Recent Change—Marine Circulation and Stratification

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Abstract

This chapter describes recent change in the circulation and stratification of the Baltic Sea. A recent warming trend in sea-surface waters has been clearly demonstrated by in situ measurements, remote sensing data and numerical models. Trends in sea-surface temperature (SST) for the past three to four decades based on remote sensing data generally agree with trends determined from in situ observations. Models suggest the current warming within the Baltic Sea lies within the range experienced during the past 500 years. The salinity and stratification of the deep waters are strongly linked to the major inflows of North Sea water that occur sporadically and bring high-saline water into the deep layers of the Baltic Sea. The major inflows normally occur during winter and spring and bring cold oxygen-rich waters into the deep basins. Since 1996, large inflows have also occurred during summer, bringing in warm low-oxygen water.

7.1 Introduction

Changes in thermohaline characteristics and stratification of the water column are usually analysed on the basis of data from repeat hydrographic observations, originating from shipborne monitoring programmes and/or permanent coastal and offshore oceanographic stations. Such datasets are described in recent books by Feistel et al. (2008) and Leppäranta and Myrberg (2009). In situ observations are often irregular in space and time, especially for offshore areas; therefore, trends and variability in the ocean state can only be determined by careful pre-processing of the data to address issues such as data homogenisation and the suppression of aliasing errors. In recent decades, horizontal undersampling by in situ measurements has been partially offset by the remote sensing of sea-surface properties from satellites; with these data free of spatial aliasing errors due to their high horizontal resolution. Satellite-derived cloud-free products for sea-surface temperature (SST) have been reasonably accurate since the 1980s. Many of the papers published over the past decade that address trends and variability in the circulation and stratification of the Baltic Sea are based on remote sensing data, often in combination with in situ observations and the results of numerical modelling. Improvements in the physical and numerical features of the models, accompanied by model validation studies, have increased confidence in the realism of the model results. Models provide dynamically balanced gridded datasets over decades or longer, including information for 'noisy' variables such as currents, transport and mixing fluxes. This chapter analyses the recent peer-reviewed literature, extending the findings from earlier review (Box 7.1).

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Box 7.1 Key findings from the first Baltic Sea assessment (BACC Author Team 2008)

Temperature

- The late 1990s were characterised by warmer summers and colder winters compared to the years before and after this period.
- Heat content maxima were identified around 1975 and 1990. A heat content minimum was found in 1987, when the winter heat content and summer heat content both showed minimum values.
- There were indications of seawater warming, but it was unclear whether this was partly or even entirely due to a change in sampling frequency and/or to changing seasonal representation in the dataset.
- Since 1988, the seasonal temperature minimum of the intermediate winter water has increased by 1.5 °C.

Salinity and saltwater inflows

- The mean salinity of the Baltic Sea decreased during the early twentieth century and during the 1980s and 1990s. No long-term trend was found during the twentieth century.
- Since the mid-1970s, the frequency and intensity of major saltwater inflows from the North Sea have decreased.
- Major inflows were absent between February 1983 and January 1993. During this low-salinity phase, the deep water of the eastern Gotland Basin was poorly ventilated, with oxygen depletion as a consequence.
- Two low-salinity phases were found: one during the 1920s/1930s and one during the 1980s/1990s. They are explained by stronger than normal freshwater inflow and zonal wind velocity.

This chapter refers to the Baltic Sea gulfs and basins as shown in Fig. 7.1. For detailed descriptions of Baltic Sea geography and topography, see the books by Feistel et al. (2008) and Leppäranta and Myrberg (2009).

7.2 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 two-layer salinity stratification. While temperature and sea ice respond rapidly to the changes in atmospheric heat fluxes, variations in salinity are governed mainly by lateral transport processes, resulting together with diapycnal mixing (i.e. mixing across the surfaces of constant water density) in response times of many decades (e.g. Stigebrandt and Gustafsson 2003; Omstedt and Hansson 2006).
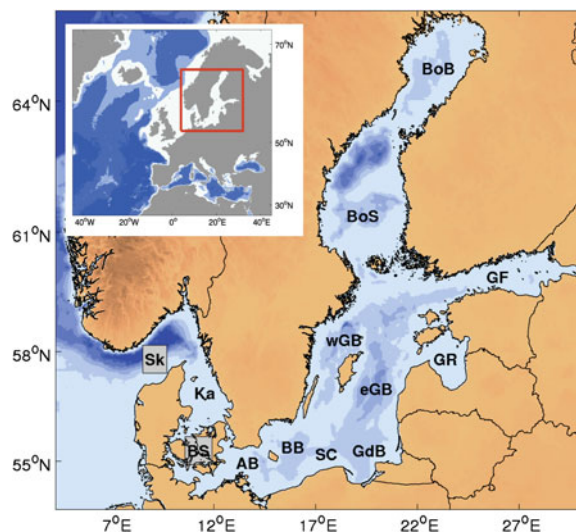

Fig. 7.1 Baltic Sea showing topography (greater depths presented by *darker blue colour*) and sub-regional notations: *Sk* Skagerrak, *Ka* Kattegat, *BS* Belt Sea, *AB* Arkona Basin, *BB* Bornholm Basin, *SC* (underwater) Stolpe Channel, *GdB* Gdansk Basin, *eGB* eastern Gotland Basin, *wGB* western Gotland Basin, *GR* Gulf of Riga, *GF* Gulf of Finland, *BoS* Bothnian Sea, *BoB* Bothnian Bay, Baltic Proper includes AB, BB, SC, GdB, eGB and wGB, Gulf of Bothnia includes BoS and BoB

Cold waters, formed during winter, extend down to the halocline which has a typical depth of 60–80 m in the Baltic Proper and somewhat less in the southern basins. During summer, when a seasonal thermocline develops in the surface waters at depths of about 15–20 m, the underlying cold intermediate layer generally retains a 'memory' of the severity of the previous winter. This dicothermal layer is often referred to as 'old winter water'. It is no surprise, therefore, that Hinrichsen et al. (2007) found the summer (July–August) temperature of the intermediate cold layer to be well correlated with the surface (down to the halocline) temperature of the preceding March. Deeper waters, below the halocline, are formed mainly by lateral advection of saline waters of North Sea origin that entrain and mix with ambient waters during their passage into and through the Baltic Sea. Below 100 m depth, the range in temperature variation within the Gotland Deep is only 5 °C (range 3–8 °C), compared to a range in surface temperature of up to 25 °C. According to the Baltic Sea hypsographic curves (the relationship between the surface area bounded by given depth contours and their depths), the volume of deep layers below 100 m represents only about 12 % (Leppäranta and Myrberg 2009) of the whole sea volume (21,205 km^3) and the contribution of lateral heat advection to the overall Baltic Sea heat content is relatively small.

