psu and obviously force the conditions in northern Baltic into a limnic state. The results show that the Baltic environment might not be so influenced by a sea level rise that is hypothesised to occur in relatively near future due to the greenhouse effect. The changes due to variations in freshwater supply are significant, but a fourfold increase is necessary to force the Baltic into being a lake. A more probable scenario could be that the freshwater supply decrease due to significantly colder climate when approaching a new glaciation. Figure 8 shows that a 50% reduction of the freshwater supply, which could correspond to no runoff in northern Baltic Sea, the surface salinity in southern Baltic increase to about 15 psu.

The salinities in Bothnian Sea and Bothnian Bay for different sea levels and freshwater supplies are shown in Figures 9 and 10. Here the freshwater supply is changed in proportion to the distribution of present day river runoff to the Baltic Sea. For modest changes in sea level and freshwater supply, the absolute changes in salinity follow the results for southern Baltic proper rather closely. However, a closer look at the results revile that the salinity difference between Baltic proper and Bothnian Sea or Bay increase for increasing sea level and decreasing freshwater supply. The relative change in Bothnian Bay is quite large even for modest changes due to the low salinities.

Other climatic changes might cause changes in the salt exchange; some of these are previously explored and found to have minor influence. However, for clarity we compute the sensitivity of the salinity in southern Baltic proper due to changes in wind mixing, deep water salinity and sea level variability in Kattegat. In Figure 11, the salinity in southern Baltic proper is drawn against friction velocity converted to wind speed for simplicity, deep water salinity and standard deviation of sea level variations in Kattegat. The friction velocity is computed from the cubic root of the mean wind cubed, i.e. $\overline{w_f} = \sqrt[3]{\overline{w^3}}$, where the overbar represents temporal average. Therefore, the present conditions are characterized by a seemingly high wind speed, i.e. 11 m/s. The sea level forcing of the model is varied by multiplying the time-series with a varying factor, thus all frequencies are changed by the same factor. The sea level variations are changed by multiplying the forcing time series with a factor whereby the amplitude is varied.

Figure 11 shows that the salinity is much more sensitive to decreased wind mixing than increased. This confirms previous investigations by /Gustafsson, 2000b; Gustafsson and Westman, 2002; Stigebrandt, 1983/. The Baltic salinity decreases to 4.5 psu for a decrease in wind speed of 50%, while it only increases with 0.5 psu for a 50% increase in wind speed.

Changes in the sea level variability in the Kattegat have a significant influence on the salinity. Figure 11 shows that changing the sea level variability (in terms of standard deviation) with 50% reduce (increase) the salinity to 4 psu (10.5 psu). The sensitivity for smaller changes is about 1 psu per 10% change. This is a higher sensitivity than previously reported by /Gustafsson and Westman, 2002/, probably because the new method to compute the efficient exchange.

Salinity can change in the deep layer of Kattegat, S_D, due to changing conditions in the North Sea or even Atlantic in general. The model experiments shown in Figure 11 demonstrate that at least in the range S_D = 30–36 psu, the change of southern Baltic proper salinity is 0.24 psu per one psu change in S_D. Thus, the salinity of the Baltic is rather insensitive to changes in S_D, which confirms previous results by e.g. /Stigebrandt, 1983/.

2.3 Validity of the results

The model is based on a series of assumptions and the validity of these needs to be examined.

Sensitivity to model parameters

There are two major parameters in the model, γ that represents the mixing ratio between Kattegat surface water and southern Baltic proper water of the water that flows into the Baltic, see Equation (2-23), and V_F that represents the volume of water that needs to pass the sills before an efficient salt exchange occur, see Equation (2-14). In Figure 12, the Baltic salinity is drawn for different combinations of γ and V_F. The model results shown above are for $\gamma = 0.5$ and $V_F = 10\times10^9$ m^3 giving a southern Baltic proper salinity of 8 psu. Figure 12 shows that 8 psu can be obtained for other combinations of γ and V_F as well, ranging from $\gamma = 0.27$ and $V_F = 0$ to $\gamma = 1$ and $V_F = 25\times10^9$ m^3. It is not surprising to find that there is a range of combinations that reproduce observed salinity because the two processes are giving similar effect, changing the efficiency of salt exchange. To further elucidate the models sensitivity to these parameters, the southern Baltic proper salinity is computed for the same range in freshwater supply and sea level change as above but using the two extreme combinations of γ and V_F given above. The results (Figure 13) show that the model gives similar results for both combinations, however, the salinity is more responsive in the case $\gamma = 1$, $V_F = 25\times10^9$ m^3 and less responsive in the case $\gamma = 0.27$, $V_F = 0$ compared to the standard case. Thus, the model results are not very sensitive to the choice of these parameters.

Other climatic effects

For large deviations in mean sea level one can expect that the sea level variations in Kattegat will change. /Gustafsson and Andersson, 2001/ showed that the sea level variations at frequencies relevant for Baltic Sea salt exchange is closely related to the regional scale east-west winds (= north-south air pressure difference). This indicates that the salt exchange is mostly due to wind set-up. The simplest form of wind set-up is when considering a constant wind blowing over a closed basin. In this case the pressure force due to sea level slope in the basin is adjusted to balance the wind stress, i.e.

$$g\eta_x = \frac{\tau^{wind}}{\rho H}. \tag{2-31}$$

Here η_x is the surface slope, g is acceleration of gravity, H the depth of the basin, ρ the density and τ^{wind} the wind stress. This simple consideration indicate that for a given wind forcing and basin geometry the sea surface slope, and hence the sea level variations, would increase if depth decrease, i.e. if mean sea level drops. This could somewhat counteract the lowering of Baltic salinity due to shallower sills. However, to definitely close this matter a more elaborate evaluation of the causes for sea level variability in Kattegat would need to be done. One can also note that changes in the flow through the straits are proportional to α, which in turn is proportional to the depth of the strait raised to the power 3/2 and linearly the width of the strait (Equation (2-7)), but only proportional to square root of the sea level difference between the Kattegat and the Baltic (Equation (2-9)). Thus, if the sea level variability changes according to Equation (2-31), it would still only influence exchange by a factor of $H^{1/2}$, which is less than the change in resistance in the straits.

Present tides are quite weak in the Kattegat with amplitudes of only 5–20 cm. This is partly due to dissipation of tidal energy in the North Sea and partly to the location of an amphidromic point just outside Skagerrak. An amphidromic point is where the tides diminish due to interaction of two or more tidal waves. In this case, one tidal wave is propagating along the shores of the North Sea and one through the Norwegian trench and these meets just outside Skagerrak. In case of a mean sea level change this pattern could change causing the tides in Kattegat to become quite significant. In principle one could imagine tidal amplitudes of several meters if the bathymetry becomes favourable for tidal resonance. If that happens tidal mixing would keep the Kattegat completely mixed in the vertical. In that case one might still assume that the exchange with Skagerrak is geostrophic, but following Equation (2-17) with the depth of Kattegat instead of a surface layer depth. The entrainment flux would be replaced by a compensating horizontal flow of Skagerrak water. Under these conditions, the salinity in northern Kattegat is given by

$$S = S_D \left(1 - \frac{F}{2h_m + z} \right) \tag{2-32}$$

where F is given by Equation (2-21). Assuming present day conditions, i.e. Q_F = 16,000 m^3/s, γ = 0.5 and Q_{IN}/Q_{OUT} = 0.5, the salinity in southern Baltic proper can be computed from Equations (2-12), (2-21), (2-32) and (2-23). It shows that a complete vertical mixing of Kattegat would results in a salinity increase from 8 to 9.8 psu. This calculation demonstrates the sensitivity of Baltic Sea salinity to that type of change, but it is hardly realistic since a dramatic change in tidal amplitudes cannot occur without a significant mean sea level change. A prognosis of tides and tidal mixing for different sea level variations is beyond the scope of this report, but can readily be performed using a two-dimensional model such as in /Gustafsson, 2003a/.

