BALTIC SEA CIRCULATION

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Introduction

The Baltic Sea consists of a number of sub-basins connected by straits and deep channels. They have an important influence on the current system. A map of the Baltic Sea with topographic subdivision and bottom topography is shown in **Figure 1**.

The North Sea, via Skagerrak and Kattegat, is connected to the Baltic Proper by three pathways, called the Danish Straits (**Figure 2**). The eastern route, the Sound, is only 2 km wide at its narrowest location, shallow (sill depth 8 m) and only about 55 km long. It is the shortest inflow route for saline water. The central pathway is about 180 km long and about 13 m deep on the average, 25–30 m along the axis. It consists of the Great Belt and the Fehmarnbelt and is terminated at the east by the Darss sill (18 m deep), the shallowest sill for the main inflow. The third connection is the Little Belt, having a cross section of only 16 000 m^2 compared to 255 000 m^2 of the Great Belt and 80 000 m^2 of the Sound. Therefore, about 70% of the in- and outflows occur through the Great Belt; the Little Belt is negligible.

Moving from west to east, the Arkona Basin (45 m) is connected to the Bornholm Basin (95 m) by the Bornholm Channel. The Stolpe Channel (20 km wide by the 60 m isobath) allows inflow into the Gdansk Basin (110 m) and the Eastern Gotland Basin with a maximum depth of 250 m. Further to the north the Farö Deep is followed by the Northern Basin (200 m) which extends to the east towards the Gulf of Finland as a deep channel with decreasing width and depth. By contrast, the Gulf of Bothnia is separated from the deeper layers of the Baltic Proper by the Aland Sea with its numerous islands. The Gulf of Bothnia consists of two basins, the Bothnian Sea and the Bothnian Bay.

The deep basins and the connecting channels are important for the water exchange between the North Sea and the Baltic Sea and determine the current structure. Due to the large river runoff, the Baltic Sea is the largest brackish water body of the world with a volume of 21 000 km^3. The mean annual total contribution of all rivers for the period 1950–1990 was 446 $km^3\,year^{-1}$. This would correspond to a sea-level rise of 1.18 $m\,year^{-1}$ if the Baltic Sea were not connected to the North Sea. An additional surplus of fresh water results from the difference of precipitation minus evaporation, which amounts to about 60 $km^3\,year^{-1}$.

The river runoff shows both a seasonal cycle and interannual variations. The lowest and highest annual values differ from the mean value by −27% and +22%, respectively. The seasonal runoff varies between 25 000 $m^3\,s^{-1}$ in spring and 12 000 $m^3\,s^{-1}$ in winter.

As a consequence of this freshwater supply the salinity in the eastern and northern parts of the Baltic Sea is reduced to about 4 PSU (practical salinity units), increasing to about 8 PSU in the central and western Baltic Sea. Due to the associated density difference saline water penetrates from the Kattegat (30–34 PSU) through the Danish Straits and the channels into the Baltic Sea and yields a strong halocline, which separates the water of the deeper layers from the brackish upper water masses (**Figure 3**). As a consequence vertical mixing is strongly reduced.

The Baltic Sea extends from about 54°N to 66°N thus ranging from mild and humid to a subarctic climate. Frequent and complex synoptic-scale cyclonic activity and subsynoptic-scale depressions are characteristic, leading to a high variability of the prevailing westerly winds. The wind fields produce a highly variable current system, especially in the upper layers, superimposed on the weak baroclinic flow field induced by the salinity differences. Beneath the wind-mixed layer bottom topography has a strong steering influence. The wind-induced currents and the associated sea-level variations may drastically change, when parts of the Baltic Sea are ice-covered. Sea ice occurs every year in the Baltic Sea. Under normal winter conditions about 45% of the Baltic Sea is covered with ice and the ice season lasts about 6 months in the northern parts. Severe winters may lead to almost total ice coverage. Ice first appears in the innermost parts of the Bothnian Bay during mid-November. In a normal winter, the entire Bothnian Sea, Aland Sea, Gulf of Finland and the northernmost part of the Baltic Proper are covered by ice. In severe ice-winters the Kattegat, the Belt Sea, the Sound and large parts of the Baltic Proper are also ice covered.

Wind and thermohaline forcing determine the currents of the Baltic Sea, strongly influenced by bottom topography and ice coverage. A large

