Rostock. Meeresbiolog. Beitr.	Heft 32	9–17	Rostock 2023

CHAPTER 1

The Baltic Sea environment: introductory remarks

The Baltic Sea is the world's largest semi-closed brackish water body. It is a temperate shelf sea with permanent salinity stratification, a unique horizontal salinity gradient, and low water turnover of 25–35 years. It is a shallow sea with a mean depth of 62.1 m, the greatest depth 459 m, an area of 415,266 km^2 (Baltic proper itself is 211,069 km^2), and a volume of ca. 22,000 km^3 (HELCOM, 2001; Wulff et al., 2001; Schiewer, 2008). The Baltic Sea catchment area covers 1,671,000 km^2 (Kortum, 1996). The presence of shallow sills at the western inlets causes stable water stratification. Climate is humid in the Baltic Sea area. The Baltic can be best compared to a stratified fiord with a rich supply of fresh water from the rivers. There is an estuarine circulation with outflow of low-saline water above the halocline and powerful periodic injections of North Sea water below the halocline that greatly affect the salinity and oxygen regimes in the deep water layers.

In the history of the Baltic Sea, periods of freshwater, marine water and brackish water predominance succeeded gradually, being sometimes interrupted by complete freezing of the whole region. The postglacial history of the Baltic region started with the melting of the glacial ice shield. As the ice shield barred the melting water from the open sea, this Baltic Ice-Lake contained fresh water. About 10,000 years ago, a first connection to the ocean was opened through mid-Sweden surface, and the brackish Yoldia Sea emerged. It was probably exposed to large gradients and fluctuations of salinity, as a second connection to the White Sea was opened during several periods. The first connection closed about 9,250 years ago due to the uplift processes, resulting in a freshwater lake. This so-called Ancylus Lake existed between 9,250 and 7,100 years ago.

The Baltic Sea, as we know it now, is a brackish water system, existing as such since approximately 7,100 years ago. But even this geologically relatively short time span cannot be considered as a stable period. Between 7,100 and 4,000 years ago, the main Baltic fossile was *Littorina littorea*, giving its name to this period. During the recent 4,000 years, the Baltic Sea has gradually become less saline, and *Littorina* was first replaced by the freshwater mollusc *Limnea ovata* (Limnea period) and later, about 1,500 years ago – by *Mya arenaria* (Mya period), which still characterises the system. With respect to this variability, fluctuations in species composition and high numbers of invaders (the non-indigenous, or alien organisms) are neither surprising nor alarming events, but rather an expected pattern in a system exposed to an ever-changing abiotic background.

The recent Baltic Sea is connected with the North Sea via the Belt Sea, the Kattegat and the Skagerrak; it stretches for 1,200 km in the west-east direction from the Kattegat to the Gulf of Finland and for 1,300 km in the south-north direction from the Odra Bight up to the Bothnian Bay, close to the polar circle (Figure 1.1).

Figure 1.1: Regions of the Baltic Sea. Shown is the division of the Baltic Sea into "natural regions" according to Wattenberg (1949). The Bornholm Sea and the eastern and western Gotland Sea are often considered jointly and termed the "Baltic proper".

The hydromorphology of the Baltic Sea is rather complicated (Köster & Lemke, 1996). Several underwater barriers and deep basins follow each other, subdividing the Baltic Sea into certain districts, as indicated in Figure 1.1. The Bothnian Bay is the outermost northern part of the Baltic Sea; its adjacent southern region is the Gulf of Bothnia (the Bothnian Sea). The easternmost part between Finland, Russia and Estonia is called the Gulf of Finland; the large semi-enclosed part between the island of Saaremaa and the city of Riga is called the Gulf of Riga. The main water body, called the Baltic proper, stretches from westernmost Finland to the Bornholm Island. The shallow region around the Danish Islands is called the Belt Sea, it is connected to the Kattegat north of the Danish Islands. The Kattegat, irrespective of being covered by Baltic-wide regulations, e.g. the Helsinki Commission (HELCOM), is not an integral part of the Baltic Sea; it is the transition area between the North Sea and the Baltic Sea.

