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Hydrographic processes and changes in the Baltic Sea

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Abstract

The paper gives the system-conceptual basis of the hydrographic conditions in the Baltic Sea. The imposed boundary conditions, such as the bathymetry, river inflow, the oceanographic setting outside the Baltic Sea, etc., act through the laws of nature, and the resulting hydrographic conditions are considered the output of the Baltic system. The hydrographic conditions are described in terms of the salinity and temperature stratification and the advection and turbulent mixing of matter. The typical annual variability of stratification and transport rates are described. The changes since the glaciation and within the last century are also described, together with variations and their link to the boundary conditions. The large, long-term variations demonstrate that the Baltic hydrography is sensitive even to small changes in the boundary conditions. This calls for careful consideration of the man-made changes to the hydrographic boundary conditions, especially when the link between the hydrographic conditions and the biology is considered. This link is demonstrated by the dependency of the oxygen content in the lower layers of the Baltic Sea on the variability of the salt water inflows. Potentially, the most important anthropogenic impacts seem to be associated with the changes in the hydrological catchment area. Although there has been large scientific and public interest in the limited effects arising from the bridge projects in the Danish Straits, there has been little interest in impacts arising from changes within the catchment areas. The latter is an area requiring research.

Keywords: Baltic Sea, oceanography, stratification, salinity, anthropogenic impact, time scale.

The Baltic Sea as a hydrographic system

The Baltic Sea is generally characterized as a semi-enclosed sea, with the open boundary towards the Skagerrak and the North Sea. According to the HELCOM (Helsinki Commission) definition, the Baltic Sea includes the area stretching as far as the Danish Straits and the Kattegat, with a boundary line between Skagen (Denmark) and Marstrand (Sweden).

The present description of the hydrographic conditions in the Baltic Sea is limited to the domain within the sill areas of Drogden and Darß in the southern part of the Danish Straits. The highly dynamical processes of the Danish Straits and the Kattegat will not be described in detail, but only as constituting the transition zone between the Baltic Sea proper and the North Sea.

The hydrography of the Baltic Sea has been studied for more than a century. There is a large amount of hydrographic information gathered in this time, including light-ship measurements together with the regular profiling at selected HELCOM stations and more specific investigations. to describe the main findings from

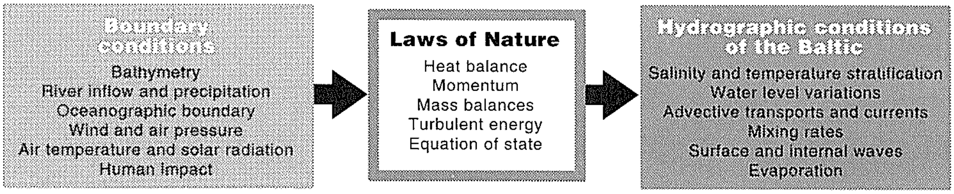

Figure 1. The Baltic Sea seen as a hydrographic system.

such a large quantity of material, a system concept has been applied. This hydrographics system concept is outlined in Figure 1.

The system concept is designed as a physical or numerical model of an environment. For the selected volume of the environment to be modelled, the conditions at the boundaries have to be specified. The main boundary conditions for the Baltic Sea can be classified as: the bathymetry describing its size and shape; the freshwater input through river inflows and precipitation; the oceanographic boundary describing the conditions at the outflow boundary at the sills of the transition area; wind and air pressure fields over the region; and air temperature and solar radiation which are of importance for the energy balance of the Baltic Sea system.

These boundary conditions are basically natural phenomena. However, during the past century human activity has reached such a capacity that the natural boundary conditions may be slightly modified. The construction of fixed links across the Danish Straits is one example of how human activity could affect the Baltic Sea system by increasing the flow resistance in the straits. Other effects, such as changes in the hydrological cycle, are also evident and therefore human impact has been included as a boundary condition for the hydrographic system of the Baltic Sea.

The system functions according to the basic laws of nature, including the mass balance of water and salt, the momentum equation (Newton's second Law), the heat balance, the energy equation of the kinetic energy and the equation of state of sea water. These laws cannot be affected by human activity.

The output from the conceptual system is the general hydrographic condition of the Baltic Sea. The important hydrographic parameters with respect to the marine life are: salinity and temperature stratification; advective transports and currents; and mixing rates, especially in the vertical direction. The output parameters vary in accordance with variations in the boundary conditions, but have a reduced and delayed signal as the hydrographic system of the Baltic Sea has a large inertia due to its large volume. The variations may be classified according to the time scales of the processes, of which the most dominant are: hour to days for changes in wave and local circulation pattern; about 10 days for low-pressure passages; one year for the weather changes; the climatic time scales of between 10 to several hundred years; and the geological time scale. The following system description will only include time scales of 10 days or more.

In this description only the physical oceanographic properties are considered. The chemical and biological parameters are not included as the hydrography of the Baltic Sea may be considered as a set of independent boundary conditions for the chemical and biological conditions. An example of this influence is illustrated by the oxygen balance of the bottom water of the Baltic Sea. The oxygen concentration of the bottom water is determined by the balance between the oxygen supply and the oxygen consumption. The oxygen supply is governed by the hydrographic transport processes, whereas the consumption rate is mainly governed by biological processes. Therefore, the oxygen changes during the last century cannot be explained by the changes in the hydrographic conditions alone as symptoms such as eutrophication must also be considered (Larsson *et al.* 1985).

The system approach clarifies such cause and effect relationships which are necessary for decision making about the future exploitation of the natural resources in and around the Baltic Sea. In addition, such an approach is in line with the ecosystem approach which has been adopted in many studies of the human impact on the Baltic ecosystem (Wulff 1987, Elmgren 1989).

Bathymetry

The Baltic Sea covers an area of 370 000 km^2 and has a volume of about 21 000 km^3, giving a mean depth of 56 m. The maximum depth of 459 m is located in the western Gotland Basin. The bathymetry is a series of basins and connecting channels. These basins have given names to the different subregions of the Baltic Sea. (Figure 2).

