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On the influence of the freshwater supply on the Baltic Sea mean salinity

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ABSTRACT

The sensitivity of the Baltic Sea mean salinity to climatic changes of the freshwater supply is analyzed. The average salinity of the Baltic Sea is about 6‰. The low salinity is an effect of a large net freshwater supply and narrow and shallow connections with the North Sea. As a result of mixing in the entrance area, a large portion of the outflowing Baltic Sea water returns with the inflowing salty water and thus lowers the salinity of the Baltic Sea deep-water considerably. This recycling of the Baltic Sea water is a key process determining the salinity of today's Baltic Sea. The sensitivity of this recycling, and thus of the Baltic Sea salinity, to climatic changes in the freshwater supply is analyzed. A simple model is formulated for the variations of the Baltic Sea freshwater content. Historical data of the freshwater supply and the salinity in the Baltic Sea are used in the model to achieve an empirical expression relating variations of the recycling of Baltic Sea water to the variations of the freshwater supply. The recycling is found to be very sensitive to the freshwater supply. We find that an increase of freshwater supply of 30% is the level above which the Baltic Sea would turn into a lake. Recent climate modeling results suggest that river runoff to the Baltic Sea may increase dramatically in the future and thus possibly put the Baltic Sea into a new state.

1. Introduction

The average salinity of the Baltic Sea is about 6‰ (Winsor et al., 2001). The reason for this low salinity is the large net freshwater supply, with a mean annual average of about 16 000 $m^3 s^{-1}$, in combination with narrow, shallow and long connections with the North Sea.

The topography of the Baltic Sea and the division between different sub-basins are shown in Fig. 1. There are two parallel connections with the North Sea through the Danish Straits. The connection through the Great and Little Belts, forming the Belt Sea, has a sill depth of about 18 m, and the connection through Öresund has a sill depth of 8 m. Both sills are found on the Baltic Sea side.

The large-scale salinity distribution from the Skagerrak to the northernmost part of the Baltic Sea is illustrated in Fig. 2. For a thorough discussion of the physical oceanography of the region the reader is referred to, e.g., the reviews by Rodhe (1998) and Stigebrandt (2001). The main feature is the restricted water exchange through the Danish Straits. These straits are also a region of intense mixing between the Baltic Sea surface water, found in the surface layer inside the straits, and the water of North Sea origin shown up as the deep water in the Kattegat. This mixing implies that the inflowing deep water is considerably diluted by Baltic Sea surface water before passing the sills to form the Baltic Sea deep water.

Stigebrandt (1983) formulated a dynamical model for the exchange of water and salt between

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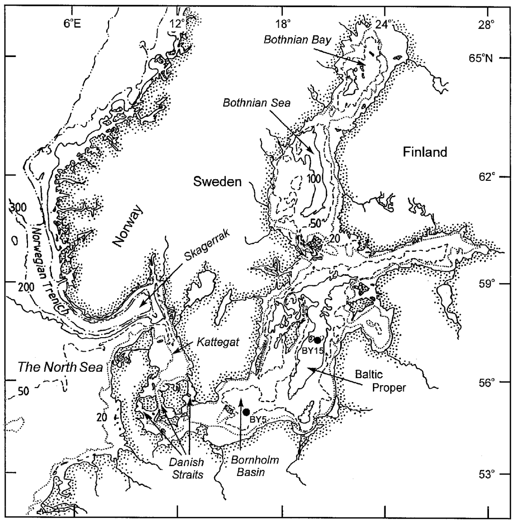

Fig. 1. Map of the Baltic Sea showing the location of the two hydrographic stations used in the analysis.

the Baltic Sea and the Skagerrak. The model was forced by daily sea level observations from the Kattegat and observed freshwater supply to the Baltic Sea. Other authors have developed models along the same line, with increasing complexity, e.g. Omstedt (1987; 1990) and Gustafsson (1997; 2000).

However, instead of starting from a mechanistic point of view, as the cited authors, the present study uses information about the slow climatic variations of the Baltic Sea mean salinity during the last century to achieve information about the mixing in the Danish Straits and how this is related to one of the large-scale forcing functions, the freshwater supply. The result is then used to estimate changes in the mean state of the Baltic Sea as a response to climatic changes of the freshwater supply.

Some relevant processes and timescales are reviewed in Section 2. This is followed by a discussion of the observed variations of salinity, freshwater supply, and water exchange through the Danish Straits (Section 3). A salt budget model for the Baltic Sea is presented in Section 4. Historical data of salinity and freshwater supply is then used to relate variations of the fraction of Kattegat deep water in the inflow to variations of the freshwater supply (Section 5). The equilibrium surface salinity of the southern Baltic Sea as a function of the freshwater supply is calculated in Section 6. Concluding remarks are made in Section 7.

