Ventilation of the Baltic Sea deep water: A brief review of present knowledge from observations and models

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Abstract

The ventilation of the Baltic Sea deep water is driven by either gale-forced barotropic or baroclinic salt water inflows. During the past two decades, the frequency of large barotropic inflows (mainly in winter) has decreased and the frequency of medium-intensity baroclinic inflows (observed in summer) has increased. As a result of entrainment of ambient oxygen-rich water, summer inflows are also important for the deep water ventilation. Recent process studies of salt water plumes suggest that the entrainment rates are generally smaller than those predicted by earlier entrainment models. In addition to the entrance area, the Słupsk Sill and the Słupsk Furrow are important locations for the transformation of water masses. Passing the Słupsk Furrow, both gravity-driven dense bottom flows and sub-surface cyclonic eddies, which are eroded laterally by thermohaline intrusions, ventilate the deep water of the eastern Gotland Basin. A recent study of the energy transfer from barotropic to baroclinic wave motion using a two-dimensional shallow water model suggests that about 30% of the energy needed below the halocline for deep water mixing is explained by the breaking of internal waves. In the deep water decade-long stagnation periods with decreasing oxygen and increasing hydrogen sulphide concentrations might be caused by anomalously large freshwater inflows and anomalously high mean zonal wind speeds. In different studies the typical response time scale of average salinity was estimated to be between approximately 20 and 30 years. The review summarizes recent research results and ends with a list of open questions and recommendations.

1. Introduction

During the fifth Baltic Sea Science Conference (BSSC) in Sopot, Poland, on June 20–24, 2005 a workshop on the 'Ventilation of the Baltic Sea deep water – observation and model results' was held. The objective of this workshop was to discuss the state-of-the-art knowledge on the ventilation of the Baltic deep water and its impact on the marine ecosystem and to improve our understanding of the physical processes involved.

In recent years the quantity and quality of available data from individual salt water inflow has increased considerably. In addition, process-oriented models and three-dimensional ocean circulation models have been applied to simulate either individual inflow events in process studies or longer periods in studies of climate variability. During the workshop these different aspects were discussed with the overall aim of bringing observers and modelers from different disciplines together for a comprehensive assessment of recent research results. In particular, still open questions and problems of available models were discussed.

In this paper the main results of the 13 oral presentations and posters (see Appendix, p. 164) are summarized. As the presentations covered a wide range of research activities, we are using this opportunity to briefly review present knowledge from observations and models on the topic (section 2). Selected processes, which are believed to be important for the ventilation of the deep water, are discussed: major Baltic inflows (2.1), small and medium-strength inflows and the dynamics of salt water plumes (2.2), near-bottom dense water pools in the Arkona Sea (2.3), entrainment (2.4), water exchange through the Słupsk Furrow (2.5), mesoscale eddies (2.6), thermohaline intrusions and interleaving (2.7), and deep water mixing (2.8). Climatological aspects of the estuarine or vertical circulation, the so-called 'haline conveyor belt' of the Baltic (2.9), including its low-frequency variability are discussed in section 2.10. Finally, estimates of the internal 'response time scale' of the average salinity of the entire Baltic are given (2.11). Section 3 lists important open research questions. The paper ends with recommendations for future activities.

2. Present knowledge

Several earlier publications gave an overview of important physical processes of the Baltic Sea system, e.g. Mälkki & Tamsalu (1985), Gustafsson (1997), Rodhe (1998), Stigebrandt & Gustafsson (2003), and Elken & Matthäus (2006). A review of recent research during the Baltic Sea Experiment (BALTEX) and related programs was presented by Omstedt et al. (2004). As during certain periods in the past 100 years oxygen conditions in the deep water of the Baltic proper have tended to be critical for organic life, the ventilation of the deep water and its impact on the chemical and biological conditions have been intensively studied in many publications. The results by Fonselius (1969, 1970) were milestones several decades ago. Systematic chemical investigations were started in the Baltic area at the beginning of the 20th century (e.g. Pettersson 1898) and several international projects were dedicated to deep water ventilation. For instance, within the DIAMIX experimental study diapycnal mixing in the virtually tideless Baltic Sea was investigated (Stigebrandt et al. 2002). An ongoing project is QuantAS – Quantification of water mass transformation processes in the Arkona Sea (Burchard et al. 2005).

2.1. Major Baltic inflows

The deep water is ventilated mainly by large perturbations, so-called major Baltic inflows (Matthäus & Franck 1992, Fischer & Matthäus 1996, Lass & Matthäus 1996). These events occur during the winter half-year forced by a sequence of easterly winds lasting for about 20 days followed by strong to very strong westerly winds of similar duration (Lass & Matthäus 1996). During the last century these events have occurred more or less randomly at intervals of one to several years. However, during the past two decades the frequency of major inflows has decreased. Significant inflows have occurred only three times: in 1983, 1993 and 2003. The lack of salt water inflows caused stagnation periods, i.e. the ventilation of the Baltic deep water ceased with decreasing oxygen and increasing hydrogen sulphide concentrations (see section 2.10).

Especially the last two major Baltic inflows in January 1993 and in January 2003 were intensively investigated and involved the analysis of either observations (inflow 1993: Matthäus et al. 1993, Håkansson et al. 1993, Dahlin et al. 1993, Jakobsen 1995, Matthäus & Lass 1995; inflow 2003: Feistel et al. 2003b, Piechura & Beszczyńska-Möller 2003) or three-dimensional circulation model results (inflow 1993: Huber et al. 1994, Lehmann 1995, Meier 1996, Andrejev et al. 2002, Meier et al. 2003; inflow 2003: Meier et al. 2004, Lehmann et al. 2004, Stips et al. 2005). It was shown that the performance of circulation models with either geopotential vertical (z-level) or bottom-following (sigma) coordinates is satisfactory (e.g. Fig. 1). Simulated volumes of inflowing high-saline water during the events in 1993 and 2003 are close to figures estimated from observations. In the case of level coordinate models the implementation of the diffusive part of the bottom boundary layer model by Beckmann & Döscher (1997) and Döscher & Beckmann (2000) improved the results of the salt flow into the Bornholm Sea deep water considerably (Meier et al. 2004).

2.2. Small and medium-strength inflows

Inflow events of medium strength occurring several times per winter season are important since they have a density signature sufficient for ventilating intermediate layers of the Baltic proper halocline, which is generally subject to oxygen depletion (Lass & Mohrholz 2003, Burchard

