

# The North Atlantic Climate Influence on the Baltic Sea Environment

by

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## **ABSTRACT**

*The prevailing local weather has a direct influence on the Baltic Sea environment. Thus, it is probable that it is also influenced by large scale atmospheric patterns like the North Atlantic Oscillation (NAO). A high NAO winter index, corresponds to an anomalous pressure difference between the Azores high and the Iceland low, resulting in increased westerlies with an increased advection of mild air masses leading to mild winters. A low NAO winter index, corresponds to weak westerlies, with increasing influence by the Eurasian winter high, leading to severe winters in the Baltic Sea. In the present study the influence of the North Atlantic climate, as described by the NAO index, is investigated with respect to its possible impact on biological, chemical and physical conditions prevailing in the Baltic Sea. These variations are compared with the known fluctuations in fish stock and food supply. It is argued that the NAO has an impact on the internal circulation of the Baltic Sea and the water mass exchange with the North Sea, hence, influencing oxic/anoxic conditions in the Baltic Sea deep basins. The study of geological sediment records from the deep basins provides information on the extent and duration of anoxic periods during the recent past, where the NAO index is available, and also during the past millennia to give a proper temporal perspective to variations in Baltic Sea conditions prior to human impact.*

## **INTRODUCTION**

The North Atlantic Oscillation (NAO) as a phenomenon responsible for climate variability in Europe has only recently become a topic of increasing interest, although the relationship between the NAO and the local climate in Europe was already mentioned by Defant (1924). The importance of the NAO for many areas in climate research including its influence on the climate of neighbouring continents as well as the ocean has been presented in a number of publications (for a review see CLIVAR implementation plan, 1998). Quantification of the NAO is generally given as an index value defined as the difference between normalized sea level pressure of the Azores high and the Iceland low.

Positive NAO index values indicate stronger-than-average westerlies over the middle latitudes associated with low pressure anomalies over the region of the Iceland low and anomalously high pressure across the subtropical Atlantic. The NAO is a major source of inter annual variability for both weather and climate. Since 1980, the NAO index has remained in a highly positive phase (figure 1), with the winters of 1983, 1989 and 1990, marked by the highest positive values of the NAO index recorded since 1864 (Hurrell and van Loon, 1997).

The NAO is related to the strength and geographical position of weather systems as they cross the North Atlantic, which in turn determine precipitation (Hurrell, 1995) and sea surface temperature (Planque and Taylor, 1998). The NAO is also likely to have an impact on the direction and flow of currents, the height of waves, wind mixing and the stability of the water column.

The hydroclimatic response to the NAO is also evident in changes in ecosystems: This was demonstrated in the North Sea by abundance variations of *Calanus finmarchius* which was inversely and highly significantly correlated with the NAO index (Fromentin and Planque, 1996). Significant changes have been observed for different biological parameters in the North Sea after 1987 (Reid et al., 1998) which indicated the beginning of what appears to have been a regime shift in the ecosystem. The new ecosystem regime coincided with the highest consistently positive NAO index (after 1988-1995) of this century. As part of a hydrodynamic response to the atmospheric changes, there is evidence for possibly stronger advection of warmer water from off

the coast of Iberia northwards in the shelf edge current to the west of the UK and into the northern North Sea (Reid et al., 1998).

For the Baltic Sea, the influence of the NAO on sea ice conditions was reported by Koslowsky and Löwe (1994) and Koslowsky and Glaser (1999). Statistically significant relations between the ice extent of the Baltic Sea and both the NAO winter index and the winter geostrophic wind over the Kattegat was described by Omstedt and Chen (1999). The causes of major Baltic inflows and their relation to atmospheric circulation patterns was reported by Matthäus and Schinke (1994) and Schinke and Mathäus (1998).

In a recent paper Lehmann *et al.* (2000) investigated the impact of high and low NAO indices on the dynamics of the Baltic Sea. They showed that the sea level pressure difference between the Skagerrak and the western Baltic Sea accounts for more than 60 % of the variability of the water mass exchange. The sea level pressure difference between those two sites was highly correlated with the NAO index.

In this paper we describe a possible impact of the North Atlantic climate variability on the physical, chemical and biological conditions in the Baltic Sea ecosystem. Within the EU-BASYS (Baltic Sea System Study) all available long-term data series on the upper part of the pelagic food web, crustacean zooplankton and fish, from the Baltic Proper and surrounding coastal regions such as the Finnish Archipelago Sea, coastal bays of Sweden and the Gulf of Riga have been collected. The three most important fish species, cod, herring and sprat, are all exposed to heavy fishing pressure. Their dynamics and those of their major prey, crustacean copepods, are governed by external physical forcing, biological interactions (mainly predation) and anthropogenic influences, particularly fishing activities and habitat alteration. Fishing and, maybe, habitat alteration might also seriously affect copepod dynamics through food chain effects which can cascade down from top predators to lower trophic levels (Möllmann and Köster, 1999).

A whole suite of climate parameters such as the NAO index, sea level pressure, SST, sea ice extent, accumulated aerial ice volume and fresh water run-off was tested for correlation with the biological data series. All these climate parameters are strongly cross-correlated with each other (Dippner and Ikaunieca, 1999). Salinity was also included in the correlation analysis. However, the haline stratification in the Baltic Sea is mainly controlled by occasional salt water intrusions and river runoff, with dramatic changes in the haline stratification happening only during major Baltic inflows (Matteus and Schinke, 1994). Such inflows lead to extended periods of anoxia in the deep basins.

In order to understand the possible correlation between these salt water intrusions and the NAO, long sediment cores representing the past 8000 years of deposition were included in the study. Detailed biological, chemical and physical analysis of the sediments provided information on the alternations between oxic and anoxic conditions in the deep basins. Whether changing redox conditions are able to mobilize nutrients from the deeps and for them to have an effect on the bioproductivity at the surface through upwelling could not at present be ascertained. To what extent this might be controlled by the NAO can only be revealed by future process studies and modelling exercises. Comparative regional analysis is necessary to ascertain the possible influence of climate on nutrient availability and zooplankton and fish populations.

## PAST DECADES AND PRESENT

Although the NAO is generally defined as the difference between normalized sea level pressure differences (SLP) of the Azores high and the Iceland low, several other indices of the NAO can be found in literature. They differ primarily in the choice of the southern station, the proxy for the Azores high, and therefore in the length of the record. Since SLP measurements at the Azores starts in 1865 but earlier measurements are available from Iceland and the Iberian Peninsula, longer NAO indices can be constructed by using the SLP from Gibraltar as a southern proxy (Jones *et al.*, 1997). However, these longer NAO indices are good proxies only during winter and early spring, because of the western shift of the Azores high during the other seasons (Hurrell and van Loon, 1997; Mächel *et al.*, 1998). In this study, we used the NAO index based on SLP observations from the Azores and a composite from different sites in south-west Iceland, as determined by Jung *et al.* (1999) (Fig. 1).