2. Review of processes and scales

2.1. The entrance area of the Baltic Sea

The average net outflow from the Baltic Sea equals the net freshwater supply. However, the outflowing water carries salt and in a steady state this must be compensated for by inflowing water with even higher salinity. This was formulated already by Knudsen (1900). Using average salinities of 8.7‰ and 17.4‰ in the outflowing and the inflowing water, respectively, and a freshwater supply of 15 000 $m^3 s^{-1}$, Knudsen concluded that the outflow of Baltic Sea surface water was about 30 000 $m^3 s^{-1}$ and that the inflow of deep water was about 15 000 $m^3 s^{-1}$. This result still holds for rough budget calculations, but does not describe the flow through the Danish Straits. Alternating barotropic flows, forced by the time-varying sea level difference between the Baltic Sea and the Kattegat, dominate the water exchange through the straits, see e.g. Welander (1974). (The baroclinic part of the flow is comparatively small.) The 'Knudsen flows' should thus be thought of as

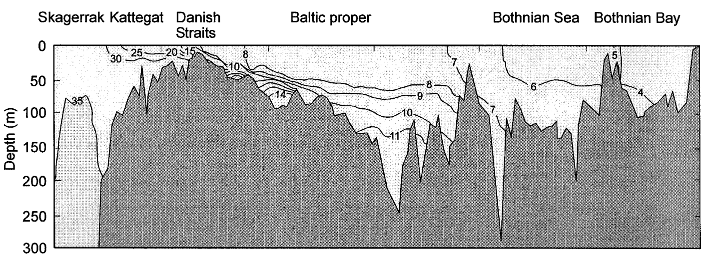

Fig. 2. Section from Kattegat to the Bothnian Bay showing the typical salinity stratification.

salinity-weighted averages of these alternating barotropic flows.

Figure 3, from Winsor et al. (2001), shows the frequency distribution of the volumes transported by all inflow events during the years 1920–1990, as calculated by the model by Stigebrandt (1980; 1983). (An inflow is defined as a period with modeled inward flow allowing for reversal of the flow with shorter duration than a day.) The average (modeled) volume of water transported by an inflow event is about 75 km^3. (This is about 0.4% of the Baltic Sea volume and about 25% of that of the transition region, consisting of the Belt Sea and Öresund.) These calculated barotropic inflow events give, averaged over time, the same volume transport as a continuous flow of about 40 000 $m^3 s^{-1}$. The corresponding outflow is then about 55 000 $m^3 s^{-1}$. These flows are considerably larger than was found by Knudsen for salt balance. The difference indicates that the barotropic in- and outflows are not so efficient in the process of exchanging salt.

Our conceptual idea of the mixing and transport of salt during in- and outflow events is illustrated in Fig. 4. The salinity of outflowing water is in general equal to the rather well defined surface salinity of the southwestern Baltic Sea. During inflows, on the other hand, the salinity increases with time from that of the recently outflowed water. The total amount of salt transported with an inflow event is related to the volume of the inflow, to the previous longitudinal salinity gradient in the straits together with the vertical stratification and mixing during the inflow. The longitudinal gradient, in turn, was essentially set by vertical mixing during the previous outflow. It is thus evident that, even though the water exchange through the straits is mainly barotropically forced, local baroclinic effects are important for the exchange of salt.

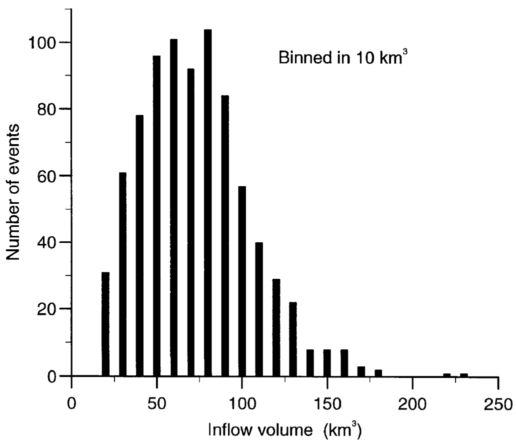

Fig. 3. Modeled frequency distribution of the volume of all inflows through the Danish Straits 1920–1990 (adopted from Winsor et al., 2001).

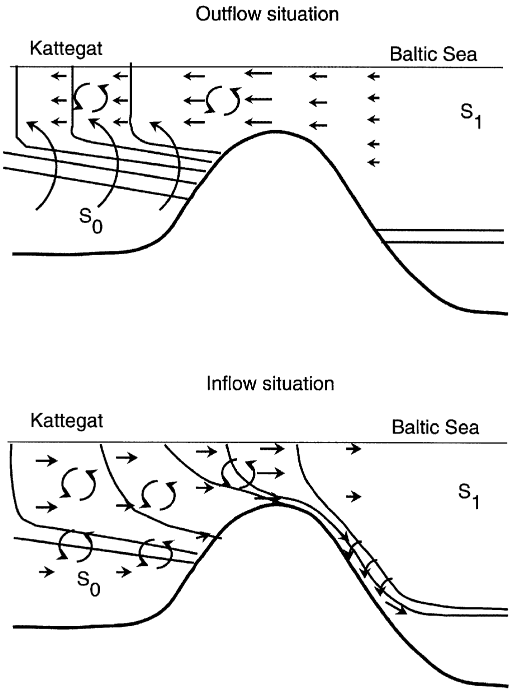

Fig. 4. Sketch illustrating the flow, mixing, and salinity stratification in the Danish Straits during outflow from (upper panel) and inflow to (lower panel) the Baltic Sea.

2.2. *The interior of the Baltic Sea*

Inside the sills the salty water flows along the bottom from basin to basin in the Baltic proper. Eventually the salty water interleaves into the basin water at a depth where its density fits in (Stigebrandt, 1987). Occasionally the density is large enough for the descending water to replace the bottom water in the deepest parts of the Baltic proper. Deepening of the main halocline during winter storms is responsible for most of the mixing of the salty deep water with the low saline surface water in the Baltic proper. The exchange with the northernmost basins is essentially determined by baroclinic flows. Surface water in one basin forms deep water in the next.