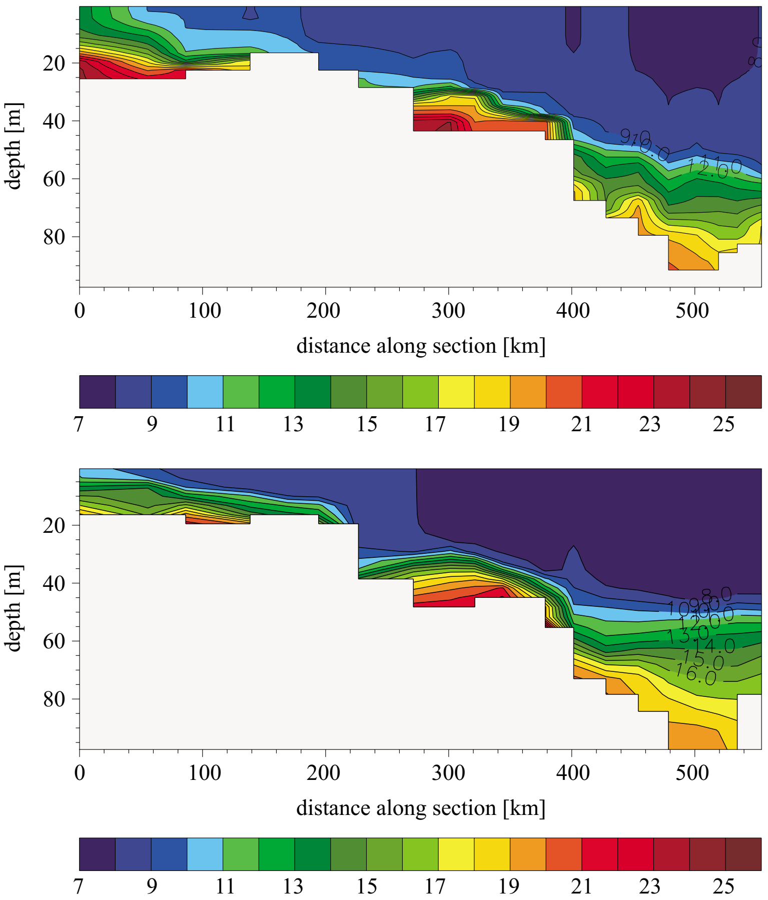

Fig. 1. Cross section of salinity [PSU] from the Fehmarn Belt to the Słupsk Furrow through the Arkona Sea and Bornholm Sea, cast between February 14 and 17, 1993: observations (upper panel) and results of the Rossby Centre Ocean model, RCO (lower panel) (from Meier 2001)

et al. 2005, Lass et al. 2005, Mohrholz et al. 2006, Sellschopp et al. 2006). As the Arkona Sea is known to significantly reduce the density of such inflowing water by means of turbulent mixing, quantification of the relevant water mass transformations in this area is essential for our understanding of the sensitivity of the Baltic Sea to climate change and human impact. For instance, it is speculated that the projected construction of extensive off-shore wind farms in the area of the Arkona Sea may have a significant impact on mixing (Burchard et al. 2005).

Lass & Mohrholz (2003) observed two medium-intensity salt water inflows in November and December 1998. Analyzing these data Lass et al. (2005) found that the salt water plumes spilling over the Drogden

Sill branched into two plumes. The northern plume flowed downhill into a trench at the northern rim of Kriegers Flak, whereas the southern plume followed the isobaths and passed through the gap between Mön Island and Kriegers Flak. The further motion of the latter plume is a spiral along the western and southern rim into the center of the Arkona Basin, where it contributes to the dense bottom water pool (Lass & Mohrholz 2003). Numerical simulations performed with the Modular Ocean Model, MOM-3 (Pacanowski & Griffies 1999), showed that the core of the northern plume had both a higher salinity and a higher eastward velocity compared with the southern plume (Lass et al. 2005). Another plume passing the Darss Sill flowed onto a wedge-shaped submarine terrace from the sill to Kap Arkona, where it joined the western Drogden Sill plume associated with mixing and eddy shedding.

In January/February 2004 another medium-intensity salt water inflow over the Drogden Sill was observed (Sellschopp et al. 2006) and intensively analyzed (e.g. Burchard et al. 2005). Several sections were carried out in the southern part of Öresund between the Drogden Sill and Kriegers Flak. At one station north of Kriegers Flak a 19-hour time series of temperature, salinity, current velocities and dissipation of turbulent kinetic energy was obtained for the dense water plume. Both the observations of this medium-intensity inflow event and idealized model simulations performed with the General Estuarine Transport Model, GETM (Burchard & Bolding 2002), suggest that most of the salt flow occurred north of Kriegers Flak (Burchard et al. 2005). Within the salt water plume the gravitational forces in the flow direction and in the cross-flow direction are balanced by bottom friction and by the Coriolis force, respectively (Arneborg et al. 2006). Simulated profiles of stratification, velocity and dissipation using a one-dimensional turbulence model are in good agreement with observations at the station north of Kriegers Flak (Arneborg et al. 2006).

In summer 2002 and 2003 exceptional warm inflow events were observed at the Darss Sill (Feistel et al. 2003c, 2004a,b, 2006, Mohrholz et al. 2006). These summer inflows were driven by baroclinic pressure gradients during calm wind conditions when in the Belt Sea and in the Arkona Sea mixing of the inflowing water with the ambient water is reduced. As a consequence, warm and saline water masses were sandwiched into the halocline of the Bornholm Basin and could be traced even in the Gotland Deep owing to the unusually high temperatures. Although the oxygen content of the inflowing warm water was relatively low (in contrast to gale-forced barotropic inflows), the inflows in summer 2002 and 2003 improved the oxygen conditions in the Bornholm Basin and in the eastern Gotland Basin following the entrainment of ambient water with a higher oxygen level (Mohrholz et al. 2006). Thus, during small and medium-intensity inflow events the oxygen concentration in the Arkona Sea is an important factor for the ventilation of the deep water.

In general, smaller inflow events like the summer inflows in 2002 and 2003 are difficult to simulate with coarse-resolution circulation models using level-coordinates. However, it was shown that within a long climate simulation using the Rossby Centre Ocean model, RCO (Meier et al. 2003), starting in May 1980 the summer inflow in 2002 is modeled at least qualitatively well (Meier et al. 2004). Traces of the small inflows in August/September 2002 and in November 2002 were identified even in the halocline of the western Gotland Basin.

During the past fifty years warm summer inflows with an impact on the Bornholm Deep temperature record have been rare events (Mohrholz et al. 2006). However, since 1988 the annual temperature minimum of the intermediate winter water at Bornholm Deep has increased by about 1.5°C (Fig. 2). The annual maximum temperature in the halocline layer (salinity between 8.95 and 14.3 PSU) has exceeded 12°C in only four out of 50 years since 1952 (1959, 1992, 1997, 2002), indicating an increased frequency of warm inflow events since the beginning of the 1990s (Mohrholz et al. 2006). The temperature in October 2002 was the highest ever observed in the halocline of the Bornholm Basin. Although these summer inflows had only little impact on the salt content of the entire Baltic, the impact on the deep water ventilation even in the Gotland Deep was found to be considerable (Feistel et al. 2006).