Wattenberg (1949) gives a more detailed, “natural” subdivision of the sea. He identifies the Åland Sea west of the Åland Islands, and the Archipelago Sea east of the Island of Åland as separate regions; the Baltic proper becomes splitted into Bornholm Sea and the Eastern and Western Gotland Sea (Figure 1.1). Another region often cited by several authors is the Quark (not shown in Figure 1.1), the area between the Bothnian Sea and the Bothnian Bay.

The maximum depths of the major regions are: the Arkona Basin – about 45 m, the Bornholm Basin – about 100 m, the Eastern and Western Gotland Basins – about 250 and 460 m, respectively, the Gulf of Finland – about 120 m; the Bothnian Sea and the Bothnian Bay are characterised by depths of 120 and 80 m, respectively (Feistel et al., 2008).

However, as any attempt to classify the natural aquatic systems, the subdivision of the Baltic Sea is largely conventional when water masses and their biota are considered, and the real borders between the areas mentioned above do not exist. This is especially relevant to the pelagic communities of living organisms (the plankton) that are mixed extensively, drift within large water masses, and may be driven by those water masses to significant distances (Telesh et al., 2009).

Irrespective of the fact that different division schemes mainly focus on morphology of the Baltic Sea, they also reflect changes in the abiotic conditions, especially salinity, which are of vital importance for the biota of this water body. That is due to the hydrological regime of the Baltic, which has only one narrow connection to the entirely marine habitat of the North Sea and is located in a humid climate zone. Fennel (1996) calculated the water budget of the entire Baltic Sea. River runoff was measured as ca. 483 km³ a^{-1}, whereby the Neva River with 77 km³ a^{-1}, located in the outermost eastern part of the Gulf of Finland, was by far the largest fresh water contributor to the Baltic Sea, followed by the Vistula River with its 34 km³ a^{-1}. The precipitation was estimated to be 266 km³ a^{-1}, and evaporation amounted to 207 km³ a^{-1}, resulting in a freshwater input of approx. 60 km³ a^{-1}. The total freshwater input therefore added up to 540 km³ a^{-1}. This surplus of freshwater input gets counteracted by the inflow of marine water via the Skagerrak and the Kattegat.