The rise in air temperature in the Baltic Sea region (see Chap. 4, Sect. 4.4) is expected to drive a corresponding rise in water temperature. Indeed, MacKenzie and Schiedek (2007a) stated that since the 1860s a record warming of the

Baltic Sea and North Sea has occurred, especially during recent decades. They used data from daily monitoring at a few long-term stations, such as Christiansø, located close to the island of Bornholm, as well as data from irregular open water sampling, and applied advanced data homogeneity and spatial synchrony matching procedures to ensure sufficient data quality for climate analysis (MacKenzie and Schiedek 2007b). Their results showed little evidence of a gradual linear increase or decrease in SST since the mid-late 1800s, however; in contrast, modelling results by Gustafsson et al. (2012) suggest a rise in SST temperature of 0.8 °C over the past 150 years. There have been earlier warm periods in the mid-late 1800s and in the mid-1900s, especially in the 1930s. However, since about 1985, a warming of surface waters is evident in all datasets and in all seasons. The probability of extremely warm surface waters in winter and summer has increased since the 1990s by two- to fourfold. MacKenzie and Schiedek (2007a) argued that summer warming rates have almost tripled compared to those that could be expected from the observed increase in air temperature. In contrast to this and to the results of many other studies, Håkanson and Lindgren (2008) concluded, 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*'. It could be that this dataset contains more observations from the cold season over recent decades and so the rising trend in SST is not visible. Careful statistical pre-processing of irregular sampling data is vital when attempting to estimate multi-decadal change for 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 Sill, the mean SST by the end of the period was 0.7 °C higher than any previous observations. Since the 1990s, surface layers are also observed to have warmed near the Lithuanian coast (Dailidienė et al. 2011), recently at 0.3–0.9 °C per decade. The changes are more complex in the Gulf of Finland (Liblik and Lips 2011) and in the Gulf of Riga (Kotta et al. 2009); these studies stress the relation of temperature variations to the atmospheric circulation patterns expressed as the North Atlantic Oscillation (NAO, see Chap. 4, Box 4.1) and/or the Baltic Sea Index (BSI, difference of sea-level air pressure anomalies between Oslo and Szczecin, Lehmann et al. 2002) indices (e.g. Lehmann et al. 2011; Dippner et al. 2012). In the northern sea areas, the recent decrease in the extent and duration of ice cover (see Chap. 8) also has a strong influence on the trends in seawater temperature (see Sect. 7.5).

Variations in SST can be well resolved by remote sensing from satellites, using infrared AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) sensors. Regular satellite coverage has been 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 SST from the remote sensing data agree well with those from in situ measurements in the offshore sea areas (Siegel et al. 2006; Bradtke et al. 2010). Lehmann et al. (2011) used remote sensing data for 1990–2008 to derive a linear trend of annual mean SST of up to 1 °C per decade in the northern part of the Bothnian Bay, but a high increase was also found in the Gulf of Finland and Gulf of Riga and in the northern Baltic Proper (Fig. 7.2). Warming of surface waters is lowest (0.3–0.5 °C per decade), north-east from Bornholm Island up to and along the Swedish coast, probably due to an increase in the frequency of coastal upwelling (Lehmann et al. 2012). Bradtke et al. (2010) also considered trends in monthly and seasonal mean values during 1986–2006 and found the highest positive trend (more than 2 °C per decade in August) in the Bothnian Sea and the northern Baltic Proper. At the same time, mean SST in March decreased. Siegel et al. (2006) studied the period 1990–2004 and found the highest rate of increase in the Bothnian Sea in July (more than 3 °C per decade), and in the Arkona and Gotland Sea in August and September (about 1.5 °C per decade). Trends in SST for the past three to four decades based on data from remote sensing generally agree well with trends determined from independent in situ observations of SST.

Deep-water temperature in the Baltic Proper is determined mainly by the lateral spread of submerged saline water of North Sea origin, reflecting surface thermal conditions during deep-water formation. Mohrholz et al. (2006) found that in Bornholm Basin, the mean temperature in the halocline increased during the period 1989–2004 by about
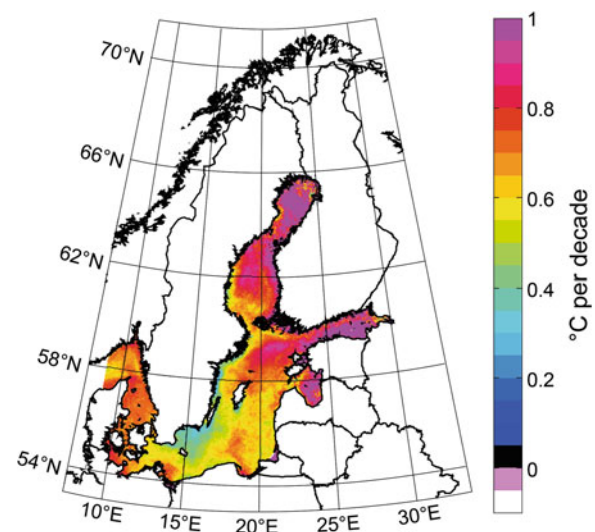

Fig. 7.2 Linear trend in annual mean sea surface temperature based on infrared satellite data (1990–2008) provided by the Federal Maritime and Hydrographic Agency (BSH), Hamburg (Lehmann et al. 2011)

1 °C compared to the longer period 1950–2004. They argued that this halocline temperature increase was caused by more frequent warm summer inflows since the 1990s.