Different timescales related to the internal circulation can be estimated. The longest of these is the flushing of the Baltic proper deep water, 5–10 yr, with the highest value for the deepest part. The vertical turnover above the halocline in the Baltic proper has a timescale of 1 yr. The exchange between the major basins of the Baltic Sea, as well as the horizontal circulation within them, takes about 2–5 yr (Wulff and Stigebrandt, 1989; Stigebrandt, 2001).

The residence time of the freshwater in the Baltic Sea is about 30 yr (Winsor et al., 2001), and thus longer than the timescale for the large-scale internal 'stirring and mixing' of the Baltic Sea. The freshwater content is here defined as the amount of freshwater which has to be added to a Baltic Sea having a specified background salinity to get the observed salinity (see Section 4 for a formal definition). The background salinity is taken to be the salinity of the deep water found in the Kattegat.

A 5-yr timescale, which is used in the present study, seems to be appropriate for discussing variations of the Baltic Sea average salinity as response to changes in the freshwater supply. However, influence of the intermittent major inflows of deep water will introduce some disturbance, though rather limited due to the small volumes involved compared to the total volume of the Baltic Sea.

3. Observed variations of salinity, freshwater supply and water exchange through the Danish Straits

A 5-yr running mean of the Baltic Sea average salinity calculated from hydrographical observations at BY15 (Fig. 1) is shown in Fig. 5 together with the surface salinity in the southwestern part of the Baltic Sea (the Bornholm Basin). The mean salinity shows large variations on a timescale of several decades. It is also evident that the surface-water salinity inside the sills more or less follows the mean salinity. The correlation is best for no lag and the correlation coefficient is 0.75 (Winsor et al., 2001).

A time series of the river runoff to the Baltic

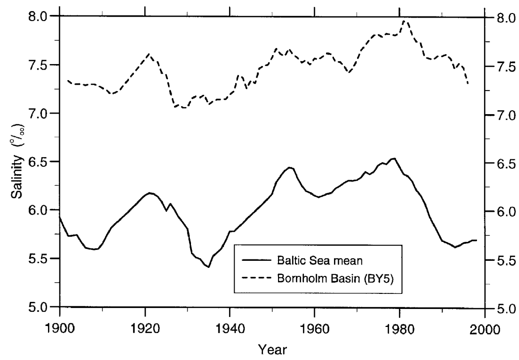

Fig. 5. 5-yr running means of the mean salinity of the Baltic Sea and the surface salinity in the Bornholm Basin (adopted from Winsor et al., 2001).

Sea, based on observations (Bergström and Carlsson, 1994) was discussed by Winsor et al. (2001) in relation to the Baltic Sea mean salinity. This time series is now extended to 1999 by the use of a hydrological model (Graham, 1999). Also, an estimate of the net precipitation, using a simple statistical model (Rutgersson and Omstedt, 2000), is added to get an estimate of the total freshwater supply. The mean is about 16 000 $m^3 s^{-1}$. Figure 6 shows a 5-yr running mean of the estimated freshwater supply to the Baltic Sea and the Baltic Sea freshwater content [defined by eqs. (1) and (2) in Section 4].

An immediate conclusion from Fig. 6 is that the freshwater content increases when the freshwater

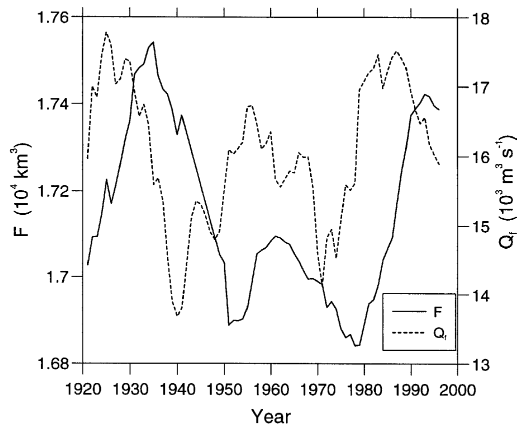

Fig. 6. Time series of the freshwater supply (Q_f) and the freshwater content (F) of the Baltic Sea. (5-yr running means.)

input is above average and vice versa. This was pointed out by Winsor et al. (2001). They also found that the variations (from a mean value) of the freshwater content was almost numerically the same as the integrated variations from the mean of the freshwater supply and that the correlation between these was best for no lag. This is illustrated later in Fig. 8a (Section 5 in the present study) and further discussed in that context. Winsor et al. (2001) concluded that this finding only could be explained by a strong feedback from the amount of outflowing Baltic Sea surface water on the salinity of the inflowing water, such that a larger net outflow increases the recycling of Baltic Sea water as part of the inflowing water, and vice versa. We will use the data in a simple model to calculate this feedback.

4. A salt budget model for the Baltic Sea

One of the key factors determining the salinity of the Baltic Sea is the mixing in the Danish Straits between the outflowing and the inflowing water. This is a complicated phenomenon, including mechanisms working on different length and timescales, e.g. small-scale turbulence due to critical two-layer flow producing local two-way mixing, entrainment of surface-layer water into bottom-layer water due to bottom-generated turbulence, entrainment of deep water into a fast-moving surface layer, longitudinal dispersion effects related to lateral and vertical shear, etc. In the present study we avoid going into details of the mixing by analyzing its effect on the Baltic Sea mean salinity. We formulate a time-dependent 'Knudsen-like' model for Baltic Sea. The model is used, in a diagnostic way, to achieve information about how the mixing varies with the net flow through the Danish Straits, on a climatological timescale. The result is then used to produce a prognosis for the response of the Baltic Sea salinity to changes in the freshwater supply.