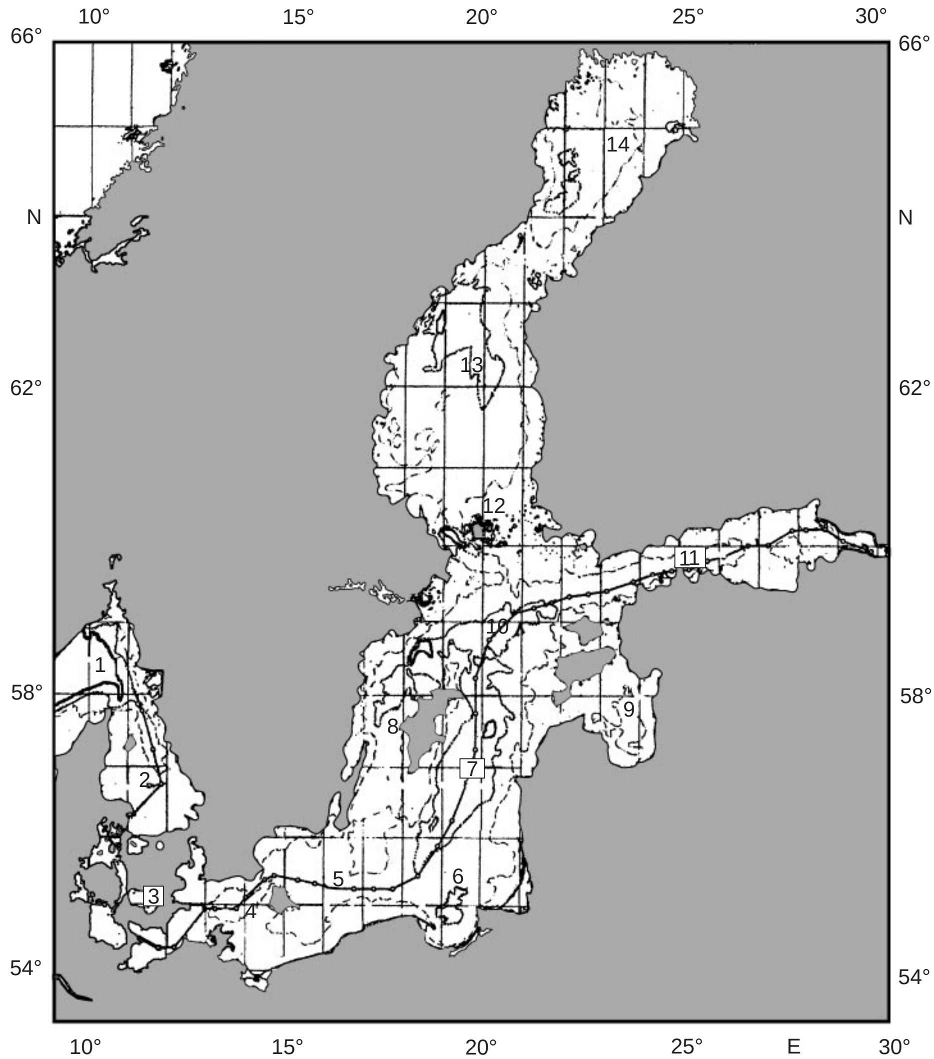

Figure 1 Skagerrak (1), Kattegat (2) and the subareas of the Baltic Sea: Beltsea (3), Arkona Basin (4), Bornholm Basin (5), Gdansk Basin (6), Eastern (7) and Western Gotland Basin (8), Gulf of Riga (9), Northern Basin (10), Gulf of Finland (11), Aland Sea (12), Bothnian Sea (13) and Bay of Bothnia (14). Depth contours: thin broken line 40 m, heavy dotted line 100 m, heavy full line 200 m. The location of the section of **Figure 3** is also shown (full line with open dots).

number of current measurements has been made in the past decades. However, due to the high variability of the wind-induced currents and the extensive fishing activities, which make it impossible to install observational systems in some areas, it was not possible in the past to derive a consistent circulation pattern from observations. In recent years, three-dimensional models, combined with data assimilation, have improved in such a way that both the mean circulation and its variability can now be described with sufficient accuracy.

The Estuarine Circulation

In a stratified sea it is generally not possible to separate wind-induced currents properly from thermohaline ones. Along the coasts and the bottom slopes wind produces up- and downwelling and thus inclinations of the density surfaces which may largely amplify the wind effects. However, some insight is gained by considering the horizontal pressure gradients, which result from the mean surface inclination and the horizontal density differences. They produce an estuarine type of circulation.

Figure 3 shows the mean salinity section from the Kattegat along the main axis of the Baltic Sea into the Gulf of Finland. Except at the level of the summer thermocline (about 25–30 m depth) the density distribution is similar. Near the bottom the density decreases from about $25\,kg\,m^{-3}$ in the Kattegat to $9\,kg\,m^{-3}$ in the Gotland Basin and less than $4\,kg\,m^{-3}$ in the interior of the Gulf of Finland.