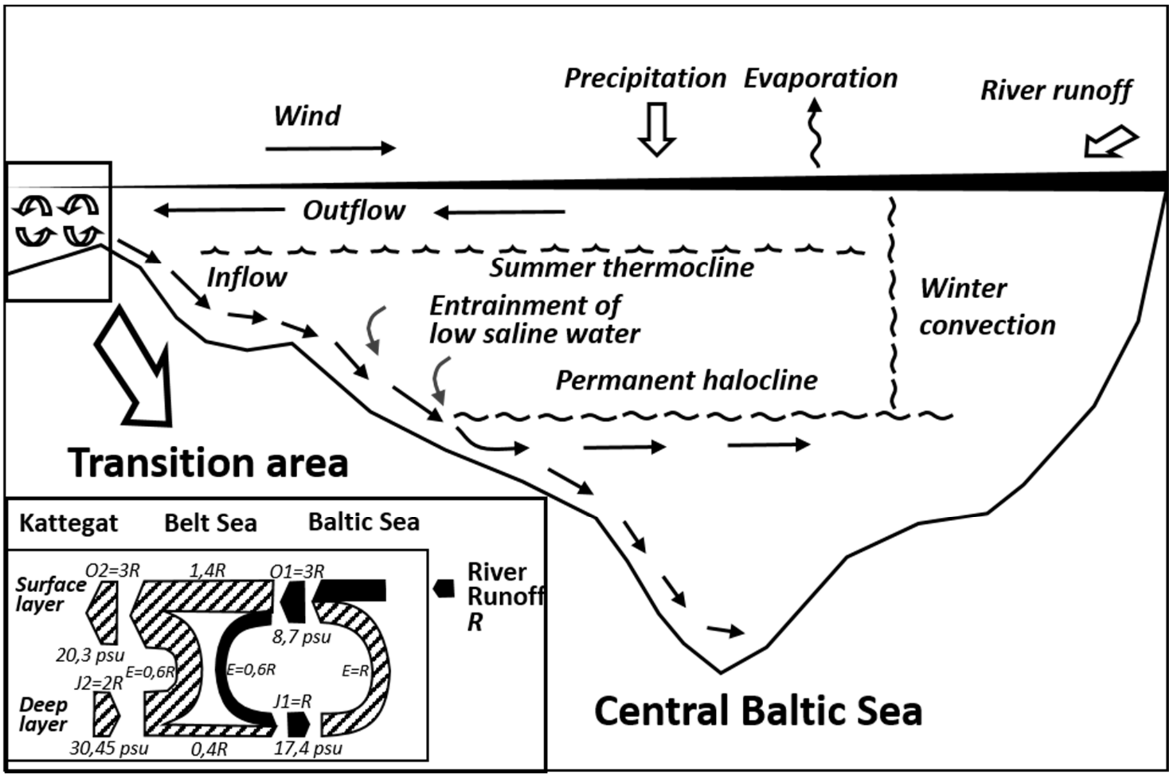

Figure 1.2: Water balance and water circulation of the Baltic Sea. Bottom left: water exchange with the North Sea in river runoff units (R): O1, O2 – outflow in the surface layer; J1, J2 – inflow compensation current in the deep layer; E – entrainment of water from the deep layer into the surface layer and vice versa (from Lass & Matthäus, 2008).

The mechanisms of water exchange between the Baltic Sea and the North Sea are very intricate. The positive water balance of the Baltic Sea determines the estuarine circulation, which is driven by the outflow of brackish surface water through the Kattegat. Due to a lower density of the brackish water compared to the Kattegat water, a deep-water compensation current is transporting saline water from the North Sea into the Baltic Sea. The compensation current is even more pronounced, the stronger the outflow at the surface layer is. These fundamental processes together with upwelling and vertical mixing processes determine the special hydrographic conditions of the Baltic Sea.

The brackish water originating from the Baltic Sea has a lower density and, therefore, moves at the surface relatively unhampered. It is driven by gravity because of the positive water budget mentioned above. Salt water inflow from the North Sea is influenced by numerous underwater barriers and sills. The most important ones are the Drogden Sill (Öresound) and the Darss Sill (Arkona Sea) reaching down to 7 m and 18 m underneath the surface, respectively. As a result, there is a steep salinity gradient along the Baltic Sea. From almost marine conditions in the Kattegat region, salinity drops within a short distance of ca. 300 km down to <10 psu in the Baltic proper. Further east, salinity declines more slowly until it reaches values of less than 2 psu in the Bothnian Bay and the easternmost parts of the Gulf of Finland. In general, salinity regime in the Baltic Sea ranges between oligohaline (0.5 psu) and mesohaline (18 psu) conditions, with an average of 7–8 psu in the major open Baltic waters (HELCOM, 2001). However, climate change and decadal scale variability of these parameters modify the hydrographic characteristics accordingly (BACC, 2008; Feistel et al., 2008).

