3. Recent (mainly 200 years) and current climate change

3.4. Baltic Sea

3.4.1 Marine circulation and stratification

by Jüri Elken, Andreas Lehmann, Kai Myrberg

Introduction

- Recent aspects
  - *Figure 0 – Baltic Sea map (topography and locations)*
- Data sources, normalization issues

3.4.1.1. Trends and variations in water temperature

The Baltic Sea is well stratified, with a seasonal cycle of temperature superimposed on the more or less permanent salinity stratification in the deeper layers. While atmospheric heat fluxes have typical response time in water temperature and sea ice about a year, then response in salinity is governed mainly by lateral transport processes, resulting together with diapycnal mixing in response times of many decades (*e.g.* Stigebrandt and Gustafsson, 2003, Omstedt and Hansson, 2006). Cold waters, formed during the winter, extend down to the halocline which has typical depths 60-80 m in the Baltic Proper. During the summer, when seasonal thermocline develops at the depths of about 20 m, the underlying cold intermediate layer keeps, as a general rule, the memory of the severity of the previous winter. Accordingly, the summer (July-August) temperature of the intermediate cold layer is well correlated with the surface (down to the halocline) temperature in March (Hinrichsen et al, 2007). Deeper waters, found below the halocline, are formed mainly by the lateral advection of saline waters of the North Sea origin entraining on its route the ambient waters from the above layers. Below 100 m, temperature variation range in the Gotland Deep is only 5 °C (from 3 °C to 8 °C), compared to the surface range up to 25 °C. According to the Baltic Sea hypsographic curves (Leppäranta and Myrberg, 2009), the volume of deep layers below 100 m is only about 12% of the whole sea volume (21 205 km^3) and the contribution of lateral heat advection to the overall Baltic Sea heat content is small.

Detected recent air temperature increase, especially in the Baltic Sea region (*e.g.* Luterbacher et al. 2004), should have a response in the water temperature increase, due to the above considerations. Indeed, MacKenzie and Schiedek (2007a) state that since the 1860s a record warming of the Baltic and North Seas has occurred during the recent decades. They used the data from daily monitoring at a few historical locations as well as the data from irregular open sea sampling, and they applied advanced data homogeneity and spatial synchrony matching procedures to ensure the data quality for climate analysis purposes (MacKenzie and Schiedek, 2007b). The results from the analysis show that there is little evidence of a gradual linear increase or decrease in sea surface temperature since the mid-late 1800s. There have been earlier warmer periods in the mid-late 1800s and in the mid-1900s. However, since about 1985 the warming of surface waters is evident by all the datasets in all the seasons and also as the annual mean values. The probability of extremely warm winters and summers has increased since the 1990s by two- to fourfold. MacKenzie and Schiedek (2007a) argue that summer warming rates are nearly triple those that could be expected from the increase of observed air temperature. In contrast to this and many other studies, Håkanson and Lindgren (2008) conclude from a simple treatment of raw irregular HELCOM data 1974-2005 that “there is no increase in surface-water temperatures in the Baltic Proper, but rather a weak opposite trend”. We note here the importance of careful statistical preprocessing of irregular sampling data, when estimating the multi-decadal variations of a variable with high seasonal amplitude. Madsen and Højerslev (2009) have shown on the basis of daily routine lightship observations in Danish waters during 1900-1998 that in Drodgen the mean temperature was at the end of the period by 0.7 °C higher than ever observed earlier. In the recent period since 1990s warming of surface layers is also evident on the basis of independent datasets near the Lithuanian coast (Dailidiene et al, 2011), recently as 0.3-0.9 °C decade^{-1}. The changes are more complex in the Gulfs of Finland (Liblik and Lips, 2011) and Riga (Kotta et al, 2009), since seasonal and/or annual mean temperatures undergo strong interannual variations, usually related to the atmospheric circulation patterns reflected as NAO and/or BSI indices (e.g. Lehmann et al, 2011).

Details of sea surface temperature variations can be well resolved by remote sensing from satellites, using infrared AVHRR and MODIS sensors. Regular satellite coverage is available in the Baltic Sea region since the mid-1980s. Although single remote sensing images are frequently disturbed by cloud coverage, skin layer uncertainties and other factors, the monthly mean temperature from the remote sensing data agree well with those from the *in-situ* measurements in the offshore sea areas (Siegel et al, 2006; Bradtke et al, 2010). Lehmann et al (2011) estimated from the remote sensing data 1990-2008 highest linear trend of annually mean SST – up to 1 °C decade^{-1} in the northern part of the Bothnian Bay, but high increase is found also in the Gulfs of Finland and Riga and in the Northern Baltic Proper (Fig. 3.4.1.). Warming of surface waters is lowest north from the Bornholm up to and along the Swedish coast, probably due to an increase of the frequency of coastal upwelling. Bradtke et al (2010) considered also seasonal cycles during 1986-2006 and found highest positive trend - more than 2 °C decade^{-1} in August, in the Bothnian Sea and the Northern Baltic Proper. At the same time, mean temperature in March decreased, by the highest rate in the Gulf of Riga and eastern part of the Baltic Proper. Siegel et al (2006) found highest increasing trend in the Bothnian Sea in July (more than 3 °C decade^{-1}), and in the Arkona and Gotland Sea in August and September (about 1.5 °C decade^{-1}). The above trend estimates, based on the data from remote sensing, agree in general well with the trends determined from the independent *in-situ* observations of sea surface temperature.

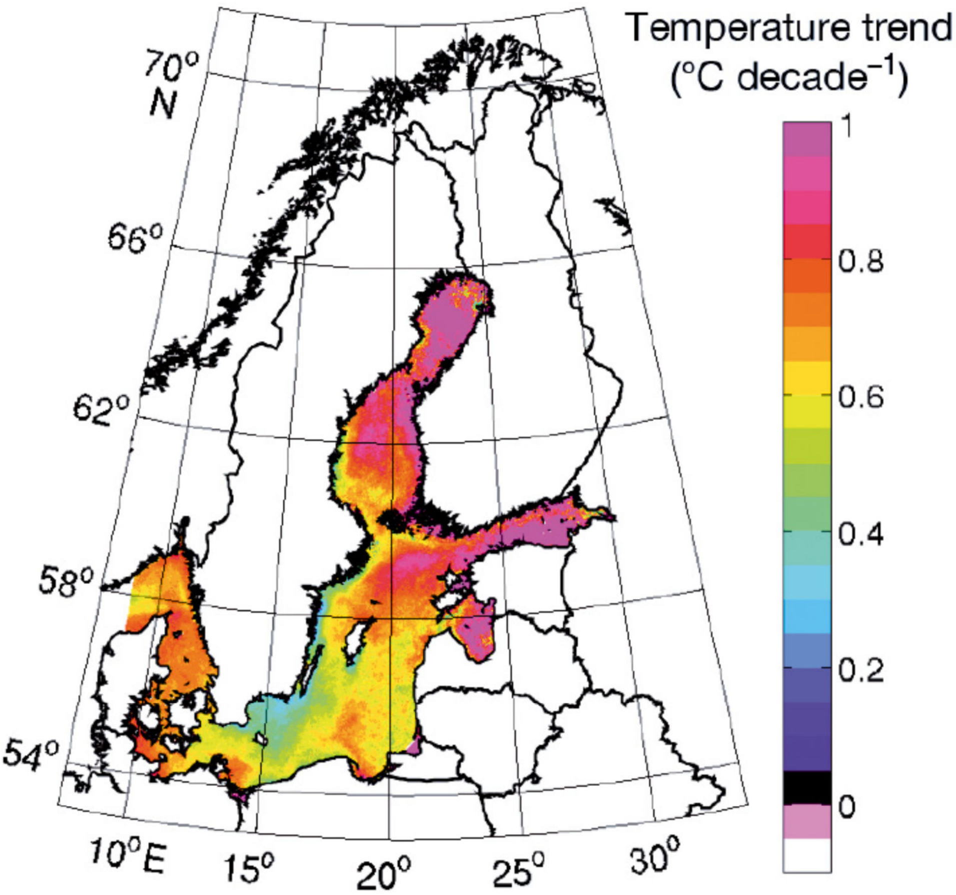


Fig. 3.4.1. Linear trend of the annual mean sea surface temperature based on infrared satellite data (1990 to 2008) provided by the Federal Maritime and Hydrographic Agency (BSH), Hamburg. (Lehmann et al, 2011).

Temperature of the deep water in the Baltic Proper is determined mainly by the lateral spreading of the submerged saline water of the North Sea origin, reflecting the surface thermal conditions during the deep water formation. Mohrholz et al (2006) have found that in the Bornholm basin the mean temperature of the halocline during the period 1989-2004 has increased by about 1 °C compared to the longer period 1950-2004. They argue that this halocline temperature increase is caused by the more frequent warm summer inflows since the 1990s.

An increase was found also in the annual minimum temperature of the cold intermediate layer, lying between the seasonal thermocline and the halocline. Regarding the Bornholm Basin, Mohrholz et al (2006) have found a $R^2 = 0.61$ correlation with the NAO winter index. In the light of the detected regime shift of NAO index since 1988, when positive values (increased westerly winds) started to dominate, the intermediate layer temperature variations were interpreted as a “regime shift” increase by about 1 °C (Mohrholz et al, 2006, Hinrichsen et al, 2007). In the Gulf of Finland, Liblik and Lips (2011) have found $R^2 = 0.81$ correlation between the cold intermediate layer temperature and the winter BSI.