Changes in the dynamics of Kattegat

Intuitively, one could expect that such large deviations in mean sea level and freshwater supply would cause drastic changes in the circulation in the Kattegat. This is, however, not really the case if the model results are to be believed. In Figure 14 and 15, the pycnocline depth and surface salinity in the Kattegat is drawn as function of freshwater supply and mean sea level. The model predicts relatively modest changes in pycnocline depth and smooth variations in salinity. The range of variations does not indicate the drastic changes that probably are necessary to change the powerful geostrophic balance of the outflow, which is the crucial assumption.

If the pycnocline depth were to be reduced significantly one could expect that deep-water could intrude directly into the Baltic over the sills. There are indications that this happens occasionally today providing a minor source of salt for the Baltic /Stigebrandt, 1983/. The model results show that the pycnocline depth does not decrease so much with increasing freshwater supply, so for present sea level one would not expect a large change in the inflow of Kattegat deep water over the sills. For decreasing mean sea level, the pycnocline depth decreases less than the depth of the sills decrease, which means that deep-water inflows would become less probable. However, for increasing mean sea level the pycnocline depth increase less than the depths of the sills. Thus, one would expect that more high-saline deep water would intrude directly into the Baltic if the sea level increases. Thus, the model prediction of salinity in the southern Baltic for increased mean sea level can be underestimated.

3 Predictions of effects from observed postglacial shoreline displacement

Since the shoreline displacement in northern Scandinavia is significant, see Figure 16, we can anticipate large changes in the exchange of the northernmost basins of the Baltic Sea relatively soon. As a basis for a forecast of salinities in Bothnian Sea and Bothnian Bay the present shoreline displacement as obtained from sea level observations is used. However, the method presented is general and computations can easily be redone for other scenarios. We assume that the shoreline displacement in the Baltic entrance is negligible and that the river runoff and sea level variability in the Kattegat remain constant. Further, we assume that even though salinity change in Gulf of Bothnia there will not be any salinity change in southern Baltic proper. This might not be entirely realistic, but the effect can be estimate using a model that takes mixing into account, e.g. the model by /Gustafsson, 2003b/.

3.1 Bothnian Sea

At present the salinity of the Bothnian Sea is about 1 psu lower than in northern Baltic proper. Assuming a freshwater supply of 7000 m^3/s to the whole Gulf of Bothnia, the effective sill depth h_{SK} in Equation (2-25) is about 40 m. We can compute the change in Bothnian Sea salinity due to rising of the Southern Kvark sill by modifying Equation (2-25). This equation gives salinity difference across the Southern Kvark for shoreline displacement z_{sd} as a function of present salinity difference ΔS and effective sill depth h_{SK}.

$$\Delta S_{up} = \frac{\Delta S}{1 - \frac{z_{sd}}{h_{SK}}} \qquad (3\text{-}1)$$

The shoreline displacement in the Southern Kvark is about 5 mm/year, which implies that the salinity difference will only change rather slightly during the next couple of thousand years, see Table 3-1.

Years from now	Shoreline displacement	Salinity difference
0	0	1
1000	5 m	1.14
2000	10 m	1.33
3000	15 m	1.6
4000	20 m	2.0

Table 3-1. Shoreline displacement and predicted salinity difference across the Southern Kvark.

3.2 Bothnian Bay

The Northern Kvark is only about half as deep as Southern Kvark and the shoreline displacement is even higher. Therefore we can expect a larger response on the salinity due to shoreline displacement. The Northern Kvark has two narrow channels; each about 20 m deep, but the eastern channel has a rather wide archipelago-like shallow region whereas the western channel has steeper sides. It has earlier been shown that as a first approximation one can treat these two channels as a single channel with depth h = 20 m and width W = 3300 m /Stigebrandt, 2001/. We assume this single representative channel for our computations. Further, we assume that the width of the channel does not change when depth decrease. We solve Equation (2-28) using a present day inflowing salinity of 5.5 psu, but lowering the salinity using the results in Table 2 in the predictions. The results are presented in Table 3. From the results we see that the present rate of salinity decrease is approximately 0.1 psu/century. The Bothnian Bay will become a freshwater lake sometime within 1750–2000 years from now. This should be regarded as a conservative estimate since the change in channel width has not been considered. Further, we have not considered potential effects by decreased salinity in Bothnian Sea due to decrease salinity in the outflow from Bothnian Bay.

Years from now	Shoreline displacement	Inflowing salinity	Bothnian Bay salinity
0	0	5.5	3.8
500	4	5.43	3.4
1000	8	5.36	2.8
1500	12	5.27	1.8
1750	14	5.22	1.1
2000	16	5.17	0

Table 3-2. Shoreline displacement in the Northern Kvark and predicted salinity in the Bothnian Bay.

4 Discussion

In this report, the sensitivity of the Baltic Sea salinities to variations in freshwater supply and sea level change is quantified. The model used is quite simple, but solidly founded in physical principles. The aim has not been to directly predict the future state of the Baltic Sea, but to present tools for quantifying the response to climatic changes. However, the result may very well be used to get a decent estimate of the Baltic Sea salinity for a given future freshwater supply and global sea level position.

A quantification of the accuracy of the results is difficult to obtain, but by making order of magnitude estimates of contributions from neglected processes and phenomena the results gain credibility. Previous estimates of the sensitivity of the Baltic salinity to climatic change, primarily freshwater supply variations, obtained with similar models by /Gustafsson, 1997b; Gustafsson and Westman, 2002; Stigebrandt and Gustafsson, 2003/ have been confirmed by computations with more complex time-dependent highly resolved models /Gustafsson, 2000b; Meier and Kauker, 2003; Omstedt et al, 2000/. Thus, using more complex models would probably only increase accuracy by a small amount.

Previous studies of the past climate have shown that variations freshwater supply has been the dominating driver of salinity variations /Gustafsson and Westman, 2002/. Approaching a glaciation one could anticipate a colder climate that cuts down river runoff primarily in the north due to build up of glaciers. On the other hand, the investigation by /Gustafsson and Westman, 2002/ indicated that warm periods were associated with dryer conditions, thus one might expect that cold periods should be associated with wetter conditions. Probably there would be a development where as the climate becomes colder, initially the freshwater supply would increase until the build up of glaciers becomes dominant.

The results show that if the global sea level sinks with about 5 m, the salinity in southern Baltic proper decrease below 1 psu, and large parts of the Baltic would become virtually limnic. To make the same change by changing freshwater supply it would need to increase to some 45,000 m^3/s (a factor of three), which probably is beyond any likely future climate.