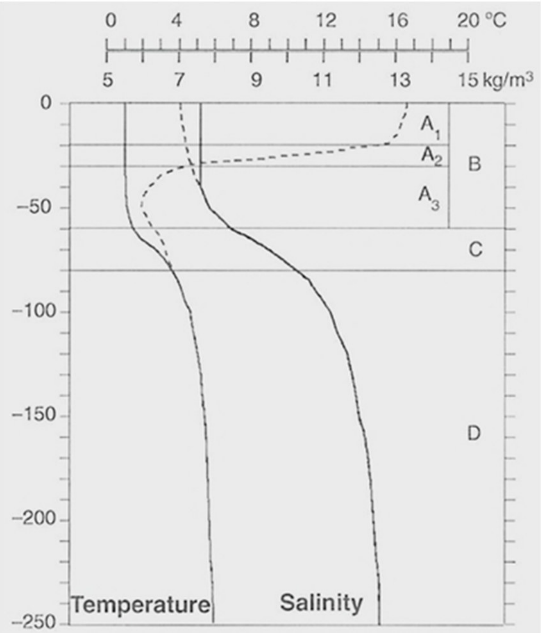

Figure 1.3: Typical thermocline stratification of the central Baltic Sea during winter (solid line) and summer (brocken line). A1 = summer upper layer; A2 = summer thermocline; A3 = cold intermediate water layer; B = cold winter water layer; C = permanent discontinuity layer; D = deep water layer (from Lass & Matthäus, 2008).

Depending on air temperature, a thermocline forms seasonally due to the warming of the surface water layer in spring and summer at a depth of 25–30 m (Figure 1.3). The thermohaline stratification is subject to spatial and temporal variations throughout a year. In winter, the permanent thermohalocline separates low saline cold winter water from higher saline warmer deep-water (Figure 1.3). During spring, the surface water is warming up and a thermocline develops, separating warm surface water from cold intermediate water. In consequence, the vertical mixing of the surface water and the intermediate water is inhibited until autumn. A stable halocline and a seasonally existing thermocline prevent vertical circulation and, consequently, ventilation of the bottom water.

The general picture of the average salinity in the open waters, however, is superimposed by different ranges of irregular fluctuations of salinity at a certain location. Sheltered lagoons and bays are influenced by freshwater runoff and therefore their average salinities differ largely from that of the adjacent Baltic Sea. The actual salinity in such locations therefore depends on (a) the current freshwater runoff, fluctuating seasonally according to the precipitation regime (which is not uniform all around the Baltic), (b) the actual water exchange with the Baltic Sea, and (c) the salinity of the adjacent Baltic Sea water. The latter can play a major role, because large changes of the salinity of the Baltic Sea water are common.

The saline inflows from the North Sea are the main source of new oxygen for bottom water of the deep Baltic Sea basins. Major saline water inflows occur most frequently between October and February whereas they have never been recorded between May and August. They either occur in clusters of several subsequent years or as isolated events. Between 1880 and 1980, major saline water inflows into the Baltic Sea occurred quite regularly with only 2 or 3 years in between. Since the middle 1980s, the situation changed dramatically. The frequency of major saline water inflows decreased significantly, to only one major Baltic inflow (MBI) per decade. These rare events in 1993, 2003 and 2014 could interrupt the anoxic bottom conditions only temporarily (Figure 1.4). The decreased frequency of inflow events caused important consequences for the chemical and biological conditions below the permanent halocline. During long stagnation periods, the salinity and oxygen concentration in the deep water layer decreases. Oxygen deficiency areas develop at the sediment and in the bottom water layer, especially in deep Baltic Sea basins.