It is a very intriguing task to reconstruct the past changes of climate elements and compare with the ongoing changes. Based on the climate reconstruction since 1500 (Luterbacher et al, 2004), Hansson and Omstedt (2008) made a reconstruction of the Baltic Sea water temperature and ice conditions for the period 1500-2001 using the PROBE-Baltic model with complete heat fluxes. For the period since 1893, they used also more detailed forcing data from the NORDKLIM database. Annually mean water temperatures (Fig. 3.4.2), averaged over the whole sea domain (both by area and depths) reveal as a decadal moving average cold anomalies down to -0.7 °C in the 1690s and 1780s, and warm anomalies up to 0.5 °C in the 1730s, 1930s and 1990s. The sea water warming during the present period is comparable in magnitude to that in the 1930s and in the first half of the 18th century. The results of the study suggest that the sea water is experiencing presently the climate change that lies within the range of changes during the past 500 years. // Discuss relation to the long-period air temperature change, air temperature shows that recent period is the warmest since 1500 //

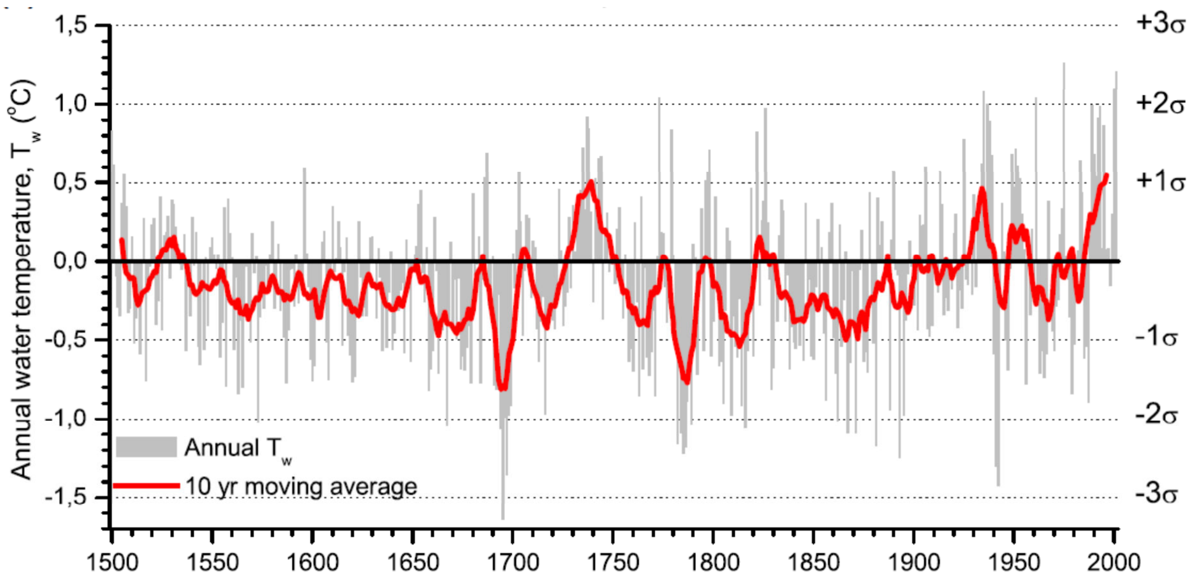


Fig. 3.4.2. Anomalies of the annual and decadal moving average of the modeled Baltic Sea spatially mean water temperature over the 1500–2001 period. The dotted horizontal lines are the standard deviations of the water temperature during the standard period 1900–1999. (Hansson and Omstedt, 2008).

3.4.1.2. Changes in salinity, stratification and water exchange

While thermal response of the Baltic Sea is similar to a large lake, freshwater discharge from the land and restricted water exchange with the North Sea create strong salinity stratification, accompanied by along-basin gradients like in estuaries and fjords. Although the water exchange with the North Sea is very intermittent – Major Baltic Inflows (MBIs, Matthäus and Franck, 1992) carrying large volumes of abnormally high saline water occur sporadically, the overall salt content of the sea depends mainly on the atmospheric net precipitation and river discharge, revealing higher salinity during the wet periods and lower salinity during the dry periods (Winsor et al, 2001, Meier and Kauker, 2003, Gustafsson and Omstedt, 2009).

The Gotland Deep is a representative location for describing the salinity and stratification of the whole Baltic Sea. Indeed, changes of mean salinity, calculated from the data of the Gotland Deep only, match with 2% difference the changes calculated from the data over all the sub-basins (Winsor et al, 2001). The observations (Fig. 3.4.3) reflect decrease of salinity during the recent period, starting from the end of 1980s. Such low-salinity periods occurred also in the 1900s and 1930s and to a less extent in the 1960s.

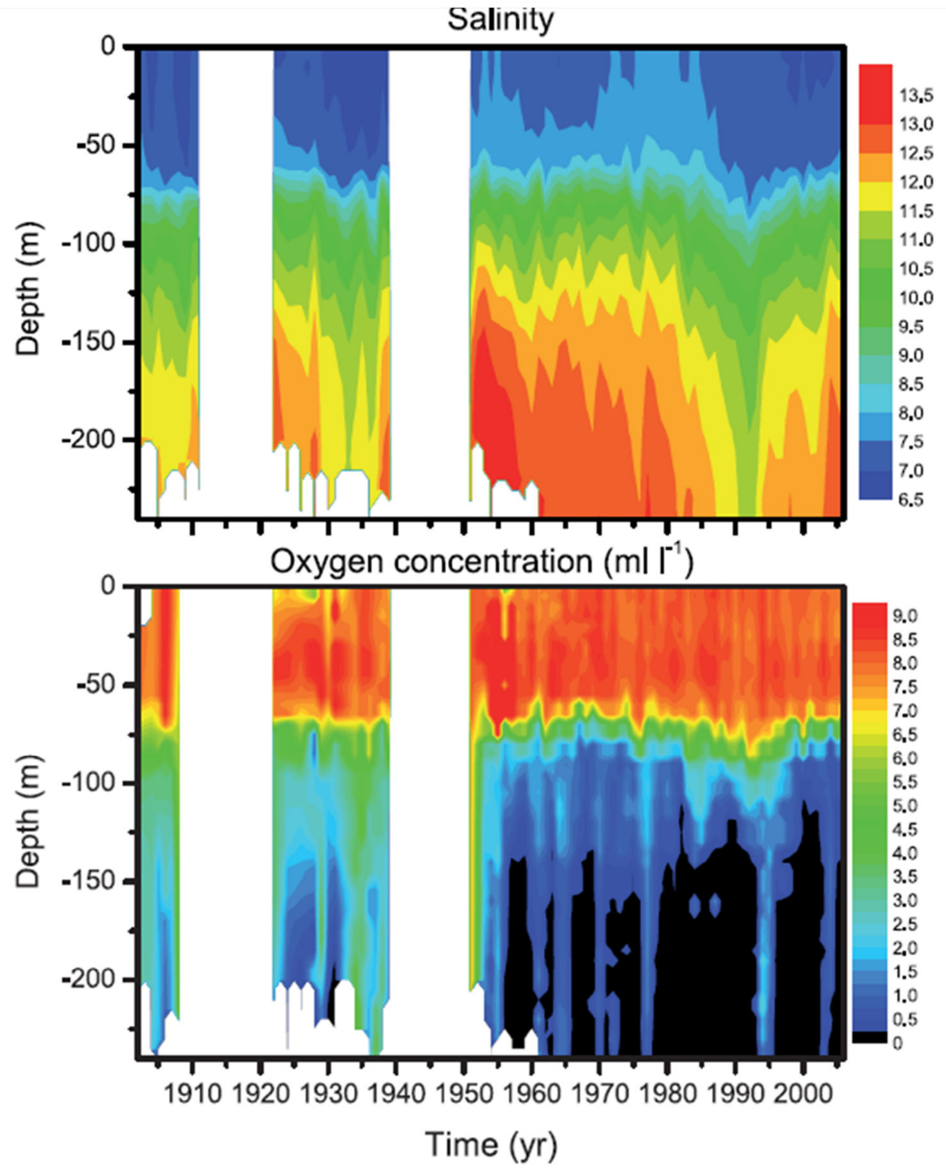


Fig. 3.4.3. Observed salinity and oxygen concentration in the Gotland Deep. // Now taken from Gustafsson and Omstedt, 2009; to be redrawn with most recent data. Perhaps a line/dot graph with vertically mean salinity could be also useful. May be oxygen can be omitted? //

Salinity and stratification of the deep layers is highly affected by the occurrence of Major Baltic Inflows of the North Sea water, requiring specific wind fields over Northern Europe: it occurs when high pressure over the Baltic region with easterly winds is followed by several weeks of strong zonal wind and pressure fields over the North Atlantic and Europe (*e.g.* Lehmann et al, 2002, Matthäus et al, 2008). During the history of observations since the 1900s, the strongest inflow took place in late November-December of 1951 (*e.g.* Madsen and Højerslev, 2009). During the inflow culmination, the sea level difference between Gedser and Hornbæk was up to 1.5 m and the normal saline stratification in the Kattegat and the strait area was collapsed by several weeks. New high saline water reaches the deep layers of the Gotland Basin with a delay up to a year (*e.g.* Kõuts and Omstedt, 1993, Matthäus et al, 2008), as can be seen also from Fig. 3.4.3. The inflow in 1977 was followed by an exceptionally long stagnation period, when until the next inflow in 1993 the saline stratification (bottom to surface salinity difference) decreased by about one and half times. A quite extensive stagnation period occurred also in the 1920s and 1930s, after the very strong inflow in winter 1921/1922, coinciding with the transfer of the wet period to a dry period over the drainage basin. Based on the water age calculation, Meier (2005) identified in addition a stagnation period exceeding 8 years in 1950s/1960s, also during the wet to dry period transition.