An increase was also found in the annual minimum temperature of the intermediate layer, lying between the seasonal thermocline and the halocline. In the Bornholm Basin, Mohrholz et al. (2006) found a positive correlation with the NAO winter index for the period 1952–2004 ($R^2 = 0.61$, January and February). In light of the decadal change in the NAO index since the 1990s, when intensified cyclonic circulation and stronger westerly winds became evident in the Baltic Sea region relative to the 1970s and 1980s (see Chap. 4, Box 4.1), the intermediate layer temperature variations were interpreted as a 'regime shift' increase of about 1 °C (Mohrholz et al. 2006; Hinrichsen et al. 2007). In the Gulf of Finland, Liblik and Lips (2011) found a positive correlation ($R^2 = 0.81$) between the intermediate layer temperature and the winter BSI for the period 1987–2008.

It is an intriguing task to reconstruct past changes in climate elements and compare them with ongoing change. Based on a climate reconstruction since 1500 (Luterbacher et al. 2004), Hansson and Omstedt (2008) reconstructed the Baltic Sea water temperature and ice conditions for the period 1500–2001 using the PROBE-Baltic model. For the period since 1893, they used more detailed forcing data from the NORDKLIM database (see Hansson and Omstedt 2008 for details). Annual mean water temperature anomalies (Fig. 7.3), averaged over the whole sea domain (both by area and depth), reveal cold anomalies of about −0.7 °C in the decadal moving average during the 1690s and 1780s, and warm anomalies of up to 0.5 °C in the 1730s, 1930s and 1990s. The seawater warming during the present period is comparable in magnitude to that of the 1930s and the first half of the eighteenth century. The results of the modelling study suggest that the current warming within the Baltic Sea lies within the range experienced during the past 500 years.
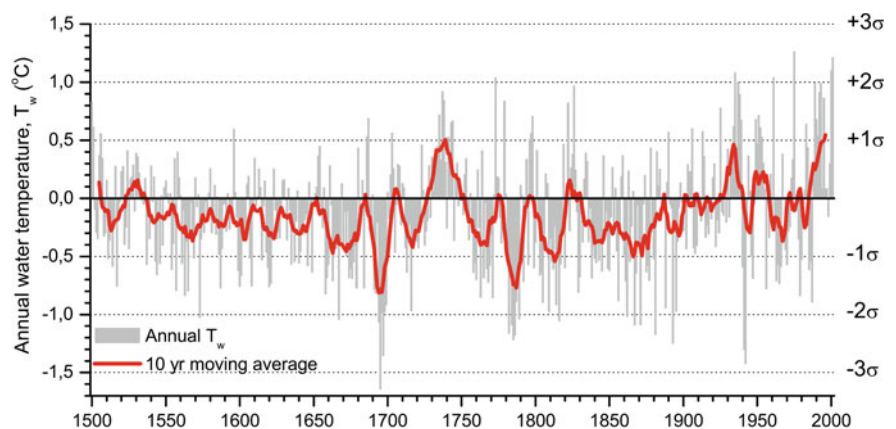
Nevertheless, the twentieth century is clearly the warmest, with the exception of the warm anomaly around the 1730s.

7.3 Changes in Salinity, Stratification and Water Exchange

While the thermal response of the Baltic Sea to the change in air temperature is similar to that of a large lake, freshwater discharge from land and restricted water exchange with the North Sea create strong salinity stratification, accompanied by along-basin gradients such as are seen in estuaries and fjords. The overall salt content of the Baltic Sea depends to a large extent on net precipitation and river discharge; with higher salinity during dry periods and lower salinity during wet periods. The salinity level is also governed by variability in the water exchange between the North Sea and Baltic Sea (Winsor et al. 2001, 2003; Meier and Kauker 2003; Gustafsson and Omstedt 2009). Termed Major Baltic Inflows (MBIs, Matthäus and Frank 1992) these events occur sporadically and bring in large volumes of highly saline water causing a sudden increase in bottom salinity.

The Gotland Deep (the deepest part of the eastern Gotland Basin, Fig. 7.1) is a representative location for describing salinity and stratification development within the Baltic Sea as a whole. Indeed, changes in mean salinity, calculated from Gotland Deep data only, are only 2 % different to changes calculated based on data from all sub-basins (Winsor et al. 2001). Observations (Fig. 7.4) reveal a low-salinity period above the halocline starting in the 1980s. Fresher periods also occurred in the 1900s and 1930s and to a less extent in the 1960s.

Salinity and stratification of the deep layers are highly affected by the occurrence of MBIs of North Sea water. These occur when high pressure over the Baltic Sea region with easterly winds is followed by several weeks of strong

Fig. 7.3 Anomalies of the annual and decadal moving average of the modelled Baltic Sea spatial mean water temperature over the period 1500–2001. The *dotted horizontal lines* are the standard deviations of water temperature during the reference period 1900–1999 (Hansson and Omstedt 2008)