That the Baltic should loose its estuarine nature and become an oceanic bay does not happen as long as the freshwater supply is positive. Negative freshwater supplies occur today in for example the Mediterranean which is partly surrounded with deserts that supply dry and warm air that favours a large evaporation. Such extreme climate in northern Europe is also quite improbable. During the warm period some 5000 years ago, there are indications that the freshwater supply was about 50% of the present supply, which led to an increase to some 15 psu in the southern Baltic. If the freshwater supply decrease was evenly distributed the model shows even more drastic changes in Bothnian Sea and Bothnian Bay where the salinities would become 13 psu and 10 psu, respectively.

The sensitivity analysis showed that reduced wind mixing in Kattegat could potentially reduce the salinity in the Baltic (Figure 11). Also the sea level variability in Kattegat had a significant influence on the salinity. Since the sea level variability at frequencies relevant for water exchange through the Danish Straits has been shown to be driven by the regional winds /Gustafsson and Andersson, 2001/. If wind setup is assumed, cf Equation (2-31), the sea level elevation is proportional to the stress which in turn is proportional to wind speed squared. Thus, the standard deviation of sea level should roughly be proportional to the variance in the wind. In a calmer climate, where both mean winds and the variability of the winds is lower than today, the combined effect of reduced mixing and reduced exchange can give significant changes to the Baltic salinity. Notable is that increase in mixing does not change the salinity that much, so for increased winds the anticipated effect is not that large.

Overlaying climate variations there is a trend in the Gulf of Bothnia due to post-glacial isostatic rebound. As an example of application of the methods presented here, the effect of shoreline displacement on the salinities in Bothnian Sea and Bothnian Bay is computed. The computation showed that relatively soon, i.e. within less than 2000 years, the Bothnian Bay would become a lake. There should be a trend in the present day salinity of about 0.1 psu/100 year in Bothnian Bay. This is too small to detect from the short instrumental records that exists, but maybe one can find proxy data that supports higher salinities in the past.

All discussion of the vertical circulation of the Baltic Sea is left out from this report. The strength of the vertical stratification and length of stagnation periods for different climate developments are extremely important for quantification of the ecological response, especially in the Baltic proper. The main reason for leaving this out of the present investigation is that the vertical circulation is influenced by the day-to-day variations in weather, while the overall salinity is more related to the long-term climate. However, recent research have shown that the major inflows causing deep-water renewal in the Baltic is, to the lowest order of magnitude, forced by the regional air pressure field in a simple manner /Gustafsson and Andersson, 2001/. Such knowledge can be combined with computationally efficient time-dependent circulation models /Gustafsson, 2003b/, in order to compute the response of the vertical circulation to changing climatic parameters. An example could be length of stagnation periods as function of storm frequency and freshwater supply.

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Appendix

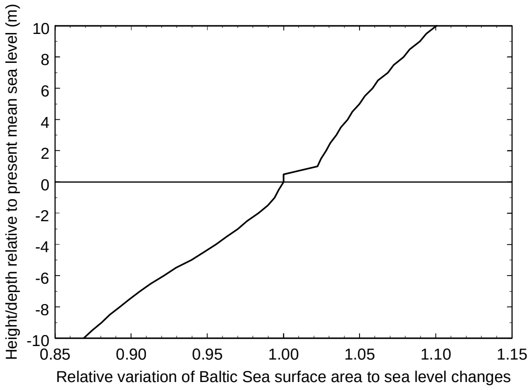

Figure 1. *Relative change of the surface area of the Baltic due to changing global sea level.*

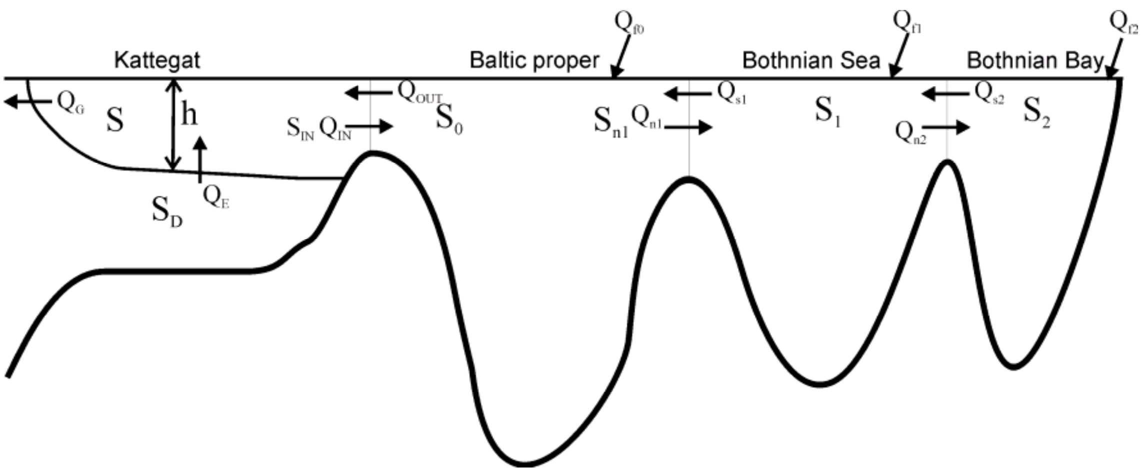

Figure 2. *Schematic of the salinity model.*

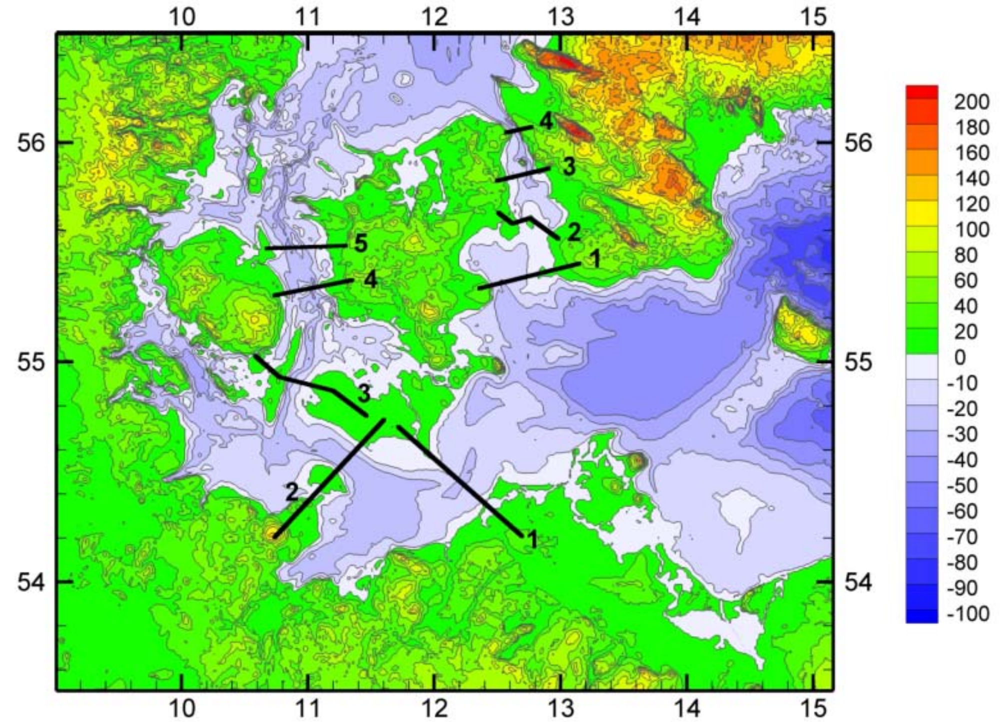

Figure 3. *Map of the entrance area. Cross-sections where computations of the topographic changes have been made are indicated.*