Since 1994, when the stratification strength was brought up to a nearly normal level of the 1960s and 1970s, the stagnation in terms of oxygen deficiency of the near bottom waters continued (Conley et al, 2009). Besides the smaller inflows, a series of larger inflows occurred. When usual barotropic (vertically uniform transport over the entrance sills) inflows occur in winter and spring, advecting the relatively cold water with high oxygen content, then the recent large inflows in 1997 and summer 2003 were of two-layer (baroclinic) origin that transported high-saline, but warm and low-oxygen water to the deep layers of the Baltic (Feistel et al, 2006). The inflow activity is well visible on the temperature daily records of the deep layers in the Gotland Deep (Fig. 3.4.4). The low temperatures apparent in the figure during 2003 reflect the normal barotropic inflow in winter 2002/2003, described in many papers (*e.g.* overview Matthäus et al, 2008, Leppäranta and Myrberg, 2009).

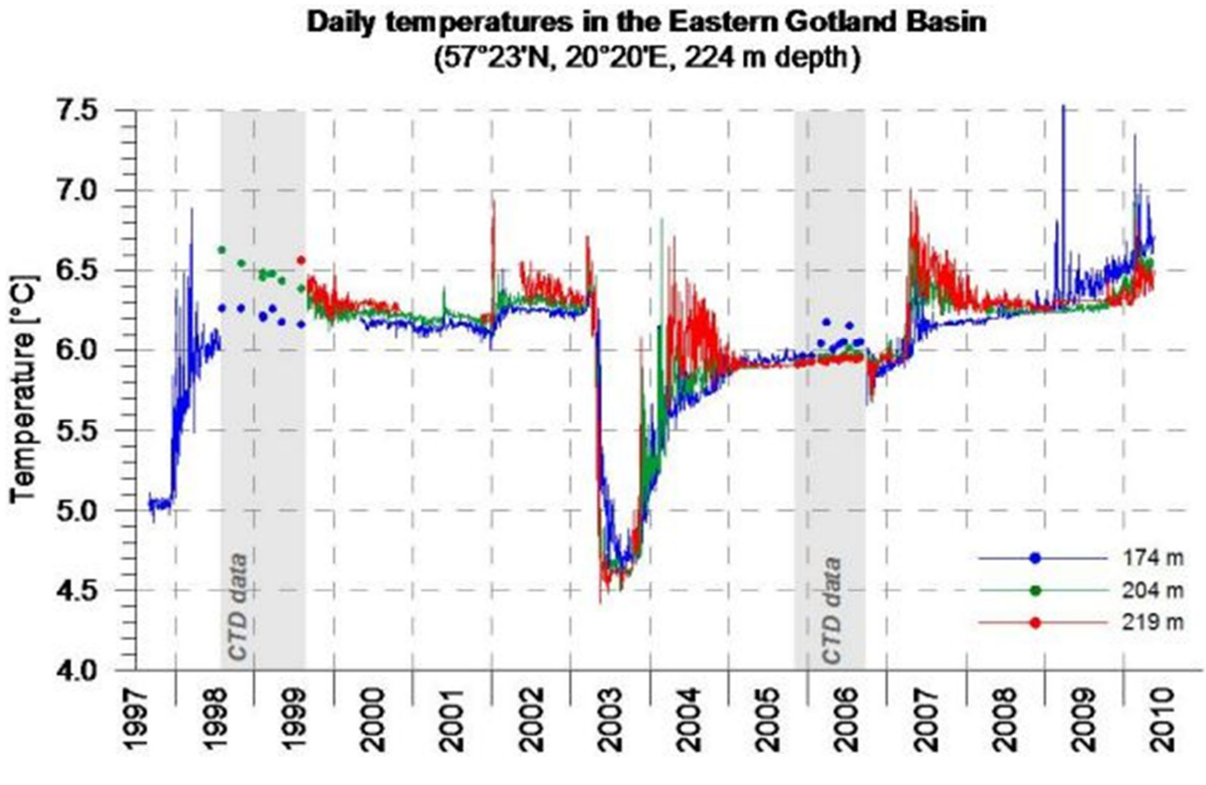


Fig. 3.4.4. Temperature series August 1997- May 2010 of the Eastern Gotland Basin mooring near the Gotland Deep at 174, 204 and 219 m depth. No important inflow events occurred since 2003. Thus, the stagnation period lasting since 2004/2005 is intensified. Some recent baroclinic inflows in 2006 and barotropic inflows in 2007 and 2009 changed the deep water temperatures and improved the oxygen situation in the southern Baltic slightly, but not in the deeps around Gotland. From Feistel et al, 2006, updated from HELCOM Indicator Fact Sheets 2010, Online.

In the sub-regional scale of salinity and stratification changes, many aspects are important in the context of ecological status and environmental and climatic impacts. When saline waters enter the Baltic, the halocline is lifted up and this signal is dynamically transferred to the downstream basins (Meier, 2007). Upstream from the Gotland Deep, the variations in the southwestern Baltic are in general of higher amplitude since along the deep water spreading pathway the variations are damped due to a wide range of mixing processes (*e.g.* Reissmann et al, 2009). In the Bornholm Basin, a buffering deep basin in the western part of the sea, major inflows fill the whole part of the Stolpe Sill level (60 m). The deep temperature changes (Mohrholz et al, 2006) are well in agreement with the changes in the Gotland Deep. The variations of bottom salinity anomalies in the Bornholm Basin during 1961-2000 (Neumann and Schernewski, 2008) show a range from -1.8 psu (1982) to 2.0 psu (1994), with no significant trend although a slight recent salinity increase could be identified. In the Lithuanian part of the Baltic Proper deep water area, Dailidiene et al (2008) have reported for the period 1984-2005 a strengthening of stratification: decrease of surface salinity and increase of deep water salinity

In the Gulf of Finland, a sub-region with a free connection to the Baltic Proper and highest freshwater discharge per unit sea volume, the salinity and stratification changes in general follow that of the Baltic Proper, but are not fully synchronous (*e.g.* Zorita and Laine, 2000). Laine et al (2007) have shown on the basis of monitoring data from the period 1965-2000 a continuous decrease in salinity and density stratification until the early 1990s, after which a slight increase took place again. Based on the independent data set from 1987-2008, Liblik and Lips (2011) obtained that the summertime deep salinities have increased after the 1993 major inflow by about 2 psu. Despite the increased mean stratification strength, ventilation of deep waters is still effective and the annual mean oxygen concentrations remain higher that during the 1960s and 1970s (Laine et al, 2007). Reasons for still effective ventilation can be found from the decreased ice coverage, favoring wind mixing (Vermaat and Bouwer, 2009) and increased frequency of temporal winter-time stratification collapse at stronger southwesterly winds due to straining effects on estuarine gradients (Elken et al, 2012).

Reconstruction of annually mean salinities since 1500 (Hansson and Gustafsson, 2011) has shown that salinity has slowly increased by 0.5 psu since 1500, peaking in the middle of 18^{th} century. The present salinity values are nearly as high as estimated for this earlier maximum salinity period. Historically, there have been several fresher periods when the mean salinity decreased from the maximum value of about 7.8 psu to about 6.5 psu. They also found a negative correlation between oxygen and salinity, indicating that the major, upper, part of the water column was more efficiently ventilated when the Baltic Sea was in a fresher state.

3.4.1.3. Circulation and transport patterns and processes

<u>General characteristics of surface circulation</u>

There are four mechanisms to induce currents in the Baltic Sea: wind-stress at the sea-surface, surface pressure gradient, thermohaline horizontal gradient of density and tidal forces. The currents are steered furthermore by the Coriolis-acceleration, topography and friction. Voluminous river runoffs can produce local changes in the sea-level height and consequently also in currents. Due to the small size of the Baltic Sea basins, friction caused by the bottom and shores damp the currents remarkably. The general circulation is typical for a stratified system. Inflowing waters into a basin are placed at the depth where the ambient water has an equal density. So, the fresher water goes into the upper layer and the more salty water masses go into a certain lower layer.

In the longest time-scale—from several months to years—a baroclinic, wind-independent basic circulation appears. This is due to the positive fresh water balance and the resulting large horizontal gradient of salinity. The fresh waters leave the Baltic Sea in the near-surface layers whereas the inflow of saline water masses takes place in the lower layer.