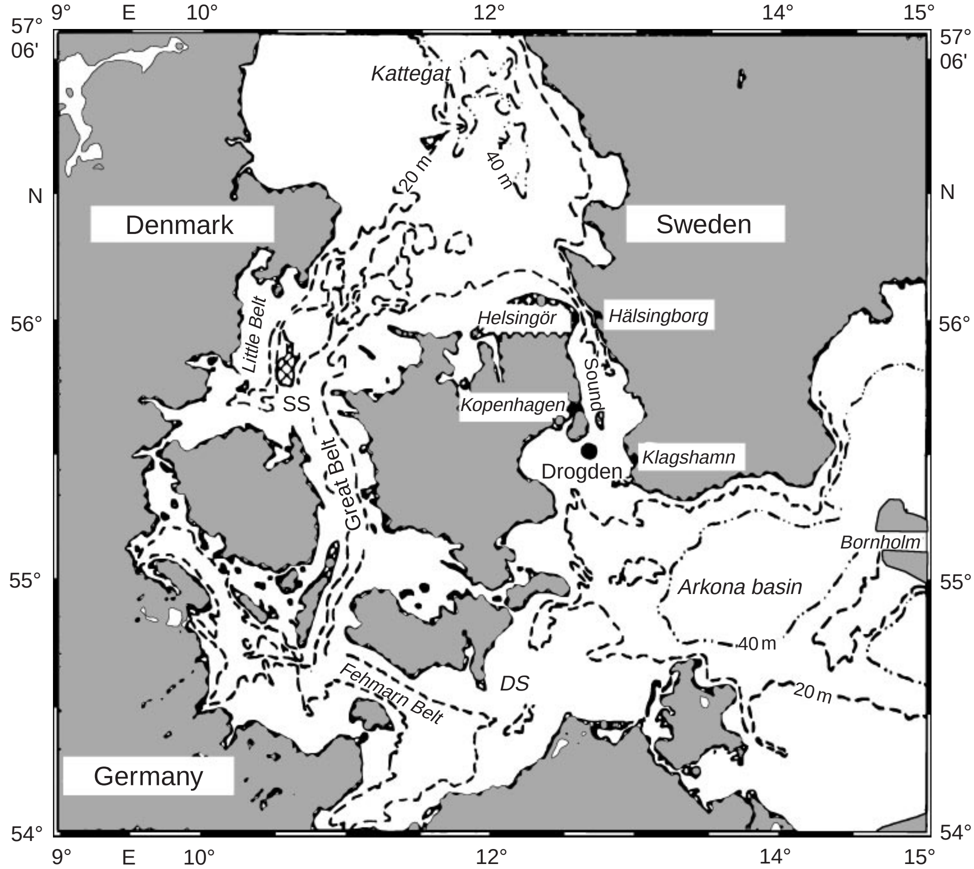

Figure 2 The Danish Straits, Kattegat and Arkona Basin. SS, Samsoe Sill, DS, Darss Sill. The Belt Sea is the area between the Kattegat and Arkona Basin.

Because of the river runoff and the low salinity in the eastern and northern Baltic Sea the sea level is higher by 0.3 m in the interior of the Gulf of Finland and the Gulf of Bothnia compared to that in the Belt Sea. This sea level inclination produces a pressure gradient which drives the upper layers out of the Baltic Sea. Due to the Coriolis force this outflow is concentrated on the Swedish coast. On average about 1250 $km^3\,year^{-1}$ leave the Baltic Sea through the Danish Straits. As compensation about 740 $km^3\,year^{-1}$ of saline, dense and oxygen-rich water penetrates in the deeper layers through the Danish Straits into the Arkona Basin and from there through the Bornholm Channel into the Bornholm

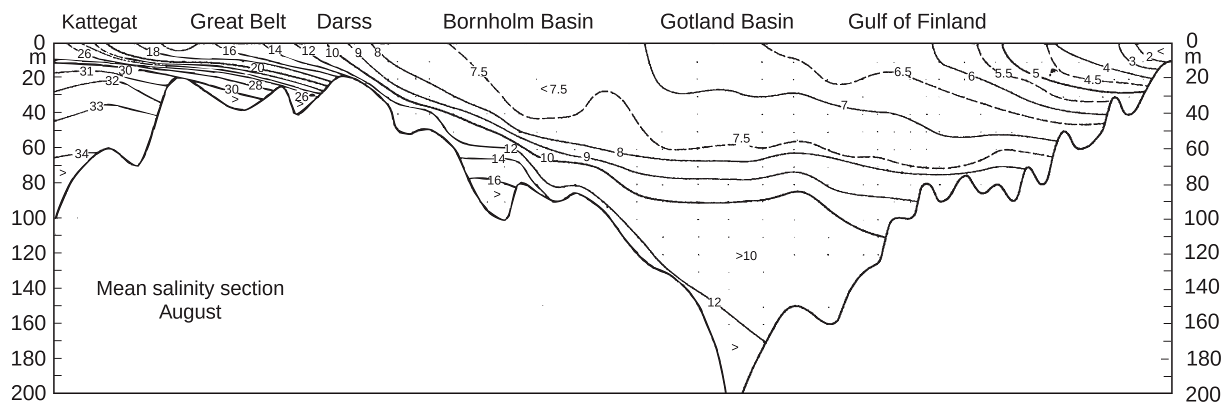

Figure 3 Mean salinity (practical salinity units) distribution (1902–1956) along a section from the Kattegat to the Gulf of Finland (for location see **Figure 1**).