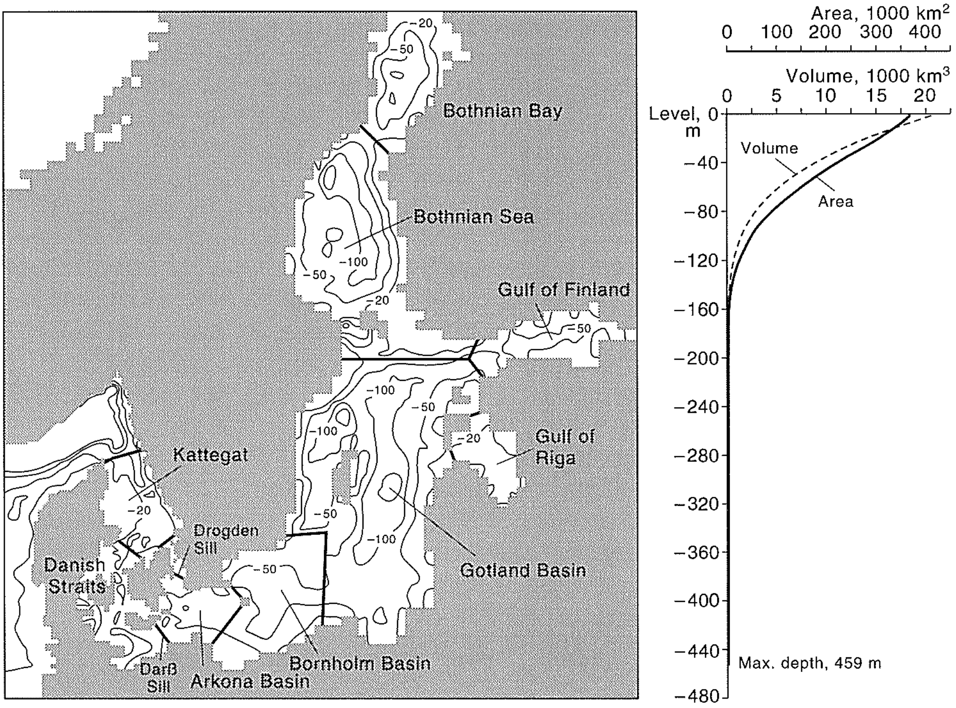

Figure 2. Bathymetry and limits of subregions of the Baltic Sea. The graph shows the horizontal area and underlying volume as a function of the depth of the Baltic Sea east of the sills of the Danish Straits.

The Drogden Sill, at the boundary between the Øresund (Danish Straits) and the Arkona Basin, has a width of only 14 km and a maximum depth of about 8 m. The Darß Sill is about 25 km wide with a maximum depth of about 17 m. From these two sills the bottom level generally declines through the Arkona Basin and the Bornholm Basin. Between the Bornholm Basin, with a maximum depth of 106 m, and the eastern Gotland Basin there is the narrow sub-surface Stolpe Channel, where the depth is only about 60 m. There are also sills to the Bothnian Sea and Bothnian Bay. These sills are of crucial importance for the flow and retention of the dense, saline water intruding from the transition area into the Baltic Sea.

Figure 2 also shows the size of the horizontal area as a function of the depth for the Baltic Sea. At level –60 m, the horizontal area is 143 000 km^2 which is only 39% of the surface area. This level is the primary halocline level of most of the Baltic Sea. Below this level is only 23% of the total volume. Furthermore, the volume below the level of –135 m only adds up to about 1% of the total volume. This level corresponds to the secondary halocline level of the Gotland Basin. Although the Baltic Sea is up to 459 m deep, the majority of the total volume is thus situated above the haloclines.

External forcings

River inflow

The annual average river inflow to the Baltic Sea amount to about 14 000 m$^3 \cdot$s^{-1} (excluding about 1000 m$^3 \cdot$s^{-1} to the transition area). The inflow, when compared to the size of the receiving basins, is largest to the Bothnian Bay and the Gulf of Finland. In these basins the water level would rise 2.6 and 3.7 m, respectively, if a year's inflow was stored up (Anon. 1986). For the Baltic Sea as a whole, the annual river inflow corresponds to about 1.2 m depth. The variation in the total river inflow volume from year to year is between 11 000 and 19 000 m$^3 \cdot$s^{-1} (Figure 3).

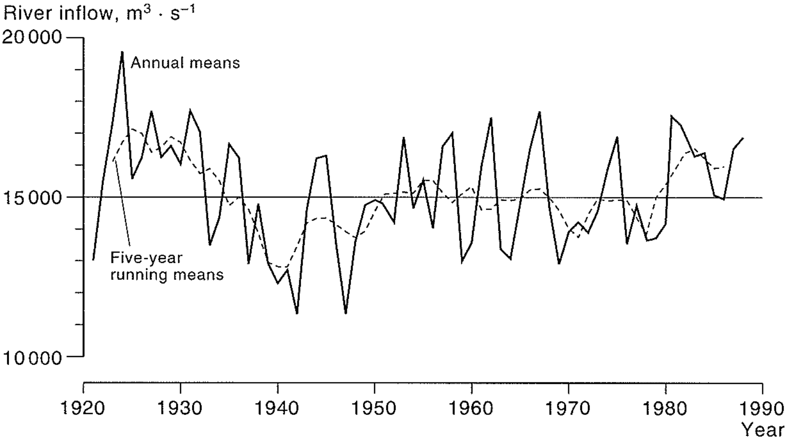

Figure 3. Total river inflow to the Baltic Sea (including the transition area). Annual means and five-year running means (HELCOM 1990).