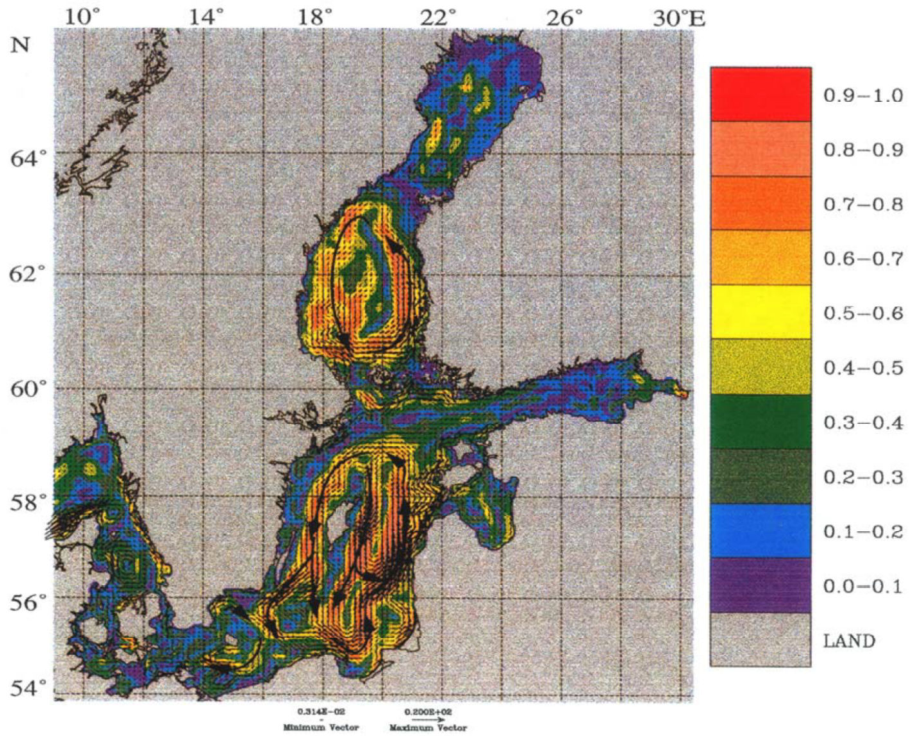
In short time-scales (1–10 days) the currents are mostly caused by the wind stress. Due to the large variability of the winds, the resulting long-term wind-driven mean circulation is weak, and transient currents are one order of magnitude larger than the average ones. Drift currents produce in coastal areas upwelling and downwelling features that are affected by Kelvin-type waves. The water body is laterally mixed by mesoscale eddies and deep-water circulation (see, e.g., Fennel and Sturm, 1992; Lass and Talpsepp, 1993; Raudsepp, 1998; Stigebrandt et al. 2002; and Elken and Matthäus, 2008). In the time-scale from 1 hour to 1 day, there are several periodic dynamical processes. The most important are inertial oscillations (13.2–14.5 hours) and seiches (less than 40 hours). For details see Leppäranta and Myrberg (2009).

In conclusion of the processes affecting the long-term mean surface circulation, the observed outcome in the Baltic Sea is based on non-linear combination of the wind-independent baroclinic mean circulation and the mean wind-driven circulation. Which one is more important is difficult to answer in case of such a non-linear system. This depends on the case studied and on the time-scale under investigation.

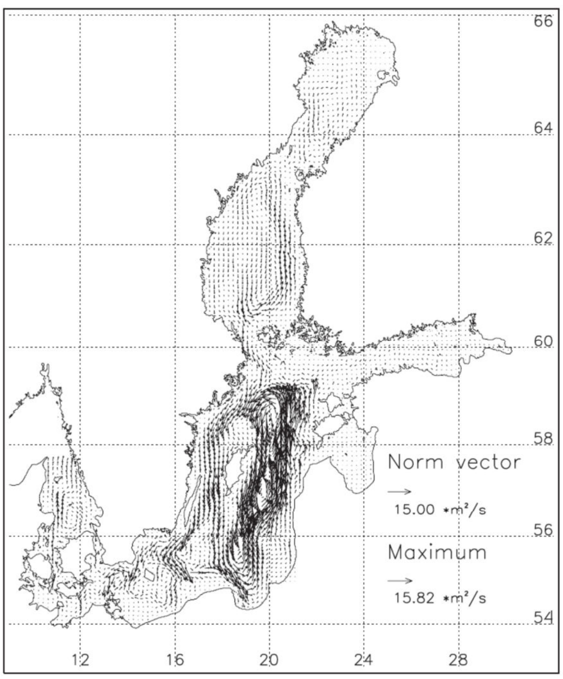
Recent findings of surface circulation system and related processes.

Mean circulation of the entire Baltic Sea was modelled recently by Meier (2007). The results (Fig. 3.4.5) confirm the main characteristics of the early findings of Palmén (1930) and the outcome of numerical modelling (Lehmann and Hinrichsen, 2000, Lehmann et al, 2002) but gives also new fine-scale characteristics. The mean transports above and below the halocline confirm the existence of strong cyclonic gyres both in the Baltic proper and in the Sea of Bothnia; these circulations have a high stability. In the Eastern Gotland Basin high transports are found around the Gotland Deep. It comes out that the strength and persistency of currents is lower in the Gulf of Riga, Gulf of Finland and Bay of Bothnia when comparing with the Baltic Sea proper. This might be due to the impact of ice during the winter. Close to the Swedish coast an intense southward-directed flow becomes visible, being a part of the cyclonic gyre of the Baltic Sea proper. This flow is directed into the Bornholm Basins and to the Arkona Basin. The main flow crosses the central Arkona Basin and bifurcates north of the Rűgen Island. One branch leaves the Baltic Sea at the Darss Sill and the flow continues through the Belt Sea and the Great Belt. The other branch recirculates and forms a cyclonic gyre in the Arkona Basin. Also a flow follows the Swedish coast into the Öresund and Kattegat. In the lower layer the flow follows very much the topography, from the Darss Sill into the Arkona Basin and further towards the Bornholm Channel passing Rűgen Island. The deep waters flow further to the Bornholm Deep and into the Stolpe Channel with a high persistency. East of the Stolpe Channel the main flow is directed along the southwestern slope of the Gdańsk Deep. In the Gotland Deep the flow is characterised by cyclonic gyres. The water masses furthermore have a cyclonic gyre which finally leads part of the water to flow into the western Gotland Basin. The mean circulation is likely variable over the longer periods, with changes in the character of wind forcing, heat fluxes and ice extent, freshwater discharge and inflow activity. Jedrasik et al. (2008) have shown on the basis of hindcast of the period 1958-2001 that yearly averaged surface velocities (mean over the whole sea area) increased by 0.21 cm s^{-1} per 10 years and 20-m velocities by 0.06 cm s^{-1} per 10 years. Based on the presented time series of annually mean current speeds, one may also interpret the increase as a regime shift that occurred in the late 1980s.

a)



b)



c)

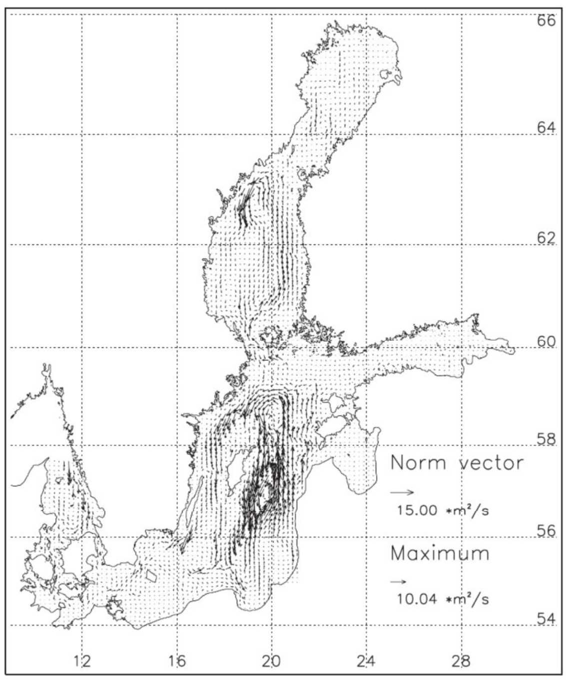


Fig.3.4.5. Baltic Sea circulation as viewed from the modeling results. Average barotropic currents (a) for 1992-1995 (in cm/s) with the flow stability contours (Lehmann and Hinrichsen, 2000), and average transports per unit length (in $m^2\ s^{-1}$) for 1981-2004 above (b) and below (c) the halocline (Meier, 2007).

For local detail investigations the mean circulation in the Gulf of Finland has been modeled by Andrejev and Myrberg (2004a,b). The cyclonic mean circulation in the Gulf of Finland generally is discernible but the resulting patterns and the persistency of the currents according to Andrejev et al. (2004a) deviate to some extent from the classical analyses by Witting (1912) and Palmén (1930). Both the mean and instantaneous circulation patterns in the Gulf of Finland contain numerous mesoscale eddies with a typical size clearly exceeding the internal Rossby-radius. The modeled circulation patterns reveal certain nontrivial and temporally and spatially varying vertical structures.

There have been some recent studies in the Gulf of Finland during the last few years, which partly support, but on the other hand in some cases give new, features of the circulation system. Elken et al. (2011) carried out the EOF (empirical orthogonal functions) analysis of hourly forecasts from the Baltic Sea operational HIROMB-SMHI model for the period 2006–2008. It is possible to distinguish two regions with a specific regime of circulation variability. The western region behaves like a wide channel. Dominant EOF modes at different sections have similar patterns and their time-dependent amplitudes are well correlated. A prevailing mode of currents (23%–42% of the variance) is barotropic (unidirectional over the whole section) and its oscillation (spectral peak at 24 h) is related to the water storage variation of the Gulf. A two-layer flow pattern (surface Ekman transport with deeper compensation flow, 19%–22%) reveals both inertial and lower frequencies. Highest outflow of surface waters occurs during north-easterly winds. The eastern wider region has more complex flow dynamics and only patterns that are nearly uniform over the whole Gulf were detected here. On the sea surface, quasi-uniform drift currents are deflected on the average by 40° to the right from the wind direction and they cover 60% of the circulation variance. Sea level variability is heavily (98%) dominated by nearly uniform changes which are caused by the water storage variations of the Gulf. Sea level gradients contain the main axis (23%) and transverse (17%) components, forced by winds of the same direction. The flows below the surface are decomposed also into the main axis (24%–40%) and transverse (13%–16%) components that are correlated with the sea level gradients according to the geostrophic relations.