Fig. 7.4 Observed salinity in the Gotland Deep around 57°19.20′ N, 20°03.00′E as a function of depth and time. Data from the ICES Marine Data Centre (www. ices.dk)
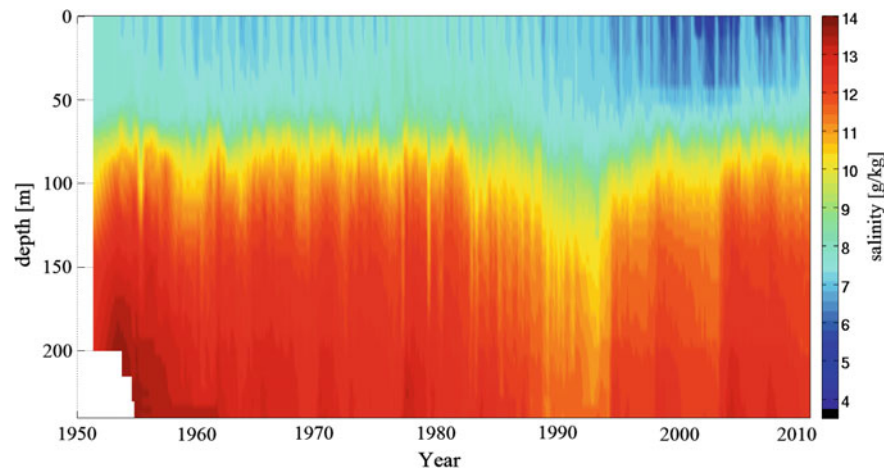
westerly winds (e.g. Lehmann et al. 2002; Matthäus et al. 2008; Leppäranta and Myrberg. 2009). During the history of observations since the 1900s, the strongest inflow took place in November–December 1951 (e.g. Madsen and Højerslev 2009; see the high bottom salinities in Fig. 7.4). During the peak inflow, the difference in sea level between Gedser and Hornbaek (i.e. between the northern and southern ends of the Danish straits) was up to 1.5 m and the normal saline stratification in the Kattegat and the strait area broke down for several weeks. A MBI of comparable magnitude occurred in December 2014. On average, new high-saline water reaches the deep layers of the Gotland Basin with a delay of up to a year (e.g. Kõuts and Omstedt 1993; Matthäus et al. 2008), as can be seen also in Fig. 7.4. The inflow during winter 1976/1977 was followed by an exceptionally long stagnation period, when the strength of the saline stratification (bottom to surface salinity difference) decreased by about one and a half times, before the next inflow in 1993. In some areas, such as the Gulf of Finland, the halocline effectively disappeared. An extensive stagnation period also occurred in the 1920s and 1930s, after the very strong inflow in winter 1921/1922, coinciding with the shift from a wet period to a dry period over the Baltic Sea basin. Based on water age calculation, Meier (2005) identified a stagnation period of more than eight years also in the 1950s/1960s.

Since 1994, when stratification strength returned to the near-normal levels of the 1960s and 1970s, stagnation in terms of oxygen deficiency of the near-bottom waters continued (Conley et al. 2009, see also Chap. 18). In addition to smaller inflows, a series of larger inflows has also occurred since then. In contrast to the usual barotropic inflows (vertically uniform transport over the entrance sills) that occur in winter and spring and advect relatively cold water with high oxygen content into the Baltic Sea, the recent large inflows

in the summers of 1997, 2002, 2003 (Feistel et al. 2006) and 2006 were of a two-layer (baroclinic) type that transported high-saline, but warm and low-oxygen water to the deep layers of the Baltic Sea. Thus, warm water inflows, whether baroclinic or barotropic, transport less oxygen to the Baltic Sea than cold water inflows, and higher temperatures increase the rate of oxygen consumption (through organic matter mineralisation) in the deep water and increase production of hydrogen sulphide (Matthäus 2006). Inflow activity is very clear in the daily temperature records for the deep layers in the Gotland Deep (Fig. 7.5). The low temperatures apparent during 2003 reflect the normal barotropic inflow in winter 2002/2003, described in many papers (e.g. Matthäus et al. 2008; Leppäranta and Myrberg 2009). Changing stratification strength also has a feedback to mixing processes. For example, Osiński et al. (2010) found that the major inflow in winter 2002/2003 increased the value of the first baroclinic Rossby radius of deformation (which determines the size of mesoscale eddies) in the southern Baltic Sea from about 4 km (in the pre-inflow period) to more than 9 km.

At the sub-regional scale, many aspects of the change in salinity and stratification are important in the context of ecological status and environmental and climatic impacts. When saline waters enter the Baltic Sea, the halocline is lifted up and this signal is dynamically transferred to the downstream basins (Meier 2007). Upstream from the Gotland Deep, in the south-western Baltic Sea, the variations in deep-water properties are generally of higher amplitude; downstream along pathways of deep-water advection they are damped due to a wide range of mixing processes (e.g. Reissmann et al. 2009). In the Bornholm Basin, deep temperature observations reveal waters of warm and cold inflows (Mohrholz et al. 2006) that can be later traced in the
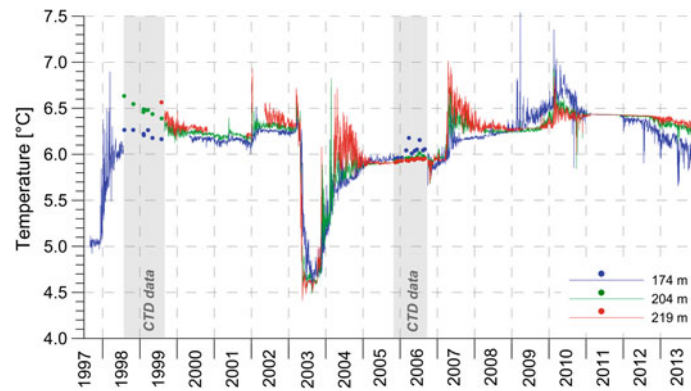
Fig. 7.5 Temperature time series from August 1997 to October 2013 recorded at the eastern Gotland Basin mooring (57°23′N, 20°20′E) near Gotland Deep at 174, 204 and 219 m depth. This 'Hagen curve' is redrawn from Feistel et al. (2008) by the authors using recent data

Gotland Deep. Bottom-salinity anomalies in the Bornholm Basin during 1961–2000 (Neumann and Schernewski 2008) range from −1.8 g kg⁻¹ (1982) to 2.0 g kg⁻¹ (1994), with no significant trend although a recent slight salinity increase could be seen. In the Lithuanian part of the Baltic Proper deep-water area, Dailidiené and Davuliene (2008) reported a strengthening of stratification for the period 1984–2005: decreased surface salinity and increased deep-water salinity.

In the Gulf of Finland, a sub-region with a free connection to the Baltic Proper and the highest freshwater discharge per unit sea volume, changes in salinity and stratification generally follow those of the Baltic Proper, but are not fully synchronous (e.g. Zorita and Laine 2000). On the basis of monitoring data for the period 1965–2000, Laine et al. (2007) found a continuous decrease in salinity and density stratification until the early 1990s, after which there was a slight increase. Based on independent data for 1987–2008, Liblik and Lips (2011) found that the deep salinities in summer increased after the 1993 major inflow by about 2 g kg⁻¹. Despite the increased mean stratification strength and more frequent occurrence of hypoxia events (see Chap. 18), at the annual scale ventilation of deep waters is still effective and the annual mean oxygen concentrations remain higher than during the 1960s and 1970s (Laine et al. 2007). This can be explained by decreased sea-ice cover (see Chap. 8), which favours wind mixing (Vermaat and Bouwer 2009) and by stronger south-westerly winds in winter that cause stratification collapse events, due to wind straining effects on estuarine gradients (Elken et al. 2014).