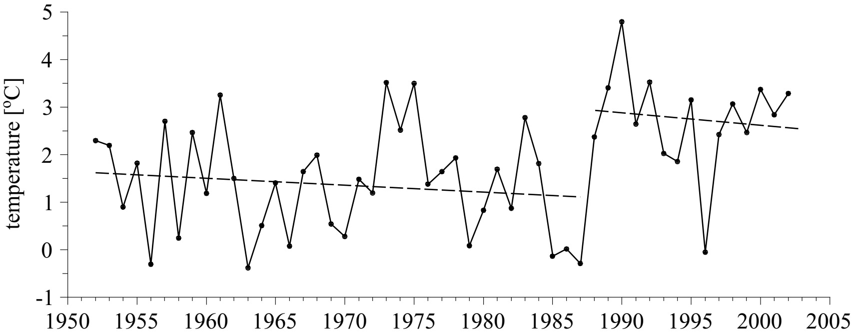

Fig. 2. Observed annual temperature minimum [°C] in the intermediate winter water at Bornholm Deep (from V. Mohrholz & I. Schuffenhauer, poster presentation at the BSSC 2005)

Warm inflows in September 1997, October 2001, August 2002 and August 2003 had a considerable impact on the water temperature at 200 m depth in the eastern Gotland Basin, which increased to more than 6°C

(Feistel et al. 2006, their Fig. 1). Although the amount of inflowing salt water in August 2003 was much smaller than that of the major Baltic inflow in January 2003, the summer inflow was able to raise the temperature in the Gotland Deep from about 4.5°C in April after the major Baltic inflow to more than 6°C in November. Thus, the recent summer inflows have been important for the ventilation of the eastern Gotland Basin deep water.

Note that a 'warm summer inflow' is not necessarily a baroclinic event. For instance, the warm inflows of 1997 and 2001 were barotropic, gale-forced ones (Hagen & Feistel 2001, Feistel et al. 2003a).

2.3. Dense water pool in the Arkona Basin

Observations made in the Arkona Basin in February 1993 after the major Baltic inflow showed the existence of a thick bottom pool of deep water separated by a halocline from the surface water of Baltic origin (Liljebladh & Stigebrandt 1996). Liljebladh & Stigebrandt (1996) showed that the deep water flow was geostrophically controlled. Assuming that the deep water flow is quasi-stationary, Gustafsson (2001) calculated from observations of the 20th century at BY2 in the Arkona Basin a mean inflowing transport of 22 400 m^3 s^{-1}. This estimate supports earlier studies by Stigebrandt (1987a).

At the end of January 1993 the amount of inflowing salty water across the Drogden and Darss Sills into the Arkona Basin is larger than the outflow through the Bornholm Channel into the Bornholm Basin. Hence, the halocline in the Arkona Basin is lifted above the level of the Darss Sill by the end of the inflow event (Matthäus & Lass 1995). Parts of the salt water left the Arkona Basin during the subsequent outflow.

Repeated observations of a medium-strength salt water inflow suggest that the residence time of the salt water pool is less than 3 months (Lass et al. 2005). Assuming that the gap in the pool is controlled by internal Kelvin wave dynamics, Lass et al. (2005) found, utilizing an analytical model and typical figures of a medium-strength inflow, that baroclinic Kelvin waves circumnavigate the Arkona Basin within 4 days and that the time to reduce the initial volume of the salt water pool by one half amounts to 1 month.

Using direct measurements and models, the outflow of the dense water pool through the Bornholm Channel was investigated by studying the significance of bottom friction, rotation, and entrainment (e.g. Pedersen 1977, Walin 1981, Lundberg 1983, Gidhagen & Håkansson 1992). According to Kõuts & Omstedt (1993) the dense bottom flow is not affected by mixing.

2.4. Entrainment

On the way from sub-basin to sub-basin, the salinity of the inflowing water decreases owing to entrainment of the ambient less saline water, whereas the volume flow increases (Stigebrandt 1987b, Kõuts & Omstedt 1993, Lass & Mohrholz 2003, Arneborg et al. 2006). The dense bottom flow carries the intruding sea water and drives the vertical circulation of the Baltic Sea (Stigebrandt 1987b). Using measurements from the period 1970–1990 Kõuts & Omstedt (1993) found that the inflowing dense water is diluted on the way from the Kattegat into the Landsort Deep by a factor of 4. They identified three main mixing zones: the Belt Sea and Sound, the Arkona Sea, and the Słupsk Furrow. For instance, the volume flow out of the Słupsk Furrow is increased by 28% as a result of entrainment.

The entrainment velocity can be calculated from the increase in potential energy due to the work against buoyancy forces by diffusion. Stigebrandt (1987b) developed a simple model for the entrainment of the dense bottom current for small Froude numbers and realistic slopes assuming a constant bulk flux Richardson number. Arneborg et al. (2006) took another approach. They calculated entrainment rates from the results of a one-dimensional turbulence model, which was validated against observations of a salt water plume in the Arkona Basin. They found that the bulk flux Richardson number is generally smaller than the constant value assumed by Stigebrandt (1987b). Thus, the entrainment rates are generally smaller than those predicted by earlier entrainment models. There seems to be no simple relationship between entrainment and Froude number according to Arneborg et al. (2006).

Evidence for wind-induced entrainment of the well-mixed salt water plume in the vicinity of the sills was also found by Lass & Mohrholz (2003). They concluded that the main mixing mechanism of a propagating salt water plume is mixing of the water ahead of its front with the bottom water behind the front by differential advection within the Ekman bottom friction layer (van Aken 1986).

2.5. Water exchange through the Słupsk Furrow

Small inflows usually ventilate only the halocline in the Bornholm Basin at that depth where the buoyancy of the inflowing water vanishes. However, major Baltic inflows have the potential to replace the bottom water even below the halocline depth. As the threshold of the Słupsk Sill at 60 m is about the same as the halocline depth, the old bottom water is lifted up and flows into the Słupsk Furrow and further into the eastern Gotland Basin. Dense flows over the Słupsk Sill into the channel occur frequently, but they are intermittent and wave-like (Piechura et al. 1997, Golenko et al. 1999).

At the sill pronounced salinity oscillations with a time scale of about 30 hours were observed, which might have been caused by internal seiches in the Bornholm Basin (Golenko et al. 1999). On the eastern side of the sill the bottom flow is often contracted, indicating an internal hydraulic jump (Piechura et al. 1997, Zhurbas et al. 2004). At least from time to time the dense bottom current seems to be hydraulically controlled.

In general, features of the water exchange in the vicinity of the Słupsk Sill are complicated and highly variable in time. Three different overflow regimes were identified: (1) a simple eastward downstream flow when the level of the dense water west of the sill was higher than the level east of the sill, (2) an eastward overflow with a large southward off-set of the dense water core, and (3) bilateral (eddy like) motion above the sill when the salinity gradients north and south the sill were directed oppositely.

During the last inflow event in January 2003, very prominent fine structures and internal waves were observed in the Bornholm Channel and in the Bornholm Basin. The Słupsk Sill operated as a specific filter passing only a mixture of inflowing new and old water. Thus, along the path of the inflowing water the vertical and horizontal exchange coefficients changed.

Overflowing the Słupsk Sill causes property exchange between the inflowing water and the ambient cold and oxygen-rich intermediate winter water layer, i.e. entrainment through the pycnocline. This is the reason for the Słupsk Furrow being permanently ventilated, and for anoxic conditions never having been observed there. In fact, the long-term oxygen average below 70 m depth is 4.1 $\text{cm}^3\ \text{dm}^{-3}$ in the Słupsk Furrow, but only 2.0 $\text{cm}^3\ \text{dm}^{-3}$ in the Bornholm Basin at the same depth (Feistel et al. 2006), in opposition to the 'rule' that near-bottom oxygen levels can only decrease with distance from the Arkona Basin. This effect may also explain the regular fall ventilation observed in the Gdańsk Deep.