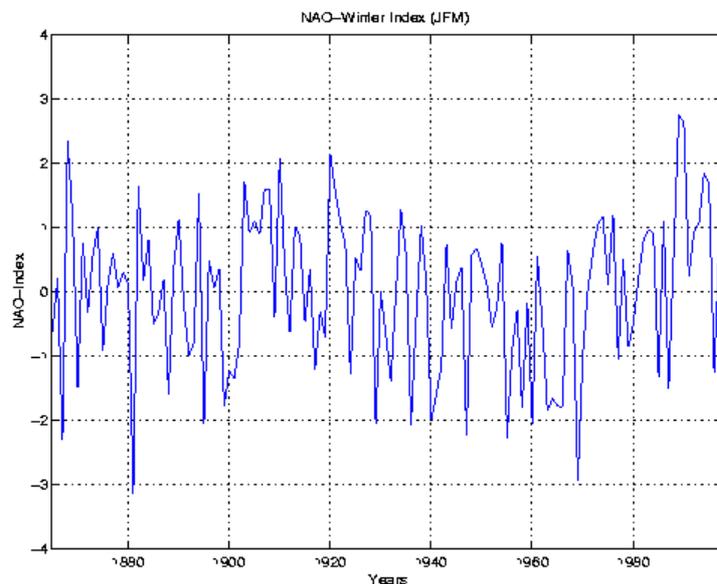


Figure 1. NAO winter index(JFM) for the years 1865-1997, after Jung *et al.* (1999).

By means of statistical analysis Jung *et al.* (1999) objectively defined the NAO winter season to the months January, February and March (JFM), which according to Hurrell (1995) do indicate some inter-decadal variability. Extending the definition of the winter season towards December and November will reduce the inter decadal variability. Enhanced westerlies can be identified during the beginning and the end of this century, and reduced westerlies can be found from about 1940 to 1970 (Fig. 1). However, the temporal evolution of monthly mean values of the NAO reveals a considerable intra-annual variability, with high fluctuations from month to month, but, nevertheless there are also periods of relatively persistent anomalies, like in the 1990s (Fig.2).

In the Baltic Sea the major inflow of 1976/77 caused the longest observed stagnation period lasting for about the 16 years. It caused a strong decrease in the haline stratification in the Baltic Proper and the formation of anoxic conditions in most of the Baltic Sea deep basins. Figure 2 shows that during this period the NAO winter index, on average, remains in a highly positive phase, with maximum values during 1989 and 1990, implying atmospheric conditions favourable for extensive water mass exchange with the North Sea.

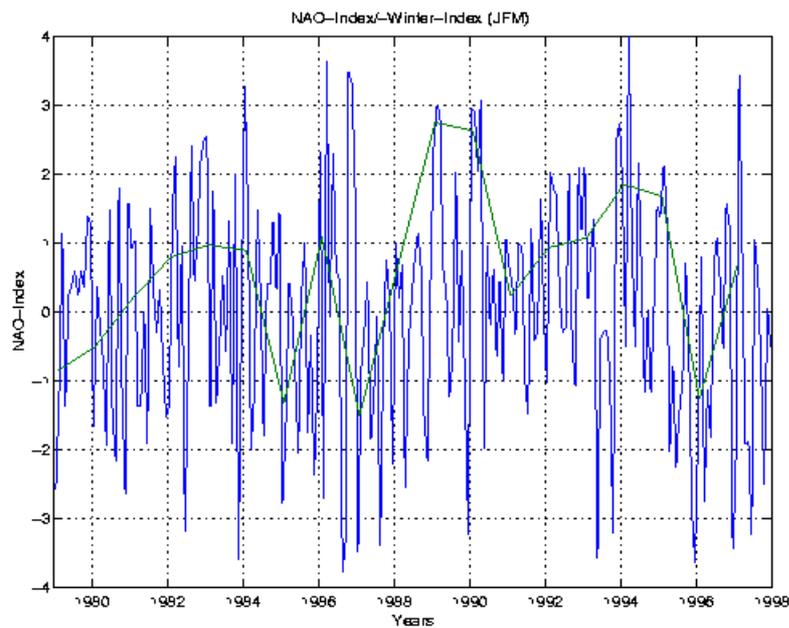


Figure 2. Monthly NAO index and NAO winter index (JFM) for the years 1979-1997, after Jung *et al.* (1999).

For the rest of this chapter we focus on the period from 1979 to 1998, because high resolution atmospheric data for the Baltic Sea are available from the SMHI meteorological data base (Lars Müller, pers. comm.). Additionally, from coupled sea ice-ocean model simulations (Lehmann and Hinrichsen, 1999a/b, Lehmann *et al.* 2000) the impact of changes in the atmospheric conditions on the Baltic Sea dynamics has been investigated.

### Atmospheric conditions during NAO+ and NAO- indices

Lehmann *et al.* (2000) defined a Baltic Sea index (hereafter BSI) which is the normalized sea level pressure difference between Oslo (Norway) and Szczecin (Poland). The BSI correlates well with monthly values of the NAO ( $r=0.52$ ) accounting for 27 % of the variance of the sea level pressure anomaly over the western Baltic Sea. Positive BSI corresponds to anomalous SLP with

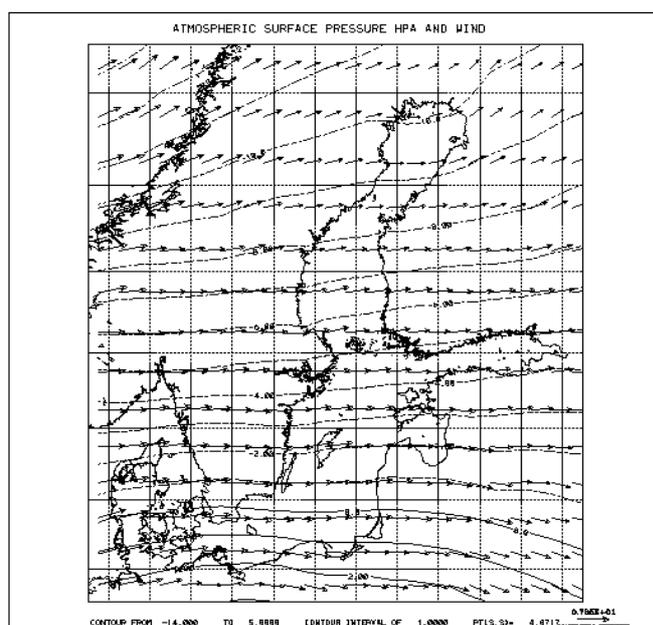


Figure 3. Anomalous SLP [hPa] and geostrophic wind [m/s], average over January, February and March 1987.