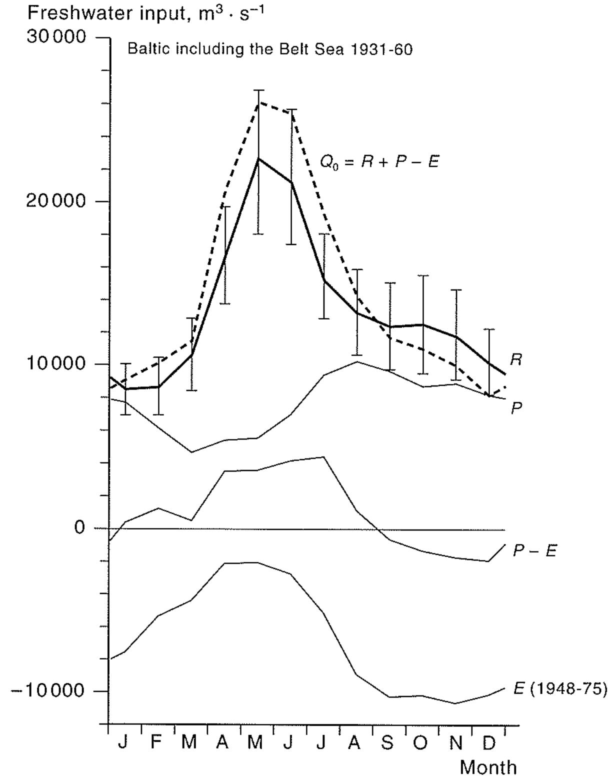

Figure 4. Freshwater components for the Baltic Sea.
R: river inflow,
P: precipitation,
E: evaporation,
Q_0 (dashed line): net freshwater input.
(Anon. 1979).

The build-up and melting of snow-cover in the catchment areas generate a seasonal variation in the river inflow (Figure 4). The range is between 9000 $m^3 \cdot s^{-1}$ in winter and 23 000 $m^3 \cdot s^{-1}$ in May-June. This variation is large enough to result in a seasonal variation in the net outflow through the Danish Straits, but this signal is also modulated by a week seasonal variation in the water level in the Baltic Sea as well as by precipitation and evaporation.

Precipitation (and evaporation)

Precipitation on the Baltic Sea averages 635 mm annually for the period 1931-1960 (Anon. 1986). Figure 4 illustrates the seasonal distribution with a maximum in late summer and a minimum in spring. The annual 635 mm corresponds to about 53% of the annual river inflow.

Evaporation is also important for the water balance. The annual average evaporation is approximately 493 mm (Anon. 1986), reducing the net freshwater input through the surface to about 1900 $m^3 \cdot s^{-1}$ on average, or 14% of the river input. Evaporation reaches a minimum in the spring. Although the evaporation is not a real boundary condition, but an output parameter of the system, it is often dealt with in combination with precipitation. The joint modulation of the freshwater input to the Baltic Sea by precipitation and evaporation amplifies the seasonal variation introduced by the river inflow.

The oceanographic boundary

The oceanographic boundary is characterized by an oceanic salinity of the water of about 35 psu, tidal variation, and regionally generated wind setups. The salinity of 35 psu has the effect of increasing the density of the water by about 3% when compared to fresh water. Temperature variation at the oceanographic boundary has far less influence than salinity on the density. The density surplus of the ocean water generates stratification in the Danish Straits, with the saline ocean water penetrating below the less saline upper layer water, starting in the northernmost Kattegat and continuing southwards to the sill areas in the south at the entrance to the Arkona Basin. From time to time the saline ocean water overflows the sills and penetrates into the Baltic Sea as a dense bottom current.

The tidal amplitude in the Kattegat is about 0.2 m but is damped to only a few centimetres in the sill areas and the Baltic Sea itself is too small for significant tidal variation to develop. Wind-generated water level variations in the northern Kattegat are generated by moving air pressure systems with accompanying wind fields passing Scandinavia and have a typical time period of 6-12 days. Westerly wind in the North Sea generally results in a water level increase in the Kattegat, whereas easterly winds result in a water level decrease. The size of the water level fluctuations is, in general, less than ±0.4 m.

Wind and pressure

Wind and pressure also have a direct effect on the Baltic Sea surface. It is the combination of this direct effect and the oceanographic boundary setup that generates the fluctuating flow in the Danish Straits. According to the Belt Project (Anon. 1976), the most favourable meteorological condition for an inflow through the Danish Straits to the Baltic Sea is a depression located in the southern part of Sweden and a high pressure over Jutland (Figure 5). When the depression is replaced by a high pressure over Scandinavia, the flow in the Danish Straits is typically out of the Baltic Sea.

The wind also causes a transfer of momentum for current generation and generates turbulence for mixing. The momentum contribution is proportional to the

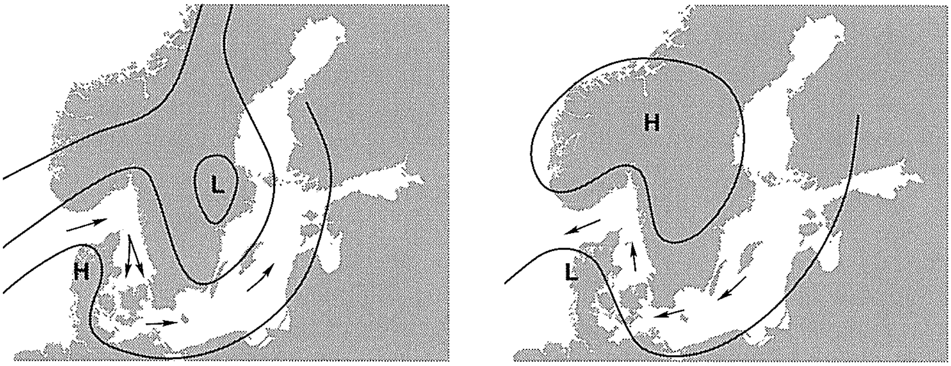

Figure 5. Typical positions of depression and high pressure during inflow and outflow events of the Baltic Sea (after Weidemann 1950).

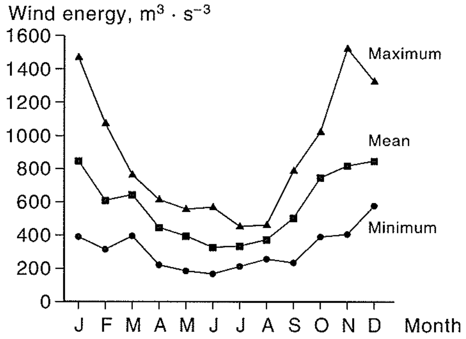

Figure 6. Seasonal variation in the wind energy. Data from the Great Belt (Sprogø) 1980-89 (Anon. 1992b).

square of the wind speed, while the turbulent input is proportional to the cubed wind speed (the wind energy). The wind energy during November-January exceeds that of the summer months, June-August, by more than 100% (Figure 6).