During a period with relatively strong easterly bottom transport in the Słupsk Furrow after the inflow event in January 2003, highly saline water in the Bornholm Basin from below the sill level was withdrawn up to the sill and spilled over into the channel (Piechura & Beszczyńska-Möller 2003, Meier et al. 2004). Both observations and model results show this process, which was also observed earlier (e.g. Piechura et al. 1997, Golenko et al. 1999). Meier et al. (2004) speculated that selective withdrawal might be important. However, details of the mechanism are not well understood and further investigations are still necessary to illuminate the processes involved.

After both medium-strength and major inflows, a cyclonic circulation at about 60 m depth is observed in the Bornholm Basin (Piechura & Beszczyńska-Möller 2003, Mohrholz et al. 2006).

Another important mechanism has been described by Krauss & Brügge (1991). Model results show that transport anomalies in the surface (bottom) layer of the Słupsk Furrow are highly correlated (anti-correlated) with anomalies of westerly or southerly winds. For instance, a westerly wind causes an Ekman transport towards the south. This Ekman transport produces a sea level rise on the southern side of the channel and a fall on the northern side. Furthermore, downwelling occurs on the southern side and upwelling on the northern side resulting in baroclinicity of the same sign on both sides of the channel. Consequently, jets are generated in the surface layer along both sides in the direction of the wind and a return flow compensates this transport in the lower layer of the channel. Such wind-dependent flow reversals have been observed elsewhere (Jakobsen 1996, Elken 1996, Golenko et al. 1999).

A similar process sometimes causes the halocline in the Gulf of Finland to disappear due to the estuarine flow being reversed by relatively strong south-westerly winds (Elken et al. 2003).

During stagnation periods (section 2.10) a small positive west wind anomaly causes a systematically reduced eastward salt flow at the bottom of the Słupsk Furrow (Meier & Kauker 2003a). Consequently, the sea surface salinity in the Bornholm Basin should be anomalously high during stagnation periods. According to observations (and model results) this is not the case because at the same time the freshwater inflow is increased which compensates the impact of the wind on the surface salinity.

2.6. Mesoscale eddies

In the 1970s regular eddy-resolving polygon CTD measurements were introduced in the Baltic deep basins to analyze synoptic scale physical (e.g. Aitsam & Elken 1982) and chemical variability (e.g. Aitsam et al. 1984). An observational highlight was the international Baltic Sea Patchiness Experiment PEX-86 which was carried out in the central Baltic proper (Hoburg Channel) in April/May 1986 (e.g. Dybern 1994). Data from PEX-86 and subsequent measurements suggested that the heterogeneity of saline stratification is created by the same mechanisms that cause heterogeneity of spring bloom development (Elken et al. 1994). It was found that the spring bloom starts within lenses/patches of slightly reduced saline water floating at the surface above cyclonic or anticyclonic eddies. Polygon observations also revealed that in the Baltic proper synoptic-scale salinity fronts are most frequent. These fronts are separated from each other by a distance of tens of kilometers, suggesting their relation to frontogensis by mesoscale eddies (Elken 1994).

Since the late 1980s investigations of mesoscale variability has focused on deep lenses (e.g. Elken et al. 1988, Kõuts et al. 1990), which were found to resemble Mediterranean water lenses (Meddies) in the Atlantic. An overview of various mesoscale structures is provided by Elken (1996).

Mesoscale eddies are often observed during salt water inflows when CTD measurements are dense enough in space (e.g. Piechura & Beszczyńska-Möller 2003, Reißmann 2002). In contrast to frequently observed anticyclonic eddies in the world ocean, fewer observations of sub-surface cyclonic eddies are available, e.g. in the outflow of the Denmark Strait, in the south-eastern Baltic proper (Zhurbas & Paka 1997), or in the Arkona Basin (Lass & Mohrholz 2003).

Lass & Mohrholz (2003) observed two well-developed cyclonic eddies, which separated from Kap Arkona into the interior of the Arkona Basin and propagated through the basin. Assuming that at the bottom the baroclinic pressure gradient is balanced by the barotropic pressure gradient, the calculated geostrophic currents fit very well with the observations, suggesting that these eddies were geostrophically adjusted. The bottom friction seems to play an important role in stabilizing these eddies. In the bottom layer dense water is driven into the center of the eddy by Ekman dynamics. The isohalines are piled up until the currents near the bottom vanish.

Under easterly and northerly wind conditions, numerical simulations using the Princeton Ocean Model, POM (Blumberg & Mellor 1983), showed sub-surface cyclonic eddies in the Słupsk Furrow to be in satisfactory agreement with observations (Zhurbas et al. 2003). Cyclonic eddies are formed by vortex stretching when the flow loses potential vorticity from the Bornholm Basin via the Słupsk Furrow into the south-eastern Gotland Basin, where the stratification is lower. Easterly or northerly winds are necessary because in this case the lower branch of the bi-directional flow in the Słupsk Furrow is directed eastwards (Krauss & Brügge 1991; see section 2.5).

In the intermediate layer of the Gulf of Gdańsk other types of cyclonic eddies were found in observations and model simulations (Zhurbas et al. 2004). Zhurbas et al. (2004) speculated that these eddies are generated during westerly wind conditions after the relaxation of the coastal downwelling jet at the tip of the Hel peninsula in the deep water, when the flow becomes baroclinic. The role of topographic slopes on the generation and decay of longshore baroclinic jets is discussed by Zhurbas et al. (2006).

In the Gotland Deep region eddies were studied intensively during the DIAMIX project (Stigebrandt et al. 2002, Svensson 2005). It was found that dissipation increased when eddies were present at the measurement site. However, it is not yet clear whether the contribution by eddies to deep water mixing is of significant importance. An estimate of locally available energy flux from one eddy suggested that the total energy contribution from eddies to deep water mixing is of only minor importance (Svensson 2005).

A detailed study of about 235 eddies in the Baltic deep water observed during 12 campaigns in 1996–1999 within the Meso-Scale Dynamics project (MESODYN) revealed that such eddies always contain 12% of the water volume of the corresponding sub-basin, independent of the sub-basin, its stratification, and the season considered (Reißmann 2002, 2005). As the mean cross section area of the eddies of 50 to 80 km^2 is constant (corresponding to a baroclinic Rossby radius of 4 to 5 km), the mean thickness increases from 10–15 m in the Arkona Basin to 20–25 m in the eastern Gotland Basin. Hence, the mean thickness is correlated with the thickness of the halocline because most eddies occur within the halocline. Approximately five eddies were found on average per 100 km^3 basin volume (Reißmann 2002).

2.7. Thermohaline intrusions and interleaving

Zhurbas & Paka (1997, 1999) proposed two mechanisms of deep water ventilation in the Baltic proper: (1) continuously inflowing gravity-driven dense bottom flows filling up the deepest layer, and (2) intermittent cyclonic eddies within the halocline (see section 2.6), which are eroded laterally by intrusions.

After the inflow in January 2003 the permanent halocline in the eastern Gotland Basin was characterized by intensive thermohaline intrusions (Zhurbas & Paka 1997). A well-defined front of the intrusive region was found which propagated north from the Słupsk Furrow to the Gotland Deep at a speed of 2 cm s^{-1} or more. In the south-eastern Gotland Basin, the passage of the front was immediately observed at the end of March 2003, changing within 71 hours the near-bottom oxygen concentration from -3.5 cm^3 dm^{-3} to $+1.8$ cm^3 dm^{-3}, the near-bottom temperature from 6.3 to 6.0°C, and the near-bottom salinity from 11.6 to 12.0 PSU (Feistel et al. 2003b). After the major inflow in January 1993 but also during the earlier stagnation period, intrusions were observed and time scales of several weeks to months were found (Elken et al. 1988, Kõuts et al. 1990, Elken 1996, Zhurbas & Paka 1997, 1999).