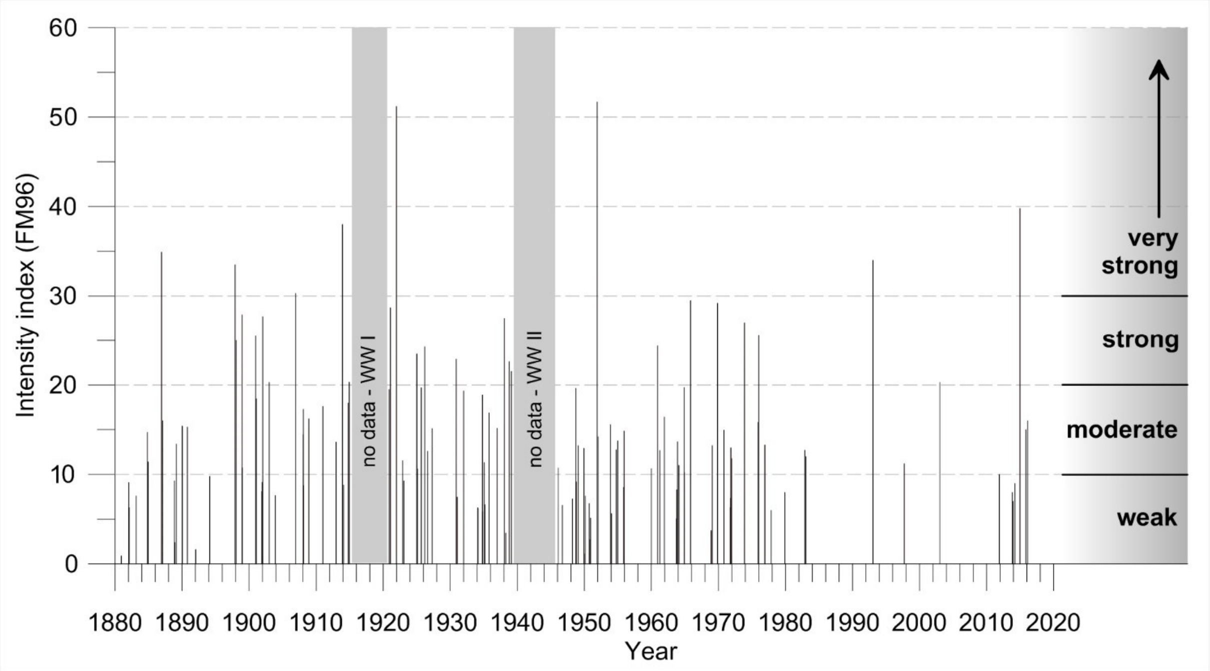

Figure 1.4: Intensity index of Major Baltic inflows (MBIs) between 1880 and 2016 according to Matthäus et al. 2008, Mohrholz et al. 2015, Feistel et al. 2016..

Major Baltic inflows cause a renewal process in the deepwater of the central Baltic Sea. Salinity and oxygen concentrations increase, especially when the inflow events take place during the cold season (January to April). Immediately after the deep water renewal, a new stagnation period begins, due to an increased stability of the salinity stratification. During stagnation period, the salinity decreases slowly in the deep water caused by vertical and horizontal mixing. Oxygen concentration decreases rapidly due to microbial consumption processes with the consequence of hydrogen formation.

The Baltic Sea is also characterised by a strong climatic gradient, as it stretches over 20 degrees of longitude and 12 degrees of latitude. Maritime temperate conditions predominate in the southern and western parts, whereas continental conditions prevail in the eastern and northern parts, becoming more arctic-influenced in the Bothnian Bay.

Due to the large north-south expansion of the Baltic Sea, the insolation and temperature regimes in this water basin vary greatly. To illustrate these differences, a southernmost location at 54° N was compared with a northernmost one at 65° N in terms of insolation (Figure 1.5; original data of H. Schubert). All data are based on potential insolation, irrespective of actual weather conditions. As shown in Figure 1.5, daily irradiance on June 22, the longest day of the year, differs only slightly between the locations. In the northern location, maximum irradiance is ca. 13% lower, but day length is prolonged by 4 h. Therefore, the overall difference in daily light dose is small between the locations. On December 22, the shortest day in the northern hemisphere, a large difference between the two locations can be observed with almost no irradiance at the northern station and still some irradiance in the southern location.