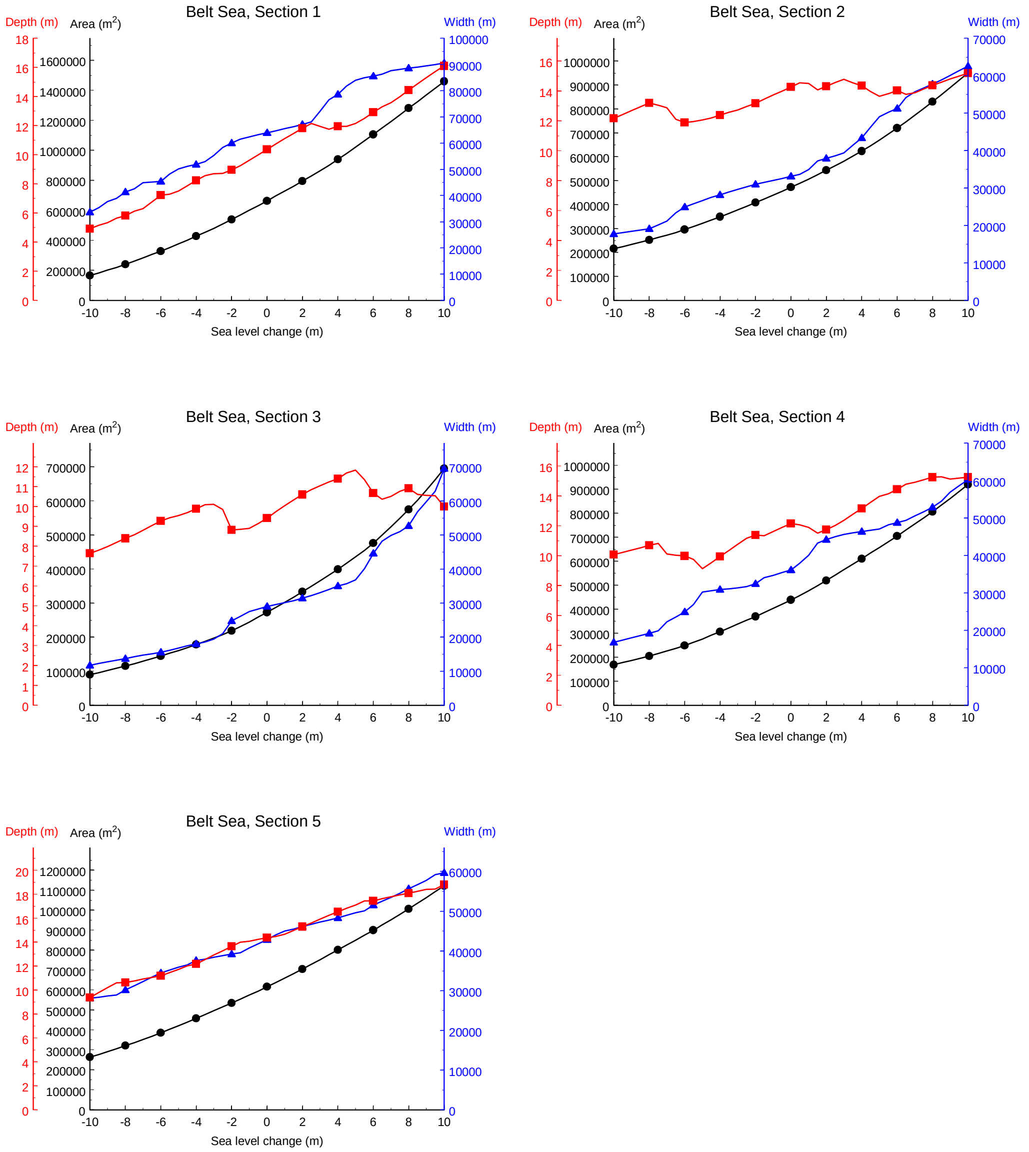

Figure 4. *Changes in topography in the five cross-sections in the Belt Sea. Red line with squares shows depth, black circles area and blue triangles width.*

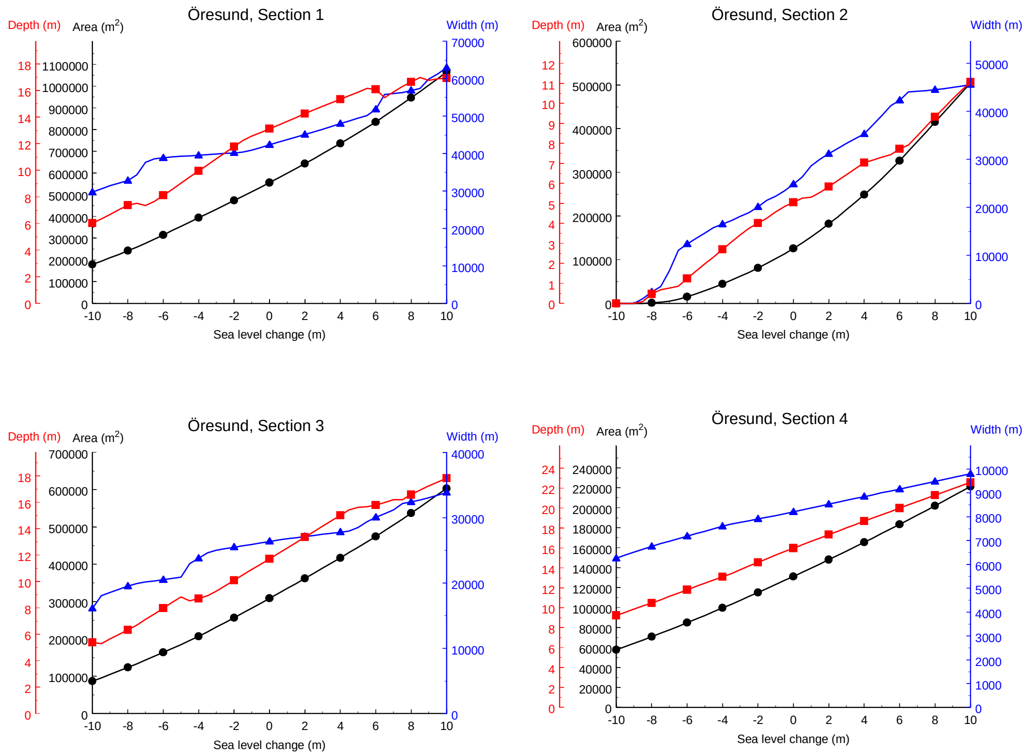

Figure 5. *Topographic changes in the Öresund at the cross-sections indicated in the map. Red line with squares shows depth, black circles area and blue triangles width.*