Kuzmina et al. (2005) investigated the structure and driving mechanisms of observed intrusions in the Baltic halocline. While most of the intrusions have a non-double-diffusive origin, two different types of intrusions are very likely driven by diffusive convection: (1) thin (3–5 m) and long (up to 8 km) intrusions inherent to high-baroclinicity regions, and (2) thick (about 10 m) and short (2–5 km) intrusions inherent to low-baroclinicity regions.

In the Gotland Deep the saline water interleaves preferably at 80–130 m depth with maximum volume transports averaged between Gotland and Latvia of about 2500 m^3 s^{-1} in 100 m depths (Stigebrandt 1987b, Elken 1996, Meier & Kauker 2003a).

2.8. Deep water mixing

Analyzing observations of the deep oceans, Gargett (1984) found an inverse proportionality between deep water mixing and the Brunt-Väisälä frequency, N. Thus, in a model of the vertical circulation of the Baltic Stigebrandt (1987b) used the following relationship between the vertical diffusion, κ, and N in the deep water:

$$\kappa = \min\left(\frac{\alpha}{N}, \kappa_{\max}\right),$$

where α and $\kappa_{\max}$ are constants. In his horizontally integrated model for the Baltic proper Stigebrandt (1987b) tuned α until the observed and computed evolutions of the stratification agreed when $\alpha = 2 \times 10^{-7}$ m^2 s^{-2}.

Using a budget method, Axell (1998) estimated from profile data observed during the stagnant period 1964–1997 an annual mean value of α of 1.5×10^{-7} m^2 s^{-2} in the Gotland Deep. However, he showed that there was a seasonal variation in the vertical diffusion well below the pycnocline and that diffusion was higher in the Landsort Deep (closer to the coast) than in the Gotland Deep. Obviously, α depends on energy fluxes from local sources, such as wind-driven inertial currents, Kelvin waves and other coastal-trapped waves. Therefore, it is assumed that mixing near the coasts and near topographic slopes is more thorough than in the open sea. In three-dimensional circulation models some types of these waves are resolved completely, others only partly and some types are not resolved at all. Thus, deep water mixing is already included in parts of the turbulence parameterization, and the explicitly prescribed deep water mixing should be smaller than the value obtained from the budget method (Meier 2001). For instance, in the RCO model a value of $\alpha = 1 \times 10^{-7}$ m^2 s^{-2} is used, which is in good agreement with results from dissipation measurements in the eastern Gotland Basin by Lass et al. (2003). They found the best fit to their data using $\alpha = 0.87 \times 10^{-7}$ m^2 s^{-2}. However, further investigations are necessary to elucidate the processes involved and to decide whether the sources of deep water mixing in circulation models have been correctly simulated.

Lass et al. (2003) published the first dissipation measurements for the Baltic Sea. In the DIAMIX project (Stigebrandt et al. 2002), they measured dissipation rates and stratification between 10 and 120 m depth during a 9-day winter period in the eastern Gotland Basin, finding two well-separated turbulence regimes. The turbulence in the surface mixed layer is well correlated with the wind speed. Compared to the calculated dissipation according to the law of the wall, the measured dissipation was larger in the upper mixed layer and smaller in the deeper mixed layer. Breaking surface waves might explain the enhanced turbulence in the surface layer. Active erosion of the Baltic halocline is expected at wind speeds greater than 14 m s^{-1}.

The turbulence in the strongly stratified interior of the water column is quite independent of the meteorological forcing at the sea surface. According to Lass et al. (2003) the integrated dissipation rate in the interior averaged over the duration of the observations amounts to 0.85 m W m^{-2}.

In a recent study presented at the workshop, the role played by breaking internal waves in total diapycnal mixing was investigated. Assuming that the areas of energy transfer from barotropic to baroclinic wave motion and of internal wave breaking are the same, i.e. no energy is radiated away from the locations where the internal waves are generated, dissipation was simulated using a two-dimensional shallow water model (Fig. 3). In this study a parameterization of the energy transfer from barotropic to baroclinic wave motion following Stigebrandt (1976) and Sjöberg & Stigebrandt (1992) was

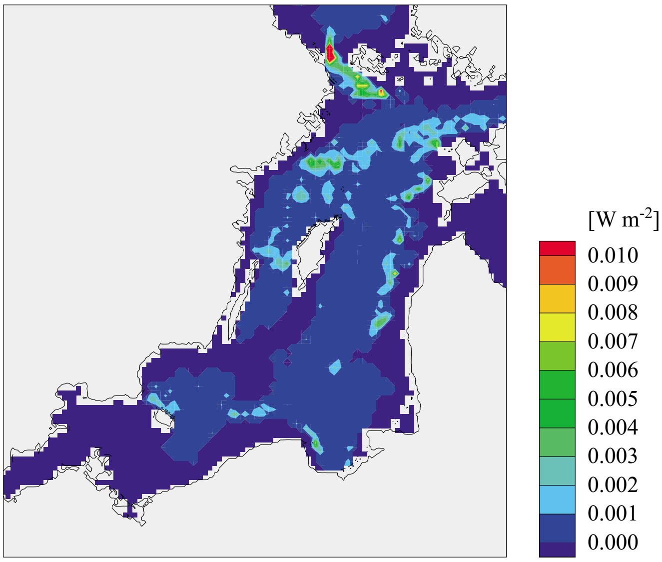

Fig. 3. Spatial distribution of time-averaged energy transfer [W m^{-2}] from wind-driven barotropic to baroclinic wave motion in the Baltic Proper simulated in a two-dimensional shallow water model with the assumption of a two-layer stratification (from C. Nohr and B. G. Gustafsson, presentation at the BSSC 2005)

used. A pronounced seasonal signal of the internal wave drag concentrated mainly to steep topographical features was found. Further, the mean annual vertical diffusivity is approximately one order of magnitude larger in the Landsort Deep than in the Gotland Deep. The dissipation of internal waves may contribute as much as c. 30% to the vertical mixing energy needed below the halocline. Hence, the breaking of internal waves generated by wind-forced barotropic motions could be an important contributor to total diapycnal mixing in the Baltic deep water.

However, the evaluation of dissipation rates and especially the quantification of annual mean values from observations is problematic. Owing to the large spatial and temporal intermittency of turbulence, the stochastic error is considerable and may exceed at least 30%. It would be very important to know the magnitudes of dissipation during both major inflow events and stagnation periods.

2.9. The haline conveyor belt of the Baltic

Based upon three-dimensional model results, the mean thermohaline and wind-driven circulation of the Baltic Sea (e.g. Lehmann & Hinrichsen 2000a,b, 2002, Lehmann et al. 2002, Meier & Kauker 2003a, Döös et al. 2004) and its sensitivity to atmospheric and hydrological forcing (Schrum & Backhaus 1999, Schrum 2001, Meier & Kauker 2003b, Schrum et al. 2003, Meier 2005) have been studied intensively. Detailed studies of certain areas, e.g. the Gulf of Finland, have also been carried out (Andrejev et al. 2004a,b).