New detailed information was also gained by Lilover et al. (2011) of the Gulf of Finland. They performed current velocity observations on Naissaar Bank in northern Tallinn Bay, Gulf of Finland, for five weeks in late autumn 2008 using a bottom-mounted ADCP deployed at 8 m depth. Strong and variable, mainly southerly winds with speeds exceeding 10 m s^{-1} dominated in the area during 60% of the whole period. Bursts of seiche-driven currents with periods of 31, 24, 19.5, 16 and 11 h were observed after the passage of wind fronts. Inertial oscillations and diurnal tidal currents were relatively weak. The low-frequency current velocities gradually decreased toward the bottom at 3 cm s^{-1} over 4-m distance. The magnitude of the complex correlation coefficient between the current and wind for the whole series was 0.69, but it was much higher (up to 0.90) within the shorter steady wind periods. The current was rotated ~35° to the right from the wind. As an exception, during one period a counterclockwise surface-to-bottom veering of the current vector was observed. A topographically steered flow was seen either along isobaths of the bank during strong winds or along the ‘channel’ at the entrance to Tallinn Bay.

Some new ideas were proposed by Soomere et al. (2011a) detailed study of circulation patterns and Lagrangian transport in the uppermost layer of the Gulf of Finland revealed several normally concealed features of surface circulation. For a certain years, a slow anticyclonic gyre may exist in the surface layer in the wide eastern and central part of the Gulf of Finland (Soomere et al. 2011a), reflecting a relatively weak coupling of the mostly Ekman-drift-driven surface-layer dynamics with that in the deeper layers. Semi-persistent (time scales about a week, Viikmäe et al. 2010) patterns of rapid Langrangian surface transport mostly follow the usually location of coastal currents but may stretch across the gulf during certain months and seasons (Soomere et al. 2011a).

The statistical analysis of Lagrangian surface transport has been employed to identify the areas from which the drift of different substances to the coast is unlikely (Soomere et al. 2011b). This transport is generally anisotropic and substances in the surface layer have generally a larger chance to reach the southern coast (Soomere et al. 2010) whereas there exists a wide area in the eastern, wide part of the gulf, surface-current-driven transport of passive tracers from which to either of the coasts in unlikely (Soomere et al. 2011c). The results, however, are highly sensitive with respect to the resolution of the underlying ocean model: the statistics of transport changes substantially when the resolution is increased from 2 miles to 1 mile, and insignificantly depends on the further increase in the resolution (Andrejev et al. 2011).

Raudsepp et al. (2011) studied wind, flow and wave measurements in November-December in 2008 in the relatively narrow and shallow Suur Strait connecting the waters of the Väinameri and the Gulf of Riga. During the measurement period wind conditions were extremely variable, including a severe storm on 23 November. The flow speed along the strait varied between ±0.2 m s^{-1}, except for the 0.4 m s^{-1} that occurred after the storm as a result of the sea level gradient. The mean and maximum significant wave heights were 0.53 m and 1.6 m respectively. Because of their longer fetch, southerly winds generated higher waves in the strait than winds from the north. All wave events caused by the stronger southerly winds induced sediment resuspension, whereas the current-induced shear velocity slightly exceeded the critical value for resuspension only when the current speed was 0.4 m s^{-1}. A triple-nested two-dimensional high resolution (100 m in the Suur Strait) circulation model and the SWAN wave model were used to simulate water exchange in 2008 and the wave-induced shear velocity field in the Suur Strait respectively. Circulation model simulations demonstrated that water exchange was highly variable, that cumulative transport followed an evident seasonal cycle, and that there was an gross annual outflow of 23 km^3 from the Gulf of Riga. The horizontal distribution of wave-induced shear velocity during the strong southerly wind event indicated large shear velocities and substantial horizontal variability. The shear velocities were less than the critical value for resuspension in the deep area of the Suur Strait.

A numerical simulation of the circulation of the whole Baltic Sea was performed for the period 1991–2000 with a special focus on the Gulf of Bothnia (Myrberg and Andrejev, 2006). Their results supported the traditional view of the cyclonic mean circulation in this basin. Its persistency ranges from 20 to 60% and is at largest close to coasts, as already showed a long time ago from observations by Witting (1912) and Palmén (1930). The calculations with a barotropic model of Myrberg and Andrejev (2006), with a fairly high horizontal resolution (3.4×3.4 km), supported the idea that the main features of circulation can be reproduced with a barotropic, wind-driven model. However, the mean current velocities were clearly larger than those according to the Witting-Palmén results. The difference apparently comes from insufficient resolution of the early measurements that did not resolve meso-scale features, such as the quite pronounced differences in the speed and direction between the coastal and open sea currents. The persistency of the mean circulation was especially in the Sea of Bothnia close to the results by Lehmann and Hinrichsen (2000), who also used a barotropic model but for a different period.

Dynamics in the bottom layer

The interaction between the upper and lowers layer is quite restricted in the Baltic Sea due to the strong stratification. In the Kattegat the dense North Sea originating waters form a deep-water pool whereas the fresher Baltic waters are located in the surface layer. The deep water circulation is characterised by dense bottom currents in the inflowing saline water at the mouth area of the Baltic Sea. Convection and mechanical mixing, entrainment and vertical advection of water masses lead to interactions between the upper and lower layers in other parts of the Baltic Sea

Döös et al. (2004) has coined a new term "haline conveyor belt" to describe at general level the Baltic Sea circulation system. The water is effectively recirculating in the Baltic Sea even with the existing low-permeable halocline. The overturning circulation may be called the Baltic Sea haline conveyor belt (Döös et al., 2004) in analogy to the deep-water conveyor belt of the World Ocean. The vertical overturning circulation consist of many important factors: the gravity-driven dense bottom currents of the inflowing waters from the North Sea, the entrainment of ambient surface waters, mixing due to diffusion, interleaving of the inflowing water masses into the deep at the level of neutral buoyancy, vertical advection due to the conservation and upward entrainment of deep water into moving surface water in the northern Baltic Proper.

Elken et al. (2003, 2006) carried out investigations of the large halocline variation and related mesoscale and basin-scale processes in the Northern Gotland Basin – Gulf of Finland system. The authors suggest that long-lasting pulses of southwesterly winds cause an increase in the water volume of the Gulf of Finland. The resulting increase of the hydrostatic pressure in the gulf leads to an outflow of deep water. Such counter-estuarine transport weakens the stratification of water masses at the entrance of the Gulf of Finland. As a consequence, the same energy input leads to an intensified diapycnal mixing as compared with the classical situation at the entrance (strong upward vertical advection). Owing to the variable topography both in the Northern Gotland Basin and in the Gulf of Finland, the basin-scale barotropic flows are converted into baroclinic mesoscale motions with a large isopycnal displacement (more than 20 m within a distance of 10–20 km), which causes intra-halocline current speeds more than 20 cm/s. So, Elken et al. (2006) concluded that the near-bottom layers of the Gulf of Finland rather actively react to the wind forcing, a reasoning which considerably modifies the traditional concept of the partially decoupled lower layer dynamics of the Baltic Sea. The multitude of processes at the entrance of the Gulf of Finland certainly makes the modelling of the deep-water inflow extremely difficult. The internal wave activity is high, the production of strong eddies and topographically controlled local currents is frequent, and thus the diapycnal mixing is intense.

<u>Water age</u>

The model simulations (Meier, 2007) were based on the idea that passive tracers are marking inflowing waters and in another case tracers are marking discharge from all Baltic rivers. It is shown according to a 96 year-run (using atmospheric forcing of 1980–2004) with tracers marking inflowing waters at the Darss Sill and the Drogden Sill.

In the case of inflowing waters from the Kattegat there are pronounced vertical and horizontal age gradients between the uppermost layers and the near-bottom layers. The spatial distribution shows also large differences in the water ages between the mouth area of the Baltic and the Bay of Bothnia. At the sea-surface the age of the Belt Sea water is smaller than 14 years whereas in the northernmost Baltic Sea the water age is up to 40 years. In the bottom layers the water age is in general less than in the surface, e.g., in the Arkona Basin less than 10 years. The halocline separates the water masses of the upper and lower layers that have in the Gotland Basins associated ages smaller or larger than 26 years. The west-east cross-section in the Gotland Sea confirms that the surface water has a larger age than the bottom water and that the Western Gotland Basin is characterised by larger ages than the Eastern Gotland Basin due to the cyclonic circulation system.

For the tracer marking freshwater from all rivers the vertical age gradients in the Gotland Deep are much smaller than in the case of inflowing water from the Kattegat. This indicates an efficient re-circulation of fresh waters in the Baltic Sea. Such circulation is due to the downward tracer flux across the halocline caused by entrainment of the surface water into deep water balanced by the upward tracer flux in the interplay of vertical advection and diffusion. According to Meier (2007) the largest surface water mean ages, more than 30 years, are found in the central Gotland Basin and Belt Sea. Water with a small age is found only at narrow coastal area and in river mouths. At the bottom the mean ages are largest in the western Gotland Deep (about 36 years). At the halocline depth the age distribution is rather homogeneous in Baltic Sea Proper–an opposite situation in comparison with the age calculation based on inflowing waters where high spatial gradients are found.

Mixing

There is a long-term approximate advective-diffusive balance in the deep water (Stigebrandt, 2001). Advective supplies of new deep water tend to increase and diffusive flows tend to decrease the salinity. However, this is not in balance in shorter time-scales due to the discontinuous character of the advective supply of deep water. Since tides are usually small in the Baltic Sea, most of the energy sustaining turbulence in the deep-water pools must be provided by the wind.