Reconstructing annual mean salinities since 1500 (Hansson and Gustafsson 2011) indicates that salinity has slowly increased by 0.5 g kg⁻¹ since 1500, peaking in the mid-eighteenth century. Present salinity values are nearly as high as reconstructed for the earlier maximum salinity period. Historically, there have been several fresher periods when the mean salinity of the Baltic Sea decreased from a maximum of about 7.8 g kg⁻¹ to about 6.5 g kg⁻¹. Hansson and Gustafsson (2011) also found a negative correlation between oxygen content 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.

7.4 Circulation and Transport Patterns and Processes

There are four mechanisms for inducing currents in the Baltic Sea: wind stress at the sea surface, a surface pressure gradient, a thermohaline horizontal density gradient and tidal forces. The currents are also steered by Coriolis-acceleration, topography and friction. Voluminous river inlets can produce local changes in sea-level height and thus also in currents. Due to the small size of the Baltic Sea basins, friction caused by the bottom and shores damp the currents considerably. The general circulation is typical of a stratified system with a positive freshwater balance. Inflowing waters settle in the receiving basin at the depth where the ambient water is of equal density; fresher water moves to the upper layer and saltier and denser water masses move to lower layers.

Over short timescales (1–10 days), the currents are mostly caused by wind stress and gradients in sea level, the latter particularly in straits. Due to the large variability in the winds over the Baltic Sea basin, the long-term wind-driven mean circulation is weak: transient currents are an order of magnitude greater than average currents. In coastal areas, drift currents generate upwelling and downwelling features that are affected by Kelvin-type waves. The Baltic Sea is laterally mixed by mesoscale eddies and deep-water circulation (e.g. Elken and Matthäus 2008). At the timescale of an hour to a day, there are several periodic dynamical processes in operation. The most important are inertial oscillations (13.2–14.5 h) and seiches (less than 40 h). For details, see Leppäranta and Myrberg (2009).

Thus, the long-term mean surface circulation observed in the Baltic Sea is principally due to the nonlinear combination of the wind-independent baroclinic mean circulation and the mean wind-driven circulation. Which of the two is more important is difficult to say in the case of a nonlinear system. The answer will depend on the particular location and on the timescale under study.

7.4.1   Surface Circulation and Related Processes—Recent Findings

Mean circulation within the Baltic Sea as a whole was recently modelled by Meier (2007). The results (Fig. 7.6) agree with the main characteristics of the early findings by Palmén (1930) and the outcome of earlier numerical modelling (Lehmann and Hinrichsen 2000; Lehmann et al. 2002) but also provide new fine-scale details. Mean transport above and below the halocline is in agreement with observational results and implies the existence of strong high-persistency cyclonic gyres both within the Baltic Proper and in the Bothnian Sea. In the eastern Gotland Basin, the model results reveal high transport around the Gotland Deep, especially below the halocline, reproducing the observed deep rim current (Hagen and Feistel 2007). Furthermore, modelling reveals that the strength and persistency of currents are lower in the Gulf of Riga, Gulf of Finland and Bothnian Bay in comparison with the Baltic Proper. This might be due to the impact of sea ice during winter. Close to the Swedish coast an intense southward-directed flow becomes visible, being a part of the cyclonic gyre of the Baltic Proper. This flow is directed into Bornholm Basin and the Arkona Basin. The main flow crosses the central Arkona Basin and bifurcates north of 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. A flow also follows the Swedish coast into the Öresund and Kattegat. In the lower layer, the flow follows 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 south-western slope of the Gdańsk Basin. In the Gotland Deep, the flow is characterised by cyclonic gyres. The water masses to the north also have a cyclonic gyre which finally leads part of the water to flow into the western Gotland Basin.

The mean circulation is likely to vary over the long term, with changes induced by wind forcing, heat fluxes and ice extent, as well as freshwater balance and inflow activity. On the basis of hindcast modelling for the period 1958–2001, Jedrasik et al. (2008) showed that annual average surface
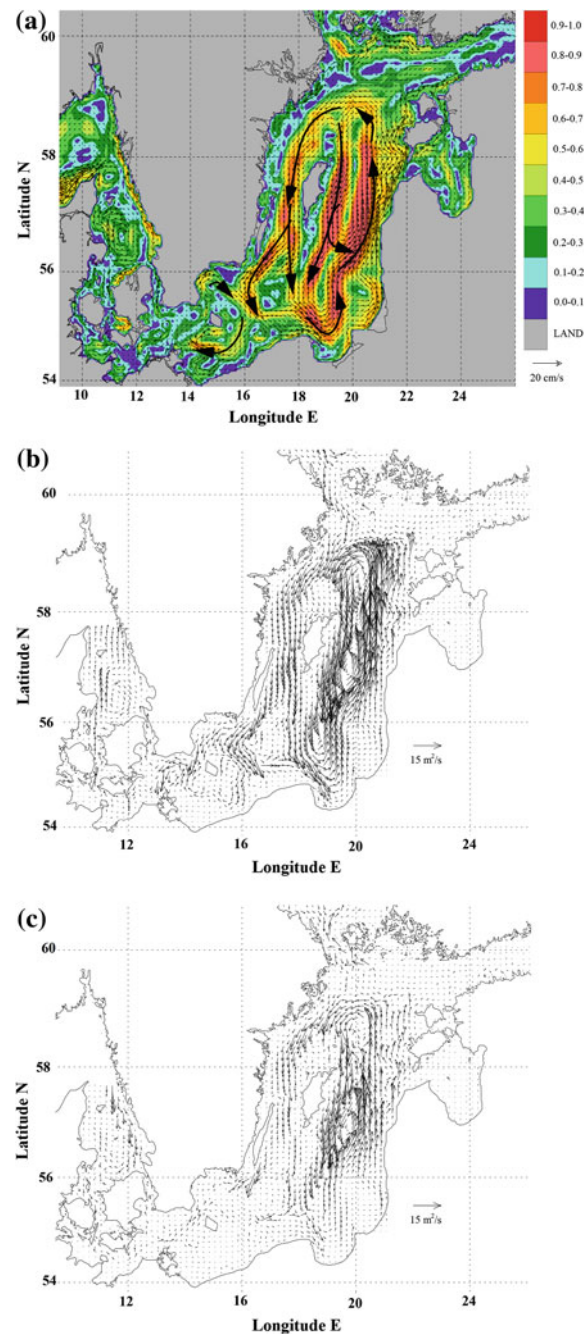