The large-scale horizontal circulation of the sub-basins is characterized by cyclonic gyres as a result of the interplay between the Earth's rotation and depth variations on time scales larger than the inertial period (Fig. 4). The general nature of the circulation can be described by a depth-integrated vorticity balance omitting bottom friction and wind stress curl (Csanady 1982, Lehmann et al. 2002).

Measurements from a sub-surface mooring station deployed north-east of the Gotland Deep showed vanishing mean currents 20 m above the sea bed in an east-west direction but a permanent northward velocity of 3 cm s^{-1} (Hagen & Feistel 2004). These observations confirm the hypothesis about a relatively intense mean cyclonic circulation in the eastern Gotland Basin from the surface down to the bottom (cf. Fig. 4).

The vertical overturning circulation is characterized by gravity-driven dense bottom currents of the inflowing highly-saline water from the Kattegat, entrainment of ambient surface water, mixing due to diffusion, interleaving of the inflowing water masses into the deep water at the level of neutral buoyancy, vertical advection due to volume conservation, and

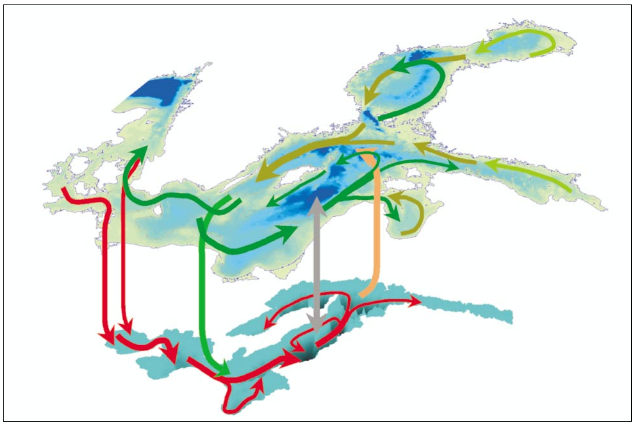

Fig. 4. Schematic view of the large-scale circulation in the Baltic Sea (from Elken & Matthäus 2006). Green and red arrows denote the surface and bottom layer circulation, respectively. The light green and beige arrows show entrainment. The gray arrow denotes diffusion

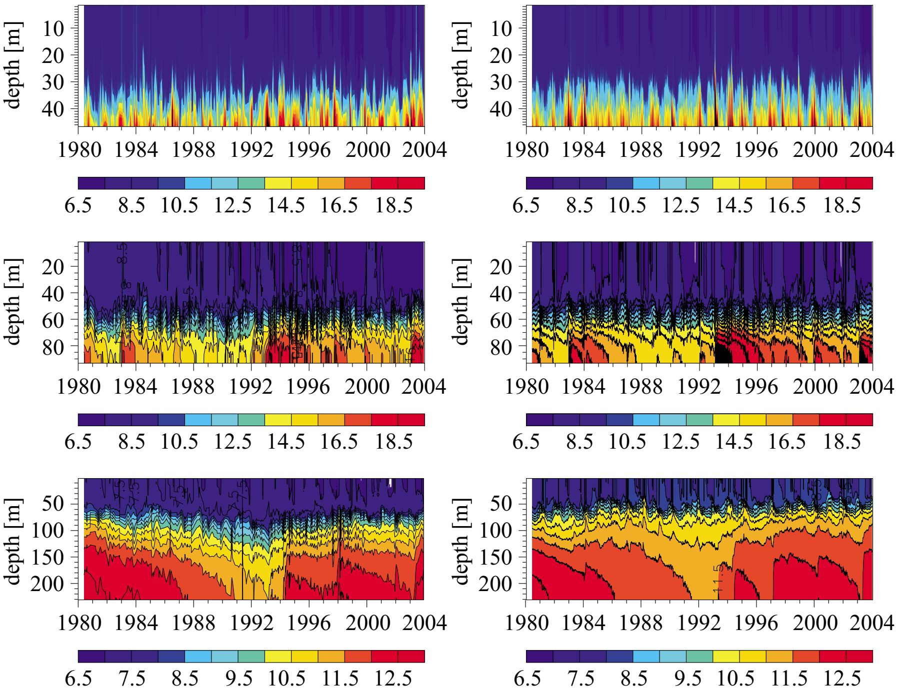

Fig. 5. Salinity [PSU] as a function of time and depth for 1980–2003 at the monitoring stations in the Arkona Deep (BY2, upper panels), Bornholm Deep (BY5, middle panels), and Gotland Deep (BY15, lower panels): observations (left panels) and results of the Rossby Centre Ocean model, RCO (right panels) (from H.E.M. Meier, R. Döscher, B. Broman, J. Piechura, presentation at the BSSC 2005)

upward entrainment of deep water into the moving surface water in the northern Baltic proper (Fig. 4). Using state-of-the-art ocean circulation models, the temporal variability of the haline conveyor belt on daily to decadal time scales is believed to be realistically simulated because salinity variations in the various sub-basins are modeled in good agreement with observations (Fig. 5).

2.10. Stagnation periods

Salinity observations at all monitoring stations in the Baltic Sea show no statistically significant trends during the 20th century (Fonselius & Valderrama 2003). In model results the trends are also statistically not significant (Meier & Kauker 2003a). For the 20th century the climatological annual mean salinity averaged over the entire Baltic was estimated to be 7.7 PSU (Winsor et al. 2003) or 7.4 PSU (Meier & Kauker 2003a). Daily and decadal variations have maximum amplitudes of 0.1 and 0.5 PSU, respectively. On longer time scales salinity variations were much larger. The maximum salinity during the Litorina Sea stage (6000–5000 B.P.) was very likely between 10 and 15 PSU owing to the increased cross-sectional areas of the inlets (Öresund and Darss) and the 15–60% lower freshwater supply than at present (Gustafsson & Westman 2002).

During low saline phases on a decadal time scale the deep water is poorly ventilated. However, even during highly saline phases, reduced deep water ventilation can occur. These phases are called stagnation periods. During the last century three stagnation periods in the 1920/1930s, 1950/1960s, and 1980/1990s were found (Meier 2005). During these periods simulated ages of the bottom water at Gotland Deep exceeded 8 years. By definition, the age of sea water is the time that has elapsed since a water particle left the sea surface (see Delhez et al. 1999, Deleersnijder et al. 2001). For the whole period 1903–1998, the median ages of the bottom water in the Bornholm Deep, in the Gotland Deep, and in the Landsort Deep were found to be 1, 5 and 7 years respectively. Besides an absolute age maximum at the bottom of the deeper sub-basins, a secondary age maximum was calculated within the halocline. For the whole Baltic a maximum age of about 11 years was recorded in the bottom water in the Landsort Deep.

Stagnation periods have a significant impact on the marine ecosystem. As the Baltic is too fresh for marine species and too salty for freshwater species, most species experience physiological stress (Voipio 1981, HELCOM 2002). Changes in salinity and oxygen concentrations may therefore have a considerable impact on species distributions, food webs and life-histories.

