Hydrographic–hydrochemical variability in the Baltic Sea during the 1990s in relation to changes during the 20th century

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The hydrographic–hydrochemical variability in the Baltic Sea during the 1990s was characterized by the general tendency of decreasing frequency and intensity of major inflows observed since the mid-1970s. At the end of the 1990s, the area of the central Baltic deep water which was affected by oxygen deficiency and anoxic conditions was the largest it had been for 15 years. The most important hydrographic events were the effects of the very strong inflow in January 1993 and the weak inflows in 1993/1994 and 1997/1998 on the central Baltic deep water. Weak inflows in 1993/1994 led to deepwater temperatures of around 4°C, i.e. among the lowest values observed in the last century. Effects of a weak inflow of very warm, saline, and oxygen-rich water in autumn 1997 resulted in temperatures up to 7°C, i.e. among the highest values ever observed. Five of the summers were the warmest of the 20th century and caused sea surface temperature anomalies up to 5–6 K in the open Baltic Sea. The decrease in surface salinity observed since the mid-1970s continued during the 1990s. The concentrations of inorganic nutrients in the surface layer are still high compared with background levels of the 1950s. A distinct decrease in phosphate concentrations has been identified, whereas there has been no observed decrease in nitrate concentrations. Nitrogen levels remain high.

Keywords: Baltic Sea, climate change, deep water, inflows, stagnation, variability.

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Introduction

The Baltic region, located in temperate latitudes of the Northern Hemisphere, consists of the sea area itself (Figure 1) and its drainage area, which is four times larger. The Baltic Sea is almost entirely landlocked. Like other landlocked seas in humid climatic regions, the Baltic Sea has a positive water balance. A narrow, shallow transition area consisting of the Kattegat and Belt Sea greatly restricts the water exchange with the North Sea, giving the water in the Baltic Sea a residence time of about 25–35 years. Because of this long residence time and the specific ecological conditions, the Baltic is extremely sensitive to any changes in its environment.

The environmental conditions of the surface and deep water depend strongly on the meteorological forcing over the Baltic, the hydrological processes in its drainage area, and the hydrographic processes in the sea, as well as the interaction between them. These processes govern the water exchange with the North Sea and between the sub-basins, as well as transport and mixing of water within the various sub-regions of the Baltic.

The water body of the central Baltic is permanently stratified, consisting of an upper layer of brackish water with salinities of about 6–8 and a more saline deep water layer of about 10–14. A strong permanent pycnocline at depths between 60 and 80 m prevents vertical circulation and, consequently, ventilation down to the bottom all the year round. During spring, a thermocline develops at 25–30 m depth and restricts additionally vertical exchange within the upper layer until late autumn. The horizontal deep water circulation is restricted by a series of sub-basins separated by submarine sills.

Effects on abiotic environmental conditions in the central Baltic deep water are mainly caused by variations in water exchange. The deep water is influenced by inflows of saline water from the Kattegat and North Sea. The very frequent but weak inflows (10–20 km³) have little impact on the deep and bottom waters because their water will be
interleaved in or flow just beneath the permanent halocline. Episodic inflows of larger volumes (100–250 km$^3$) of highly saline (17–25) and oxygenated water—termed major Baltic inflows (MBIs)—represent the only mechanism by which the central Baltic deep water is renewed to a significant degree. A total of 111 MBIs has been identified between 1880 and 2001. The water entering the sea during MBIs is dense enough to replace the deep and bottom waters. The criteria used to identify MBIs have been published by Matthäus and Franck (1992) and Fischer and Matthäus (1996). The relative intensity of MBIs between 1880 and 2001 was re-estimated after a method given by Fischer and Matthäus (1996).

Because such inflows are restricted by narrow channels (Little Belt, Great Belt, Sound) and shallow sills (Darsø Sill: 0.8 km$^2$ cross section, 18 m sill depth; Drogden Sill: 0.1 km$^2$ cross section, 7 m sill depth; location cf. Figure 1B), the deep water in the central basins tends to stagnate for periods of several years. The consequences are depletion of nitrate, increasing phosphate and ammonium concentrations, decreasing salinity and oxygen content, sometimes culminating in the formation of considerable hydrogen sulphide concentrations in the deep basins.