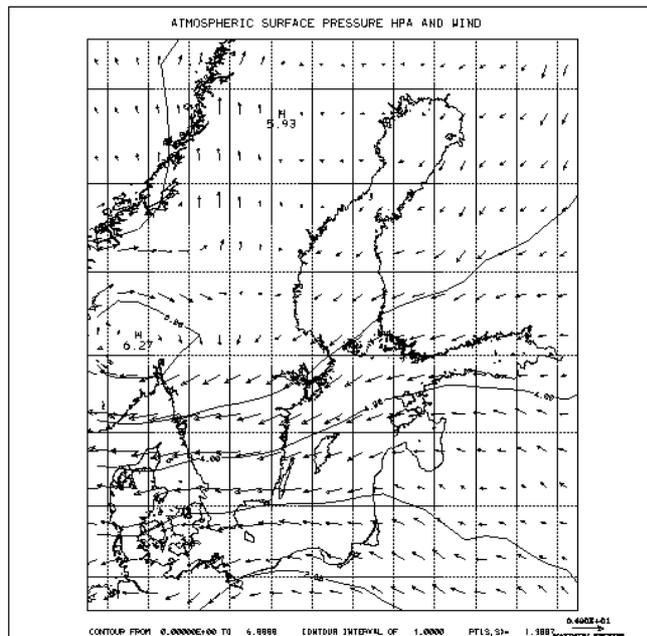


Figure 4. Anomalous SLP [hPa] and geostrophic wind [m/s] average over January, February and March 1989.

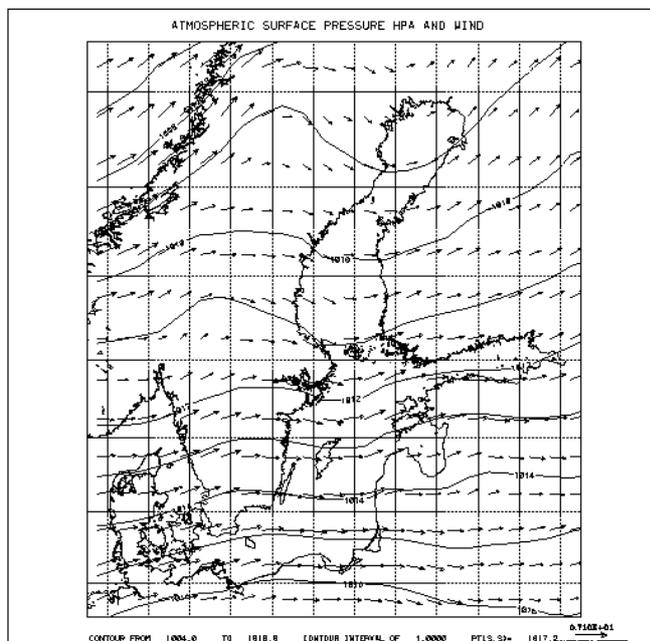


Figure 5. Mean SLP [hPa] and geostrophic wind [m/s], average over 1979 to 1998.

westerly winds over the Skagerrak/Kattegat and the western Baltic Sea, which pile up the water in the Kattegat and lower the sea level in the western Baltic, yielding inflow. Negative BSI corresponds to easterly winds favouring outflow conditions. Typical anomalous sea level pressure distributions of NAO+ and NAO- indices are depicted in Figs.3 and 4. In 1987 a severe winter caused almost the entire Baltic Sea to freeze over (Haapala and Leppäranta, 1996). Correspondingly, the NAO (-1.5) and BSI (-4.1) show minimum values. The centre of an anomalous high pressure cell was situated over Scandinavia leading to easterly winds over most parts of the Baltic Sea and favouring outflow conditions. In 1989, the winter was mild with ice only in the most northern and eastern parts of the Baltic Sea. The NAO (2.75) and BSI (7.6) reached a local maximum, and correspondingly strong westerly winds over the total Baltic Sea area occurred (Fig. 4). For comparison the mean SLP and geostrophic wind field is depicted in Fig. 5. The 20-year average shows a zonal SLP distribution with mainly westerly winds reaching wind speeds up to 7 m/s.

### General circulation during NAO+ and NAO- indices

The Baltic Sea, with its mean depth of approximately 55 m. responds instantaneously to changes in atmospheric forcing. Due to the ephemeral nature of the atmospheric wind and air pressure field over the Baltic Sea, the corresponding current field is highly fluctuating. However, if the currents are averaged over a certain period (monthly or annually), a characteristic circulation can be obtained. Lehmann and Hinrichsen (1999) showed that the 4-year-average of the barotropic circulation of the Baltic Sea revealed rather persistent cyclonic circulations cells comprising mainly the subbasins with less transport between. With an averaging period of about one month, persistent circulation patterns will be obtained.

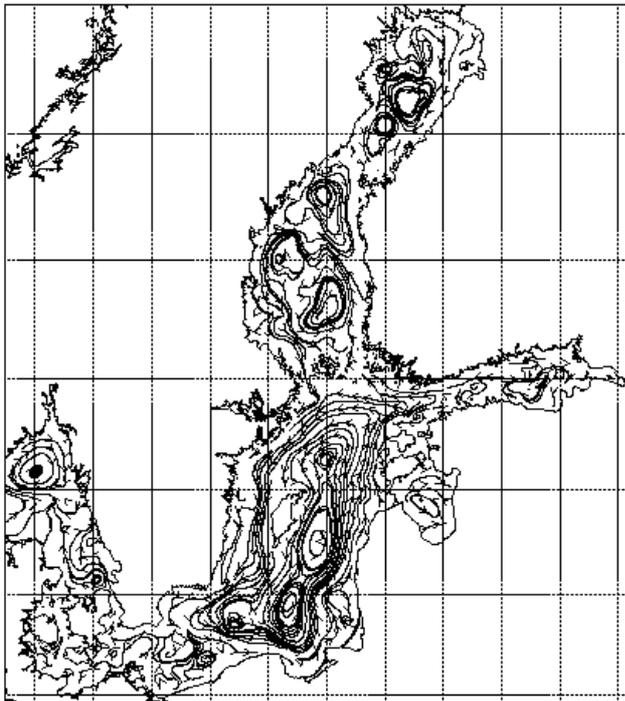


Figure 6. Streamlines representing the averaged circulation of the Baltic Sea for January, February and March 1987.

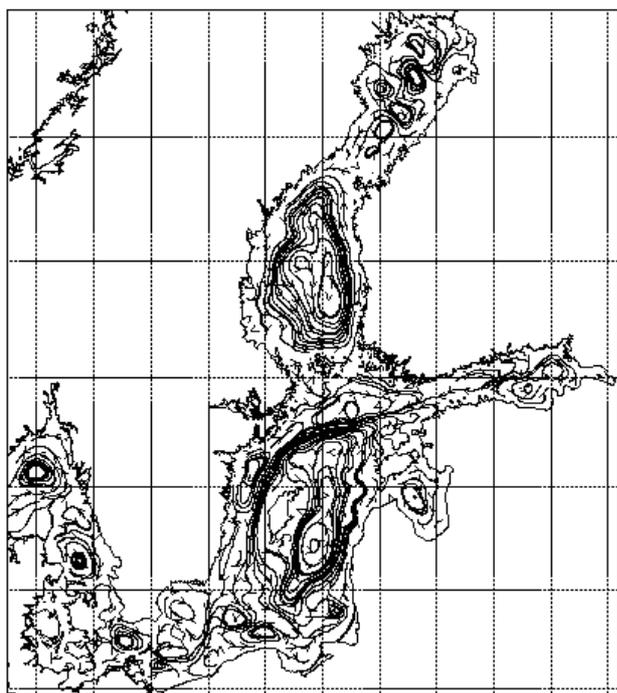


Figure 7. Streamlines representing the averaged circulation of the Baltic Sea for January, February and March 1989.