The model is defined as follows. (a) The Baltic Sea is treated as one box, open to the North Sea through the Danish Straits. (b) We are considering variations on a timescale shorter than the residence time of the freshwater in the Baltic Sea but longer than the time for internal stirring and mixing, and much longer than the timescale of the seasonal variations. (In the calculations we will use 5-yr running means of the variables, see comments at the end of Section 2.) (c) The outflow is assumed to carry the salinity of the surface layer in the southwestern part of the Baltic Sea. (d) The inflowing water is a mixture of the outflowing water and the Kattegat deep water (assumed to have a constant salinity).

Note that at this point we do not need to make any assumptions about the nature of the flow in the straits, whether it is purely barotropically forced or in part driven by baroclinic pressure gradients. The model concept is illustrated in Fig. 7.

We formulate a conservation equation for the freshwater content F of the Baltic Sea defined by:

$$F \equiv \iiint_V f \, \mathrm{d}v. \tag{1}$$

V is the volume of the Baltic Sea and f is the specific freshwater content, defined as:

$$f \equiv \frac{s_0 - s}{s_0}, \tag{2}$$

where s is salinity and s_0 is the background salinity, found in the Kattegat deep water.

An equation for the rate of change of the freshwater content of the Baltic Sea can be formulated:

$$\frac{\mathrm{d}F}{\mathrm{d}t} = Q_\mathrm{f} - Q_\mathrm{out}\frac{s_0 - s_1}{s_0} + Q_\mathrm{in}\frac{s_0 - s_2}{s_0}, \tag{3}$$

where Q_f is the net freshwater supply to the Baltic

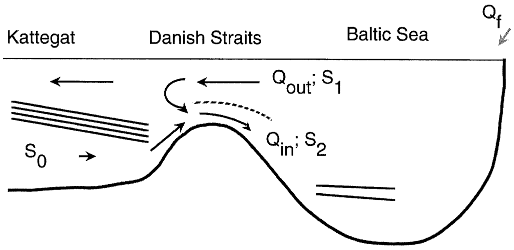

Fig. 7. Sketch illustrating the model used for calculations of the climatic variations of the salinity of the Baltic Sea. Q_f, Q_out and Q_in are the freshwater supply, the outflow of Baltic Sea surface water and the inflow of salty water, respectively. s_0, s_1 and s_2 are the salinities of the Kattegat deep water, the outflowing Baltic Sea surface water and the inflowing salty water, respectively. The salinity stratification is indicated.

Sea, Q_{out} is the outflow through the Danish Strait, carrying the salinity s_1. Q_{in} is the inflow, having a salinity s_2.

We reformulate the variables on the right-hand side of eq. (3): $Q_{out} = Q_f + Q_b$ and $Q_{in} = Q_b$. (The net outflow equals the freshwater supply on the timescales under consideration.) The flow-part Q_b might have barotropic and baroclinic components. We also introduce $f_1 = (s_0 - s_1)/s_0$ and $\Delta f = (s_2 - s_1)/s_0$. f_1 is thus the specific freshwater content of the outflowing water and Δf is the difference in specific freshwater content between the outflowing and the inflowing water. With this definition Δf equals the fraction of Kattegat deep water which has to be mixed into the outflowing surface water to form the inflow water. The recycling of Baltic Sea surface water, which follows with the inflow, is thus $(1 - \Delta f)Q_b$. Equation (3) can now be written:

$$\frac{dF}{dt} = Q_f(1 - f_1) - Q_b \Delta f. \tag{4}$$

Equation (4) relates the change of the freshwater content, F, to the functions Q_f, Q_b, f_1 and Δf. Q_f and the barotropic part of Q_b are external forcing functions. The (small) baroclinic part of Q_b, f_1 and Δf are dependent variables. The baroclinic part of Q_b is a function of the difference in density between the Baltic Sea surface water and that of the Kattegat deep water, i.e. of f_1, and of the energy input forcing the mixing in the transition region, which in turn is related to the barotropic flow, the local wind and the baroclinic forcing. f_1 is in some unknown way related to F and the internal mixing in the Baltic Sea. It seems reasonable to assume that f_1 increases with F for a constant forcing of the internal mixing. This is shown to be the case as illustrated in Fig. 5, in which surface salinity in the Bornholm Basin is shown together with the mean salinity. If the recycling of Baltic Sea surface water in the straits becomes complete, i.e. for $\Delta f = 0$, F will increase (and so will f_1) until it equals the total volume, whereby $f_1 = 1$.

We shall now apply the model to observations of F and f_1 to analyze how the variations of Δf are related to observed variations of Q_f. We separate the variables in steady-state parts and variable parts:

$$Q_f = Q_f^0 + Q_f'; \quad F = F^0 + F; \quad f_1 = f_1^0 + f_1';$$

$$\Delta f = \Delta^0 f + \Delta' f, \tag{5}$$

such that

$$0 = Q_f^0 - Q_f^0 f_1^0 - Q_b \Delta^0 f, \tag{6}$$

and

$$\frac{dF^0}{dt} = 0. \tag{7}$$

Equations (6) and (7) describe conservation of salt (similar to the Knudsen relations). Note that the state F^0 is not determined by these equations.