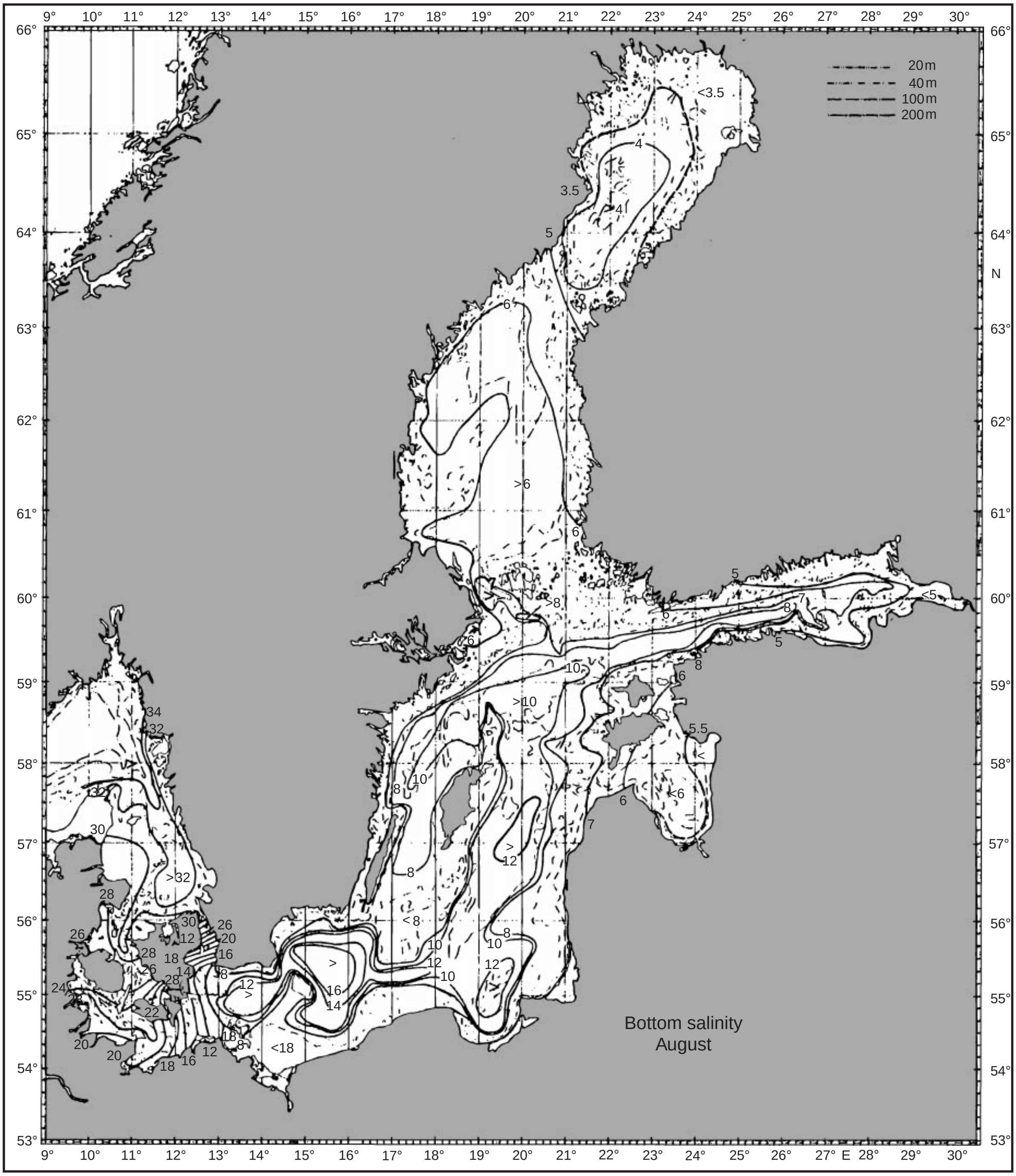

Figure 4 Mean salinity (practical salinity units; PSU) distribution at the bottom of the Baltic Sea (1902–1956).

Basin. Horizontal pressure gradients due to the density gradients, which overcompensate the sea level gradient, act as forcing term. The path of this inflow further to the north is shown in **Figure 4** by the salinity distribution close to the bottom. Water of 12 PSU flows through the Stolpe Channel into the Gdansk Basin and further into the Eastern Gotland Basin. Part of this water continues into the Northern Basin, and another part flows around Gotland and south into the Western Gotland Basin. However, these observations also represent the cyclonic wind-produced circulation in the Baltic Proper and are only partially due to thermohaline driving (see next section).

Only in the Danish Straits, where the salinity differences are large and the flow is channeled, are baroclinic currents as strong as 0.1–0.2 $\mathrm{m\,s^{-1}}$ observed. During light and moderate winds, a two-layer system of currents prevails in the Belt, with outflow from the Baltic Sea in the upper and inflow in the deeper layers. This bidirectional flow is driven by the contrast in density and the surface inclination and includes the outflow from the Baltic Sea due to the fresh water surplus. In the Fehmarnbelt this flow system is observed in 50% of all cases in summer and 29% in winter. In the Great Belt the corresponding numbers are 95% in summer and 65% in winter. In contrast to the Belt with its typical bidirectional current system, outflow into the Kattegat extends over the entire Sound, reaching maximum values of $0.2\,\mathrm{m\,s^{-1}}$ near the surface. This flow forms the Baltic Current along the Swedish coast in the Kattegat and Skagerrak which becomes the Norwegian Coastal Current further to the north.

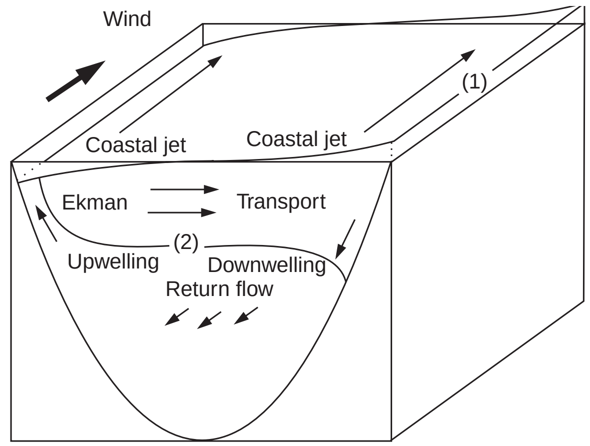

Figure 5 Schematic of wind-produced currents in an infinitely long basin. Sea surface (1) and density surfaces (2) are inclined due to the Ekman transport perpendicular to the coast.