Fig. 7.6 Baltic Sea circulation in the Gotland Basin and adjacent sea areas from modelling results. Average barotropic currents (**a**) for 1992–1995 with the flow stability contours (redrawn from Lehmann and Hinrichsen 2000), and average transport per unit length for 1981–2004 above (**b**) and below (**c**) the halocline (redrawn from Meier 2007)

velocities (mean over the whole sea area, annual values of 16.5–19 cm s^{-1}) increased by 0.21 cm s^{-1} per decade. Over shorter periods (months), there is evidence from other researchers that water mass movements may take alternative paths. For instance, after the MBI in January 2003, saline water passing the Stolpe Channel flowed directly

north-eastward along the eastern slope of the Hoburg Channel (the passage from the Stolpe Channel towards the eastern Gotland Basin) but after the baroclinic summer inflow in August/September 2002 the deep-water flow took the loop along the south-western slope of the Gdansk Basin (e.g. Meier 2007). Another example is from the Gulf of Finland, where less saline waters originating from the large rivers lying in the eastern part of the gulf usually spread along the northern coast. These less saline waters can occasionally detach from the coast and move for several months near the central axis of the gulf (Lips et al. 2011), as observed recently.

Finer-scale circulation in the Gulf of Finland was modelled by Andrejev et al. (2004a, b). Although the typical cyclonic mean circulation in the Gulf of Finland is apparent, the patterns and persistency of the currents according to Andrejev et al. (2004a) differ 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 many loops with a typical size that clearly exceeds the internal Rossby radius. The modelled circulation patterns reveal some non-trivial and temporally and spatially varying vertical structures.

Recent circulation studies in the Gulf of Finland have identified some new features of the system. Elken et al. (2011) carried out an EOF (Empirical Orthogonal Functions) analysis of hourly forecasts from the Baltic Sea operational High Resolution Operational Model for the Baltic, a version by the Swedish Meteorological and Hydrological Institute (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 (change in water volume) of the gulf. A two-layer flow pattern (surface Ekman transport with deeper compensation flow, 19–22 %) reveals both inertial and lower frequencies. The 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 there. On the sea surface, quasi-uniform drift currents are deflected on average by 40° to the right of the wind direction (based on the best correlation between wind and rotated current deviations from their mean values; the model does not take into account wave effects on surface currents) 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 variation 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 into the main axis (24–40 %) and transverse (13–16 %) components that are correlated with the sea-level gradients according to geostrophic relations.

New detailed observational information for the Gulf of Finland was obtained by Lilover et al. (2011). They performed current velocity observations on Naissaar Bank in northern Tallinn Bay for 5 weeks in late autumn 2008 using a bottom-mounted ADCP (Acoustic Doppler Current Profiler) 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 study 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 towards 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 was much higher (up to 0.90) within the shorter steady wind periods. The current was rotated $\sim$35° to the right of the wind. As an exception, during one period an anticlockwise 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.

Soomere et al. (2011a) studied modelled circulation patterns and Lagrangian transport in the uppermost layer of the Gulf of Finland. Using the RCO (Rossby Centre Ocean) model data for 1987–1991, they revealed several normally concealed features of surface circulation. For certain years, a slow anticyclonic gyre may exist in the surface layer in the wide eastern and central part of the Gulf of Finland, reflecting a relatively weak coupling of the mostly Ekman-drift-driven surface-layer dynamics with that in the deeper layers. Semi-persistent (timescales of about a week, Viikmäe et al. 2010) patterns of rapid Lagrangian surface transport mostly follow the usual 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 those areas of the Gulf of Finland from which the drift of passive tracers to the coast is unlikely (Soomere et al. 2011b). Transport is generally anisotropic and tracers in the surface layer generally have a greater chance of reaching the southern coast (Soomere et al. 2010), whereas in the eastern, wide part of the gulf, there is an extensive area of closed circulation from which transport to either of the coasts in unlikely (Soomere et al. 2011c). The results, however, are highly sensitive to the resolution of the underlying ocean model: the statistics of transport change substantially when the grid step is reduced from 2 miles to 1

mile; with a 1-mile grid step, all the significant eddies are resolved and a further decrease in grid step has little effect on results (Andrejev et al. 2011).

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. Persistency of currents ranges from 20 to 60 % and is greatest close to coasts, as observed many years ago by Witting (1912) and Palmén (1930). The simulation was performed using a barotropic model (Myrberg and Andrejev 2006), with a relatively high horizontal resolution (3.4 × 3.4 km), supporting the idea that the main features of the circulation can be reproduced with a barotropic, wind-driven model. However, the mean current velocities simulated by the model were clearly greater than those observed by Witting (1912) and Palmén (1930). The difference is apparently due to the insufficient resolution of the early measurements; these did not resolve mesoscale features, such as the pronounced differences in speed and direction of the coastal and open sea currents. In particular in the Bothnian Bay, the persistency pattern of the mean circulation was close to the results of Lehmann and Hinrichsen (2000), who presented depth-mean currents from the baroclinic model for a different period.

7.4.2 Dynamics in the Bottom Layer

Interaction between the upper and lower water layers is limited 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 high-saline water at the mouth of the Baltic Sea. Convection and mechanical mixing, entrainment and vertical advection of water masses lead to interaction between the upper and lower water layers in other parts of the Baltic Sea.