During the late 19th and the first three quarters of the 20th century, MBIs were recorded more or less regularly (Figure 2). Since the mid-1970s, their frequency and intensity have decreased (Schinke and Matthäus, 1998). The abiotic environmental conditions changed dramatically during this period, which culminated in the two most significant stagnation periods, from 1977–1992 and from 1995 onward, ever observed in the Baltic Sea (cf. Figures 3, 4).

The general meteorological conditions during the 1990s were characterized by a series of mild winters, several unusually warm summers and above normal precipitation. The winter run-off (September–March) was unusually high since the late 1970s (cf. Figure 2). Details are published in Bergström and Matthäus (1996), Bergström et al. (2001), and Matthäus et al. (2002).

The general hydrographic conditions were characterized by both mainly positive anomalies in sea surface temperatures (SSTs) in winter due to the mild winters and positive anomalies in SST (cf. also Siegel et al., 1999) in the upper layer during summer (cf. e.g. Matthäus et al., 1998) due to the unusually warm summers. The latter caused temperatures between 20°C and 23°C in the upper 15 m layer of the open Baltic Sea. Positive anomalies of 5–6 K
were recorded in the central Baltic in the unusually warm summers of 1994 and 1997 (Nehring et al., 1995a; Matthäus et al., 1998). Since the late 1970s, a decrease in surface salinity has been observed (cf. also Samuelsson, 1996).

During the first half of the 1990s, the conditions in the central Baltic deep water were dominated by the late phase of the long stagnation period 1977–1992 (Matthäus, 1990; Nehring and Matthäus, 1991, 1991/92; Nehring et al., 1993), by the effects of the very strong inflow of saline and oxygen-rich water in January 1993 (Håkansson et al., 1993; Jakobsen, 1995; Matthäus and Lass, 1995) and the subsequent weak inflow events in 1993/1994 (Nehring et al., 1995a). The second half was characterized by the early phase of a new stagnation with a large extension of areas of oxygen depletion and anoxic conditions. A weak inflow in early autumn 1997 caused extraordinary high temperatures in the deep water (Matthäus et al., 1999).

This article is focused on the hydrographic–hydrochemical conditions of the Baltic Sea during the 1990s in relation to changes during the 20th century. The main basis for hydrographic and nutrient data is the ICES and HELCOM database and the data collected under the German National Monitoring Programme 1969–2000. Numerous tables on annual means of hydrographic data and nutrient concentrations during the 1990s are given in Matthäus et al. (2001).

Conditions during the 1990s

Stagnation in the central Baltic deep water

Stagnation is a natural process in the deep water of nearly completely landlocked sea areas like the Baltic Sea. Stagnation periods are characterized by the depletion of nitrate, increasing phosphate and ammonium concentrations and decreasing salinity and oxygen depletion due to remineralization of organic material that has settled from the surface layers. This can completely consume the dissolved oxygen, thereby creating anoxic conditions and leading to the formation of considerable concentrations of hydrogen sulphide.

Role of the Bornholm Basin

Realizing the topography of the Baltic Sea along the main transport route of the inflowing saline water (cf. Figure 1A), the thermohaline conditions in the first Baltic deep basin downstream from the entrance sills, the Bornholm Basin, are of considerable importance for the evolution of stagnation in the central Baltic deep water. In general, there is a frequent inflow of lower amounts of highly saline water which penetrates across the sills into the Arkona Basin during each baroclinic or weak
barotropic inflow event. This water is trapped in the Bornholm Basin, renewing the ambient deep water to a certain extent and causing an annual variation in the deep water.

The filling stage of the Bornholm Basin with saline water, below the permanent halocline, is a measure of the estimation of the impact of weak inflows on the central Baltic deep water. During periods of low inflow activity, salinity and thus density of the Bornholm Basin deep water decreases (Figure 3). Depending on the inflowing volume of saline water, weak inflows and even MBIs only fill up this basin and the saline water generally does not pass the Stolpe Sill downstream through the Stolpe Channel into the central Baltic.