A period of strong westerly winds will force a different circulation in the Baltic Sea than one induced by a period of easterly winds. Thus, changes in the atmospheric conditions apparent in the monthly average will cause corresponding changes in the circulation and water mass exchange with the North Sea. The changes in the winter circulation (average over January, February and March) for 1987 and 1989 are depicted in Fig. 6 and 7, respectively. The barotropic transport is represented by streamlines giving only information about the directional characteristics of the flow field without the variations in the intensity. For annual averages, the highest transports of about 1000 - 2000 km<sup>3</sup>/year can be found in the branches of the cyclonic circulation cell comprising the Baltic Proper (Lehmann and Hinrichsen, 1999a/b). For the winter 1987, a pronounced circulation cell covering the Gotland Basin and Bornholm Basin with a return flow through the Stolpe Channel is obtained. Several smaller cyclonic and anticyclonic cells can be found in the eastern Gotland Basin, the Gulf of Bothnia, Gulf of Finland, Gulf of Riga and in the Kattegat/Skagerrak (Fig. 6).

### **Atmospheric conditions during NAO+ and NAO- indices**

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From January to March 1987, the Gulf of Bothnia and the Gulf of Finland were mainly covered by sea ice which modifies the momentum flux from the atmosphere to the ocean. Thus, the corresponding circulation cells could not be directly excited by the wind. In contrast, for the winter 1989 (Fig. 7) the circulation is different for most parts of the Baltic Sea. Note, the changes in the directional characteristics of the flow in the Arkona and Bornholm Basin, the Gulf of Riga and also in the Kattegat and Skagerrak. It has been demonstrated in Lehmann *et al.* (2000) that a characteristic horizontal circulation pattern is associated with a corresponding vertical velocity field. It is obvious that the different atmospheric conditions cause differences in the three-dimensional circulation in the Baltic Sea.

As can be seen from Fig. 1, the intra-annual variability of the NAO is rather high, which is also the case for the BSI (Lehmann *et al.*, 2000). Thus, changes from a high to low index will cause significant changes in the circulation of the Baltic Sea and the water mass exchange with the North Sea. Furthermore, changes in characteristic circulation patterns from one case to the other will be accompanied by increased turbulent mixing and will thus have an influence on the environmental conditions (salinity, temperature, oxygen, nutrients, etc.) in the Baltic Sea.

Changes in the atmospheric conditions over the Baltic Sea cause changes in the circulation (advection and turbulent mixing) and as a direct consequence this will have an impact on the evolution of marine organisms and on sedimentary processes (erosion and deposition).

### **The impact of physical forcing on fish stocks**

The impact of climate variability on fish stocks can be direct, or indirect by physical forcing on their food organisms. Direct impacts are changes in temperature, salinity, current patterns, wind stress and wind direction.

Sprat is a zooplanktivorous species which is euryhaline and eurytherm. In the Baltic Sea, sprat lives at the border of its distribution area. It cannot tolerate very low salinity values as its pelagic eggs need at least 6 psu (Ojaveer, 1998). The abundance of sprat year classes is positively correlated with SST of the 0-40 m surface layer in spring and summer (Ojaveer et al., 1985; Ojaveer, 1998) and temperature is particularly critical for recruitment success of sprat, although a simple relationship is not to be expected (Schnack, 1997). Long-term dynamics of the Bohuslän herring in the Skagerrak are forced by the NAO (Alheit and Hagen, 1997). The euryhaline and eurotherm herring seems to be well adapted to Baltic Sea conditions and year-class strength is positively correlated with temperature (Ojaveer, 1998).

Despite being an eurytherm and euryhaline species, cod is insufficiently adapted to Baltic Sea conditions. During periods of low salinity, it cannot reproduce in the Gotland Basin and Northern Baltic Proper and its spawning activities are restricted to the western and southern deeps of the Central Baltic Sea. Its pelagic spawn needs minimum salinities of at least 11 psu (Ojaveer, 1998). Recruitment success of cod in the Baltic Sea depends on a number of factors including the size of the so-called "reproduction volume" which is determined by salinity and oxygen concentrations (Schnack, 1997; Ojaveer, 1998). The reproduction volume seems to be mainly influenced by aperiodic salt water inflows. Although these salt water intrusions from the North Sea are obviously influenced by the NAO, the nature of climate dependence of cod dynamics in the Baltic Sea remains obscure.

### **The impact of physical forcing on zooplankton**

The dynamics of crustacean zooplankton such as copepods and cladocerans, the main food source of the planktivorous herring and sprat, seem to depend largely on variations in SST and/or salinity. Table 1 gives a summary of correlations between long-term fluctuations of some zooplankton groups and of temperature and salinity which are statistically significant. As several climate parameters are cross-correlated with each other (Dippner and Ikauniece, 1999), the NAO index or sea level pressure can be taken as proxies for temperature. In some cases the same biological data series was analysed by different authors using different statistical methods. In all these cases, the results agreed with each other. Also, all species (except *Centropages hamatus* and *Limnocalanus macrurus*) or groups in this analysis were studied at least in two different subsystems of the Baltic Sea. Again, there was no contradiction in the relationships between long-term dynamics of zooplankton and temperature or salinity between different subsystems. Thus, results from different authors or from different subsystems support each other and indicate the validity of the results.

The smaller copepod species *Acartia* spp., *Eurytemora affinis*, *Temora longicornis* and *Limnocalanus macrurus* exhibit a positive correlation with temperature in the upper layer, usually in spring (Table 1). In some subsystems, *Acartia* spp., *L. macrurus* and *E. affinis* show a negative correlation with salinity, whereas *C.hamatus* and *T. longicornis* in the Finnish Archipelago Sea are positively correlated with salinity. The larger copepod *Pseudoocalanus elongatus* is positively correlated with salinity. The cladocerans *Bosmina longispina*, *Evadne nordmanni* and *Podon* spp. are positively correlated with temperature.

## Past Centuries and Millennia

Because of abundant precipitation and a large catchment area, the net outflow through the Danish Straits should keep the salinity of the Baltic Sea at a very low level, were it not for the sporadic massive inflows of saline North Sea waters. These inflows of saline waters into the Baltic Sea are, as stated above, governed by the weather (SLP and NAO). Thus, also the periodic development of anoxia in the deep basins of the Baltic Sea can be mainly attributed to climatic factors and not to man-made reasons, e.g. eutrophication. New geological records, i.e. long sediment cores from the deep basins, clearly show that oxygen depletion and anoxia has been a common phenomenon in the Baltic Sea ever since the beginning of the Litorina Sea phase 8000 years ago, when the previous Ancylus Lake became a brackish water basin as a result of the opening of the Danish Straits to the sporadic inflows of North Sea waters. In addition to a rather slow metachronous increase in salinity of the whole water body, (transitional phase Winterhalter 1992), it is obvious that occasional massive inflows also occurred (onset of the Litorina Sea).