Stigebrandt (1987, 2001) concluded, according to results of long-term modelling of the large-scale vertical circulation in the Baltic Sea Proper, that under contemporary conditions the basin-wide vertical diapycnal diffusivity (or diapycnal mixing coefficient) in the deep-water pools can be reasonable well described by

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

where α and κ_{max} are constants and N is the Brunt-Väisälä frequency. In his horizontally integrated model for the Baltic Sea Proper Stigebrandt (1987) tuned α to equal $2 \cdot 10^{-7}$ $m^2 s^{-2}$. According to Meier et al. (2006) α depends on energy fluxes from local sources, such as wind-driven inertial currents, Kelvin waves and other coastally trapped waves. This means that mixing near the coasts and near topographic slopes is more thorough than in the open sea. Axell (1998) found, based on measurements, $\alpha = 1.5 \cdot 10^{-7}$ $m^2 s^{-2}$ and that there is seasonal variability as well. For $N = 10^{-2}$ s^{-1} we have $\alpha/N \sim 1.5 \cdot 10^{-5}$ $m^2 s^{-1}$, while normal level in mixed layer is 10^{-3}–10^{-2} $m^2 s^{-1}$, which serves as a reference for κ_{max}.

The processes interlinked to diapycnal mixing are not yet fully understood. A key question is to find the sources and paths for energy sustaining the turbulence. It has been anticipated that internal waves and their dissipation plays a key role in the transfer of energy down into the deep water. Several mechanisms may generate internal waves.

Lass et al. (2003) measured in DIAMIX-project dissipation rates and stratification between 10 and 120 metres depths during a 9-day experiment in the Eastern Gotland Basin. The main finding was that there are two well-separated turbulent regimes. The turbulence in the surface layer, as expected, was closely connected to the wind. However, in the strongly stratified deeper water turbulence was quite independent of the meteorological forcing at the sea-surface. The integrated production of the turbulent kinetic energy exceeded the energy loss of inertial oscillations in the surface layer suggesting that additional energy sinks might have been inertial wave radiation during geostrophic adjustment of coastal jets and mesoscale eddies. The diapycnal mixing coefficient (κ) of Stigebrandt (1987) was estimated to be $7 \cdot 10^{-7}$ $m^2 s^{-2}$.

Until now the knowledge of the Baltic Sea mixing has been based on quite few publications as shown earlier here. An important recent summary was prepared by Reissmann et al. (2009). The review paper by Reissmann et al. (2009) summarizes the different mechanisms how mixing takes place in the Baltic Sea. One major process is caused by the episodic overflow of water over the sills into the Baltic Sea bringing through bottom currents in more saline waters, this leading to entrainment and interleaving of the incoming water masses to the level of neutral buoyancy (e.g. Lass and Mohrholz, 2003). Through this mechanism the Baltic deep waters are ventilated (e.g. Meier et al. 2006). Because of volume conservation, this process leads to uplift of waters masses in the central Baltic. Also mixing due to inertial waves and breaking of internal waves lead to enhanced vertical turbulent transport as does the effect due to Baltic Sea eddies (e.g. Lass et al. 2003). Also the coastal upwelling (Lehmann and Myrberg, 2008) plays a certain role. In addition to that the winter-time convection and wind-induced mixing takes place. However, these latter processes only affect in the layer above the halocline (see e.g. Leppäranta and Myrberg, 2009). In addition, the surface waves effect the vertical mixing directly through wave breaking and indirectly through Langmuir circulation (e.g. Smith, 1998). The effect of surface wave breaking is usually thought to penetrate to depths of only a few meters in the surface layer and it is often considered through the wind-speed-dependent (not the wave-dependent) friction velocity. Kantha and Clayson (2004) have shown (see also the Baltic case study by Kantha et al, 2010) that the Stokes production of turbulent kinetic energy in the mixed layer is of the same order of magnitude as the shear production and must therefore be included in mixed layer models. The Stokes drift together with mean shear generates Langmuir cells. Taking Langmuir circulations into account in the vertical turbulence schemes affects the deepening of the mixed layer (e.g. Ming and Garret, 1997 and Kukulka et al., 2010). Even though the small size of the Baltic Sea limits the growth of surface waves, the waves are high enough to be of significance even in the small sub-basins of the Baltic Sea (e.g. Soomere and Räämet, 2011 and Tuomi et al., 2011). Summer is typically the season with smallest mean and maximum values of significant wave height and winter highest (excluding the seasonally ice-covered areas). Importance of including the parameterization of internal waves and Langmuir circulations in the vertical turbulence schemes in multi-year simulations in the Baltic Sea has been shown by Axell (2002).

The dynamics of near-inertial motions (Van der Lee and Umlauf, 2011), and their relation to mixing, is investigated here with an extensive data set, including turbulence and high-resolution velocity observations from two cruises conducted in 2008 (summer) and 2010 (winter) in the Bornholm Basin of the Baltic Sea. In the absence of tides, it is found that the basin-scale energetics are governed by inertial oscillations and low-mode near-inertial wave motions that are generated near the lateral slopes of the basin. These motions are shown to be associated with persistent narrow shear-bands, strongly correlated with bands of enhanced dissipation rates that are the major source of mixing inside the permanent halocline of the basin. In spite of different stratification, near-inertial wave structure, and atmospheric forcing during summer and winter conditions, respectively, the observed dissipation rates were found to scale with local shear and stratification in a nearly identical way. This scaling was different from the Gregg-Henyey-type models used for the open ocean, but largely consistent with the MacKinnon-Gregg scaling developed for the continental shelf.

Rossby-radius

The first baroclinic Rossby radius of deformation (R_1) is a fundamental horizontal scale of mesoscale processes. This scale is important for planning both numerical modeling and study areas. R_1 was computed on the basis of an 11-year series of high resolution CTD measurements collected during r/v "Oceania" cruises (Osiński, et al. 2010). The data set covered the three main basins of the Baltic Proper: the Bornholm Basin (BB), the Słupsk Furrow (SF) and the Gdańsk Basin (GB). The smallest mean value of R_1 was found in the Gdańsk Basin (5.2 km), the largest one in the Bornholm Deep (7.3 km). The seasonal variability of R_1 is lower in the western basin than in the eastern one. The seasonal cycle of R_1 may be broken by extreme events, e.g. main Baltic inflows (MBI) of saline water. The inflowing water rebuilds the vertical stratification in the southern Baltic Sea and dramatically changes the R_1 values. The difference of R_1 between a stagnation period and an inflow situation is shown on the basis of observations made during 2002–2003. The main inflow occurred in winter, after ten years of stagnation, and the very low values of R_1 (about 4 km) changed to very high ones (more than 9 km).

Analysis of stagnation and saltwater inflow events may throw light on the value of R_1 in future climatic scenarios. The potential influence of climate change on Baltic Sea salinity, especially a decrease in MBI activity, may change the baroclinic Rossby radius of deformation and the mesoscale dynamics. Values of R_1 are expected to be lower in the future climate than those measured nowadays.

3.4.1.4. Sensitivity to changes in forcing

Due to the ephemeral nature of the atmospheric conditions over the Baltic Sea, the flow field is highly variable, and thus, changes in the resulting circulation and upwelling are difficult to observe. However, three-dimensional models, forced by realistic atmospheric forcing conditions and river runoff have reached a state of accuracy that the highly fluctuating current field and the associated evolution of the temperature and salinity field can be realistically simulated. Changes in the characteristics of the large-scale atmospheric wind field over the central and eastern North Atlantic can be described by the North Atlantic Oscillation (NAO). The NAO is related to the strength and geographical positions of weather systems as they cross the North Atlantic and thus has a direct impact on the climate in Europe (Hurrel 1995). This is especially true under high NAO^+ conditions, where the spatial correlation length is extended to northern Europe. Under low NAO^+ or NAO^- conditions, the spatial correlation length scale decreases, and the influence of the westerlies on northern Europe becomes small, so that the continental influence on the climate increases. However, the weakened influence of the westerlies for northern Europe is a precondition of outflow for the Baltic Sea. Thus, NAO^- phases also have the potential to indirectly affect the circulation in the Baltic Sea and the water mass exchange with the North Sea (Lehmann et al. 2002). The linear correlation index between the volume exchange of the Baltic Sea and the NAO index is only r=0.28 (r=0.49 for the NAO winter index DJFM). A better relation of the local wind field over the Baltic Sea to the large-scale atmospheric circulation is given by the Baltic Sea Index (BSI) defined by Lehmann et al (2002). The NAO is significantly related to the BSI. Furthermore, the BSI is highly correlated with the storage variations of the Baltic Sea and the volume exchange with the Danish Sounds. For northern Europe, the NAO accounts for about 50% of the dominant climate winter regimes, The 'Blocking' and 'Atlantic Ridge' regime accounts for another 27 and 23%, respectively (Hurrel and Deser 2009, Lehmann et al. 2011). The local BSI includes all 4 regimes and thus better describes the SLP variability over the Baltic Sea rather than the NAO alone.

Changes in the general wind conditions over the Baltic Sea lead to changes in typical upwelling zones and frequencies. In a statistical approach on upwelling based on satellite data for the period 1990-2009 Lehmann et al. (2012) analysed location and upwelling frequencies along the Baltic Sea coast during the thermal stratified period of the year. Most frequent upwelling could be found along the Swedish east coast and the Finnish coast of the Gulf of Finland.