When the buffering capacity of the Bornholm Basin is exhausted, weak inflows of saline and oxygen-rich water crossing the entrance sills into the
Baltic can pass that basin in depths of 50-60 m, propagate downstream relatively quickly and cause significant effects in the central Baltic deep water.

Stagnation period during the 1990s

The inflow into the Bornholm Basin strengthened during the early 1990s and both salinity and oxygen concentration increased in the deep water of that basin (cf. Bornholm Deep in Figures 3 and 4). In the central Baltic deep water, however, salinity continued decreasing. The stagnation period with high hydrogen sulphide concentrations in the deep water continued in the eastern Gotland Basin (Gotland and Farö Deeps), while the oxygen concentrations of the western Gotland Basin deep water (Landsort and Karlsö Deeps) increased until 1993.
The MBI in January 1993 filled up the Bornholm Basin with highly saline and oxygen-rich water (Figures 3, 4); the impact on the central Baltic deep water remained small (Nehringer et al., 1994). In May 1994, the deep water of the whole Baltic Sea was free of hydrogen sulphide. In the 200 m level of the Gotland Deep, temperature decreased by 1.1 K and salinity increased by 1 (Figure 3). The oxygen concentration of 3–3.8 cm$^3$ dm$^{-3}$ measured between 170 m depth and bottom were the highest since the 1930s (Figure 4 and Mattheus, 1990).

The absence of MBIs since then has resulted in a new stagnation period in central Baltic deep water. After the renewal, oxygen depletion started and anoxic conditions developed (cf. Figure 4). In the deep water of the western Gotland Basin, continuous oxygen depletion started in 1993 (cf. Landsort and Karlsö Deeps in Figure 4). The decrease in oxygen concentration, which is characteristic of this basin for the early phase of stagnation periods (Matthäus, 1995), led in 1993 to the lowest oxygen content since the mid-1980s and the formation of hydrogen sulphide in the near-bottom layers (Figure 4).

The weak inflow events in December 1993 and March 1994 transported cold, saline, and oxygen-rich water into the central deep basins. The temperatures below 100 m depth in the Gotland Deep decreased from >5°C at the beginning of the year to 4–4.5°C in May 1994. Temperatures of 4°C are among the lowest values observed in the deep water of the Gotland and Färö Deeps during the present century (cf. Matthäus et al., 1999).

The exceptionally high SSTs in summer 1997 led to an unusual increase in deep water temperatures in late autumn due to an inflow in September and early October. This inflow of warm (7–8°C), saline (14–15), and oxygen-rich deep water (2 cm$^3$ dm$^{-3}$) reached the Gotland Deep in spring 1998. As a result, temperature and salinity increased to >7°C and 12.7, respectively, in the near-bottom water. The inflow process into the central Baltic was settled in May 1998 (cf. Hagen and Feistel, 2001).

In 1999/2000, the areas of both oxygen deficiency and anoxic conditions in the central Baltic deep water reached their largest extent since 1993.

Nutrient situation in the deep water during the 1990s

The nutrient situation in the deep basins is mainly characterized by the alternation between MBIs and stagnation periods. In the presence of oxygen, phosphate is partly bound in the sediment and onto sedimented particles as iron-III-hydroxophosphate complexes, resulting in phosphate concentrations of only 1–2 μmol dm$^{-3}$ (compare Figures 4 and 5). If the redox status changes, this complex is reduced by hydrogen sulphide. Phosphate and iron-II-ions are liberated.

Inorganic nitrogen compounds are also strongly influenced by the presence or absence of oxygen and hydrogen sulphide, respectively. Under aerobic conditions, inorganic nitrogen compounds are present nearly exclusively in the oxidized form as nitrate. Under anoxic conditions, the available nitrate is denitrified to dinitrogen gas. On the other hand, ammonium, which is liberated due to the mineralization processes, cannot be oxidized. As a result, ammonium is enriched and nitrate vanishes.