Recent inflows of North Sea waters into the Baltic Sea have been studied by e.g. Matthäus and Lass (1995). Due to their higher density the inflowing waters have a tendency to spread as near-bottom gravity currents into the deep basins. Due to biodegradation of organic matter and poor vertical mixing these bottom-near waters may be depleted of oxygen, and anoxic conditions are formed. It is commonly accepted that due to lack of strong bottom-near currents and bioturbation, i.e. absence of benthic meio- and megafauna, the occurrence of laminated sediments are proof of rather persistent periods of anoxia (e.g. Emelyanov 1988, Winterhalter 1992, Sohlenius and Westman 1998, Lepland and Stevens 1998, E. Andrén 1999, Kunzendorf 1999)

A detailed study of long sediment cores from the Gotland Basin and from the Bornholm Basin (Andrén, T and Andrén, E. 1999) suggests that much of the environmental variability recorded in the sediments can be correlated with variations in the North Atlantic climate. It was also suggested by Kotilainen and Winterhalter (1999) that the alternation between laminated and homogenous sediment sequences could be correlated with climatic fluctuations recorded in Greenland ice cores, which in turn seem to be governed by the NAO. Furthermore, massive inflows of saline water seem to occur during positive NAO conditions.

## Anoxia in the deeps

A massive inflow of dense water from the North Sea is the prerequisite for the formation of a stable density stratification, halocline, isolating the bottom waters from vertical mixing with the waters above. Since mixing with oxygenated surface waters will not take place, the dissolved oxygen will be used up by benthic organisms and aerobic bacteria breaking down organic matter formed both *in situ* and derived from the detritus sinking from the photic layer. When the oxygen concentration falls below the acceptable minimum for the aerobic bacteria to survive, sulfate reducing bacteria take over biodegradation of organic matter. It is plausible that bacterial mats,

often found to cover soft seabed sediments, increase the sharpness of the redoxcline at the sediment/water interface. The highly reducing environment within the sediment leads to the formation of a suite of chemical compounds (minerals) typical of anoxic sediments.

The persistency of the bottom-near anoxia is a function of several factors, A new major inflow may flush out the anoxic bottom waters, or a slow but persistent inflow (“trickle”) of saline waters over a longer time period may keep the bottom waters sufficiently oxidized to facilitate bioturbation of the sediment surface. The destruction of the density stratification through turbulent mixing may also enhance oxygenation of the bottom waters. The formation of homogenous sediments (bioturbated) is an indication of faunal activity at the water/sediment interface.

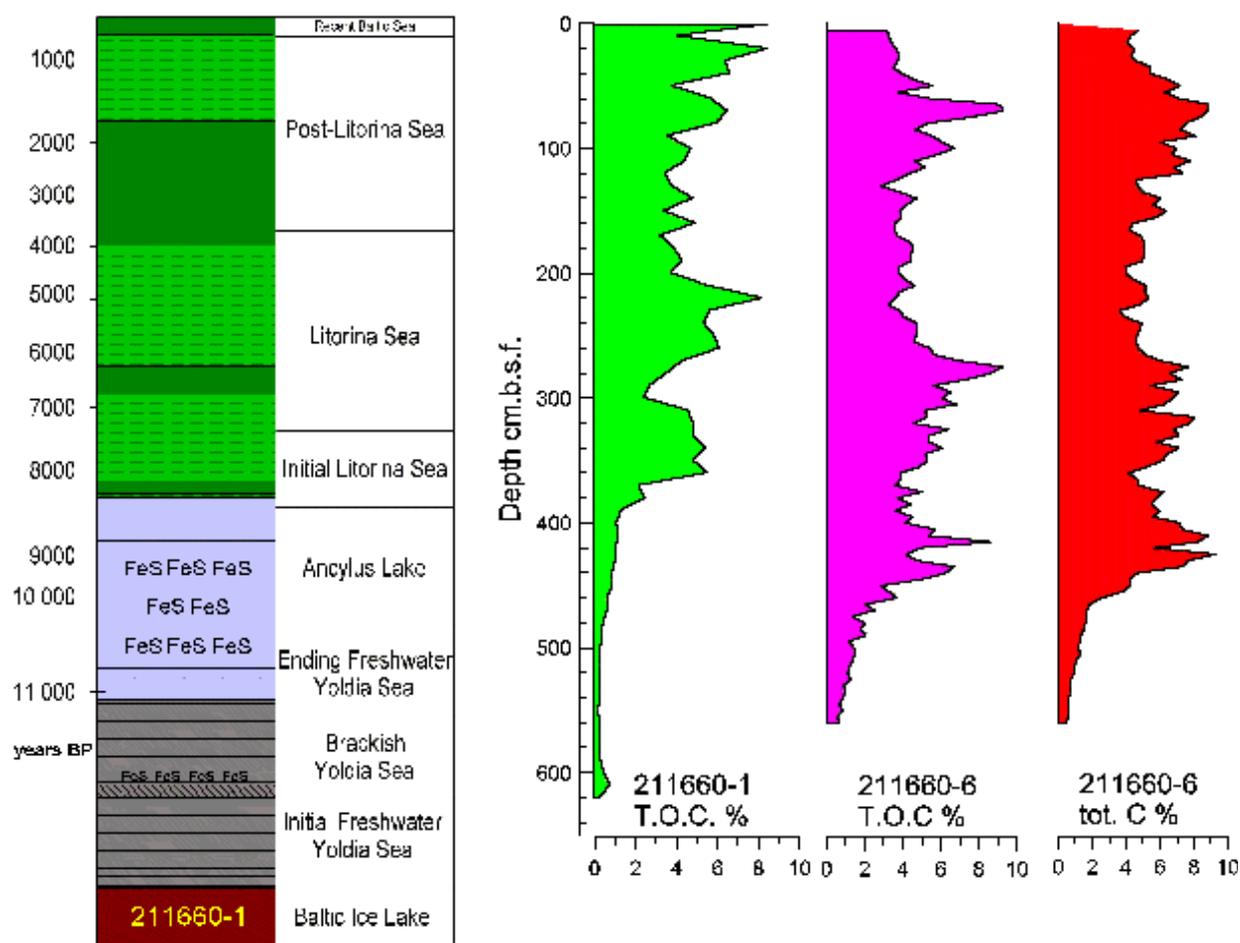
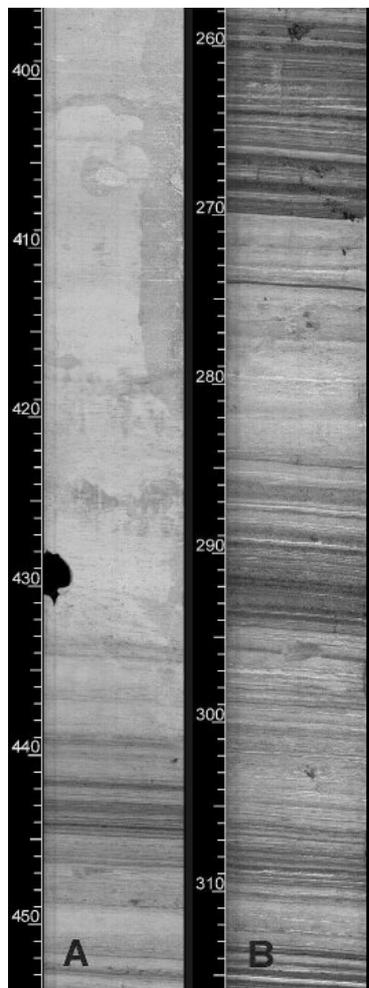


Figure 8 The carbon content in two cores (211660-1 and 211660-6) from the Gotland Basin taken about 100 metres from each other. The left hand stratigraphic column (courtesy of T. Andrén) shows the main phases in the Holocene development of the Baltic Sea. The graphs show the variations in total organic carbon in cores 211660-1 and 211660-6. The last graph shows the total carbon in core 211660-6 and clearly indicates that most of the carbon is of organic origin. Note that the Ancyclus/Litorina boundary in core 211660-1 is located at about 350 cm below sea floor, but in core 211660-6 the same boundary is at about 450 cm due to combined difference in core recovery and in rate of sedimentation. This is probably due to near-bottom currents, possibly induced by the saline inflows.