Wind-driven and Thermohaline Circulation

As mentioned above the wind field over the Baltic Sea is highly variable with a well pronounced annual cycle. Maximum speed is reached during November–March with an absolute maximum in December. The minimum occurs in May/June. In December the maximum mean speed is $7–9\,\mathrm{m\,s^{-1}}$, the minimum in May/June is $4–5\,\mathrm{m\,s^{-1}}$. The mean wind direction is from south west/west towards north east/east, i.e., nearly along the line from the western Baltic to the Gulf of Finland.

The current system produced by wind blowing in the direction of an infinitely long basin with constant cross-section and horizontally uniform stratification is depicted in **Figure 5**.

1. In the surface layers there results an Ekman current which is deflected to the right of the wind direction by the Coriolis force, yielding an Ekman transport in cross direction.
2. This Ekman transport produces a sea-level rise on the right-hand coast (looking in wind direction) and a fall on the left-hand side. Furthermore, downwelling occurs on the right-hand side and upwelling on the left-hand side, resulting in baroclinicity of the same sign at both coasts. Note the different length scales of deflection of the sea surface and the isopycnals, which are governed by the external and internal Rossby radius, a measure which describes the adjustment of the deflection under gravity of a rotating fluid.
3. Consequently, geostrophically balanced coastal jets are produced by the inclination of the sea surface along both coasts in wind direction and a slow return flow compensates this transport in the central area of the basin. The inclination of the density surfaces enhances these currents.

If the depth contours are closed, as in the deep basins of the Baltic Sea, the return flow in the center is prohibited. Instead topographic effects become dominant. Outside of the up- and downwelling regions along the coasts the flow in the basins is determined by the sea level inclination of **Figure 5**. For these regions Rossby's potential vorticity theorem holds,

$$\mathrm{d}/\mathrm{d}t((\zeta + f)/H) = 0 \qquad [1]$$

where ζ is the relative vorticity, f is the Coriolis parameter and H is depth. In basins like the Baltic, which are large enough for rotation to play an important role in the dynamics, but not so large that variations of the Coriolis parameter must be taken into account, and where the mean currents are weak ($\zeta \ll f$), the vorticity theorem for the mean flow, $\mathbf{v}$, can be reduced to

$$\mathbf{v}.\mathrm{grad}\,H = 0 \qquad [2]$$

i.e. the vertically averaged currents below the Ekman layer try to follow the depth contours.

The wind-driven currents of the Baltic Sea show much of this typical response besides the strong vertical stratification, e.g. coastal jets are often observed along the eastern slopes with current speeds up to $1\,\mathrm{m\,s^{-1}}$. Numerical models reveal clear evidence of characteristic persistent circulation patterns which comprise mostly the sub-basins with less transport between the basins. **Figure 6** shows the annual average of the vertically integrated transport

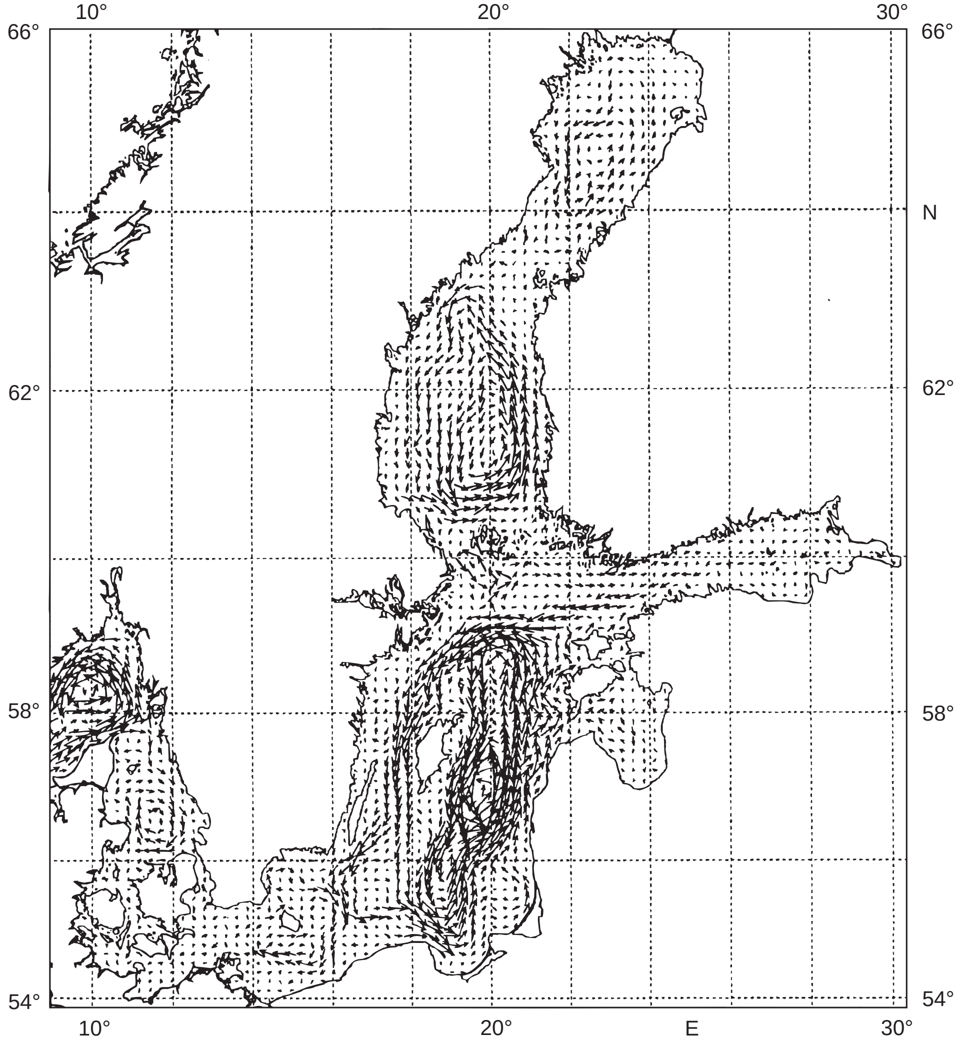

Figure 6 Annual average of the depth-integrated transports ($m^3 s^{-1}$) for 1992 (model results). Maximum vector $0.934 \times 10^5 m^3 s^{-1}$.