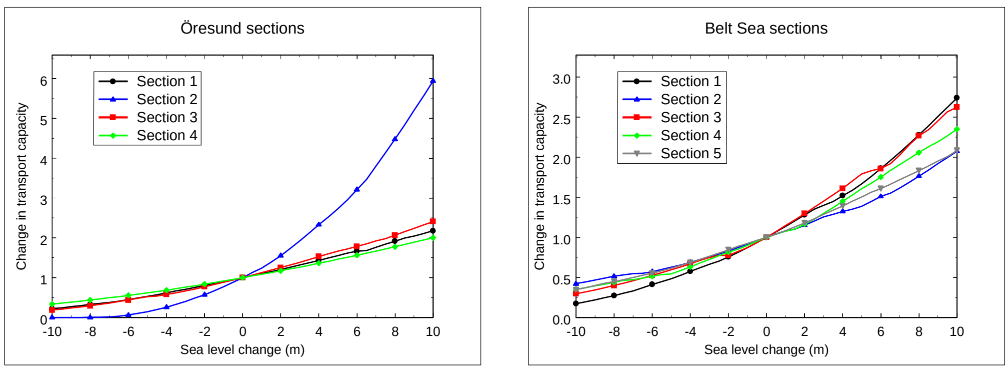

Figure 6. *Computed α's for the cross-sections in Belt Sea and Öresund.*

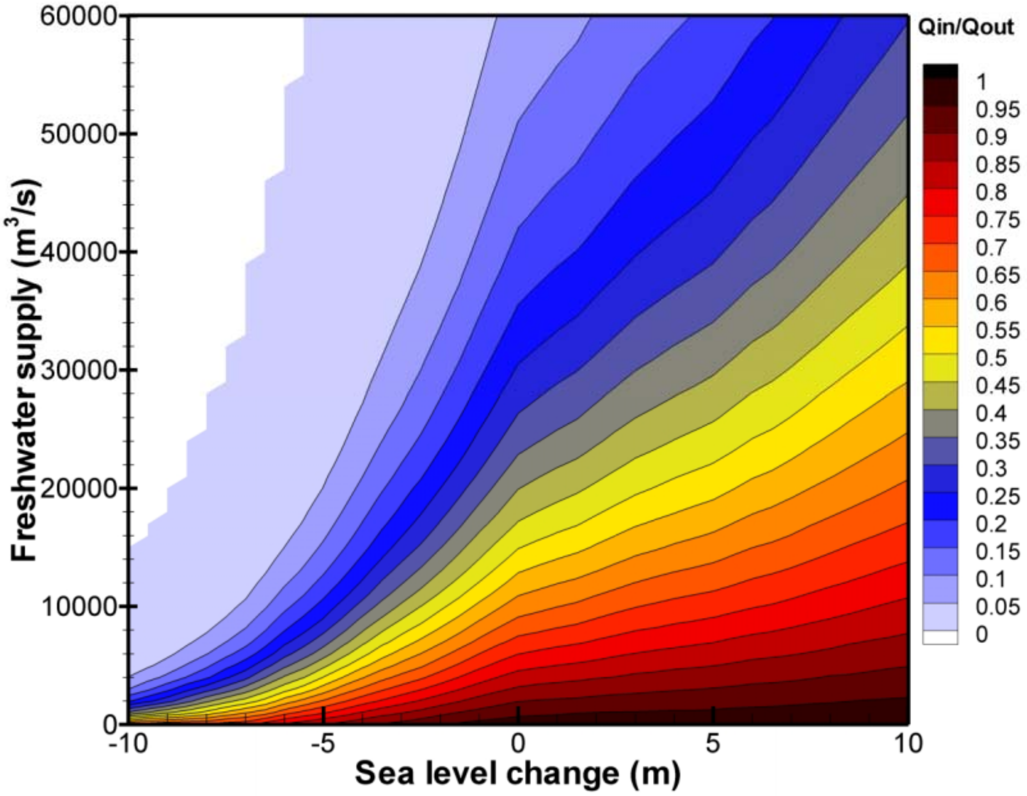

Figure 7. *The ratio between inflows and outflows through the Danish Straits for different combinations of freshwater supply and mean sea level change.*

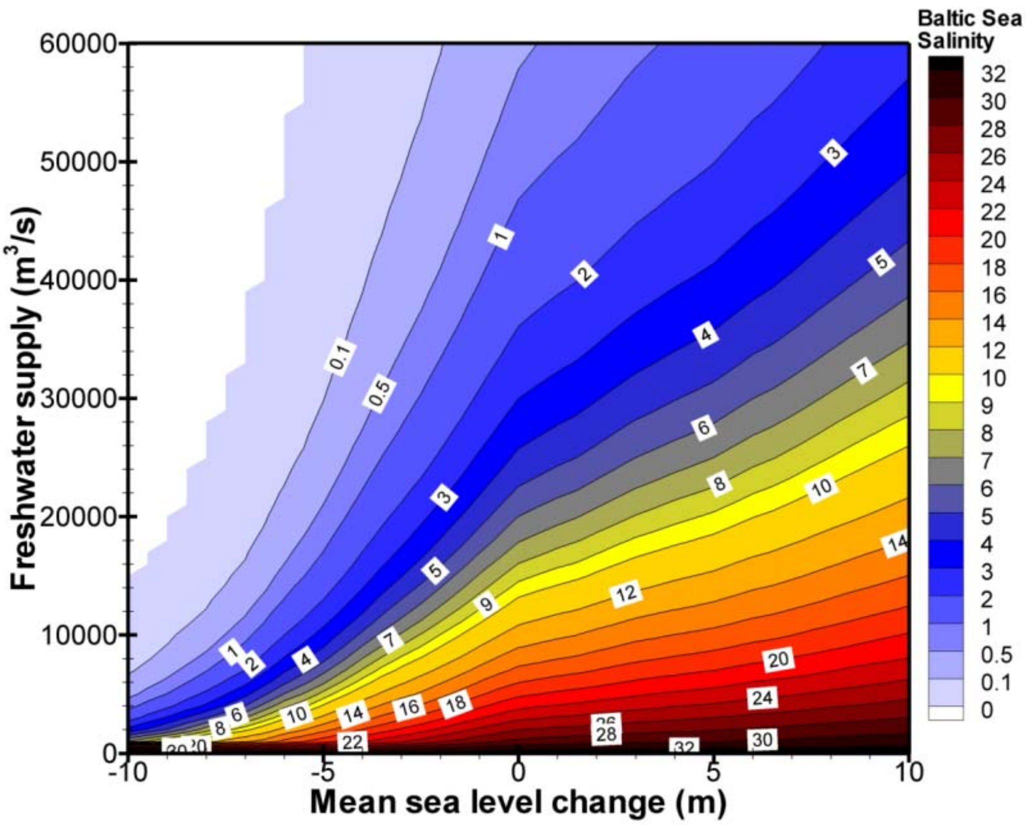

Figure 8. *The salinity in southern Baltic proper for different combinations of freshwater supply and mean sea level change.*