## The laminated sediments

With the opening of the Danish Straits some 8000 years ago, large quantities of saline water from the North Sea made their way into the Baltic Sea depression changing the fresh water Ancylus Lake into the brackish Litorina Sea, the precursor to the present Baltic Sea. According to T. Andrén (pers. comm. , and Andrén and Andrén 2000) some inflows of saline waters had occurred earlier as a result of rising sea level and the opening of the Öresund strait around 8800 cal yr BP.



This also explains the slow rise in the content of organic carbon observed in the sediments deposited at the end of the Ancylus Lake stage. Winterhalter (1992) suggests that the waters of the preceding Ancylus Lake phase were probably rather turbid due to abundant meltwater, but that rapid flocculation of the suspended mineral matter as a result of increased salinity improved the transparency and thickness of the photic layer leading to a dramatic increase in organic production. The rise of the global sea level, changes in climatic conditions, and possibly according to Andrén (*op. cit.*) the catastrophic submarine Storegga slide off Norway in the North Atlantic around 8000 cal yr BP all facilitated massive saline inflows and the onset of the Litorina Sea stage, the precursor to the present brackish Baltic Sea.

Figure 9. The left (x-ray image) picture (A) is part of the core from the North Central Basin (water depth 179 m), where laminated sediments were observed only at the onset of the Litorina Sea about 8000 years ago, after that most traces of anoxia in the form of laminae were obliterated by bioturbation except for a vague laminated sequence deposited about 1000 years BP. The right hand picture shows that only minor portions of the core from the Gotland Basin (B) were bioturbated (water depth 241 m). Almost the entire sequence starting from the onset of the Litorina Sea exhibits laminated sediments

The salinity stratification and high organic productivity of the initial phase of the Litorina Sea led to near-bottom anoxia especially in the deep basins (Fig. 8). The lack of bioturbation by benthic macro-fauna has been the prerequisite for the formation of layered or laminated sediments typically associated with anoxic basin deposits. The laminae of the organic-rich sediments will be preserved unless the oxygen concentration in the waters overlying the sea floor increases, either due to a renewed inflow of oxygenated North Sea water or diffusive mixing, to a level capable of sustaining benthic macro-fauna. The burrowing benthos, if in sufficient numbers, will tend to destroy the laminated structures probably down to a depth of a few centimetres. This explains the homogenous sequences often observed in sediment cores (Fig. 9).

The formation of thick sequences of laminated sediments is thus a definite indication of long term anoxia. The lack of clearly laminated sediments is not, however, proof of continuous well oxygenated conditions, but only an indication that sufficient oxygen has been temporally available to allow benthic fauna (*Harmotoe*, *Pontoporeia*, *Mesidotea*, *Mysis* and some others) sufficient feeding time in the uppermost sediment layers to mix the top centimetres and to

obliterate the previously formed sediment laminae. It is, however, possible that mats of e.g. *Beggiatoa*-bacteria covering the sea floor may form a blanket, which may hamper penetration of benthic fauna. Some of the observed laminae in the sediments may also be the remains of such bacterial mats.

### The BASYS cores

The study of the past and present environment of the Baltic Sea, as part of the BASYS-project, was based on detailed analysis of long sediment cores taken from the Bornholm, Gotland and North Central Baltic basins. These three basins were known to have encountered anoxia during periods of various length. In the Gotland Basin the laminated sediments were found to be most pronounced, covering most of the Litorina and post-Litorina stages (Fig. 8), while the least laminated features were observed in the cores from the Bornholm Basin. This can be easily explained by the fact that the Bornholm Basin is the first area to be affected by minor, more frequently occurring, inflows of oxygenated saline North Sea waters, while only major inflows will be able to exert influence on the near-bottom waters in the Gotland Basin. The often occurring shells of *Macoma calcaria* (Kottsov report 1997) are clear indications of rather lengthy and good oxygen conditions prevailing in the Bornholm Basin.

The sediments from the North Central Basin are, like those from the Bornholm Basin, less laminated than those from the Gotland Deep. This is obviously due to the fact that only exceptionally strong inflows could have reached this somewhat shallower (170-220 m) and further north located basin. Thus, due to diffusive and possibly turbulent mixing, anoxic conditions have rarely been of sufficient duration in the North Central Basin to lead to the formation and preservation of laminated sediments. Bioturbation has been able to destroy most of the features formed during the short spells of anoxia.

The sediment cores obtained from the three basins were subjected to a number of various analytical procedures by a large number of researchers working in different laboratories. The multi-disciplinary approach provided a very detailed insight in the variability of the Baltic Sea environment from the onset of the Litorina Sea up to the present day. Although urbanisation and industrialisation has left clear marks in the marine environment, many of the features commonly attributed to man, are also found in the sediments deposited in the deep basins prior to man's invasion of the region. It is obvious that not only man is affecting the Baltic Sea environment, in fact the North Atlantic climate and the often occurring inflows of saline waters seem to be an even greater factor. The massive cyanobacterial blooms popularly associated with increased anthropogenic input of nutrients were on the basis of detailed analysis of chlorins (Kowalewska et al. 1998) and zeaxanthin (Bianchi et al. 1998) found to have occurred ever so often throughout most of the brackish water phase of the Baltic Sea, i.e. for the past 8000 years. According to Kunzendorf (1999) molybdenum concentrations in the sediments seem to correlate with organic carbon and also to be indicative of cyanobacterial blooms.

In an attempt to understand the coupling between the Baltic Sea environment and known climate variations, various parameters were studied. Since periodic inflow of salt water obviously has a great influence on the hydrography and the ecosystem of the Baltic Sea, one of the main tasks was to link sediment chemistry and mineralogy to salinity variations. Many microfossils are known to be excellent indicators of salinity and temperature fluctuations (e.g. Westman and Sohlenius 1998, Andrén, E. 1999, Kunzendorf et al. 1999, Winterhalter 1999), but due to redeposition and other factors they do not provide as good a temporal resolution as the laminae (Fig. 10) and some of the studied elements.