Using eqs. (5)–(7) in eq. (4) we get the following equation describing the perturbations of the freshwater content:

$$\frac{dF'}{dt} = Q_f' - Q_f^0 f_1' - Q_f' f_1^0 - Q_f' f_1' - Q_b \Delta' f. \tag{8}$$

We have not defined a perturbation variable of Q_b. The overall reason is that we are looking for a relation between the re-circulation of the Baltic Sea surface water in the transition area and the freshwater input, and fortunately enough Q_b can be treated as a constant. The arguments are as follows. Seasonal variations (not small) are evened out, since we are looking at 5-yr running means of the variables. The relative variations of the barotropic flow in the straits (dominating part of Q_b) are, on this timescale, much smaller (by a factor 3) than those of Q_f. Also, these two flows are uncorrelated (Winsor et al., 2001). The variations of Q_b will thus only have a quantitative influence on the accuracy of the result, and not give any systematic error. This also includes variations of the baroclinic part of Q_b, which are related to changes in the mixing in the transition region. The reason being that the mixing is essentially related to the barotropic forcing.

The baroclinic forcing (and the baroclinic part of the flow) is small in comparison with the barotropic on the timescales under consideration, but its variations are related to the variations of f_1, and are thus not evened out by the 5-yr smoothing. We can estimate the importance of these variations in comparison with the variations of the freshwater input. The latter has a relative variation of about 0.25 (Fig. 6). We estimate the overall baroclinic forcing to be proportional to the square root of the density difference between the Baltic Sea surface water and the Kattegat deep water, relative to that of the Kattegat deep water.

Thus, a variation of the Baltic Sea surface water of 1‰ (Fig. 5) corresponds to a relative variation of the baroclinic forcing of about 0.02. The conclusion is that we can neglect effects of variations of the baroclinic part of Q_b.

(A note should be included here. Even though we have concluded and that the variations of Q_b is dominated by barotropic effects on the time-scales under consideration, the analyses could easily be changed to a pure baroclinic exchange. To do so we keep Δf constant, assuming a constant salinity of the inflowing deep water, and instead introduce a perturbation Q_b'. The analysis and the results which follow will be the same except that the product $Q_b\Delta' f$ should be substituted by $Q_b'\Delta f$.)

5. Application of the model to historical data of Baltic Sea salinity and freshwater supply

Knowledge of the varying freshwater supply to the Baltic Sea and observed variations of the Baltic-Sea freshwater content (Section 3) will now be used in the model to find an expression relating the variations of the undisturbed Kattegat deep water, as part of the inflowing water to the variations of the freshwater supply, Q_f. By numerical reasons we use the integrated form of eq. (8) (The use of the integrated form is necessary to cope with difficulties arising from the large short-term variability of the time derivative of the freshwater content when this is estimated from observations.):

$$\int_0^t Q_b \Delta' f \,dt' = \int_0^t Q_f' \,dt' - F' - \int_0^t Q_f^0 f_1' \,dt' - \int_0^t Q_f' f_1^0 \,dt' - \int_0^t Q_f' f_1' \,dt' + C, \tag{9}$$

where C is a constant which appears since the basic state F^0 is undetermined by eq. (7).

The surface salinity in the Bornholm Basin is used to represent the salinity of the outflowing surface water (s_1). One reason is that this region is close to the Danish Straits, but not so close that it is influenced by occasional large inflows of salty water. Another reason is that there is a good record of data from this region. Figure 5 (Section 3) showed that the smoothed time series of the surface salinity at the Bornholm Basin and of the Baltic Sea average salinity are well correlated and that the surface salinity in the Bornholm Basin can (within this range of variations) be estimated by adding a constant salinity Δs to the Baltic Sea average salinity. The best fit is found for $\Delta s = 1.4$‰. This will be used in the calculations. We now reformulate eq. (9) (remembering that Q_b should be treated as a constant):

$$Q_b \int_0^t \Delta' f \,dt' = \left[1 - \left(\frac{F^0}{V} - \frac{\Delta s}{s_0}\right)\right] \int_0^t Q_f' \,dt' - F' - Q_f^0 \int_0^t \frac{F'}{V} \,dt' - \int_0^t Q_f' \frac{F'}{V} \,dt' + C. \tag{10}$$

1 2a 2b 3 4 5 6

Term 1 is the integrated loss (gain) of freshwater due to the variations of the mixing in the transition area; term 2a is the gain (loss) due to the variations of the freshwater supply; term 2b is the loss (gain) due to the variations of the net outflow through the straits; term 3 is the variations of the freshwater content; terms 4 and 5 are the variations of the loss (gain) of the freshwater due to the variations of the freshwater content of the net outflow.

A problem we face when we apply the model to the observations is that we can choose the mean value over any period of the freshwater supply as Q_f^0, but we have no obvious way to determine the hereto belonging freshwater content F^0. However, since we are analyzing a period which is more than twice the residence time for freshwater in the Baltic Sea, and including periods with increasing as well as decreasing freshwater supply, we conclude that the total mean of F cannot be far from that which should describe the stationary state for a freshwater supply equal to the total mean of Q_f. (The sensitivity of the result, as presented in Fig. 10, to realistic estimates of F^0 is smaller than that related to the uncertainty of α.)