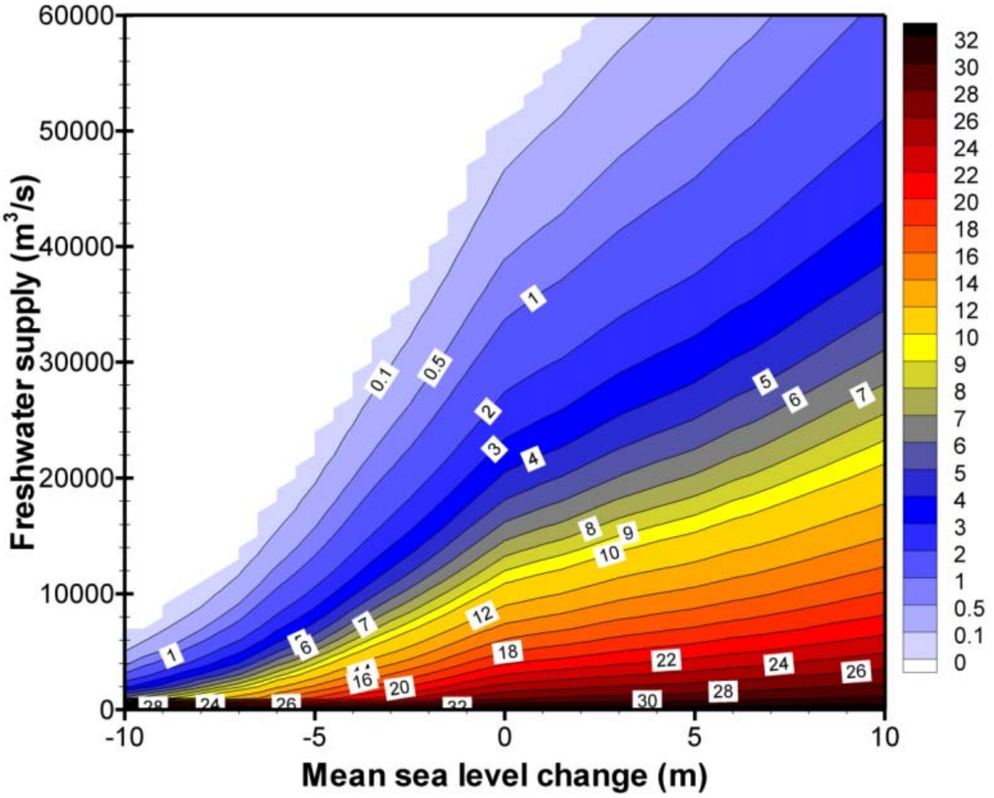

Figure 9. *The salinity in Bothnian Sea for different combinations of freshwater supply and mean sea level change.*

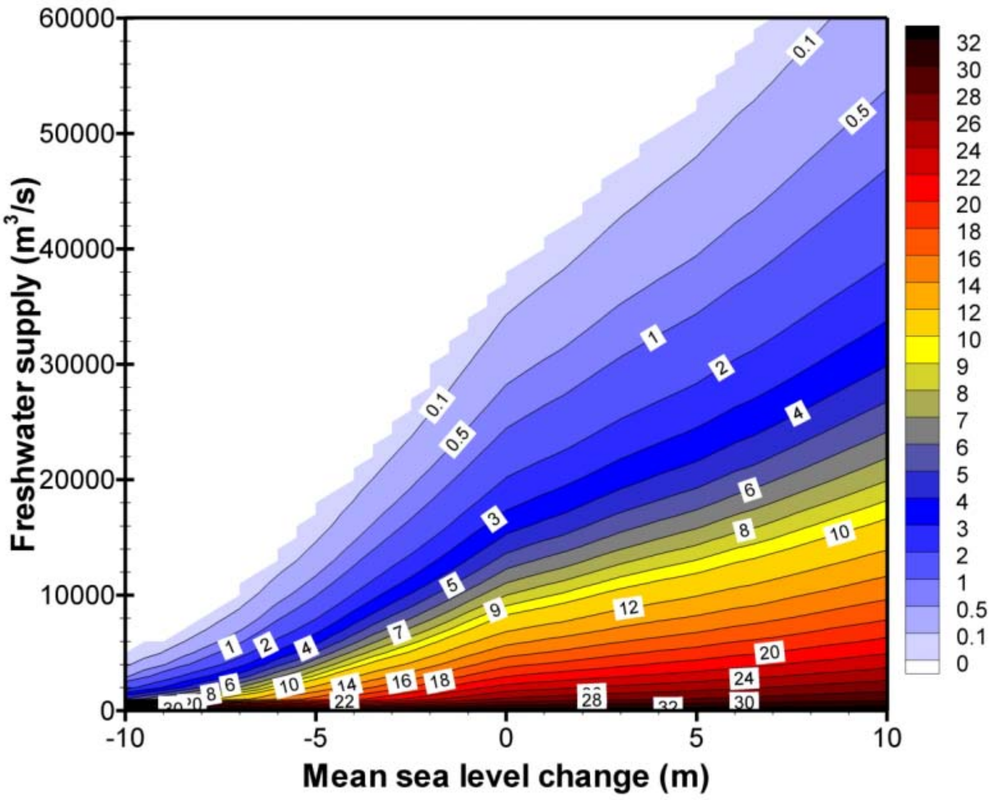

Figure 10. *The salinity in Bothnian Bay for different combinations of freshwater supply and mean sea level change.*

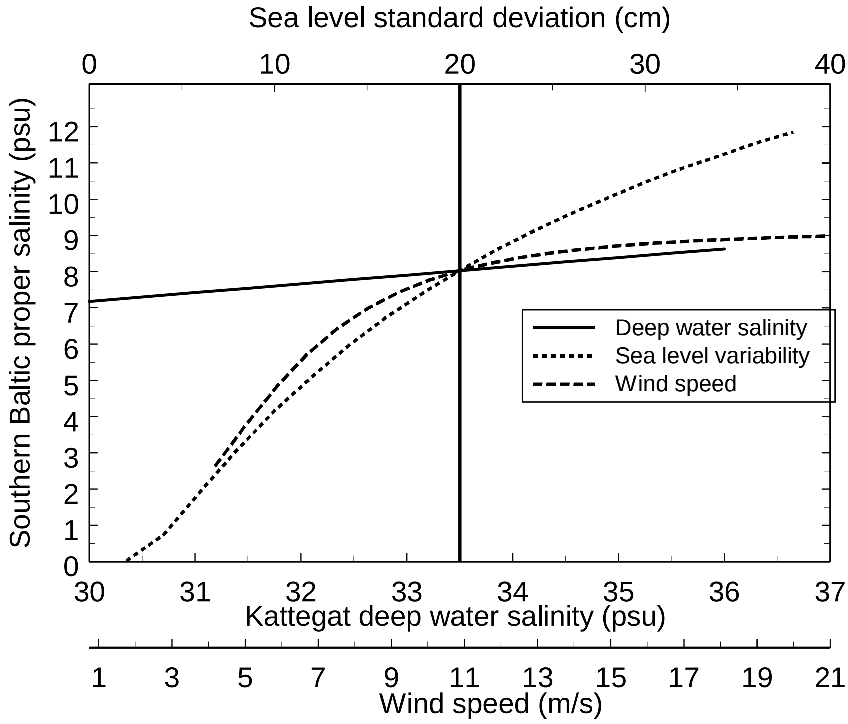

Figure 11. *Southern Baltic proper salinity as function of wind speed causing varying mixing in Kattegat, sea level variability in Kattegat in form of standard deviation and salinity in the deep water of Kattegat. The vertical reference line indicates present day conditions given by the parameters in Table 2-1.*