for the year 1992. As can be seen from this figure the most pronounced structure with the highest stability is a cyclonic circulation cell comprising the Eastern Gotland basin. Most of the water is recirculating in the Eastern Gotland Basin, but part of it flows back along the western slope of the Western Gotland Basin, continues towards the Bornholm Basin and closes the return flow through the Stolpe Channel. On average the stability of this circulation pattern is higher than 50%. The northward flow along the eastern Baltic slope is much more pronounced than the southward flow along the Swedish slope. This can be interpreted according to **Figure 5**: the currents along the eastern slope are intensified by the coastal jet and correspondingly reduced along the Swedish coast. Similar patterns as in the Gotland Basin are observed in all other basins.

The transport associated with these wind-induced patterns is about an order of magnitude higher in the Stolpe Channel than the fresh water supply by the river runoff. Although highly variable between the years, this area shows the most intense transport rates of the entire Baltic Sea.

The bottom currents are only slightly different from the vertically averaged ones. Bottom currents towards the east are found in the Bornholm and in the Stolpe Channel with stabilities higher than 50%. The annual average of the bottom currents in the Bornholm Channel reaches about $0.1 m s^{-1}$ and in the Stolpe Channel $0.05–0.08 m s^{-1}$. This demonstrates the importance of these channels for the inflow of saline water into the eastern basins. However, the strongest bottom currents are in most cases not coincident with the highest stability. This indicates that these bottom currents are not as permanent as the vertically averaged currents.

As expected from **Figure 5** up- and downwelling occurs along the coasts. **Figure 7** shows the vertical

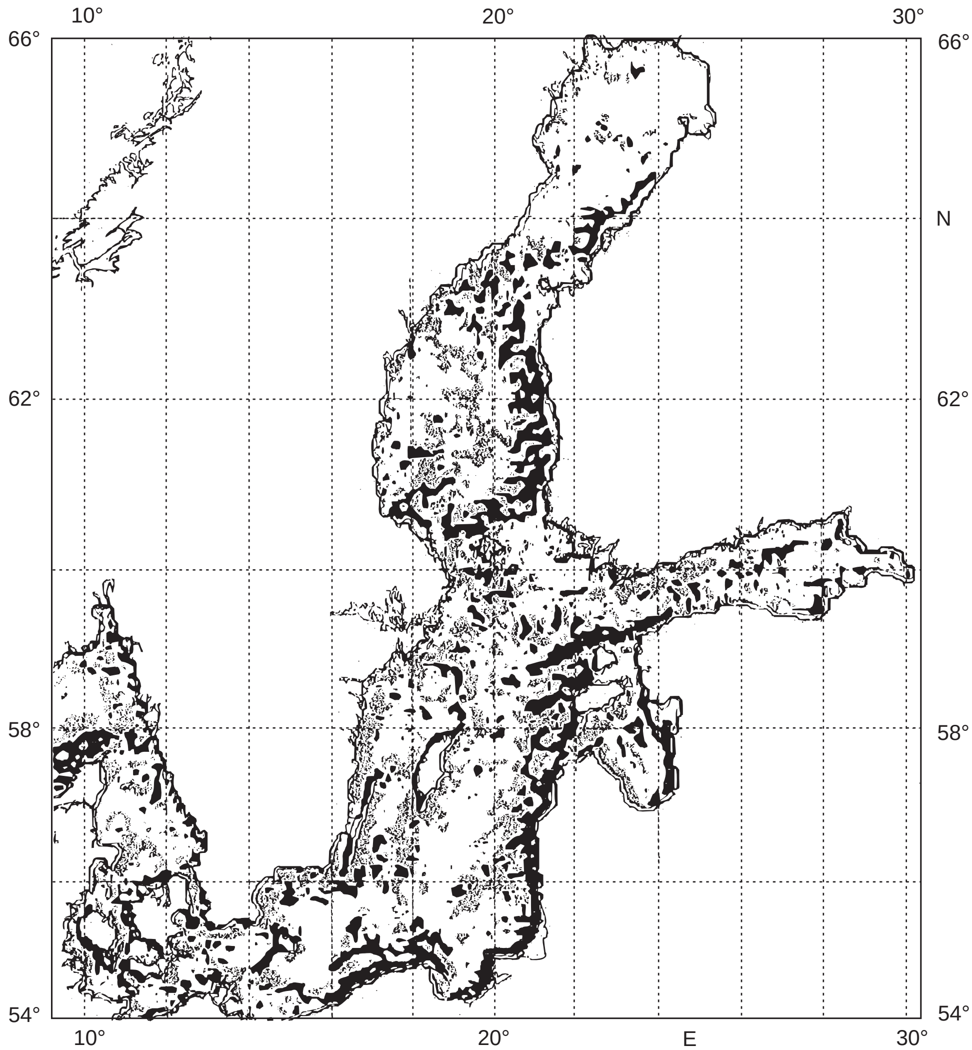

Figure 7 Upwelling and downwelling in the Baltic Sea based on four-year vertical averages of vertical velocities (model results). Grey areas, upwelling $> 4 \times 10^{-6}\,\mathrm{m\,s^{-1}}$; black areas, downwelling $< 4 \times 10^{-6}\,\mathrm{m\,s^{-1}}$.