Air temperature and solar radiation

Air temperature and solar radiation are very important for the seasonal heating and cooling of the surface layer in the Baltic Sea. Besides the seasonal variation, which varies within the Baltic Sea area, there is a year-to-year variation (Figure 7). Together with the wind, these two parameters control evaporation and the generation of the thermocline. Furthermore, the ice coverage is dependent upon these parameters.

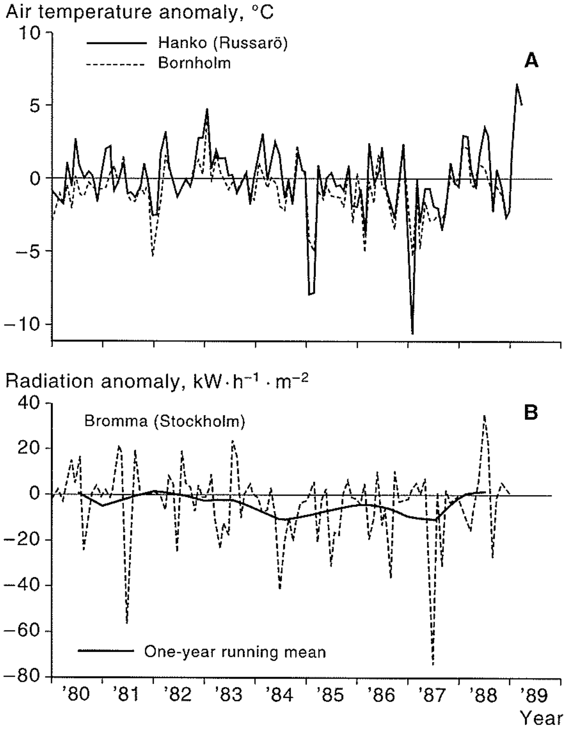

Figure 7. A: monthly air temperature anomaly; B: global radiation anomaly compared to the 1931-60 means at selected stations (HELCOM 1990).

Human impact

Among the potential human impacts which may have affected the marine environment of the Baltic Sea are the effects on the hydrological cycle. The effects on the cycle include regulation of the river flows, e.g. due to hydropower plants, and changes in the land use such as afforestation and agricultural development. It is considered here, however, that there is no quantified information about such impacts on the hydrological cycle today.

Another human impact is the effect of ship traffic in the Danish Straits, where the turbulence induced by the propellers potentially affects the mixing of dense bottom layer water up into the buoyant surface layer (see p. 97). Effects of the construction of fixed links in the Danish Straits are also discussed later.

Typical variability in the hydrographic regime

Due to the retention time of the Baltic Sea of approximately 20 years, calculated from the net freshwater input and the ocean inflow, and the time varying signals in the boundary conditions are reduced and delayed in the output hydrographic conditions of the system. In this section intra- and inter-annual variability in the retention time are discussed.

Salinity and temperature stratification

The combination of the freshwater input and the oscillating flow through the oceanographic boundary, which results in saline water entering the Baltic Sea and getting trapped, generates the annual means of salinity (Figures 8 & 9). The horizontal gradients are generated by the local distribution of the freshwater inflow and is particularly strong in the uppermost bays of the system. At the exit to the transition area, the surface salinity has an annual average value of about 7.5 psu. Vertically, the important stratification is clearly seen with an incline in the salinity from 8 to 10 psu within 20 m. This halocline is situated between 50 and 70 m below the surface in the Gotland Basin and also penetrates into the Gulf of Finland and the Bothnian Sea. The salinity in the offshore parts of the Baltic Sea is nearly con-

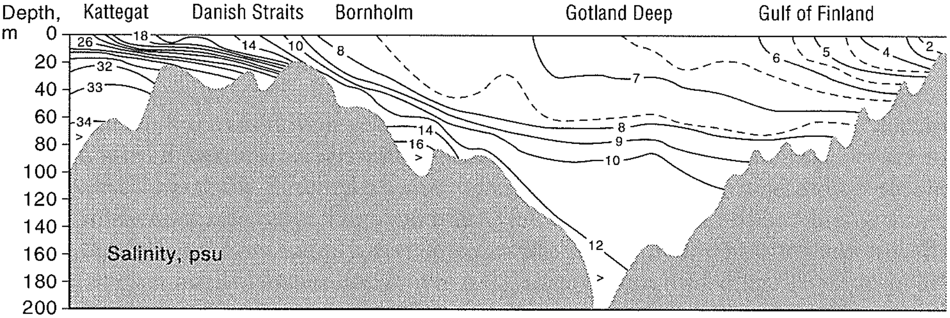

Figure 8. Depth profile of the Baltic Sea from Kattegat to the Gulf of Finland showing the average salinity stratification (Falkenmark & Mikulski 1975).

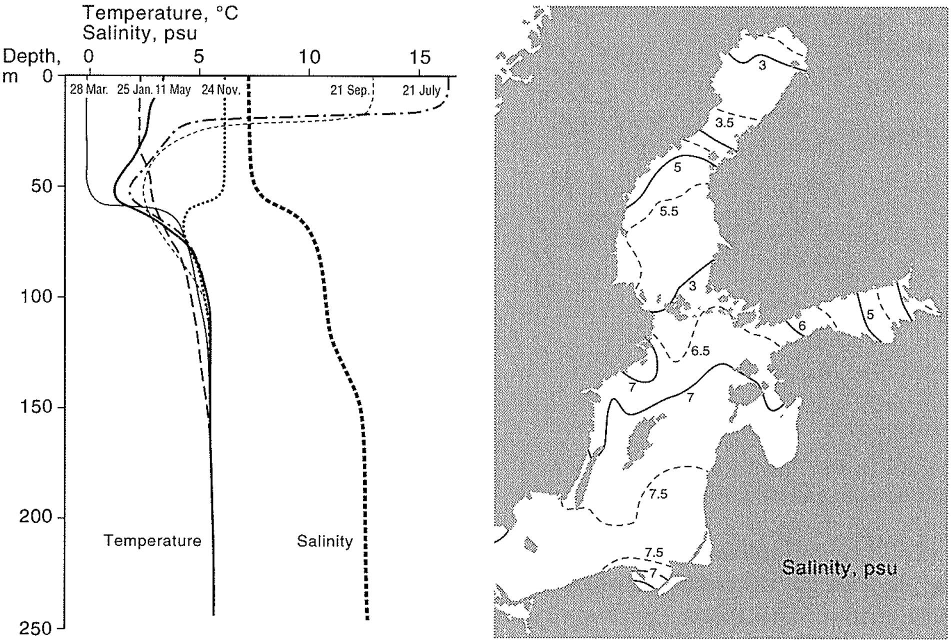

Figure 9. Mean salinity profile and temperature profile variations during the year. Profiles measured east of Gotland (Kullenberg & Jacobsen 1981). Mean surface salinity distribution 1960-80 (ICES 1993).