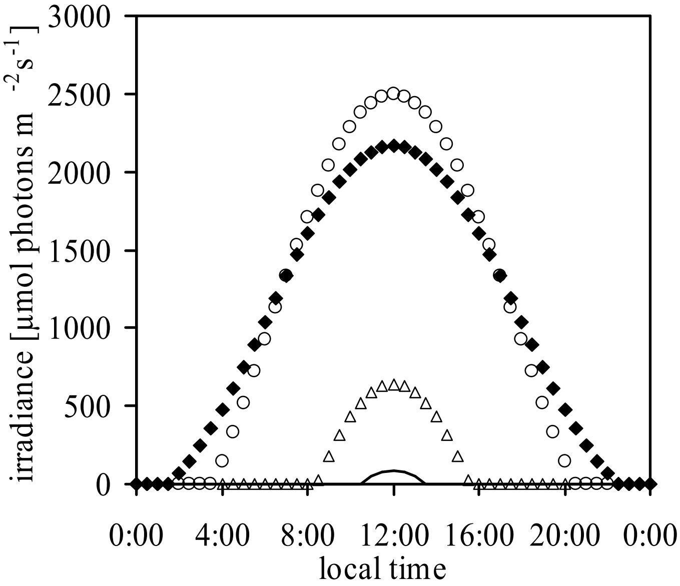

Figure 1.5: Daily irradiance curve. Shown are the daily irradiance curves at a northernmost location (65°N) and at a southernmost location (54°N) of the Baltic Sea. Calculations were made irrespective of actual weather conditions and thus show potential insolation (original data of H. Schubert).
Symbols used: open circles - 54°N, June 22; open triangles - 54°N, December 22; filled rhombs - 65°N, June 22; solid line - 65°N, December 22.

The temperature regime is related to the insolation regime and thus exhibits large differences across the Baltic Sea. The average water temperature is about 8.4 °C at the southern Baltic coast (Warnemünde), but in St. Petersburg and in Helsinki, located on the eastern Baltic coast, the average temperature only amounts to 4.5 °C. Furthermore, the annual temperature amplitude (monthly means) forms a gradient across the Baltic Sea, reaching only 18 °C in the south-western regions and 28 °C in the north-eastern regions (Heyer, 1977).

The great variation in the temperature amplitude mentioned above results in the differences in probability and duration of ice cover across the Baltic Sea (Figure 1.6). The Bothnian Bay and some parts of the innermost Gulf of Finland have the highest probability of ice cover formation and are covered with ice completely every winter. Sheltered lagoons and coastal enclosures around the Baltic are covered with ice during most winters, but large differences can be observed in thickness and duration of the ice cover. As shown in Figure 1.6, other regions of the Baltic Sea are not covered by ice every winter. In some years, almost the whole Baltic Sea is frozen and only small areas of the Baltic proper are kept open, whereas in other winters ice cover is restricted to the northern and eastern parts of the sea. The probability of ice formation ranges from about 30% in exposed locations of the Baltic proper and Kattegat to about 70% along the Baltic proper coastline and 100% along the coastlines of Finland, Russia and northern Sweden. A corresponding gradient in the duration of ice cover can be observed. Average duration of ice cover, in the caces when ice-forming conditions are present, is about 30 days in the exposed regions of the Baltic proper and in the Kattegat, about 60 days along the coastline of the Baltic proper, and more than 180 days in the Bothnian Bay (Strübing, 1996).

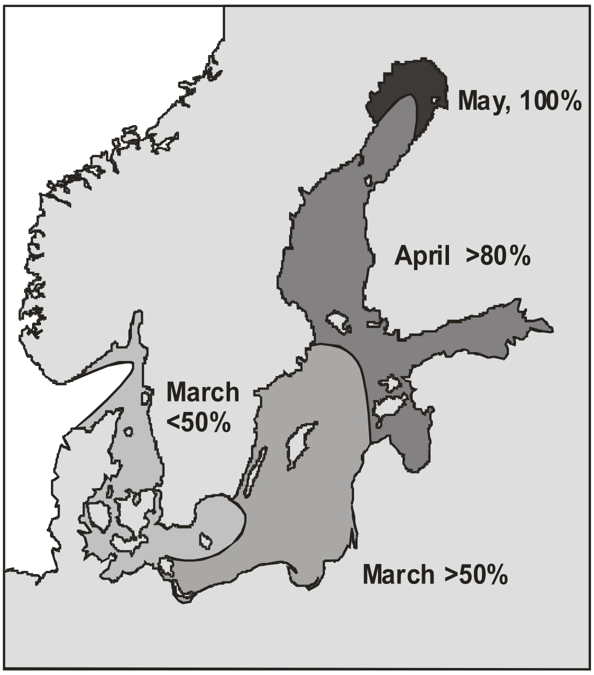

Figure 1.6: End of ice cover period and probability of ice cover formation. Shown are the month of average ice break-up and the percentual probability of ice cover formation. Data are taken from Strübing (1996).