average of the vertical velocities for a four-year modeling period. Along the western coast of the Baltic upwelling occurs at a distance of about 20–30 km offshore, and along the eastern coast a continuous band of downwelling can be seen. Larger islands and topographic features have similar effects. The areas can be regarded as the most active areas in the vertical exchange of water masses.

Currents in the Danish Straits and Major Inflow Events

The currents in the Danish Straits are highly variable, mainly determined by the sea-level differences between the Skagerrak and the Arkona Basin. Westerly winds, for example, pile up water in the Skagerrak–Kattegat area and simultaneously lower the sea level in the Arkona Basin. Large sea-level differences are therefore common along the Danish Straits. The flow in these straits responds like the flow in a manometer between two large basins.

Table 1 depicts the mean daily outflow rates and the standard deviations through the straits for some years (model results). Typically the standard deviation is 30–40 times larger than the mean flow. Actual mass transport across Darss Sill calculated from observations is depicted in **Figure 8** for 1994 and 1995, showing this high variability. In the Great Belt the speed reaches more than $\pm 1\,\mathrm{m\,s^{-1}}$, and in the Öresund as much as $\pm 1.5\,\mathrm{m\,s^{-1}}$. At Darss Sill, where the central channel widens, $\pm 0.5\,\mathrm{m\,s^{-1}}$ is observed.

The inflow of saline and oxygen-rich water along the bottom of the Baltic Sea is essential for bottom-living animals in the Baltic Proper. Oxygen

Table 1 Mean daily outflow rates and standard deviation through the Danish Straits (model results) ($1\ km^3\ day^{-1} = 11.6 \times 10^{-3}$ Sv)

Year	*Mean outflow ($km^3\ day^{-1}$)*	*Standard deviation ($km^3\ day^{-1}$)*
1986	1.28	41.0
1988	1.39	54.4
1993	2.26	63.6
1994	1.02	59.1

depletion in the deep basins causes oxygen deficiencies and the production of hydrogen sulfide after long periods of stagnation.

Inflow of water of intermediate salinity occurs more or less continuously, as mentioned above, but this water is normally not dense enough to replace the bottom water in the deep basins. Renewal occurs only intermittently after periods of strong and persistent westerly winds. The greatest renewal during the last 50 years occurred in 1951, followed by a stagnation period until 1963. By then about one-third of the area of the Gotland Basin was covered with hydrogen sulfide-enriched water near the bottom. The inflows in 1963 and 1969 only partially replaced these water masses. The situation became worse during the next decades; the last major inflow occurred in 1993, which is the best documented and modeled inflow event.

The following conditions are most favorable for a major inflow, which usually occurs between November and January.

1. An extended period of easterly winds must drive water out of the Baltic and lower the sea level in the entire Baltic Sea. Maximum observed sea-level difference between Kattegat and Baltic Sea then amounts to about 0.7 m on average (maximum value 1.66 m). During this period the Kattegat front, which separates the saline Kattegat water from the outflowing Baltic Sea water, is pushed far to the north.
2. This period must be followed by a phase of strong westerly winds over the North Sea and the Baltic, such that the sea level and barocline gradients drive the water back into the Baltic. This period lasts typically 2–3 weeks, during which the brackish water of the Straits is flowing into the Arkona Basin and allows the saline water of the Kattegat to penetrate towards Darss and Drogden Sill. Due to this inflow, sea level rises in the Baltic up to normal or even above normal.
3. A major inflow of saline water starts when the Kattegat water, usually reduced in salinity to