stant throughout the year, as the retention time for salt in the Baltic Sea is also about 20 years. The vertical profile in Figure 9 indicates the three main layers of the Baltic Sea: the upper more brackish layer down to approximately 60 m depth; the intermediate more saline layer between 60 and 140 m depth originating from more regular inflows of saline water from the transition area; and the bottom layer with the higher salinity originating from the 'major inflow' events of high-saline water over the sills. As indicated above (Figure 2), the intermediate layer and the bottom layer only occupy 22% and 1% of the total volume, respectively. The haloclines reduce the vertical mixing of the water column between the layers.

The temperature profiles in Figure 9 show the system's heat balance effect. During spring and summer a thermocline is formed 15-20 m below the surface. The temperature difference across the summer thermocline is up to about 10°C. The implication of this on the water density is sufficient to reduce the vertical mixing within the layer above the upper halocline. During autumn and winter the thermocline is eroded due to increased wind mixing and penetrative convection as a result of the surface cooling.

Inflow and outflow through the Danish Straits

The system response to the meteorological forcing are the inflows and outflows of water through the Danish Straits. From the salinity balance of the Baltic Sea, the net inflow of saline water from the Danish Straits can be calculated as about 20 000 $m^3 \cdot s^{-1}$ (annual average) and the outflow of upper layer water from the Baltic as

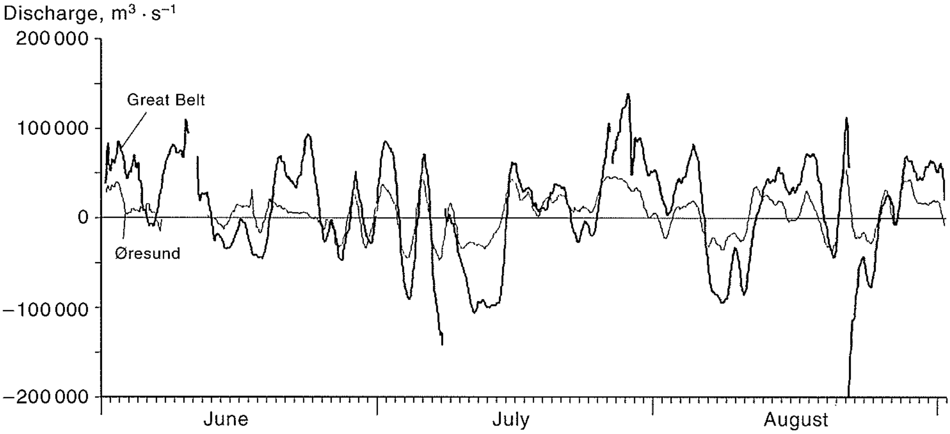

Figure 10. Discharge in upper layer through the Great Belt and the Øresund calculated from measured currents. Positive values for outflow of the Baltic Sea (Møller & Pedersen 1993).

35 000 $m^3 \cdot s^{-1}$. However, the actual flow oscillates with a typical range of ± 150 000 $m^3 \cdot s^{-1}$ for the connection through the Great Belt and ± 70 000 $m^3 \cdot s^{-1}$ through the Øresund (Figure 10).

The salinity of the inflowing water is dependent upon the duration of the inflow events. During the first days of an inflow event, the water flowing into the Baltic Sea will mainly be surface layer water of about 12 psu from the southern part of the Danish Straits. For longer durations the reservoir of low-saline water in the Danish Straits will be emptied, and water of higher salinities will start to pass the sills. These events are named 'major inflows', and may include salinities as high as 28.1 psu and 30.5 psu for the Darß and Drogden Sills, respectively. Thus, the major inflows may be considered extreme developments of normal inflow events.

Major inflows, defined as inflows with salinities exceeding 17 psu at the Darß Sill, have occurred 90 times within a 70 years period up to 1977 (Matthäus & Franck 1992). The frequency distribution of the events (Figure 11), shows a decreasing frequency of events for increasing inflow volume. Based upon these data, the salt flux into the Baltic Sea during major inflows has been estimated to average about 1600 million tonnes per year. This corresponds to about 30% of the total salt inflow to the Baltic Sea necessary to retain the status quo for the Baltic Sea salinity. Thus, the remaining part, about 70%, enters with medium-salinity water. The major inflow events are clearly seen as suddenly increasing salinity levels in time series from the deeper parts of for example the Gotland Basin (Matthäus & Franck 1992).

The different behaviour between the regular and the major inflows can be seen in the computed distribution of volume flows interleaving at different levels (Figure 12). After passing the sills, the inflows flow as dense bottom currents through the Arkona Basin, the Bornholm Basin and through the Stolpe Channel into the eastern Gotland Basin. On its way the bottom current entrains water from the water column above, which reduces its salinity. Where the declining dense current reaches a density level equal to that in the reservoir, the bottom flow is of neutral density and

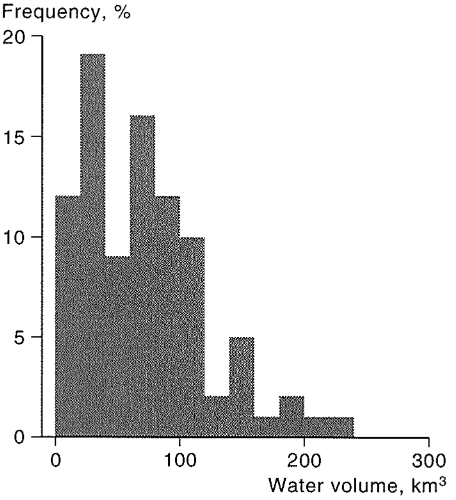

Figure 11. Frequency distribution of the high-saline (> 17 psu) water volume penetrating during major inflow events (Matthäus & Franck 1992).