The Baltic Sea is a so-called microtidal system, exhibiting less than 15 cm amplitude of the daily tidal component, except for the Kattegat, which is influenced by the tides of the North Sea. Despite several details, dealing with resonance effects of the individual regions etc., tidal changes of the water level are generally of minor importance in the whole Baltic Sea. Of higher importance are wind-driven changes of the water level that are usually less than 1 m in amplitude, but sometimes reach maximum values of –2.5 m below and +3 m above average water level. Such great differences occur only rarely and in most of the cases they last just a few hours. In shallow lagoons and enclosures, however, already minor changes of 0.5 m, which are common events, can cause flooding and drying of large areas. In these habitats, such minor changes can have a major impact, even if they prevail only for a short time, as they are always accompanied by drastic changes in salinity. Within a few hours, inflow of salt water can cause an increase in salinity of more than 100% and thus lead to massive hyperosmotic stress. This effect can be amplified further by dry conditions occurring a few hours or a day later, or by hypoosmotic stress in the case of rain.

The above mentioned water level changes of 0.5 m can be caused just by air pressure differences across the Baltic region, solely or in combination with wind. Tiesel (1996) described a typical seasonal pattern of air pressure gradients across the Baltic Sea. Strong pressure gradients across the whole Baltic Sea are present in winter (October–February) and can also be expected during May. During summer, mainly the south-western part of the Baltic Sea is influenced by strong air pressure gradients, leading to remarkable water level changes, whereas the northern part is less influenced. During the growth period, especially the south-western part is thus exposed to high water level changes and considerable fluctuations in salinity, as described above.

The ion composition of the brackish water in the Baltic Sea is also of pronounced ecological importance. While the ion composition of water is more or less constant in oceanic systems, this assumption may fail for brackish water systems due to the following reasons: (1) large impact of freshwater runoff with different chemical composition, (2) lower total amount of ions and, therefore, higher probability of influencing their concentrations by biological processes, (3) possibility of stagnation of the water body, leading to accumulation of compounds in the stagnant deep water where the ions can be reduced under anoxia, and (4) incomplete mixing of water bodies of different origin. Additionally, strong local anomalies occur in regions of low salinity for, e.g., the SO_4^{2-} to Cl^- ratio, reflecting the high contribution of riverine runoff to the SO_4^{2-} pool of the Baltic Sea (Kremling, 1996). Regarding those anomalies, at least on a small scale, differences between the trace element composition of the Baltic Sea and oceanic systems can be expected. Especially in the anoxic systems and regions heavily influenced by fresh water, significant deviations for numerous elements can be registered (HELCOM, 1990).

At least some of these elements are further influenced by the high concentration of dissolved organic matter in the Baltic Sea, particularly the so-called chromophoric dissolved organic matter (cDOM), which originates from incomplete lignin metabolisation. Freshwater runoff is the main source of cDOM but, unfortunately, little is known about its Baltic Sea-wide distribution in relation to salinity. The few investigations (Scheer, 1998; Blümel et al., 2002) showed a significant dependency of cDOM on salinity in coastal enclosures, but also indicated potential non-terrestrial sources of cDOM and complex changes in its composition during transport in brackish water systems. These cDOM's are of interest for two reasons. First, they are strongly attenuated by short wavelengths of photosynthetically active radiation and, therefore, limit the depth distribution of autotrophs (Schubert et al., 2001). Second, they are able to form stable complexes with many transition metals, such as copper, iron, and nickel. The first effect is well investigated and can be quantified by attenuation measurements. The second effect, however, is difficult to quantify so far, because the currently used analytical methods can hardly distinguish the complex-bound and free metals. Schlungbaum (1979) as well as Nessim (1980) assumed that most of the iron determined in the water is bound in complexes with cDOM and, therefore, is of diminished biological availability.