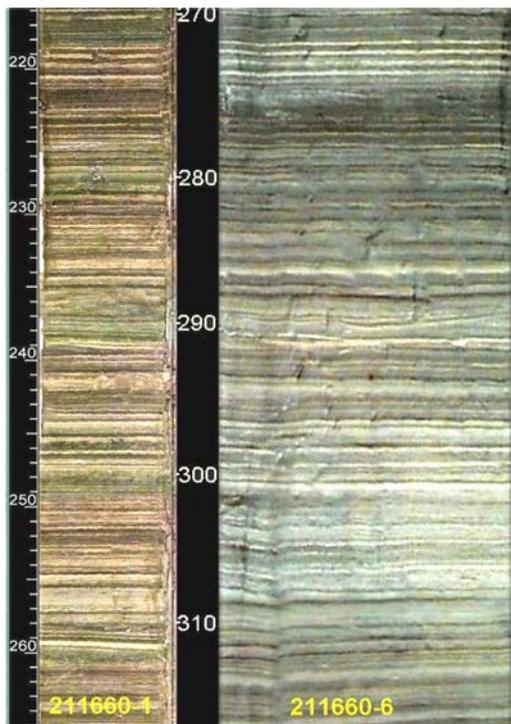


Figure 10. Detail images of the corresponding mid sections from two cores mentioned in Fig.8 and located about 100 m from each other in the deep part of the Gotland Basin. Although the general features are identical there are definite differences between individual laminae, indicating bottom current induced variations in very local sediment accumulation.

## Manganese

Especially in crystalline bedrock areas, weathering of soils and to some extent also the bedrock in a podsollic and humus rich environment will ultimately liberate manganese and also iron into the hydrosphere, where they will readily form oxyhydroxides. Such oxides are known to form precipitates (Fe-Mn-concretions) in bogs, lakes and the seas (Manheim 1961, Winterhalter 1986). Part of the manganese and iron finds its way also into deep sedimentary basins of the Baltic Sea.

It has been suggested that in anoxic conditions, where manganese in its oxidized form is unstable, it will be precipitated and stored in the sediments as a carbonate (e.g. Manheim 1961, Emelyanov 1988, Huckriede et al. 1995, Neuman et al. 1997, Lepland and Stevens 1998). Chemical analysis of the BASYS sediment cores clearly shows that manganese, often identified as Ca-rhodocrosite, correlates with the occurrence of laminated sediments, which, as stated above, are indicative of anoxic conditions in the bottom-near waters. Furthermore, the manganese correlates extremely well with calcium (e.g. Kunzendorf, 1999).

Manganese precipitated in an oxidizing environment will be reduced to its divalent state and go into solution if anoxia evolves. The final development of anoxia at the water/sediment interface may be enhanced by anaerobic sulfate-reducing bacteria utilizing the oxygen bound in the sulphate ion in saline pore water. The bacterial metabolism liberates carbon dioxide and hydrogen sulphide causing the pore water alkalinity to increase (cf. Fig 5-24, in Principles of Sedimentology, by Friedman and Sanders 1978). Thus, the  $MnO_2$  originally precipitated in the oxidizing environment of surface waters, will be reduced when reaching the anoxic seabed. The coexistence of reactive Mn and Ca and the bicarbonate ion form the prerequisite for the formation of Ca-Mn-carbonates commonly found in the anoxic Baltic Sea sediments.

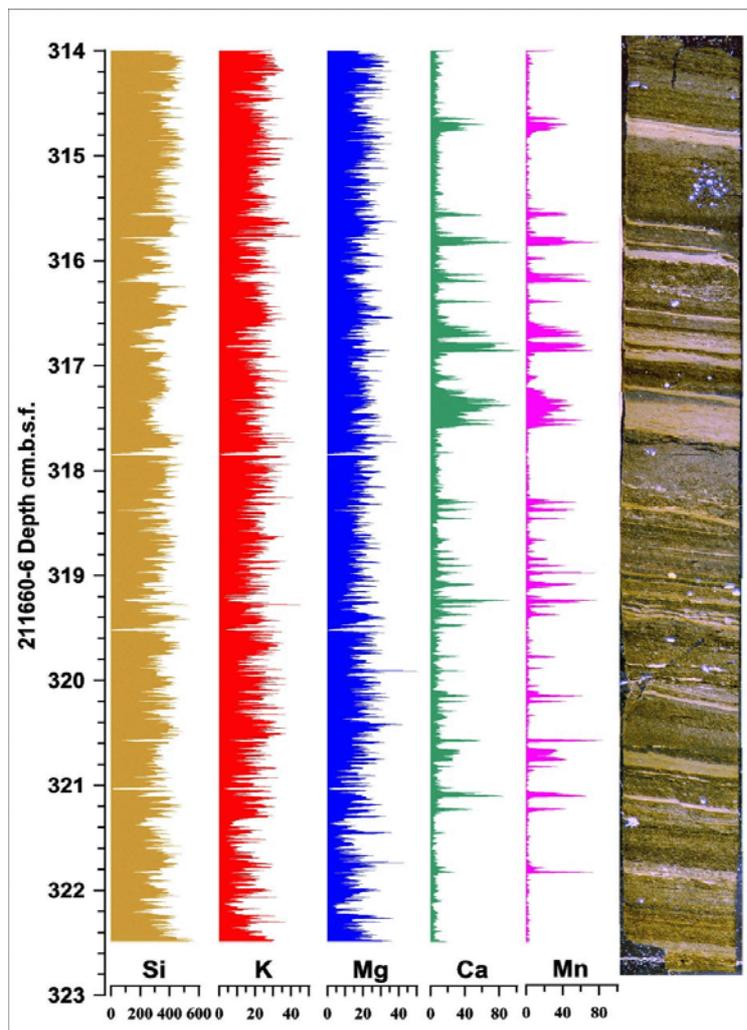


Figure 11. Microscope image in cross-polarized light of a thin section from core 211660-6 (Gotland Basin) between 314 to 322.9 cm below sea floor. The graphs showing the distribution in relative counts of silicon, magnesium, calcium and manganese are based on microprobe analysis. The correlation between calcium and manganese in the light-coloured carbonate bands is very striking, and is typical of the entire Litorina sequence.

The close correlation between calcium and manganese (Fig. 11) has been studied extensively and attributed to a mixed Mn-carbonate containing lesser amounts of Ca and Mg (e.g. Lepland and Stevens 1998). X-ray diffraction analysis of the small authigenic carbonate grains found in the anoxic sediments does not give a consistent crystal structure. Because of the variability in relative Mn, Ca, and Mg amounts, various mineral names, ranging from Ca-rhodocrosite to Kutnohorite, etc., have been proposed. Detailed electron microprobe studies (Winterhalter and Alvi, 2000) have shown that the probable explanation to this discrepancy lies in the fact that the carbonate grains actually most often consist of a dolomitic (Ca-Mg-carbonate) nucleus probably of detrital origin surrounded by a Mg-free Ca-Mn-carbonate (Fig. 12).