Before going into the discussion about the choice of F^0 we can compare the integrated Q_f' and F' (Fig. 8a). Just for illustration we have chosen F^0 so that F' equals zero at the starting point. Looking at the two curves we see that the rise and fall of the freshwater content numerically quite well follows the rise and fall of the accumu-

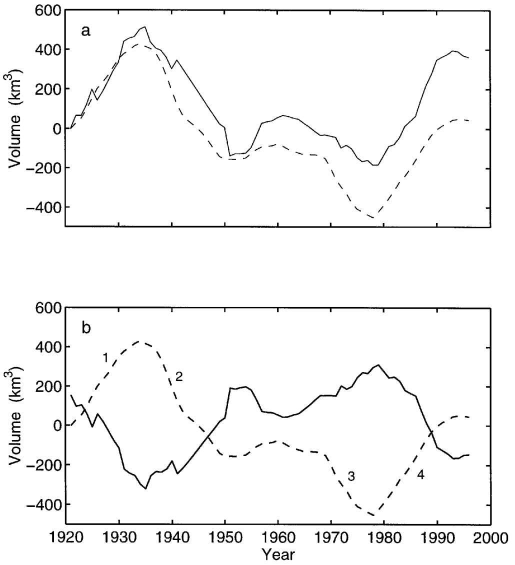

Fig. 8. Time series of the terms in eq. (10), related to the salt budget of the Baltic Sea, see text for explanation. (a) The accumulated variation of the freshwater input (dashed line) and the variation of the freshwater content (solid line). These quantities are represented by terms 2a and 3, respectively. (b) The sum of the right-hand side terms (solid line) and the accumulated variation of the freshwater input (dashed line). The numbers refer to different estimates of the slope in Fig. 9.

lated variations of the freshwater input. (The absolute deviation of the curves at the end of the time series corresponds to a systematic underestimate in the freshwater supply of only 1%.) We conclude that during periods with high freshwater supply most of the excess of freshwater shows up as an increase in the freshwater content of the Baltic Sea. During periods with low freshwater supply there is a corresponding net loss of freshwater though the Danish Straits. What is compared in Fig. 8a are terms 2a and 3 in eq. (10). However, these two terms cannot constitute the first-order balance in the equation. Term 2b represents, together with the very small term 5, the variations in the loss of freshwater related to the varying net outflow of surface water, which by necessity follows from the variations of the freshwater supply. Since the specific freshwater content of the outflowing water today is about 80%, term 2 can only balance about 20% of term 3. Further, since term 4 is phase shifted in relation to F', that term cannot alone compensate for this unbalance. We thus conclude that term 1 has to be of first order in the equation.

A problem in the application of the model to observations comes from term 4. The magnitude of this term is sensitive to the choice of F^0. On the other hand, from a physical point of view we do not expect this term to have more than a marginal influence on the variations of the mixing between the two water masses in the inflow region. The reason is that this term represents variations in the mixing due to changes in the density difference between the two water masses. These changes are very small, in a relative sense. Following this we chose F^0 such that the disturbance of term 4 is minimized. In Fig. 8b we have plotted the time development of the sum of all terms on the right-hand side of eq. (10), and also the accumulated freshwater supply. We conclude from this figure that the modeled quantity $\Delta' f$ shows a strong negative correlation with the freshwater supply. The interrelation is shown in Fig. 9. The observations are grouped with somewhat different slopes and different levels [different values of the constant C in eq. (10)]. Slopes calculated for some distinct groups are indicated in the figure. The corresponding time sequences are indi-

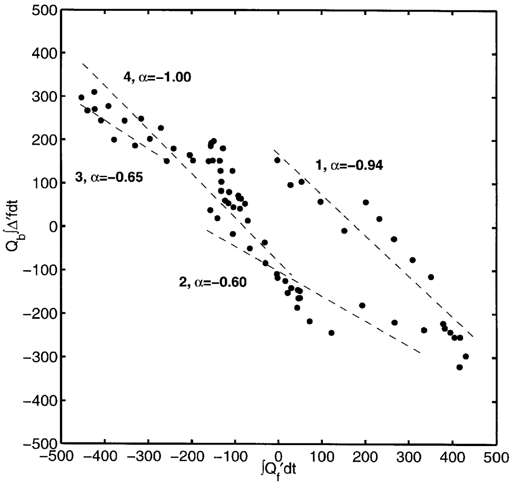

Fig. 9. The same quantities as in Fig. 8(b). Each dot represents one year. The figure illustrates the dependence of the perturbation from the mean of the background water in the inflow, $Q_b \Delta' f$ [calculated according to eq. (10)] on the perturbation of the freshwater supply, Q_f'. The different slopes refer to different time periods, see Fig. 8(b).

cated in Fig. 8b. We thus feel safe using a linear dependence as a first approximation:

$$\Delta' f = \alpha \frac{Q_f'}{Q_b}. \tag{11}$$

Q_b should here be thought of as a constant. α is found to be close to -1 (Fig. 9). An interpretation of the result shown in eq. (11) is that the variations of the recirculation of Baltic Sea surface water (which is $-\Delta' f Q_b$) is equal to $-\alpha Q_f'$, i.e. proportional to the variations of the freshwater supply.

Is this a realistic result? We think so. Our conceptual idea of the flow in the transition area is a continuous barotropic outflow (Q_f) added to a barotropic two-way flow (Q_b); see Fig. 4, where the upper panel represents a flow $2Q_b + Q_f$ directed outwards and $2Q_b - Q_f$ is the magnitude of the inward flow (lower panel). We also think of a longitudinal salinity gradient in the transition area, formed by the local mixing, which is not strongly influenced by the net outflow. With this in mind it seems reasonable that the average volume of the inflows, and thus the average salinity (and $\Delta' f$) decreases with slope of order 1 for increasing Q_f/Q_b and vice versa. [If we had assumed a baroclinic flow in the entrance, eq. (11) should hold with the change of variables discussed in the note at the end of Section 4. Also, if this were the case we should expect a magnitude of the response of order 1.]