Hence, the reasons for the occurrence of stagnation have been discussed in several publications (e.g. Fonselius 1969, Lass & Matthäus 1996, Schinke

& Matthäus 1998, Matthäus & Schinke 1999, Meier & Kauker 2003a). The positive anomaly of the freshwater inflow from rivers and net precipitation seems to be the most important factor for phases of low salinity in the Baltic (Samuelsson 1996, Schinke & Matthäus 1998, Winsor et al. 2001, Meier & Kauker 2003a). Meier & Kauker (2003a) found that about half of the decadal variability of the average salinity of the Baltic is related to the accumulated freshwater inflow in periods longer than 4 years. An additional supply of freshwater shifts the Kattegat-Skagerrak front to the north. Thus, in the shallow entrance area inflowing deep saline water from the Kattegat is mixed with larger portions of brackish surface water from the Baltic interior. In this way the recirculation of Baltic water masses is increased (Rodhe & Winsor 2002, Stigebrandt 2003).

Another significant part of the decadal variability in salinity is caused by the low-frequency variability of the zonal wind (Zorita & Laine 2000). These authors found that stronger than normal westerly winds are related to lower than normal salinities in the upper and lower layers in all areas of the Baltic Sea. Their analysis of this link between the large-scale atmospheric circulation and annual mean salinity observations reveals that roughly one half of the salinity variability is correlated with the meridional atmospheric pressure gradient over the North Atlantic, and thus with the strength of the westerly zonal winds. This finding is confirmed by model results (Meier & Kauker 2003a). The wind stress anomaly is balanced by a sea level slope anomaly between the Kattegat and the central Baltic. Consequently, an anomalous barotropic pressure gradient hampers salt water inflows through the Danish Straits (Schrum 2001).

Lass & Matthäus (1996) found an anomalous west wind component at the Kap Arkona station between August and October for seasons without a major Baltic inflow as compared with the corresponding seasons with major Baltic inflows during 1951–1990. They suggested that in the years without a major Baltic inflow the prevailing easterly winds of the one-month-long preconditioning phase prior to the main inflow event, when the Baltic Sea is emptied, are reduced. Possible changes in the high-frequency variability of the zonal wind on the c. 10–20 day time scales typical of major Baltic inflows are not excluded by the studies of Zorita & Laine (2000) and Meier & Kauker (2003a). These changes may cause the remaining decadal variability of salinity, which is explained neither by the accumulated freshwater inflow nor by the low-frequency variability of the zonal wind.

Another mechanism with a possible impact on the variability of salinity is the blocking of inflow events due to the already high salinities in the bottom water. For instance, the less pronounced stagnation period during the 1950/1960s (a period of high salinities) might have been caused by the very strong inflow of 1951, which filled the Baltic deep water with very highly saline water. Subsequent salt water inflows may not have been sufficiently saline to replace the dense water masses of the 1951 event.

2.11. Time scales

The ventilation of the Baltic Sea deep water is characterized by various time scales. The advective time scale is rather short. For instance, the salt water of the major Baltic inflow in January 2003 arrived at the Bornholm Deep on January 24–25th, 12 days after the start of the event at the sills (Feistel et al. 2003b, Piechura & Beszczyńska-Möller 2003). A spreading time of 12 days between the Drogden Sill and the Bornholm Channel was also found for the small and medium-strength inflows in November and December 1998 (Lass & Mohrholz 2003) and August/September 2002 (Mohrholz et al. 2006). The residence time of the salt water pool in the Arkona Basin was estimated to be 1 month (Lass et al. 2005; see also section 2.3).

After about 3 months the first signs of the inflowing water were observed in the Gotland Deep (Feistel et al. 2003b). Indeed, during the major inflow of 2003 the movement was remarkably rapid compared to previous events, probably caused by the dense water in the deep Bornholm Basin, which got there earlier during the smaller inflows in 2002. In addition, the saline water of the major inflow was very likely pushed by subsequent smaller inflows in spring 2003.

In contrast to the relatively short advective time scale, the diffusive time scale is much longer. Of special interest is the overall internal 'response time scale' of the average salinity or average freshwater content of the Baltic Sea to perturbations of the external atmospheric or hydrological forcing. As diapycnal mixing (diffusion and entrainment) across the halocline is much smaller than mixing within the homogeneous surface layer, the 'response time scale' or residence time of the surface layer is determined approximately by the turn-over time of the freshwater content in the Baltic Sea. In the steady-state, turn-over and residence times are the same (Bolin & Rodhe 1973). The time scale of the deep water is very likely determined by the mean intensity and frequency of salt water inflows and the erosion of the halocline, which is lifted up depending on the inflow activity.

During the 20th century the total mean net freshwater supply from river discharge and net precipitation amounts to about 16 000 $\mathrm{m}^3\ \mathrm{s}^{-1}$ (Meier & Kauker 2003a). Winsor et al. (2003) and Meier & Kauker (2003a) calculated the freshwater content from observations (1.67×10^4 km^3) and model results (1.77×10^4 km^3), respectively. Thus, the corresponding turn-over times are 33 and 35 years.

Döös et al. (2004) calculated residence times of various simulated Baltic water masses using Lagrangian particles released either at the sills in the Baltic entrance area or at the mouth of the river Neva. They found residence times of 26–29 years for the entire Baltic. The temporal evolution of the residence of the Neva water in the Baltic is very similar to the water for the entire Baltic.

This result is supported by sensitivity experiments (Meier 2006, Omstedt & Hanssen 2006). Meier (2006) found an e-folding time scale of the response of salinity in the Baltic to changes in the atmospheric and hydrological forcing of about 20 years. In most of his experiments the response of the deep water was somewhat faster than the response of the upper layer. A 65% larger e-folding time scale of the salinity response of 33 years was calculated in spin-up experiments from lake or ocean conditions by Omstedt & Hanssen (2006).

Based on salinity observations in the Gotland Deep between 1968 and 2005 and using a simple dynamic model consisting of two boxes, Feistel et al. (2006) calculated residence times of the surface layer and deep water of 33 and 21 years, respectively.

If the time scale of a forcing anomaly is larger than the 'response time scale' of about 20 years, the Baltic Sea system will drift into a new state with a significantly changed salinity but with only slightly altered stability and deep water ventilation (Meier 2005, 2006). These model results are based upon the assumption that the changes in the fresh- or salt water inflow or in the low-frequency wind are smaller than 30%. When the perturbation starts, the deep water flow decreases immediately. After a typical e-folding time scale of about 20 years, the vertical overturning circulation is partially recovered. In contrast, long-term changes of the high-frequency wind affect deep water ventilation considerably. Thus, on long time scales significant changes of the thermohaline circulation can be expected only if diapycnal mixing in the Baltic is changing.

3. Open questions

The Baltic is one of the best observed seas on Earth and can be used as a laboratory for process studies. However, there are many still open questions, inter alia, related to the deep water ventilation. Here, we list some of them.