Water effectively recirculates within the Baltic Sea even with the low-permeable halocline. This overturning circulation was termed the Baltic Sea 'haline conveyor belt' by Döös et al. (2004) as an analogy to the deep-water conveyor belt of the World Ocean. This vertical overturning circulation involves many important components: 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, and 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) investigated the large halocline variation and related mesoscale and basin-scale processes in the northern Gotland Basin—Gulf of Finland system. The authors suggested that long-lasting pulses of south-westerly winds cause an increase in the water volume of the Gulf of Finland. The resulting increase in 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 to 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 of more than 20 cm s^{-1}. So, Elken et al. (2006) concluded that the near-bottom layers of the Gulf of Finland 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 makes modelling the deep-water inflow extremely difficult. The internal wave activity is high, the production of strong eddies and topographically controlled local currents are frequent, and thus the diapycnal mixing is intense.

7.4.3 Mixing

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

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

$$\kappa = \min(\alpha/N, \kappa_{\max})$$

where α and $\kappa_{\max}$ are constants and N is the Brunt-Väisälä frequency. In the horizontally integrated model for the Baltic Proper, Stigebrandt (1987) tuned α to equal 2×10^{-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, that $\alpha = 1.5 \times 10^{-7}$ m^2 s^{-2} and that there is also seasonal variability. For $N = 10^{-2}$ s^{-1} (typical for the halocline), the values of α/N are about 1.5×10^{-5} m^2 s^{-1}, while the normal level in the 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 issue is to find the sources and paths for the 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.

In the DIAMIX (DIApycnal MIXing) project (Stigebrandt et al. 2002), Lass et al. (2003) measured dissipation rates and stratification between 10 and 120 m depths during a nine-day experiment in the eastern Gotland Basin. Their 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 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 (α) of Stigebrandt (1987) was estimated to be 0.87×10^{-7} m^2 s^{-2}, several times less than earlier estimates based on the bulk methods.

A recent review paper by Reissmann et al. (2009) summarised the different mechanisms through which mixing takes place within the Baltic Sea. One involves the episodic overflow of high-saline water over the sills into the Baltic Sea, leading to entrainment and interleaving of the incoming water masses to the level of neutral buoyancy (e.g. Lass and Mohrholtz 2003). It is this mechanism that ventilates the Baltic deep waters (e.g. Meier et al. 2006). Owing to volume conservation, these episodic deep-water inflows drive vertical advection in the central Baltic Sea. Mixing due to inertial waves and the breaking of internal waves (Van der Lee and Umlauf 2011) also enhances vertical turbulent transport, as do Baltic Sea eddies (e.g. Lass et al. 2003) and coastal upwelling (Lehmann and Myrberg 2008). Winter convection and wind-induced mixing are also important mixing processes, but these only affect the layer above the halocline (e.g. Leppäranta and Myrberg 2009). Surface waves cause 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 metres in the surface layer and it is often considered through the wind-speed-dependent (not the wave-dependent) friction velocity. Kantha and Clayson (2004) showed that the Stokes production of turbulent kinetic energy in the surface mixed layer is of the same order of magnitude as the shear production and must therefore be included in mixed layer models (see also the Baltic Sea case study by Kantha et al. 2010). The Stokes drift together with mean shear generates Langmuir cells. Taking Langmuir circulation into account in the vertical turbulence schemes affects the deepening of the mixed layer (e.g. Ming and Garrett 1997; 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 (e.g. Soomere and Räämet 2011; Tuomi et al. 2011). Summer is typically the season with the smallest mean and maximum significant wave height and winter the highest (excluding the seasonally ice-covered areas, see Chap. 9, Sect. 9.5). The importance of including the parameterisation of internal waves and Langmuir circulation in vertical turbulence schemes in multi-year simulations for the Baltic Sea was shown by Axell (2002).

7.5 Sensitivity to Changes in Forcing

Owing to the transient 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 run-off, have reached a state of accuracy such that the highly fluctuating current field and associated evolution of the temperature and salinity fields 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, see Chap. 4, Box 4.1). Weakened westerlies across northern Europe, which is characteristic of the negative phase of the NAO, are a precondition for outflow from the Baltic Sea. Thus, negative phases of the NAO have the potential to indirectly affect circulation in the Baltic Sea and water mass exchange with the North Sea (Lehmann et al. 2002). The linear correlation 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, December through March). A better relation of the wind field over the Baltic Sea to the large-scale atmospheric circulation is given by the (BSI), which is significantly related to the NAO. Furthermore, the BSI is highly correlated with the variation in water storage in the Baltic Sea and 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' regimes account for another 27 and 23 %, respectively (Hurrell and Deser 2009; Lehmann et al. 2011). The local BSI includes all four regimes and thus better describes sea-level pressure variability over the Baltic Sea rather than the NAO alone.

Changes in the general wind conditions over the Baltic Sea lead to changes in upwelling. In a statistical study of 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 thermally stratified period of the year. The most frequent upwelling occurred along the Swedish east coast (up to 40 % of the time) and the Finnish coast of the Gulf of Finland (15–20 %).

Generally, there was a positive trend in upwelling frequency 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 coasts (Fig. 7.7). This is in line with the warming trend of annual mean SST derived from infrared satellite images (1990–2008) presented by Lehmann et al. (2011). The smallest trends occurred along the east coast of Sweden 0.3–0.5 °C per decade compared to 0.5–0.9 °C per decade in the central part of the Baltic Proper. The authors suggested 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 favourable wind conditions derived from wind station data for May to September over the period 1990–2009 supports this (Lehmann et al. 2012). 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 of north-easterly and easterly winds along the east coast of the Baltic Proper, 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 partial reverse of the trends occurs (see also Chap. 4, Sect. 4.3).