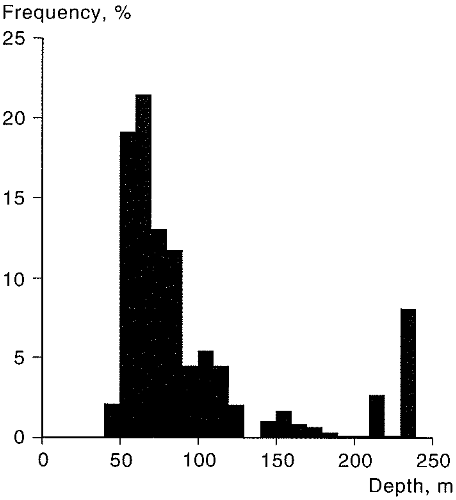

Figure 12. Computed distribution of volume inflows interleaving at different levels in the Baltic Sea (Stigebrandt 1987).

will continue horizontally, interleaving the water column. As the major inflows have the highest initial salinities, they interleave at the largest depths. A simple calculation shows that the bottom and the intermediate layer in the Baltic Sea have retention times of about one year and four years, respectively.

Currents

The dominating current pattern in the Baltic Sea is the large-scale circulation created by the dense bottom currents entering from the sills. The bottom current entrains about 150% additional water during the downward flow through the system (Pedersen & Møller 1981) and is eventually mixed into the upper layer and into the freshwater inflow. A part of the upper layer is mixed into the bottom current and thus creating an extra cycle, while the remainder leaves the Baltic Sea through the transition area. The dense bottom current has a speed of up to 0.3 $m^3 \cdot s^{-1}$, while the upper layer velocity component from the large-scale circulation is very small.

The upper layer velocity is dominated by currents generated by the local wind, forming vertical as well as horizontal circulation within the layer. On average, there is a weak cyclonal circulation in the Baltic proper, the Gulf of Finland and the Bothnian Sea with current velocities of the order of centimetres (Kullenberg & Jacobsen 1981). The wind action also generates surface setups, which result in seiching in the Baltic Sea if the wind is suddenly reduced. These seiching events are registered for the surface layer, but may also be transmitted to the lower layers. For example, a large flooding event in the southern part of the Danish Straits in 1872, with water levels up to about +3 m, was caused by a sudden change in wind direction during a storm, creating a seiching in the Baltic Sea which, in the western part, became amplified by the wind setup of the subsequent wind direction.

Others

In order to obtain a long-term hydrostatic pressure equilibrium between the Baltic Sea and the North Sea, the sea level in the Baltic Sea is generally 0.1-0.2 m above the North Sea level due to the lower salinity and thereby the lower density of the surface water in the Baltic Sea. Short-time variations due to the air pressures passing Scandinavia, and seasonal variations generally dominate the sea level variation in the Baltic Sea.

The oxygen concentrations below the surface layer reflect the balance between the horizontal inflow of new, oxygen rich water, the reduced vertical mixing of oxygen and the local oxygen consumption. While the surface layer typically varies within the range of 95-130% saturation (about 9 ml oxygen $\cdot$ l^{-1}), the layer below the primary halocline has oxygen concentrations of only a few ml $\cdot$ l^{-1}. Below the secondary halocline, the deep water oxygen concentration ranges between 2 and -4 ml $\cdot$ l^{-1}, where negative oxygen values correspond to dissolved hydrogen sulphide.

Evolution of the Baltic

Geological time scale

The Baltic has experienced dramatic changes since the last glaciation; even during historical time man has lived beside an ever changing Baltic Sea.

At the end of the last Ice Age, 14 000 years ago, the Baltic Ice-dammed Lake was formed as a freshwater reservoir above the ocean level with water from the melting ice cover. The outflow took place through the lake region in Sweden. As the ice cover melted, the ocean level rose and, with some delay, also the land due to isostatic rebound. When the ocean flooded the barrier to the Baltic Ice-dammed Lake the saline Yoldia Sea was formed. About 1000 years later the land elevation took over and a new freshwater lake was formed, the Ancylus Lake, with an outflow through the Great Belt. However, the oceans continued to rise and the southern part of the present Danish Straits declined, and 1000 years later a new saline reservoir, the Littorina Sea, had developed. This sea had a somewhat higher salinity than the Baltic Sea today, but a slow land elevation in the Danish Straits during the last thousands of years has resulted in a reduction in the inflow of ocean water, reducing the salinity in the Baltic Sea. On the geological time scale, bathymetrical changes are thus the main reasons for the changing conditions of the Baltic Sea. Today there is a land height rise of up to 1 cm per year in the northern part of the Baltic Sea, while there is no height rise in the Danish Straits (Binderup & Frich 1993).

Recent 100 years

Measurements of the hydrographic conditions in the Baltic Sea exist since 1870. The time series show a fluctuating pattern and for some parameters a general trend. The review of the recent evolution will be divided into the period up to about 1977 and the period after 1978, as the 1978-1992 period is characterized as a stagnation period with respect to major inflows to the Baltic Sea.

There was an increase in the salinity in the period 1900-77. The increase was largest for the bottom waters, 0.8 to 1.7 psu, and less in the surface waters, 0.2 to 0.5 psu (Matthäus 1979). During the same period the temperature of the bottom waters increased 0.6 to 2.7°C. The trend comes out of larger year-to-year variations in salinity (Figure 14), whereas the increases in salinity are known to coincide with periods of intensive, major inflow events (Frank & Matthäus 1992). Studies of the long-term trend of the salinity gradients across the halocline do not show any significant trend in the stability and the halocline level has not varied more than 10% in the Gotland Basin (Matthäus 1979). There is, however, a tendency for a slight increase in the halocline which may have affected the deep water penetration into the Bothnian Sea.

The cause of the trends may be related to the freshwater inflow as well as the oceanographic boundary (major inflows). There is a good correlation between the deep water salinity and the river inflow, with increasing salinity for decreasing inflow (Anon. 1990) (Figure 14). It is not known, however, whether the correlation is a result of the direct relation between the two parameters, or if they only merge due to a common external parameter variation, such as changing meteorological conditions. Studies have shown that the frequency of strong winds (above 9 Beaufort) has decreased from 2 to 0.5% of time during the last century (Kristensen & Frydendahl 1991).