6. The equilibrium salinity of the Baltic Sea

Equation (11) will now be used to estimate the equilibrium salinity of the outflowing water for different freshwater supply.

Define a new state:

$$Q_f = Q_f^0 + dQ_f, \tag{12}$$

$$s_1 = s_1^0 + ds_1, \tag{13}$$

$$s_2 = s_2^0 + ds_2, \tag{14}$$

for which there is no net transport of salt through the Danish Straits. The old basic state (denoted by superscript 0) also satisfies the condition of no salt transport, cf. eq. (6). Going to the new state, the change in salt transport should thus be zero. This implies:

$$0 = Q_f\, ds_1 + s_1\, dQ_f + Q_b(ds_1 - ds_2). \tag{15}$$

The term within parentheses in eq. (15) is by definition equal to $-\Delta' f$ multiplied by the background salinity s_0. Using the empirical relation (11) we then get:

$$0 = Q_f\, ds_1 + s_1\, dQ_f - Q_b \alpha \frac{dQ_f}{Q_b} s_0, \tag{16}$$

or as a differential equation:

$$Q_f \frac{ds_1}{dQ_f} = -s_1 + \alpha s_0. \tag{17}$$

Subjected to the condition defined by the old basic state, this equation has the solution:

$$s_1 = s_1^0 \left[1 - \frac{Q_f - Q_f^0}{Q_f} \left(1 - \alpha \frac{s_0}{s_1^0} \right) \right], \tag{18}$$

where the empirical constant α is negative and of order 1.

Knowing one steady state we can use eq. (18) to find the steady-state salinity of the outflowing water for any freshwater supply.

The empirical functional relation (11), used to derive eq. (18), was found for a certain regime of values for each quantity involved (freshwater supply, in–outflow through the Danish Straits, Kattegat deep-water salinity and surface salinity inside the straits). What are the main limitations for the applicability of expression (11)?

Of crucial importance for the analyses is that the salinity of the outflowing water today is well defined as the surface salinity inside the straits. This is an effect of the long residence time, the homogeneity of the surface water in the Baltic proper, and the deep-reaching vertical mixing of the surface layer. There is no reason to believe that this condition should change even for large variations of the freshwater content in the Baltic Sea.

Vertical mixing in the straits is dependent on the density difference between the Kattegat deep water and the outflowing water. However, even relatively large changes in this density difference will only have a minor quantitative influence on the large-scale mixing, which is more related to transported volumes in each in–outflow event (see the discussion at the end of Section 4). Thus there is no reason to believe that even comparatively large variations in the salinity of the outflowing water will violate the relation shown in eq. (11).

Thus, the restriction of the use of eq. (11) is probably given by the range of Q_f for which it was derived.

We have considered changes of the Baltic Sea mean salinity related to changes of the freshwater supply and assumed that the barotropic forcing of the flow in the entrance area is statistically constant. The effect of changes of the barotropic forcing is thus not included.

We will now use eq. (18) and knowledge of today's state to give a prediction of the steady-state value of the salinity of the outflowing Baltic Sea surface water as function of the freshwater input to the Baltic Sea. We take today's steady state to be described by $Q_f^0 = 15\,000$ m^3 s^{-1}, $s_0 =$ 33‰ and $s_1^0 = 8.7$‰, i.e. the 'Knudsen' case. Figure 10 shows the resulting salinity of the outflowing surface water for some different values of α within the range indicated in Fig. 9.

Accepting a relatively modest extrapolation outside the range in Q_f for which eq. (11) was derived, the findings indicate that the critical freshwater input for which the Baltic Sea would head towards a lake ($s_1 = 0$‰) is somewhere in the range 19 000–21 500 m^3 s^{-1}. This can be compared with the simplest possible estimate of this critical freshwater input shown in Fig. 11. With no freshwater input the salinity in the Baltic Sea would be that of today's Kattegat deep water, i.e. 33‰. This state is indicated by the cross at $Q_f = 0$. (Note that we are discussing the effects of changes in the freshwater supply to the Baltic Sea only. If the freshwater supply to the southern North Sea changed then the salinity of the Kattegat deep water would change.) Since the freshwater supply have changed considerably during the last century we do not know which steady-state freshwater supply corresponds to today's mean Baltic Sea salinity of about 6‰. As a high estimate of this uncertainty we have chosen the span in freshwater supply shown by the 5-yr smoothed curve in Fig. 6, i.e. a freshwater supply in the interval 14 000–18 000 m^3 s^{-1}. Linear extrapolations (thin lines in Fig. 11) indicate a critical freshwater supply somewhere between 16 000 and 21 000 m^3 s^{-1}. The thick line, which passes the cross at $Q_f = 16\,000$ m^3 s^{-1} indicates the 'best guess'. Note that Fig. 10 shows how the salinity of the outflowing water varies with the freshwater supply, whereas Fig. 11 shows how the Baltic Sea mean salinity varies with the same quantity. However, for the Baltic Sea being a lake these two salinities coincides.

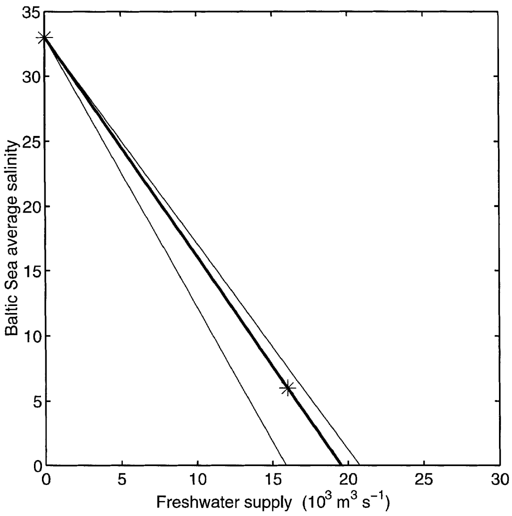

Fig. 11. A simple estimate of the relation between the steady state Baltic Sea mean salinity and the freshwater supply to the Baltic Sea. See text for explanation.