Generally, there was a positive trend of upwelling frequencies along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland and a negative trend along the Polish, Latvian and Estonian coast (Fig.3.4.6). This is in line with the warming trend of annual mean SST derived from infrared satellite images (1990–2008) presented in Lehmann et al. (2011). Smallest trends occurred along the east coast of Sweden 0.3 to 0.5°C decade^{-1} compared to 0.5 to 0.9°C decade^{-1} in the central part of the Baltic Proper. They supposed that the decrease in the warming trend along the coast was due to increased upwelling connected with a shift in the dominant wind directions. The trend analysis of favorable wind conditions derived from wind station data May-September for the period 1990–2009 support this. There is a positive trend of south-westerly and westerly wind conditions along the Swedish coast and the Finnish coast of the Gulf of Finland and a corresponding negative trend along the east coast of the Baltic Proper and the Estonian coast of the Gulf of Finland and the Finnish coast of the Gulf of Bothnia. September contributes most to this trend, whereas in June and August a partially reverse of the trends occurs.

Fig. 3.4.6. Changes in upwelling frequencies. Figure missing at the moment.

In a three-dimensional modeling study Meier (2005) investigated the sensitivities of modeled salinity and age on freshwater supply, wind speed and amplitude of the sea level in Kattegat. In steady state the average salinity of the Baltic Sea is most sensitive to perturbations of freshwater inflow. Increased freshwater inflow and wind speed resulted both in decreased salinity. Whereas increased amplitude of the Kattegat sea level resulted in increased salinity. The average age was most sensitive to perturbations of the wind speed. Especially, decreased wind speed causes significantly increased age of the deepwater. Long-term changes of fresh- and salt water inflows and of low-frequent wind anomalies cause the Baltic Sea to drift into a new steady-state with altered salinity, stability and ventilation are approximately invariant. Thus, the timescale of perturbations needs to be long compared to the turn-over time of freshwater content. By contrast, long-term changes of the high frequent wind affect deepwater ventilation significantly.

Omstedt and Hansson (2006) analysed the Baltic Sea climate memory and response to change using both observations and modelling. Their findings can be summarized as follows. The averaged salinity of the Baltic Sea is non-lineary dependent on and strongly sensitive to changes in freshwater inflow. The annual maximum ice extent is strongly sensitive to changes in the winter air temperature over the Baltic Sea. It will become completely ice covered or ice free at Baltic Sea winter air temperatures of -6 and 2°C, respectively. In the Baltic Sea climate system at least two important time scales need to be considered: one is associated with the water balance (salinity) and the e-folding time is approximately 33 years, while the other is associated with the heat balance and is approximately 1 year. Change in Baltic Sea annual mean water temperature is closely related to change in the air temperature above the sea. However, in climate warming experiments the water and air temperatures may differ due to changes in the surface heat balance components.

A study of climate change effects on the Baltic Sea ecosystem has been presented by Neumann (2010). Two regional data sets for greenhouse gas emission scenarios, A1B and B1, for the period 1960 to 2100, were used to force transient simulations with a 3D ecosystem model of the Baltic Sea. The results showed that the expected warming of the Baltic Sea is 1–4 K, with a decrease in salinity and a much reduced sea–ice cover in winter. Most of the findings were consistent with an earlier study presented by Meier (2006). From the comparison of both studies it turned out, that the warming was simular in both studies, thus demonstrating that warming is a robust feature whereas the salinity decrease was differently pronounced, indicating salinity-change simulations remain relatively uncertain, albeit with a tendency towards reduced salinty. In addition, the season favoring cyanobacterial blooms is prolonged, with the spring bloom in the Northern Baltic Sea beginning earlier in the season, while the oxygen conditions in deep water are expected to improve slightly.

Hordoir and Meier (2011) analysed changes in future stratification in the upper part of the water column using a three-dimensional circulation ocean model. They found a switch between processes controlling the seasonal cycle of stratification in the Baltic sea at the end of twenty first century. Solely, the air temperature increase was responsible for increased stratification at the bottom of the mixed layer. As in present climate winter temperatures in the Baltic are often below the temperature of maximum density, warming causes thermal convection. Re-stratification during the beginning of spring is then triggered by the spreading of freshwater. This process is believed to be important for the onset of the spring bloom. In future climate, temperatures are expected to be usually higher than the temperature of maximum density and thermally induced stratification will start without prior thermal convection. Thus, freshwater controlled re-stratification during spring is not an important process anymore, and thus this changes in stratification might have an important impact on vertical nutrient fluxes and the intensity of the spring bloom in future. Changes in processes controlling the seasonal cylce of stratification also have been investigated by Demchenko et al. (2011). They found differences in the formation and evolution of seasonal strucural thermal fronts after winters of different severity. Structural fronts are related to the temperature of density maximum. In spring the front advances northwards at a speed af about 11-16 km d^{-1} traversing the breadth of the Baltic Sea within 8 to 10 weeks. After severe winters the horizontal temperature gradient is much more pronounced and the traversal speed is reduced compared with mild winters.

Concluding remarks(to be written)

References

Andrejev O, Myrberg K, Alenius P, Lundberg PA (2004a) Mean circulation and water exchange in the Gulf of Finland—a study based on three-dimensional modelling. Boreal Env Res 9:9–16

Andrejev O, Myrberg K, Lundberg PA (2004b) Age and renewal time of water masses in a semi-enclosed basin—Application to the Gulf of Finland. Tellus 56A:548–558

Andrejev O, Soomere T, Sokolov A Myrberg K (2011) The role of spatial resolution of a 3D hydrodynamic model for marine transport risk assessment. Oceanologia 53:335-371

Axell LB (1998) On the variability of the Baltic Sea deepwater mixing. J Geophys Res 103:21667–21682

Axell LB (2002) Wind-driven internal waves and Langmuir circulations in a numerical ocean model of the southern Baltic Sea. J Geophys Res 107 doi:10.1029/2001JC000922

Bradtke K, Herman A, Urbanski JA (2010) Spatial and interannual variations of seasonal sea surface temperature patterns in the Baltic Sea. Oceanologia 52:345-362

Conley DJ, Björck S, Bonsdorff E, et al. (2009) Hypoxia-Related Processes in the Baltic Sea. Envir Sci & Tech 43:3412-3420

Dailidiene I, Baudler H, Chubarenko B, Navrotskaya S (2011) Long term water level and surface temperature changes in the lagoons of the southern and eastern Baltic. Oceanologia 53:293-308

Dailidiene I, Davuliene L (2008) Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984-2005. J Mar Sys 74:S20-S29

Demchenko N, Chubarenko I, Kaitala S (2011) The development of seasonal structural fronts in the Baltic Sea after winters of varying severity. Clim Res 48:73-84

Döös K, Meier HEM, Döscher R (2004) The Baltic haline conveyor belt or the overturning circulation and mixing in the Baltic. Ambio 33:261–266

Elken J, Mälkki P, Alenius P, Stipa T (2006) Large halocline variations in the Northern Baltic Proper and associated meso- and basin-scale processes. Oceanologia 48(S):91–117

Elken J, Matthäus W (2008) Physical System Description, Annex A1. In: The BACC Author Team (ed.), Assessment of Climate Change for the Baltic Sea Basin. Springer-Verlag, Berlin Heidelberg, pp. 379–386.

Elken J, Nõmm M, Lagemaa P (2011) Circulation patterns in the Gulf of Finland derived from the EOF analysis of model results. Boreal Env Res 16A:84–102.

Elken J, Raudsepp U, Laanemets J, Passenko J, Maljutenko I, Pärn O (2012) Increased frequency of winter-time stratification collapse in the Gulf of Finland since 1990s. (submitted)

Elken J, Raudsepp U, Lips U. (2003) On the estuarine transport reversal in deep layers of the Gulf of Finland. J Sea Res 49:267– 274

Feistel R, Nausch G, Hagen E (2006) Unusual Baltic inflow activity in 2002-2003 and varying deep-water properties. Oceanologia 48:21-35

Fennel W, Sturm M (1992) Dynamics of the western Baltic. J Mar Sys 3:183–205

Hakanson L, Lindgren D (2008) On regime shifts and budgets for nutrients in the open Baltic Proper: Evaluations based on extensive data between 1974 and 2005. J Coastal Res 24: 246-260

Hansson D, Omstedt A (2008) Modelling the Baltic Sea ocean climate on centennial time scale: temperature and sea ice. Clim Dyn 30:763-778

Hansson D, Gustafsson E(2011) Salinity and hypoxia in the Baltic Sea since A.D. 1500. J Geophys Res 116: doi:10.1029/2010JC006676

Hinrichsen HH, Lehmann A, Petereit C, Schmidt J (2007) Correlation analyses of Baltic Sea winter water mass formation and its impact on secondary and tertiary production. Oceanologia 49:381-395

Hordoir R, Meier HEM (2011) Effect of climate change on the thermal stratification of the Baltic Sea: a sensitivity experiment. Clim Dyn doi 10.1007/s00382-011-1036-y

Hurrell JW (1995) Decadal trends in the north-Atlantic oscillation – regional temperatures and precipitation. Science 269:676–679

Hurrell JW, Deser C (2009) North Atlantic climate variability: the role of the North Atlantic Oscillation. J Mar Syst 78:28–41

Jedrasik J, Cieslikiewicz W, Kowalewski M, Bradtke K, Jankowski A (2008) 44 Years Hindcast of the sea level and circulation in the Baltic Sea. Coastal Eng 55:849-860