The increase in upper layer salinity of the Baltic Sea may be related to increased mixing in the Danish Straits as a result of the shipping intensity. A modelling study has shown a good correspondence between the increase in the measured salinity of the upper layer and the modelled salinity evolution taking the ship effect into account, whereas no increase was found when the ship effect was omitted (Jürgensen 1989).

Periods of minimum intensity of major inflows have occurred from 1900 to 1977. These stagnation periods include the late 1920s and the late 1950s. Since

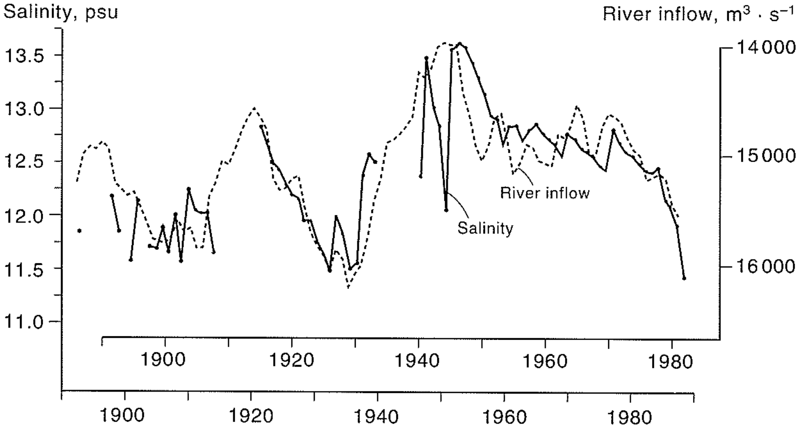

Figure 13. Long-term variation of the deep-water (200 m) salinity in the Gotland Deep in comparison with the estimated river inflow to the Baltic Sea (Q_{BT}). For the best fit, the time axis of the low-pass filtered (15-year running average) river inflow has to be shifted forward 6 years (HELCOM 1990).

1978 the Baltic Sea has experienced a longer stagnation period, where only three smaller events of major inflows have occurred up until 1990 (November-December 1978, November 1982, January 1983; Franck & Matthäus 1992). This is the longest stagnation period ever recorded. The effect of the stagnation period appears in the salinity from 80 m depth downwards, where the salinity decreased about 1.5-2.5 psu (see Figure 13). The effect of the stagnation is also obvious in time series of the oxygen content in the deep water, where the average concentration decreased from about 0 $\mathrm{ml \cdot l^{-1}}$ in the 1970s to -2 $\mathrm{ml \cdot l^{-1}}$ in the 1980s (Figure 14). In the intermediate waters, where the water renewal mainly takes place by the regular lower saline inflows, the negative trend in oxygen conditions since 1978 is less pronounced. Before 1977 there is even a slight positive trend in this level (Figure 14).

Different trends in salinity and oxygen may be very important for reproduction of cod, for example, as cod eggs are dependent upon the acceptable oxygen concentrations in the level of neutral buoyancy (Carlberg & Sjöberg 1992). This may occur if eutrophication reduces the oxygen, but does not affect the salinity.

In January-February 1993 a new major inflow event occurred, resulting in about 154 $\mathrm{km^3}$ of high-saline water entering the Baltic Sea (Jakobsen 1995). This inflow event is among the 12 largest recorded. After the 1993-event the salinity of the deep waters has again been increasing (J. Svensson, Swedish Meteorological and Hydrological Institute, pers. comm.).

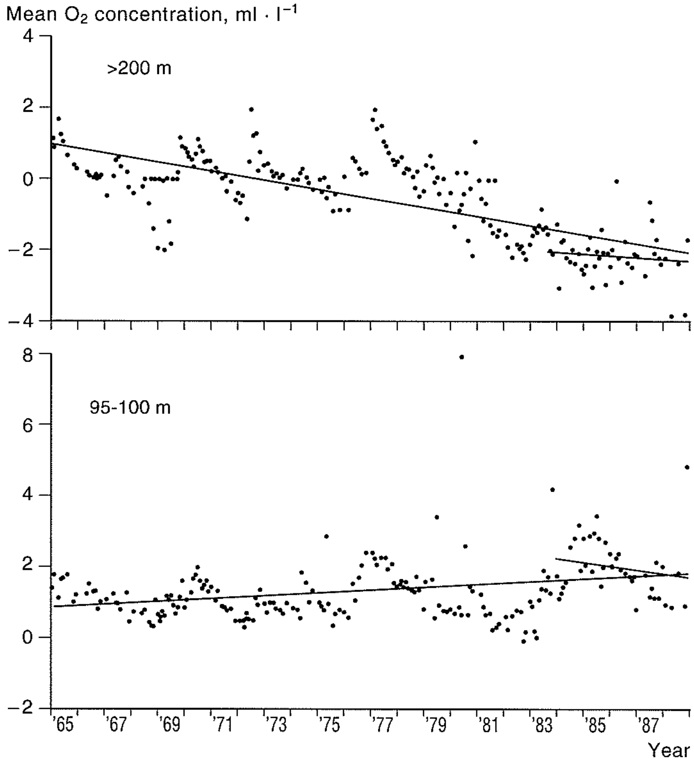

Figure 14. Trend in the monthly means of oxygen concentrations in the intermediate water (95-100 m) and the deep water (> 200 m) of the Gotland Deep for the period 1965-1988 (HELCOM 1990).
In the text is given an alternative interpretation of the measurements than indicated by the regression line of the total period.

Potential anthropogenic changes in the future

Climate

The greenhouse effect will inevitably affect the hydrography of the Baltic. A direct approach to the understanding of the effect of the climate change response of regional seas is demonstrated by Backhaus (1989). The actual impact of the greenhouse effect on the boundary conditions of the Baltic system is difficult to assess. However, the 'best estimate' for the global mean sea level rise during the next hundred years is 40-60 cm, although the regional distribution is unknown (J.O. Backhaus, pers. comm.).