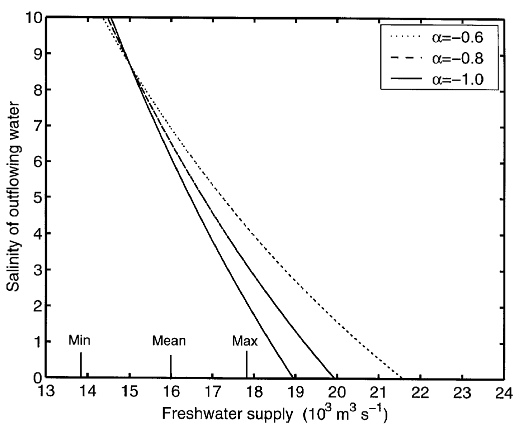

Fig. 10. Modeled steady-state salinity of the outflowing Baltic Sea surface water as function of the freshwater supply to the Baltic Sea for different values of α [see eq. (11) in the text and Fig. 9]. Extremes and mean of the freshwater supply, as shown in Fig. 6, are indicated.

The time for adjustment to a new steady state can be measured by the residence time T_r for the freshwater in the Baltic Sea:

$$T_r = \frac{F}{Q_f} = \frac{[(s_0 - \bar{s})/s_0]V}{Q_f}, \tag{19}$$

where $\bar{s}$ is the Baltic Sea average salinity. For today's state, with $Q_f = 16\,000$ m^3 s^{-1} and an average salinity of about 6‰, the residence time is about 30 yr. What is the adjustment time for the Baltic Sea becoming a lake? If we use a high estimate, $Q_f = 21\,500\ \text{m}^3\ \text{s}^{-1}$ (Fig. 10), the adjustment time turns out to be 31 yr. A literary interpretation of this is that 31 yr after an abrupt change in the freshwater supply the mean salinity is 2.2‰.

7. Concluding remarks

We have formulated a time dependent 'Knudsen like' conservation equation for the Baltic Sea inside the Danish Straits. The model has been applied to smoothed variations of the mean salinity and the freshwater input, as observed during 75 yr. The primary aim was to analyze how the variations of the mixture between the outflowing Baltic Sea surface water and the Kattegat deep water, forming the inflowing salty water to the Baltic Sea, was related to variations of the freshwater supply.

The diagnosis showed a negative relationship between the variations of the freshwater supply and the fraction of undisturbed Kattegat deep water in the inflowing water. This kind of relationship is also in qualitative agreement with what we should expect from a simple mechanistic idea of how the changes in the flow properties in the Danish Straits are likely to influence the salt transport to the Baltic Sea. In our minds we see the water pumping to and fro in the straits. The inflow of salt depends on the volume of water transported over the sill in each 'piston stroke' in combination with the along-the-straits salinity gradient. Given the same intensity of the pumping, we expect that an increase in the freshwater input to the Baltic Sea, i.e., in the net outflow, imply that a larger proportion of low saline Baltic Sea surface water returns with the inflows, and vice versa.

The secondary aim was to achieve a relation between the freshwater supply and the steady-state salinity of the Baltic Sea surface water. As a lower limit, the results indicate that the inflow of Kattegat deep water vanishes at a freshwater supply of about $21\,500\ \text{m}^3\ \text{s}^{-1}$, i.e., at an increase of about 30% from today's value. All inflowing water is in this limit recycled Baltic Sea surface water, i.e., the net outflow through the straits is at this freshwater input so large that the salt water is blocked from entering the Baltic Sea during the intermittent barotropic inflows. However, we have in the analysis assumed that the pumping of water through the straits is statistically steady and 'well behaving'. In reality there will always be a transport of salt in cases of extremely long-lasting inflows. This will set a lower limit on the salt content inside the sill. A detailed discussion of the quantitative effect of these extreme inflows is beyond the scope of this study. We note that the effect today's major inflows have contributed to the variations of today's state, and are thus included in our result. However, if the salt content of the Baltic Sea is of the same order as what is supplied by one extreme inflow, we are at the limit of the application of the present model. The obvious reason is that there cannot be a negative salt content to absorb the incoming salt. An extreme inflow can raise the mean salinity by a tenth of a salinity unit (estimated from the amount of salt carried by the major inflow in January 1993, see Gustafsson, 2000). The lover limit of the Baltic Sea mean salinity should thus be of that order.

Our results show a greater sensitivity to changes in the freshwater supply than was previously found by Stigebrandt (1983), Gustafsson (1997) and Omstedt et al. (2000). One reason for this difference might be that our 'tuning' of the sensitivity is done on a climatological timescale, whereas the cited authors have used models tuned on a daily basis.

The Swedish regional climate modeling program (SWECLIM) and other climate modeling programs have produced scenarios which indicate that the river runoff to the Baltic Sea would increase considerably in case of a future increased greenhouse effect. If this kind of change will occur we can, according to the present study, expect dramatic changes of the salinity of the Baltic Sea and thus on the whole ecosystem, which already is stressed by the present day low salinity.

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