The water renewal during the first half of the 1990s and the subsequent development of a new stagnation period can be recognized most distinctly by the variations of nutrient concentrations in the eastern Gotland Basin (cf. e.g. Gotland and Farö Deeps in Figure 5). At the end of the 16-year stagnation period in 1992 hydrogen sulphide concentrations up to 8 cm$^3$ O$_2$ dm$^{-3}$, in the near-bottom layer up to −10 cm$^3$ O$_2$ dm$^{-3}$, were measured with a high degree of variability (Figure 4). The nutrient situation is characterized by the absence of nitrate and nitrite and a considerable enrichment of ammonium up to 40 μmol dm$^{-3}$ (Nehringer et al. 1995).

In 1993, the nutrient distribution reacted distinctly to the changes in the redox regime in the eastern Gotland Basin (for phosphate, cf. Figure 5) despite the impact of the January event remaining small in the central Baltic. Ammonium decreased strongly and was not detectable in June and August 1993. Nitrate concentrations increased and the amount of phosphate was reduced (Nausch and Nehring, 1994). But the layer below 200 m depth became anoxic again in November 1993. Only the weak inflows at the end of 1993/beginning of 1994 resulted in a longer improvement in the aerobic situation in the Gotland Deep (Figure 4) due to their fast penetration into the eastern Gotland Basin. As a result, lowest annual means in phosphate (Figure 5) and ammonium concentrations but highest nitrate concentrations were observed in 1995 before the new stagnation had started. From mid-1998 onwards, when permanent anoxic conditions prevailed, nitrate was not detectable and phosphate and ammonium concentrations were increasing. However, the concentrations had not yet achieved the high values measured at the end of the stagnation period 1977–1992 (Figure 5). The development in the Faroe Deep can be compared with the conditions in the Gotland Deep, but the processes are delayed and reduced in their intensity due to the submarine sill between the two basins.

In the western Gotland Basin, nitrate concentrations in the 1990s were stable over a longer period with around 10 μmol dm$^{-3}$. At the end of 1998, however, oxygen conditions had depleted so much that denitrification could take place (Goering, 1968).
Figure 5. Long-term variation of phosphate concentrations in the central Baltic deep water during the second half of the past century.

resulting in a decrease in nitrate which is clearly marked in 1999. In 1999, the highest ammonium concentrations were measured (Matthäus et al., 2001). The increase in phosphate concentrations, especially in the Landsort Deep, is lower compared to the eastern Gotland Basin (Figure 5), probably because of the different structure of the sea floor. This development in nutrient balance seems to be characteristic for the early stage of stagnation.

State of eutrophication during the 1990s

The increasing supply of inorganic nutrients due to human impacts in the drainage area and the subsequently increasing primary production are known as eutrophication. Therefore nutrients have been used to describe the state of eutrophication. Phosphate and nitrate are the final products of biochemical
mineralization of organic matter under aerobic conditions. They are therefore the most important nutrients in trend analysis.

In the whole Baltic Sea, the nutrient concentrations are characterized by a pronounced seasonality with high concentrations in winter and often a decrease near to the detection limit during the period of high biological activity beginning in spring and ending in late autumn (Nausch and Nehring, 1996). For nutrient trend studies only the mixed surface layer in winter can be used when the biological productivity is low and nutrient concentrations are high (Nehring and Matthäus, 1991; Nausch and Nehring, 1996). The duration of this “winter plateau” differs in the Baltic Sea regions and is best developed in the eastern and western Gotland Basins (Matthäus et al., 1998). In general, trend analysis should identify long-term developments in relation to changes in load. In the past decade, they have to answer the question whether reduction measures, initiated within the Joint Comprehensive Environmental Action Plan (Helcom, 1993) and by the decrease in fertilizer application in the drainage area (Nehring et al., 1995b), result in decreased phosphate and nitrate concentrations in the mixed winter surface layer.