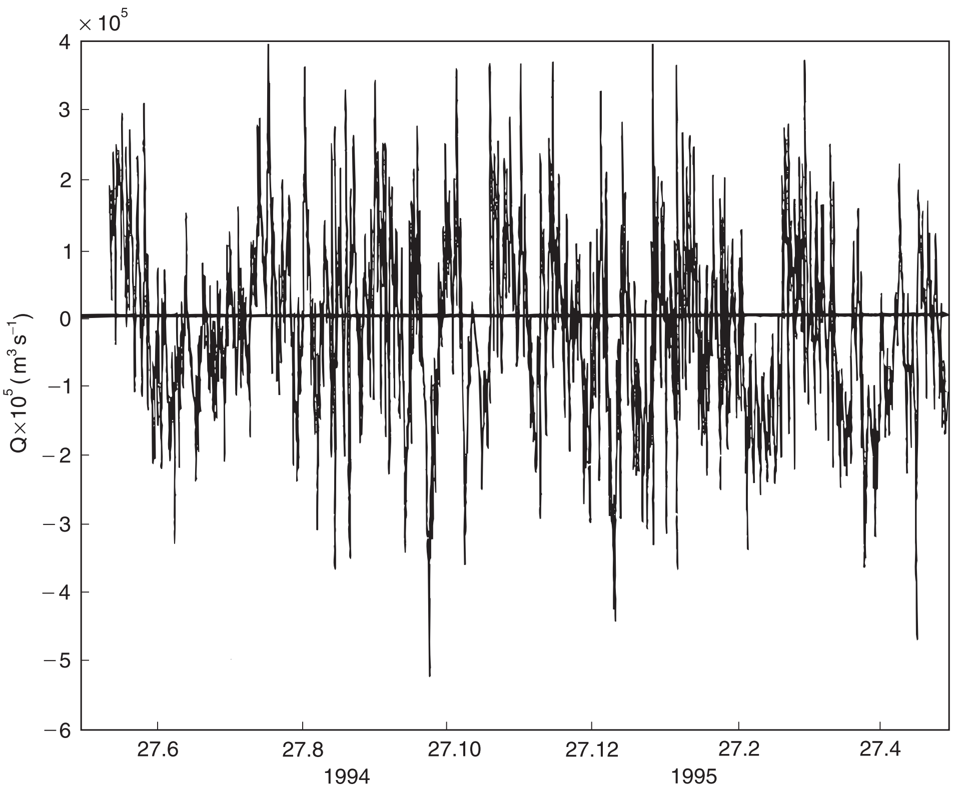

Figure 8 Mass transport over Darss Sill during June 1994–April 1995 based on two stations at the sill. '27.6' on the time axis means 27 June.

22 PSU by vertical mixing, reaches Darss and Drogden Sill. It then penetrates along the bottom into the Arkona Basin. During major inflows the water transports 2×10^9–5×10^9 tonnes of salt into the Baltic Sea. The water takes about 22 days on average ($0.11\,\mathrm{m\,s^{-1}}$) to pass the Arkona Basin. The reason for this slow propagation is doming of the inflowing water. The heavy water forms a large cyclonic eddy (geostrophic flow around the dense water) which prevents the water from flowing rapidly through the basin. Thus the heavy water remains there as a pool over extended periods, its salinity may be further reduced by wind-induced mixing and the water in the upper layers may even flow back into the Danish Straits. After passing Bornholm Channel the same occurs in the Bornholm Basin, where the water takes about 40 days to reach the center. In many cases it does not fill the basin up to 60 m (the sill depth of Stolpe Channel) and its further penetration into the Gotland Basin depends on the wind conditions.

Oscillatory Currents

A pronounced phenomenon in the current variations is the appearance of inertial oscillations, a response of the Ekman currents to the varying wind conditions. They include about 30% of the observed kinetic energy within the wind-mixed layer. Their frequency is determined by the Coriolis parameter, slightly modified by stratification.

Furthermore, seiches (standing waves of the entire Baltic Sea, transformed to amphidromic systems due to the Earth's rotation) are a dominant feature in all tide gauge records, especially at the Finnish coast. These free oscillations were first recognized by F. A. Farel in Lake Geneva, and the local name 'seiches' has generally been adopted as a term for free oscillations of more or less enclosed water basins. They occur when the wind decreases after piling-up of water at one end of the basin. In the Baltic Sea the seiches are heavily damped due to the complicated configuration of the sea, the division into several sub-basins and the open connection to the North Sea, which allow water exchange up to $4 \times 10^5\,\mathrm{m^3\,s^{-1}}$ (**Figure 8**). Typically, we find only two or three oscillations.

Observations indicate that the dominant oscillation belongs to the western Baltic–Gulf of Finland system, which represents the second mode of the entire Baltic. The period varies between 26 and 27 h (theoretically 26.4 h). The Gulf of Bothnia is little influenced by this mode, in contrast to the first mode (period 31 h). Both the first and second modes show amphidromic points north of Gotland, where the vertical displacement vanishes. This allows the tide gauge of Landsort (south of Stockholm) to be used as reference station for the mean sea level of the Baltic Sea.

Currents due to seiches are most pronounced in the shallow areas. Tidal currents are negligible in the Baltic Sea east of Darss Sill.

See also

Ekman Transport and Pumping. Estuarine Circulation. Rossby Waves. Thermohaline Circulation. Wave Generation by Wind.

Further Reading

Bock KH (1971) Monatskarten des Salzgehaltes der Ostsee, dargestelt für verschiedene Tiefenhorizonte. *Deutsche Hydrographische Zeitschrift, Ergänzungsheft Reihe B* 12: 1–147.

Lehman A and Hinrichsen H-H (2000) On the wind driven and thermohaline circulation of the Baltic Sea. *Physics and Chemistry of the Earth* B 25(2): 183–189.

Mälkki P and Tamsalu R (1985) *Physical Features of the Baltic Sea*. Finnish Marine Research No. 252, 110 pp. Helsinki.

Rheinheimer G (ed.) (1996) *Meereskunde der Ostsee*, 2nd edn. Berlin: Springer.

Simons TJ (1980) *Circulation Models of Lakes and Inland Seas*. Canadian Bulletin of Fisheries and Aquatic Sciences, Bulletin 203. Ottawa: Department of Fisheries and Oceans.

Wübber Ch and Krauss W (1979) The two-dimensional seiches of the Baltic Sea. *Oceanologica Acta* 2: 435–446.

BEACHES

See **BEACHES, PHYSICAL PROCESSES AFFECTING; SANDY BEACHES, BIOLOGY OF; VIRAL AND BACTERIAL CONTAMINATION OF BEACHES; WAVES ON BEACHES**