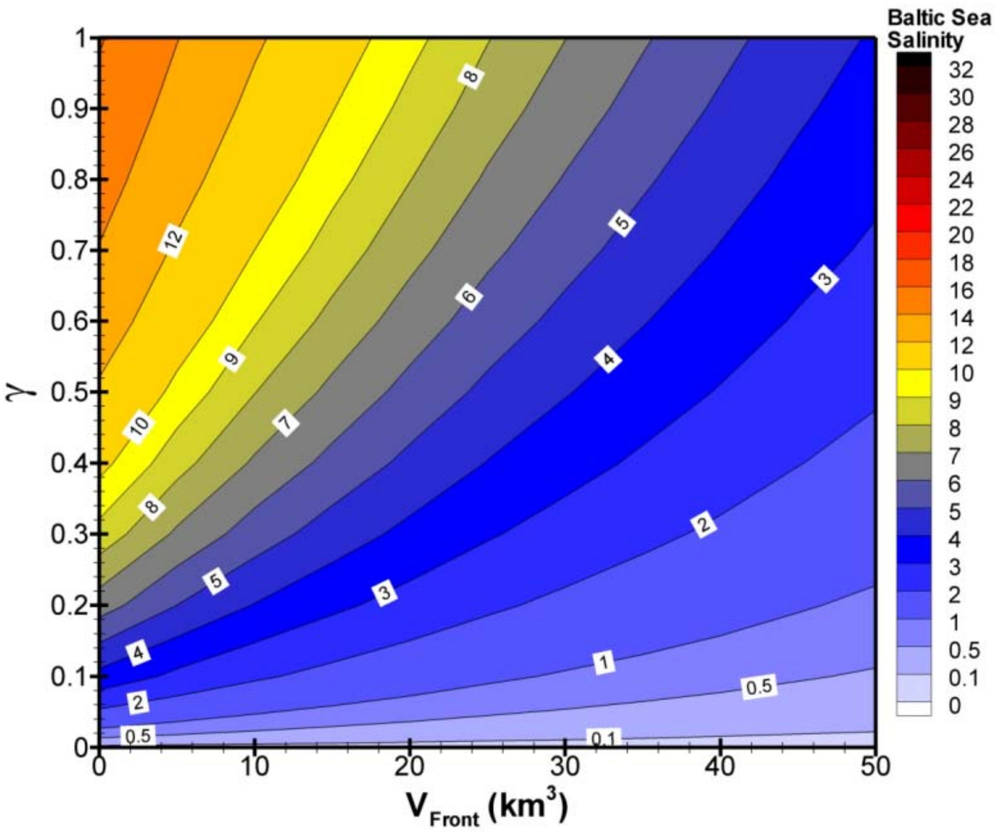

Figure 12. *Sensitivity of the salinity in southern Baltic proper to changes in model parameters.*

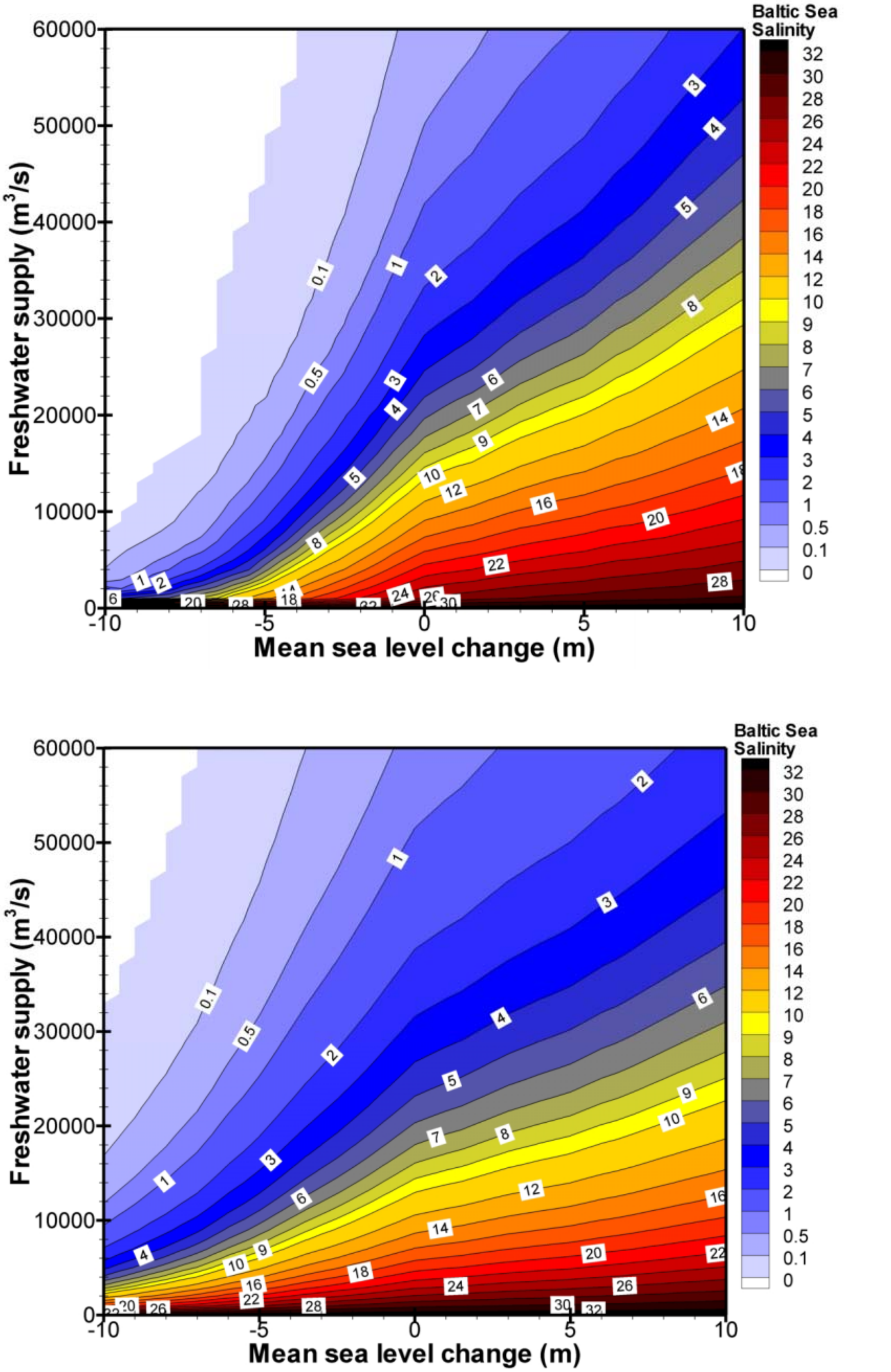

Figure 13. *The response of Baltic proper salinity for changes in freshwater supply and mean sea level using two extreme parameter settings in the model. Upper panel shows results for* $\gamma = 1$, $V_F = 25 \times 10^9\ m^3$ *and lower panel shows results for* $\gamma = 0.27$, $V_F = 0$.