The foreseen rise in water level may favour the salt inflow to the Baltic by making a parallel to the geological history of the Baltic Sea. However, many climate scenarios suggest that the precipitation over the Baltic catchment area will increase, which would tend to decrease the salinity of the Baltic.

The largest impacts from the greenhouse warming on the Baltic, however, will most likely not be related to changes in the average boundary conditions, but rather to the changes in the variability of the forcing. Because of the salinity balance being so closely related to the variability of the exchange flows through the Danish Straits, and because of the exchange flows being strongly correlated with the variability of the weather (especially the routing of the low pressure systems), even small displacements in the existing weather system may cause large effects on the Baltic hydrography.

Hydrological cycle

The close and strong correlation between the river inflow and the hydrography of the Baltic demonstrates the sensitivity of the Baltic to changes within the hydrological catchment area. Human exploitation of the natural resources, such as hydropower and agriculture/forestry, have a significant impact on the hydrological cycle of the catchment area. The hydropower development directly changes the annual variation of the freshwater input. The storage capacity of the hydropower dams delays the spring runoff and hence alters the annual variation in the freshwater driven, large-scale circulation of the Baltic. A potentially more important impact from human activity is the changes in land use. Since 1960 the volume of wood in the Nordic forests has increased by about 20%. Also the forestry practice, especially the drainage of large forest areas, has changed considerably, leading to a shift in the hydrology of the catchment characteristics (Nordisk Ministerråd, 1993). The future economical development of Eastern Europe will inevitably also influence the land use of the catchment area. In spite of the potential large-scale effects, these changes have not been investigated and are subject to speculation. Pedersen & Møller (1981) and Pedersen (1982) demonstrate the sensitivity of the Baltic to the changes in the hydrological cycle by studying the large-scale effects of relocation of fresh water to other catchment areas by diversion of the river Neva.

Fixed links

Bridges and tunnels are being constructed across the Danish Straits. The locations of the three large infrastructure projects (The Great Belt Link, the Øresund Link

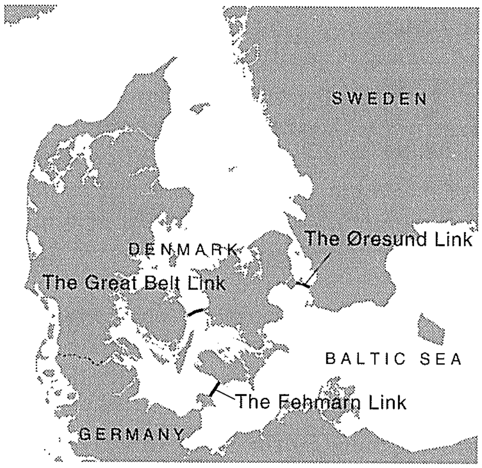

Figure 15. The location of the three fixed link projects across the Danish Straits.

and the Fehmarn Link) are shown in Figure 15. The Great Belt Link is presently (1994) under construction. A joint governmental agreement between Sweden and Denmark has laid the foundation of the Øresund Link for which construction works commenced in 1994. The Fehmarn Link is still under negotiation between the Danish and the German governments.

Because of the crucial importance of the Danish Straits for the salinity balance of the Baltic, numerous technical and scientific studies have been and are being carried out in order to assess the impact of the links on the exchange flows through the straits (Møller 1989, Farmer & Møller 1990, Jensen *et al.* 1992, Ellegaard & Jakobsen 1992).

The potential impact of the links on the Baltic is a reduction of the exchange flow through the Danish Straits. Such a reduction will cause a slight reduction in the salinity of the Baltic. Assessments of this impact (Anon. 1992a, Stigebrandt 1992) agree that the potential impact is very small. Typical changes of the mean surface salinity of the Baltic Proper of 0.03 psu (from e.g. 7.05 to 7.02 psu) due to the Øresund Link are reported. For the Great Belt Link the Danish Construction Law states that: '... the work is to be carried out ... in such a way that the water flow through the Great Belt shall remain unchanged ... for the sake of the marine environment of the Baltic.' This strict environmental design criteria for the impact of the link is denoted the 'zero blocking solution'. It is seen from the systems description of the Baltic that the zero blocking solution means that the link does not influence the oceanographic boundary condition for the Baltic. Consequently, the link does not influence either the hydrography or the ecosystem of the Baltic. The zero blocking solution is achieved by compensating the increased flow resistance induced by bridge piers and causeways by means of dredging close to the link (Møller & Ottesen Hansen 1990).

When compared to the potentially much larger impacts from man-made changes of the hydrological cycle of the catchment area for the Baltic and the greenhouse effect, it is surprising that the majority of the scientific effort in describing the man-made impacts has to date merely described the minor effects of the fixed links.

Future research

The systems description of the Baltic given here suggests that future research areas of priority should be focused on combined hydrological and hydrographic studies and their links to the ecosystem of the Baltic.

Particular physical oceanography topics which need attention are the mechanisms linking the weather variability with the major salt inflows. A valuable approach would be a combination of statistical methods (viewing the inflows as extreme events of the daily inflows) and deterministic studies where recorded inflows are modelled with numerical hydrodynamic models driven by meteorological models (in analogy with storm-surge hindcasting).

The climatic changes may be investigated through a detailed analysis of the large amount of available data, which have, until now, not been analysed in full and certainly not brought to a format comparable with present modelling and analysis tools. By testing budget models, basin-integrated models and fully baroclinic, numerical 3D models against the long time series of hydrographic boundary and internal data, it is possible to assess the predictive ability of the models and afterwards use the models to predict the response of the Baltic to various climate scenarios.

The field observations and the measurement methods are undergoing extensive development. In particular, Acoustic Doppler Current Profilers (ADCP) and related acoustic methods will be practical, standard tools in the future and it is necessary that the field work is planned in close coordination with the development of predictive methods. Data collected but not used and relevent data not collected hinder the process of understanding and predicting the hydrography of the Baltic.

It is considered that the Baltic countries could develop a forecasting model for the marine weather as shown by the meteorologists when the common weather model HIRLAM was developed. The objective of such a large-scale project should be to develop an operational model and implement the necessary data collection system necessary to run the model. The gain from such a project would not only be an improved understanding of the Baltic but also a leading edge within predictive physical oceanography.

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