The dynamics of salt water plumes after small and medium-strength inflows are not well understood because such events are difficult to observe. The event in January/February 2004 is an exception. Just by chance a research cruise organized by the FWG Kiel (Germany) was taking place when a medium-intensity salt water inflow over Drogden Sill occurred

(Sellschopp et al. 2006). The unique measurements suggest that plumes of this type flow through a trench at the northern rim of Kriegers Flak into the central Arkona Basin (Burchard et al. 2005; see also section 2.2). Perhaps if the volume flow of a plume exceeds the transport capacity of this trench, salt water will also pass through the gap between Mön Island and Kriegers Flak, as suggested by other observations (Lass & Mohrholz 2003, Lass et al. 2005). More detailed information about general pathways, mixing, and related climatological mean salt flows of small and medium-intensity salt water plumes in the Arkona Basin and in other sub-basins is needed.

Another region where the pathway of the deep water is unknown is the southern Gotland Basin. Saline water passing the Słupsk Furrow may flow either northeastwards along the eastern slope of the Hoburg Channel or may spread along the southwestern slope of the Gdańsk Basin. Model experiments have suggested that inflowing water makes a cyclonic loop along the slopes of the Gdańsk Basin with wind forcing playing only a minor role (Elken 1996). Hence, it is assumed that the Gdańsk Basin acts as a buffer zone for the inflowing water before it spreads further towards the Gotland Deep.

Although during recent years our knowledge of mixing processes between inflowing and ambient water masses (e.g. entrainment, thermohaline intrusions) and of deep water mixing has increased considerably, many details are still unknown. For instance, it was found that the dissipation caused by the breaking of internal waves might explain about 30% of the vertical mixing energy needed below the halocline. In this calculation it was assumed that no energy is radiated away from locations where internal waves are generated. The details of the mechanism are not well understood. In addition, the processes causing the remainder of the mixing are unknown. Thus, further research on the temporal and spatial variations of the vertical salt flux and on the relative contributions of advection, diffusion and entrainment is needed. This knowledge is also important for further model development because appropriate mixing parameterizations are still not available.

The analysis of long records of observations indicates a change in the inflow features (see section 2.2). During the past two decades the frequency of major Baltic inflows has decreased and the frequency of warm baroclinic summer inflows has increased, causing warmer deep water masses (Feistel et al. 2006, Mohrholz et al. 2006). Model results suggest that major inflows are hampered due to the larger freshwater supply and mean zonal wind speeds (see section 2.10). However, the causes of the increased frequency of baroclinic inflows are still unknown.

Different kinds of models (process-oriented, one-, two-, or three-dimensional) have been applied to study the vertical circulation of the Baltic. At the workshop the results of various, very different models were presented and the added value of modeling was demonstrated. More recently, three-dimensional general circulation models have become available. However, there is no general agreement regarding which vertical coordinate system is to be used. Geopotential vertical (z-level), bottom-following (sigma), and isopycnal coordinate models are most common (e.g. Haidvogel & Beckmann 1999). In Baltic Sea applications, it is usually the level or bottom-following coordinate models that are used.

When a state-of-the-art resolution of the horizontal and vertical grid in level models is used, the bottom boundary layer is usually poorly resolved with the consequence that the mixing of plumes with ambient water is overestimated and plumes become less dense, because the downhill flow is simulated as a sequence of successive horizontal advection and vertical convection processes between neighboring grid boxes (Beckmann & Döscher 1997). In the Baltic this is mainly a problem for small and medium-intensity salt water inflows, whereas major Baltic inflows are less affected because the salt water plumes are thicker. However, the performance of level models can be improved using so-called bottom boundary layer models allowing for direct communication between bottom boxes of the step-like topography (Beckmann & Döscher 1997, Döscher & Beckmann 2000).

Sigma-coordinate models solve the overflow problem, but they also have disadvantages. For instance, the topography has to be smoothed to limit the pressure-gradient error (Haidvogel & Beckmann 1999). Artificial density currents occur at places where isopycnals intersect with the steep topography. Mixing in many bottom-following models seems to be too high.

In general, none of the three different vertical coordinate systems is superior, as shown in a model inter-comparison project for the North Atlantic (Willebrand et al. 2001). All model types have certain shortcomings. Whether this conclusion also holds for Baltic Sea models, is an unsolved question. Hence, a model inter-comparison project was suggested at the workshop.

4. Recommendations

Our recommendations for future research activities are summarized below.

1. To study climate variability in the Baltic Sea and to detect climate changes, long-term records of observations with relatively high temporal and vertical resolutions at strategic locations (e.g. mooring data in all sub-basins) are needed. Such a climate-observing

system should include physical parameters like temperature, salinity, current velocity, dissipation, and even key parameters of the marine ecosystem, like oxygen, nutrients and chlorophyll. These data are also needed to validate coupled biogeochemical-physical models of the Baltic Sea. In addition, field experiments will help to understand selected processes with an impact on the large-scale dynamics of the Baltic Sea.

2. To understand the processes involved, all kinds of numerical models are needed. In addition, models are useful tools for investigating past and future climate, when observations are not available or when the data coverage is poor. Available model results could be analyzed better using more advanced tools, like advanced statistical methods, Lagrangian trajectories and Eulerian tracers. As the advantages and disadvantages of different Baltic Sea models are not yet really clear, a model inter-comparison project would help to improve modeling skills. State-of-the-art three-dimensional ocean circulation models for the entire Baltic suffer from low spatial grid resolution and from insufficient parameterizations of unresolved processes, like turbulent mixing caused by internal waves. Further model development and new model approaches are thus needed.

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Appendix: Presentations

- Arneborg L., Fiekas V., Burchard H.: Mixing and dynamics of a gravity plume – observations, theory, and modeling (Oral)
- Burchard H., Lass H. U., Mohrholz V., Umlauf L., Sellschopp J., Fiekas V., Bolding K., Arneborg L.: Dynamics of medium-intensity dense water plumes in the Arkona Basin (Oral)
- Feistel R., Nausch G., Hagen E.: Unusual inflow activity 2002/2003 and varying deep-water properties (Oral)
- Fiekas V., Arneborg L., Prandke H., Sellschopp J., Knoll M.: Finestructure and mixing during a salt water inflow into the wintry Arkona Sea (Oral)
- Kuzmina N., Rudels B., Stipa T., Zhurbas V.: The structure and driving mechanisms of the Baltic intrusions (Poster)
- Meier H. E. M., Döscher R., Broman B., Piechura J.: The major Baltic inflow in January 2003 and preconditioning by smaller inflows in summer/autumn 2002: a model study (Oral)
- Mohrholz V.: On the contribution of small inflow events to the ventilation of the subhalocline layers of the Baltic (Poster)
- Mohrholz V., Schuffenhauer I.: Climatological aspects of the exceptional Baltic summer inflows 2002/2003 (Poster)
- Nohr C., Gustafsson B. G.: Wind-driven diapycnical mixing in the Baltic Sea deep-water (Oral)
- Paka V. T., Golenko N. N.: Features of water exchange in vicinity of the Słupsk Sill and adjoining areas – field experiment (Oral)
- Sellschopp J., Fiekas V., Knoll M., Gerdes F., Arneborg L., Lass U., Mohrholz V., Burchard H., Umlauf L.: Repeated observations during an inflow event into the Arkona Sea (Oral)
- Stips A., Feistel R., Bolding K., Burchard H.: Can we trace salt water inflows into the Gotland Deep with the 3D hydrodynamical model GETM? (Oral)
- Zhurbas V., Stipa T., Paka V. T., Golenko N. N.: Observations and numerical modeling of subsurface cyclonic eddies in the Baltic Sea (Oral)