Largely impacted, or even driven by the abiotic factors of the environment, the biotic components of the ecosystem differ significantly in their diversity, structural features and functional characteristics throughout the Baltic Sea.

Early investigations of macrozoobenthic diversity by Remane (1934) revealed the existence of a salinity-dependent gradient in species number, which was decreasing from marine conditions to "critical salinities" of about 5–8 psu (Khlebovich, 1968), the so-called horohalinicum (Kinne, 1971). At salinity of about 8 psu, only few brackish-water species that can perform hypertonic as well as hypotonic regulation are present. When salinity decreases further, the benthic species' number increases again because of numerous freshwater species which are able to tolerate low salinities.

Later surveys of macrophytobenthos diversity confirmed the decrease in species number during the transition from marine to brackish conditions. However, the lowest species numbers were found at salinities far below 8 psu (Nielsen et al., 1995; Schubert et al., 2011). The reasons are still being investigated; however, the effect itself points to a reduced interspecific competition within phytobenthos at low salinities.

For planktonic organisms, including phytoplankton and zooplankton, but mostly for protists, Telesh et al. (2011a) discovered the opposite rule: a species maximum at the horohalinicum. There exists a number of possible explanations of this astonishing finding; Telesh et al. (2013, 2015) especially highlight the effects of environmental variability, size of organisms, evolution rate and planktonic lifestyle to explain the above salinity vs. species number pattern in a broader context. For example, it is known that aquatic bacteria, including the Cyanobacteria, and the eukaryotic, mostly single-celled Protista (algae, fungi and protozoa) demonstrate high physiological adaptability to changes in salinity. These taxa show extensive adaptive radiation. Members of the Protista have retained a considerable evolutionary euryhalinity and are, therefore, widely distributed in different aquatic environments. This is reflected in high bacterial and maximal protistan species richness in brackish waters, especially at critical salinities 5–8 psu (Herlemann et al., 2011; Telesh et al., 2011a, 2011b, 2013).

Recently, the cell size minimum was shown to back up the protistan species maximum concept, proving statistically that the smallest unicellular eukaryotic plankton are particularly diverse under the conditions of the brackish Baltic Sea waters that are stressful for larger, sessile organisms (Telesh et al., 2015).

The shallowness and the consequently vast area occupied by the coastal ecosystems in the Baltic Sea are the major reasons for the pronounced mixture of the coastal and open-water plankton communities and for the penetration of brackish, euryhaline and even freshwater species of zooplankton with the wide salinity tolerance range far into the open Baltic waters (Telesh et al., 2009). For this reason, the strict definition of the “open Baltic Sea” and its discrimination from the “coastal waters” in respect to the pelagic algoflora and fauna can hardly be given.

To summarise, we can state that for the Baltic Sea, as well as for other brackishwater systems, high variability of almost all environmental parameters in time and space is typical. Salinity fluctuation is an important factor for biodiversity formation. Due to peculiarities of the salinity regime, the pelagic ecosystem component in the Baltic Sea consists mainly of plankton communities dominated by euryhaline species. The planktonic organisms in the Baltic Sea are well adapted to the brackish water environment; however, only a few true brackish water species have evolved there. The present-day species composition of the Baltic Sea is a result of the selection process, where the organisms with a high osmotic resistance have been able to survive. The community structure and spatial distribution of zooplankton in the Baltic Sea are governed largely by the patterns and fluctuations of the environmental conditions. Meanwhile, recent studies showed that stability of major abiotic characteristics in the Baltic coastal ecosystems can be high during rather long period of 1–5 weeks, and that abiotic stability (but not just the absolute critical values of environmental parameters!) can act as one of the major promoters of water stagnation, oxygen depletion and other devastating events like harmful algal blooms (Telesh et al., 2021).