In a three-dimensional modelling study, Meier (2005) investigated the sensitivities of modelled salinity and water age on freshwater supply, wind-speed and sea-level amplitude in the Kattegat. Under steady-state conditions, the average salinity of the Baltic Sea is most sensitive to perturbations of freshwater inflow. Increased freshwater inflow and wind speed both resulted in decreased salinity, whereas increased amplitude of the Kattegat sea level resulted in increased salinity. The average water age was most sensitive to perturbations of the wind speed. In particular, decreased wind speed causes a significant increase in the age of the deep water. Long-term changes in freshwater and saltwater inflows and of low-frequency wind anomalies cause the Baltic Sea to adapt to a new steady state with a new salinity; stability and ventilation remain largely unchanged. Thus, for a change in state, the timescale of perturbations needs to be long compared to the turnover time of the freshwater content. By contrast, long-term changes in the high-frequency wind characteristics affect deep-water 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 summarised as follows. The averaged salinity of the Baltic Sea is nonlinearly dependent on and strongly sensitive to changes in freshwater inflow. The annual maximum ice extent is strongly sensitive to changes in the mean winter (DJF) air temperature over the Baltic Sea: at a mean air temperature of −6 °C the sea will become completely ice covered, whereas at 2 °C ice cover will not appear. In the Baltic Sea climate system at least two important timescales need to be considered: the first is associated with the water balance (salinity) and the e-folding time (i.e. the time interval for a change by the factor e) is approximately 33 years, while the other is associated with the heat balance and is approximately one year. Change in Baltic Sea annual mean water

Fig. 7.7 Upwelling frequencies for May–September during the period 1990–2009 based on the automatic detection method for upwelling based on 443 sea-surface temperature maps (**a**) and the trend in upwelling frequencies (**b**), adopted from Lehmann et al. (2012)
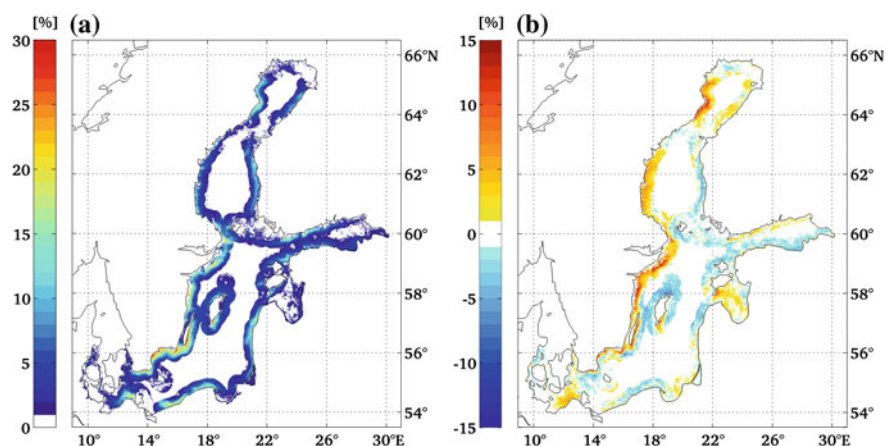
temperature is closely related to the change in air temperature above the sea. However, in climate warming experiments, the water and air temperatures may differ due to changes in the surface heat balance components.

A study of climate change effects on the Baltic Sea ecosystem was presented by Neumann (2010). Two regional datasets for greenhouse gas emission scenarios (A1B and B1) for the period 1960–2100 were used to force transient simulations with a three-dimensional ecosystem model of the Baltic Sea. The outcome was a projected warming of the Baltic Sea of 1–4 °C, 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 a comparison of both studies using the same scenarios, it is clear that the magnitude of the warming is similar, thus demonstrating that warming is a robust feature. At the same time, the decrease in salinity differed, indicating far greater uncertainty with salinity-change simulations, albeit with a tendency towards reduced salinity. In addition, the season favouring cyanobacteria blooms is prolonged due to the change in temperature and mixing, 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) examined changes in future stratification in the upper water column using a three-dimensional ocean circulation model. They found a switch between processes controlling the seasonal cycle of stratification in the Baltic Sea at the end of twenty-first century. The air temperature increase was solely responsible for increased stratification at the bottom of the surface mixed layer. As in the present-day climate, winter temperatures in the Baltic Sea are often below the temperature of maximum seawater density at a given salinity, which means early warming causes thermal convection. Re-stratification at the beginning of spring is then triggered by the spread of freshwater. This process is believed to be important for the onset of the phytoplankton spring bloom. In a future climate, temperatures in the surface layers are likely to be higher than the temperature of maximum density for large parts of the year and thermally induced stratification would then start without prior thermal convection. Thus, freshwater-controlled re-stratification during spring would become considerably less important, and so this change in stratification might have an important impact on vertical nutrient fluxes and the intensity of the phytoplankton spring bloom in future. On the other hand, the freshening of waters will increase the temperature of maximum density and this would oppose the effect of increasing surface temperature. Changes in processes controlling the seasonal cycle of stratification were also investigated by Demchenko et al. (2011). The authors found differences in the formation and evolution of seasonal structural thermal fronts after winters of different severity. Structural fronts are related to the temperature of maximum water density. In spring, the front advances northwards at a rate of about 11–16 km d^{-1} traversing the breadth of the Baltic Sea within 8–10 weeks. After severe winters, the horizontal temperature gradient is more pronounced and the rate at which the Baltic Sea is traversed decreases. For a full overview of the potential impacts of these processes on biogeochemistry and ecosystems, see Chaps. 18 and 19, respectively.

7.6   Conclusion

A recent warming trend in sea-surface waters has been clearly demonstrated by in situ measurements, remote sensing data and modelling results. In particular, remote sensing data for the period 1990–2008 indicate that the annual mean SST has increased by up to 1 °C per decade, with the greatest increase in the northern Bothnian Bay and large increases in the Gulf of Finland, the Gulf of Riga and the northern Baltic Proper. Although the increase in the northern areas is affected by the recent decline in the extent and duration of sea ice, warming is still evident during all seasons and with the greatest increase occurring in summer. The least warming of surface waters (0.3–0.5 °C per decade) occurred north-east of Bornholm Island up to and along the Swedish coast, probably owing to an increase in the frequency of coastal upwelling. The latter is explained by the change in atmospheric circulation. Comparing observations with the results of centennial-scale modelling, recent changes in seawater temperature, appear to be within the range of the variability observed during the past 500 years.

The salinity and stratification of the deep waters, governed by interacting circulation, transport and mixing processes, are strongly linked to the Major Baltic Inflows of North Sea water that occur sporadically and bring high-saline water into the deep layers of the Baltic Sea. These major inflows are often followed by a period of stagnation during which saline stratification decreases and oxygen deficiency develops in the bottom waters. Major inflows normally occur during winter and spring; they bring relatively cold and oxygen-rich waters to the deep basins. Since 1996, several large inflows have occurred during summer. These baroclinic inflows have transported high-saline, but warm and low-oxygen water into the deep layers of the Baltic Sea.

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