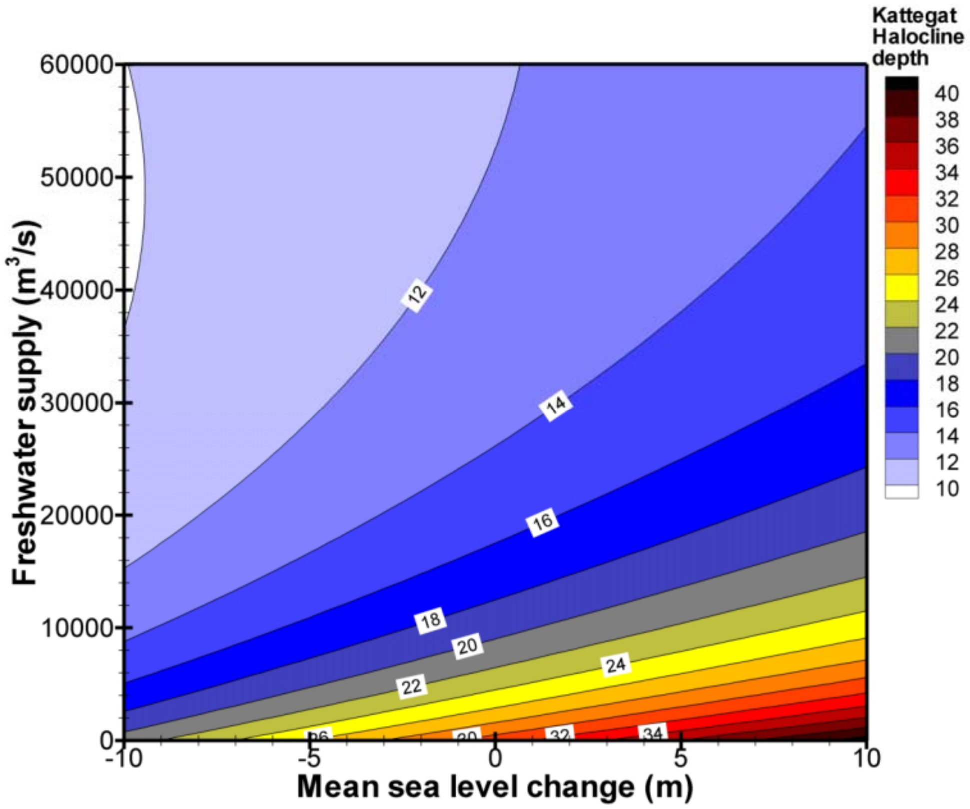

Figure 14. *The halocline depth in Kattegat for different combinations of freshwater supply and mean sea level change.*

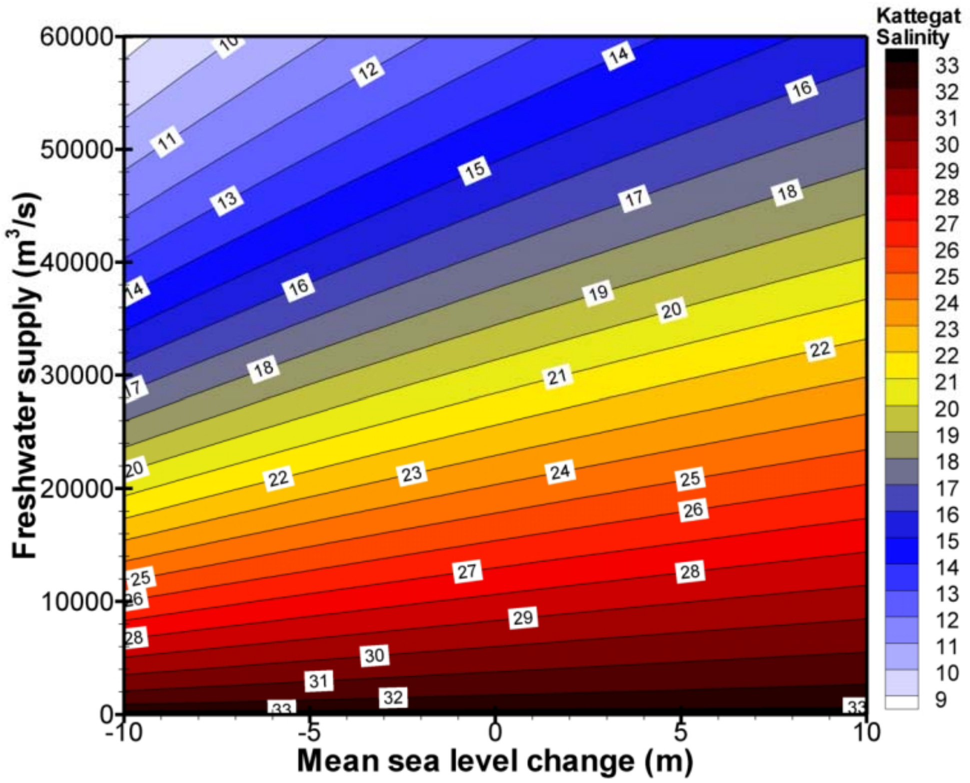

Figure 15. *The surface salinity in Kattegat for different combinations of freshwater supply and mean sea level changes.*

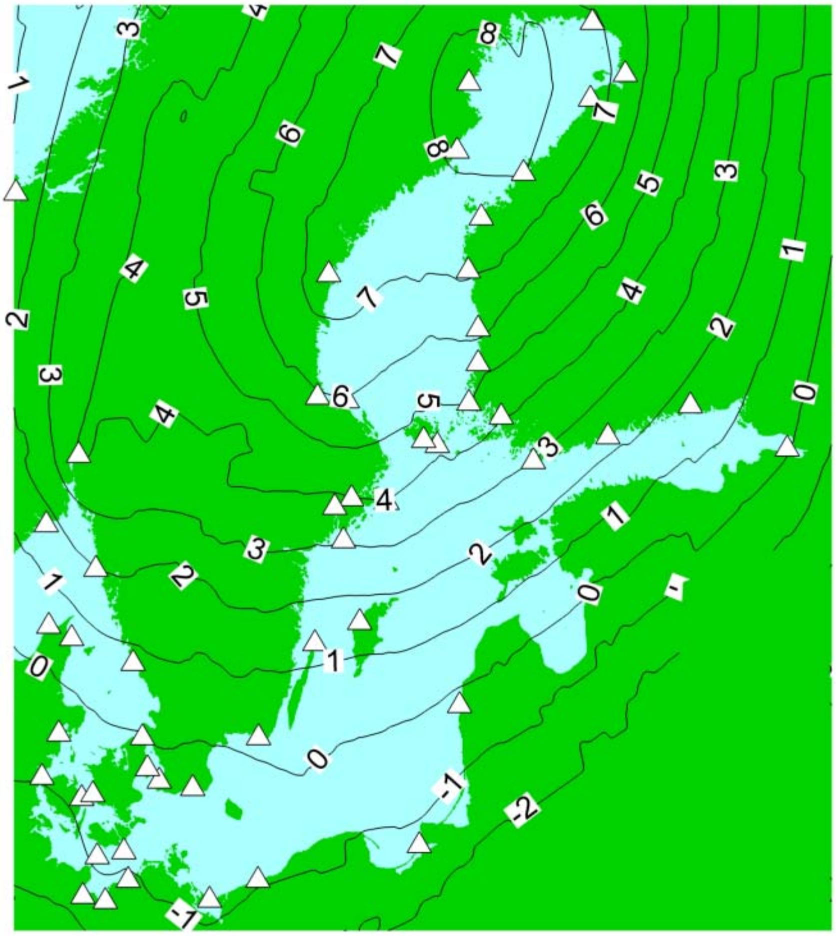

Figure 16. *The shoreline displacement (in mm/yr) as observed from sea level recordings. The positions of the sea level observations are indicated by triangles. Reproduced from /Ekman, 1996/.*

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