This can be shown more clearly by comparing the periods 1989/1993 and 1994/1998 (Figure 6). Comparing the second with the first half of the 1990s, a distinct decrease in phosphate winter concentrations was identified, mainly in the nearshore areas of the western Baltic (Lübeck, Mecklenburg and Pomeranian Bights), but also in the central Baltic Sea (Figure 6A). Measures undertaken to reduce phosphate input from point sources in the drainage area seem to be effective. A clear relation can be drawn to the riverine discharge. Thus, the phosphate concentrations in the Oder river decrease from 1986 to 1999 (Helcom, 2002). Recent measurements, however, show that a new equilibrium is already established, and therefore a further decrease in phosphate concentrations cannot be expected. But this reduction is not evident in all regions. For example, phosphate concentrations have increased in the inner Gulf of Gdansk, thereby influencing the whole bight. The reasons can be assumed to be less effective reduction of phosphate discharge from point sources and the specific character of the Vistula river drainage area dominated by diffuse nutrient inputs (Helcom, 2002).

Nitrate concentrations do not show any significant decrease between both periods in most of the investigated regions. Moreover, the concentrations in the Pomeranian Bight and in the Gdansk Bight are higher (Figure 6B). Several reasons can be mentioned for the failing reduction. In the central Baltic Sea, the atmospheric input still plays an important role despite first signs of positive developments for this route (Helcom, 1997). Also the yearly input of nitrogen through nitrogen-fixing cyanobacteria in summer must be taken into consideration (Wasmund et al., 2001). The most important reason, however, is that nitrate originates mainly from diffuse sources in the drainage area.

Figure 6. Changes in phosphate (A) and nitrate+nitrite concentrations (B) in the winter surface layer (February; 0–10 m depth) of the western and central Baltic Sea during the periods 1989-1993 (left column) and 1994-1998 (right column).
Thus the input into the coastal areas is closely related to the freshwater run-off (Pastuszak et al., 1996; Nausch et al., 1999). Therefore reduction measures are much more complicated to convert and need longer time perspectives.

Climate change and Baltic deep water

Backhaus (1996) investigated the climate sensitivity of the Baltic Sea based on regional model results. According to him the Baltic seems to be much more susceptible to climate change than the North Sea because of a strong feedback between sea surface and air temperatures with the haline stratification.

Air–sea interactions are a main source of the observed variability in seas in time scales ranging from years to centuries. On decadal time scales, variations in atmospheric circulation over the northern Atlantic Ocean and Europe govern fluctuations in the water exchange between the North Sea and the Baltic and are mainly reflected in marine climatic changes in the central Baltic deep water (e.g. Hupfer, 1975; Makkonen et al., 1984; Matthäus, 1984; Launiainen and Vihma, 1990; Matthäus, 1995).

The schematic diagram in Figure 7 illustrates the pathway of the influence of the atmospheric circulation on the central Baltic deep water. The variability in atmospheric circulation governs the water exchange of the Baltic with the ocean, especially the occurrence or absence of major inflows (Matthäus and Schinke, 1994; Gustafsson, 2000). MBIs have an essential impact on the oceanographic conditions in the deep water (temperature, salinity, oxygen, inorganic nutrients). There are indications that MBIs may also affect the transformation of contaminants (PAHs) and the modification of their distribution in the deep water (cf. Witt and Matthäus, 2001). There seems to be an impact of run-off variation on the occurrence of MBIs. Drastic changes in environmental conditions in the deep water can be explained by increased zonal circulation linked with more intensive precipitation in the Baltic region and increased river run-off into the Baltic (Matthäus and Schinke, 1999; Hänninen et al., 2000; Zorita and Laine, 2000). Launiainen and Vihma (1990) demonstrated a correlation between river run-off and Baltic deep water salinity (cf. also Samuelsson, 1996). There is also a connection between aerobic/anoxic conditions and the concentration of inorganic nutrients (Nehring, 1987, 1989).