Kantha L, Clayson CA (2004) On the effect of surface gravity waves on mixing in an oceanic mixed layer. Ocean Mod 6:101–124

Kantha L, Lass HU, Prandke H (2010) A note on Stokes production of turbulence kinetic energy in the oceanic mixed layer: observations in the Baltic Sea. Ocean Dyn 60:171-180

Kotta J, Kotta I, Simm M, Põllupüü M (2009) Separate and interactive effects of eutrophication and climate variables on the ecosystem elements of the Gulf of Riga. Est Coast Shelf Sci 84:509–518

Kõuts T, Omstedt A (1993) Deep water exchange in the Baltic Proper. Tellus 45A:311-324

Kukulka T, Plueddemann AJ, Trowbridge JH, Sullivan PP (2010). Rapid Mixed Layer Deepening by the Combination of Langmuir and Shear Instabilities: A Case Study. J Phys Oceanogr 40:2381–2400

Laine AO, Andersin AB, Leinio S, Zuur AF (2007) Stratification-induced hypoxia as a structuring factor of macrozoobenthos in the open Gulf of Finland (Baltic Sea). J Sea Res 57:65-77

Lass HU Talpsepp L (1993) Observations of coastal jets in the Southern Baltic. Cont Shelf Res 13:189–203

Lass HU, Mohrholtz V (2003) On the dynamics and mixing of inflowing saltwater in the Arkona Sea. J Geophys Res 108: doi:10.1029/2002JC001465

Lass HU, Prandke H, Liljebladh B (2003) Dissipation in the Baltic proper during winter stratification. J Geophys Res 108: doi:10.1029/2002JC001401

Lehmann A, et al. (2012). … Frequency of upwelling in the Baltic Sea … (submitted)

Lehmann A, Getzlaff K, Harlass J (2011) Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. Clim Dyn 46:185-196

Lehmann A, Hinrichsen HH (2000) On the wind driven and thermohaline circulation of the Baltic Sea. Phys Chem Earth B 25:183–189

Lehmann A, Krauss W, Hinrichsen HH (2002) Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. Tellus 54A:299-319

Lehmann A, Myrberg K (2008) Upwelling in the Baltic Sea – a review. J Mar Sys 74:S3–S12

Leppäranta M, Myrberg K (2009). The physical oceanography of the Baltic Sea. Springer-Verlag, Berlin-Heidelberg-New York, 387 pp.

Liblik T, Lips U (2011) Characteristics and variability of the vertical thermohaline structure in the Gulf of Finland in summer. Boreal Env Res 16A:73 - 83

Lilover MJ, Pavelson J, Kõuts T (2011) Wind forced currents over the shallow Naissaar Bank in the Gulf of Finland. Boreal Env Res 16A:164–174

Luterbacher J, Dietrich D, Xoplaki E, Grosjean M (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303:1499-1503

MacKenzie BR, Schiedek D (2007a) Daily ocean monitoring since the 1860s shows record warming of northern European seas. Global Change Biol 13:1335–1347

MacKenzie BR, Schiedek D (2007b) Long-term sea surface temperature baselines—time series, spatial covariation and implications for biological processes. J Mar Sys 68:405–420

Madsen KS, Hojerslev NK (2009) Long-term temperature and salinity records from the Baltic Sea transition zone. Boreal Env Res 14:125-131

Matthäus W, Frank H, (1992) Characteristics of major Baltic inflows – a statistical analysis. Cont Shelf Res 12:1375-1400

Matthäus W, Nehring D, Feistel R, Nausch G, Mohrholz V, Lass HU (2008) The Inflow of Highly Saline Water into the Baltic Sea In: State and Evolution of the Baltic Sea, 1952-2005: A Detailed 50-Year Survey of Meteorology and Climate, Physics, Chemistry, Biology, and Marine Environment. Wiley

Meier HEM (2005) Modeling the age of Baltic Seawater masses: Quantification and steady state sensitivity experiments. J Geophys Res 110: doi:10.1029/2004JC002607

Meier HEM (2007) Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. Est Coast Shelf Sci 74:610–627

Meier HEM, Feistel R, Piechura J, Arneborg L, Burchard H, Fiekas V, Golenko N, Kuzmina N, Mohrholz V, Nohr C, Paka VT, Sellschopp J, Stips A, Zhurbas V (2006) Ventilation of the Baltic Sea deep water: A brief review of present knowledge from observations and models. Oceanologia 48:133–164

Meier HEM, Kauker F (2003) Sensitivity of the Baltic Sea salinity to the freshwater supply. Clim Res 24:231-242

Ming L, Garrett C (1997) Mixed Layer Deepening Due to Langmuir Circulation. J Phys Oceanogr 27:121–132

Mohrholz V, Dutz J, Kraus G (2006) The impact of exceptionally warm summer inflow events on the environmental conditions in the Bornholm Basin. J Mar Sys 60:285-301

Myrberg K, Andrejev O (2006) Modelling of the circulation, water exchange and water age properties of the Gulf of Bothnia. Oceanologia 48(S):55–74

Neumann T (2010) Climate-change effects on the Baltic Sea ecosystem: A model study. J Mar Sys 81:213-224

Neumann T, Schernewski G (2008) Eutrophication in the Baltic Sea and shifts in nitrogen fixation analyzed with a 3D ecosystem model. J Mar Sys 74:592-602

Omstedt A, Hansson D (2006) The Baltic Sea ocean climate system memory and response to changes in the water and heat balance components. Cont Shelf Res 26:236-251

Osiński R, Rak D, Walczowski W, Piechura J (2010). Baroclinic Rossby radius of deformation in the southern Baltic Sea. Oceanologia 52:417–429

Palmén E (1930) Untersuchungen über die Strömungen in den Finnland umgebenden Meeren. Commentationes physico-mathematicae / Societas Scientarium Fennica 12, 93 pp.

Raudsepp U, Laanemets J, Haran G, Alari V, Pavelson J, Kõuts T (2011). Flow, waves and water exchange in the Suur Strait, Gulf of Riga, in 2008. Oceanologia 53: 35–56

Raudsepp, U. (1998) Current dynamics of estuarine circulation in the lateral boundary layer. Estuarine, Coastal and Shelf Science 47, 715–730.

Reissmann JH, Burchard H, Hagen RFE, Lass HU, Nausch VMG, Umlauf L, Wieczorek G (2009) Vertical mixing in the Baltic Sea and consequences for eutrophication - A review. Progr Oceanogr 82:47–80

Siegel H, Gerth M, Tscherich G (2006) Sea surface temperature development of the Baltic Sea in the period 1990–2004. Oceanologia 48S:119–131

Soomere T, Andrejev O, Myrberg K, Sokolov A (2011b) The use of Lagrangian trajectories for the identification of the environmentally safe fairways. Mar Poll Bull 62:1410–1420

Soomere T, Berezovski M, Quak E, Viikmäe B (2011c) Modeling environmentally friendly fairways using Lagrangian trajectories: a case study for the Gulf of Finland, the Baltic Sea. Ocean Dyn 61:1669–1680

Soomere T, Delpeche N, Viikmäe B, Quak E, Meier HEM, Döös K (2011a). Patterns of current-induced transport in the surface layer of the Gulf of Finland. Boreal Env Res 16A:49–63

Soomere T, Räämet A (2011) Long-term spatial variations in the Baltic Sea wave fields. Ocean Sci, 7:141–150

Soomere T, Viikmäe B, Delpeche N, Myrberg K (2010) Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. Proc Estonian Acad Sci 59:156–165

Stigebrandt A (1987) A model for vertical circulation of the Baltic deep water. J Phys Oceanogr 17:1772–1785

Stigebrandt A (2001) Physical oceanography of the Baltic Sea. In: F. Wulff et al. (ed.), A system analysis of the Baltic Sea. Ecological studies, 148, 19–74. Berlin–Heidelberg, Springer-Verlag.

Stigebrandt A, Gustafsson BG (2003) Response of the Baltic Sea to climate change—theory and observations. J Sea Res 49:243– 256

Stigebrandt A., Lass HU, Liljebladh B, Alenius P, Piechura J, Hietala R Beszczynska A (2002) DIAMIX: an experimental study of diapycnal deepwater mixing in the virtually tideless Baltic Sea. Boreal Env Res 7:363–369

Tuomi L, Kahma KK Pettersson H (2011) Wave hindcast statistics in the seasonally ice-covered Baltic Sea. Boreal Env Res (in press)

Van der Lee EM, Umlauf L (2011) Internal wave mixing in the Baltic Sea: Near-inertial waves in the absence of tide. J Geophys Res doi:10.1029/2011JC007072

Vermaat JE, Bouwer LM (2009) Less ice on the Baltic reduces the extent of hypoxic bottom waters and sedimentary phosphorus release. Est Coast Shelf Sci 82:689-691

Viikmäe B, Soomere T, Viidebaum M, Berezovski A (2010) Temporal scales for transport patterns in the Gulf of Finland. Estonian J Eng 16:211–227

Winsor P, Rohde J, Omstedt A (2001) Baltic Sea ocean climate: an analysis of 100 yr of hydrographic data with focus on the freshwater budget. Clim Res 18:5–15

Witting R (1912) Zusammenfassende ¨Übersicht der Hydrographie des Bottnischen und Finnischen Meerbusens und der Nördlichen Ostsee. Finn. Hydrogr.-biol. Unters. No 7.

Zorita E, Laine A (2000) Dependence of salinity and oxygen concentrations in the Baltic Sea on large-scale atmospheric circulation: Clim Res 14:25–41