Changed conditions in the central Baltic deep water could be an indicator of climate change. Climate model simulations predict a climate change due to the increasing concentrations of greenhouse gases and sulphate aerosols in the atmosphere. World-wide human activities may already have affected the global climate (Storch and Hasselmann 1995; Santer et al., 1996; Hasselmann, 1997) and caused changes in the atmospheric circulation affecting the water exchange between the North Sea and the Baltic. The sensitivity of MBIs to variations in climatic factors has been modelled by Gustafsson (2000) and Gustafsson and Andersson (2001).

An attempt to analyse potential impacts of future climate change on the run-off from the drainage area to the Baltic Sea indicated that global warming may lead to a changed annual cycle and less pronounced spring run-off as winters become less stable (Graham et al., 2001). Run-off seems generally to increase from the northernmost parts of the drainage area and decrease to the central Baltic.

In order to estimate the impact of climate change on the central Baltic deep water the effects of human activities on the deep water must be identified. Man-made impacts affect the concentration of both inorganic nutrients (cf. e.g. Elmgren 1989; Jansson and Dahlberg, 1999; Nausch et al., 1999; Wulff et al., 2001) and contaminants (cf. e.g. Helcom, 1991, 1997, 1998; Bernes, 1999; Skei et al., 2000; Elmgren and Larsson, 2001; Wulff et al., 2001) in the surface layer via land-based (point and diffuse sources) and airborne inputs (precipitation). Increases in nutrient levels lead to higher organic productivity in the euphotic layer (Cederwall and Elmgren, 1990; Wulff et al., 1990). This causes an increase in dead organic material partly loaded with contaminants which, settling to the bottom, have an impact on both oxygen regime and concentrations of contaminants in the deep water. Both the lack of MBIs and man-made impacts are responsible for oxygen depletion and increase in hydrogen sulphide concentrations. However, it is not possible presently to state how much of this variability is due to which cause. Moreover, there are indications that the man-made

![Figure 7. Schematic diagram of the influence of variability in atmospheric circulation on the central Baltic deep water.](image-url)
Conclusions

During the 1990s, a distinct decrease in phosphate winter concentrations but no significant change in the nitrate concentrations of the mixed winter surface layer was observed. The general tendency of decreasing frequency and intensity of MBIs continued, interrupted only by the very strong single MBI in January 1993.

Investigating the long stagnation periods in the Baltic deep water, there are similarities between the current stagnation period and the stagnation in 1977–1992. The maximum extent of oxygen deficiency and anoxic conditions occurred during both periods about 5–7 years after a strong MBI, i.e. 1982/1983 during the previous stagnation and 1999/2000 during the present stagnation period. After 1982/1983, an increase in oxygen concentration started in the western Gotland Basin deep water (cf. Landsort and Karlssö Deeps in Figure 4) and is assumed to be caused by both increased vertical exchange due to decreasing stability of the water column and the effects of weak inflows. The water of such inflows propagates along the main transport route (cf. Figure 1A) and can relatively quickly pass the eastern Gotland Basin at intermediate depths below the halocline. Because of the density it can penetrate up to the near-bottom layers of the western Gotland Basin.

The area of central Baltic deep water affected by oxygen deficiency and anoxic conditions at the turn of the century was the largest for 15 years. In general, the anoxic layer seems to be thickest when the area affected by oxygen deficiency and anoxic conditions is largest. This was also observed during the stagnation period of 1977–1992. As the stagnation continues the redoxcline moves to greater depths because of weak inflows in intermediate layers below the permanent halocline, and the hydrogen sulphide concentrations increase in the deep water. In general, an intensive phosphate accumulation occurs at the beginning of stagnation periods. Thereafter, the concentrations increase only slowly and fluctuate around an average (cf. Figure 5). The phosphate reserves seemed to be exhausted and the further increase in hydrogen sulphide concentrations did not result in a further liberation of phosphate.

If the decrease in frequency and intensity of MBIs and, thus, the present stagnation in the central Baltic continue, a decrease in the extent of areas affected by oxygen deficiency and anoxic conditions in the deep basins and a further increase in hydrogen sulphide concentration in the deep water of the eastern Gotland Basin will occur. However, an increase in oxygen concentration can be expected in the deep water of the western Gotland Basin starting within the next few years.

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