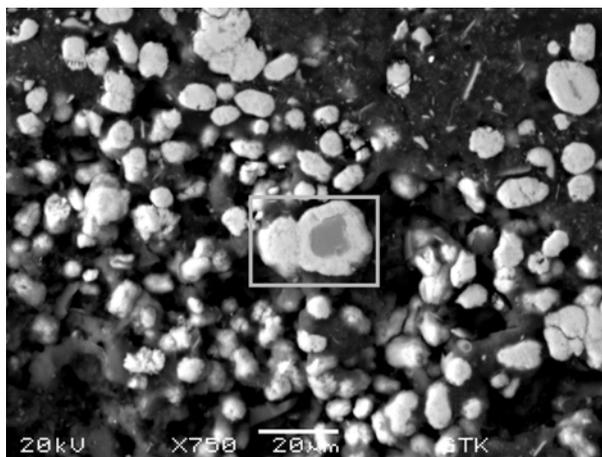


Figure 12. Scanning electron microscope image of a polished section of a manganese carbonate rich layer in core 211660-6. The Ca-rhodocrosite grain within the greyed box shows a dolomitic nucleus (grey) surrounded by a lighter manganese carbonate layer. The central grey part contained Mg 19.5 %, Al 0.6 %, Si 2.2 %, Ca 38.8 %, Mn 4.1 %, and Fe 1.3 %, while the outer light-coloured shell contained Mg 2.1 %, no Al, Si 1.9 %, Ca 19.8 %, Mn 48 %, and no Fe. Note the 20 um scale line at bottom of image.

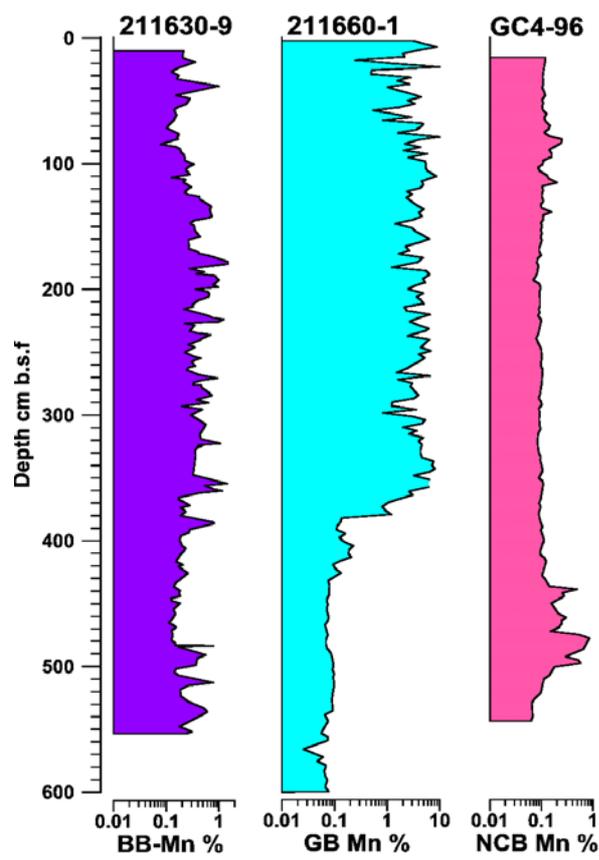


Figure 13. Graph showing the distribution of manganese in cores from three deep basins. Since accumulation of manganese is directly coupled to anoxia, it is obvious that the redox conditions in the three basins have been quite different. The highest Mn concentrations (due to Mn-carbonate) are found in the Litorina and post-Litorina sediments of the Gotland Basin (GB). The manganese in the Bornholm Basin (BB) is probably related to detrital minerals and manganese oxides. This is also true of the sediments from the North Central Basin (NCB) except for the elevated values during the initial stages of the Litorina Sea between 440 and 510 cm and traces between 80 and 120 cm in core GC4 collected in 1996 on board the *r/v Kottsov*.

A comparison of the Mn concentrations (Fig. 13) in the sediment cores from the three basins clearly shows that extensive anoxia with abundant Ca-Mn-carbonate (Ca-rhodocrosite) formation has occurred only in the Gotland Basin. The fact that average Mn concentrations in the BB are clearly lower than in the GB is an indication that the basin is located closest to the Danish Straits and therefore encounters rather frequent inflows of oxygenated saline water. In the North Central Basin persistent anoxic conditions prevailed only during the onset of the Litorina Sea.

## Iron

Depending on the redox potential, iron oxyhydroxides are also dissolved. The liberated Fe-ion will react with hydrogen sulphide and form a ferrous monosulphide. This black smeary amorphous compound together with free hydrogen sulphide is the main cause for the characteristic appearance and smell of the anoxic sediments found in most of the sedimentary basins exhibiting a rather fast rate of deposition of organic detritus. In some specific environments the ferrous sulphide may also crystallize and form pyrite or marcasite (Ignatius et al. 1968).

## Summary and Discussion

It has been demonstrated that the atmospheric conditions mainly control the three-dimensional circulation in the Baltic Sea and the water mass exchange with the North Sea. This leads to characteristic circulation patterns and corresponding areas of up- and down welling. Due to increased mixing which will be established if the circulation will change from one state to the

other, the impact on biological and chemical process can be imagined. However, there are a number of open questions which deserves further research.

- What is the role of the variability of the river runoff on the circulation and the water mass exchange with the North Sea?
- More generally, what is the role of the fresh water budget on the circulation and the water mass exchange?
- What controls the salt flux into the Baltic Sea and the further flow of haline and (often) oxygenated water through the deep basins?
- What are the characteristic oxygen depletion and diffusion rates in the deep basins of the Baltic Sea?
- Where is the turnover happening and what is its characteristic period?
- What is the impact of long-term changes of the NAO on the Baltic Sea dynamics?

From the knowledge we have now, the role of major Baltic inflows is two-fold. On the one hand, massive inflows are necessary to displace old oxygen depleted bottom water. However, it takes several month or even up to a year, depending on the amount of water penetrated into the Baltic Sea and on the atmospheric conditions after the inflow event, before the deep basins of the Baltic Sea downstream will be affected by the inflow. On the other hand after a major Baltic inflow the haline stratification has increased, and only water with higher density (salinity) can displace the highly saline bottom water. The reduction of the salinity of the bottom water depends on mixing and diffusion processes which act mainly on the diffusivity time scale. The rate of oxygen depletion is governed by biological and chemical processes which act on a shorter time scale, i.e. the oxygen depletion is much faster than the diffusive mixing of the haline bottom water. Although it is tempting to assign an increased rate of oxygen depletion due to anthropogenic influence (eutrophication), the amount of organic matter and manganous carbonate deposited in the sediments seems to have been rather constant through the millennia. The diffusive mixing rate has probably varied only as a function of the degree of density stratification and wind forcing.

The oxygen depletion is controlled by a variety of both biological and chemical processes, although bacterial consumption of organic detritus is probably one of the most important. Especially massive occurrence of sulfur bacteria seems to be an important factor paving the road for complete stagnation and production of hydrogen sulphide.

It is obvious that anoxia in the deep basins and the rather strong cyanobacterial blooms are natural phenomena and can only marginally be attributed to increased anthropogenic input of nutrients into the Baltic Sea (e.g. Kowalewska et al. 1999). Furthermore, a comparison of the chemistry of the most recent sediments with those deposited during former millennia does not show any clear evidence that a drastic change has occurred as a result of mans increased activities around the Baltic Sea. Only increases in some pollutants (some heavy metals and industrial organic compounds) in both the water and the sediments can clearly be related to the doings of man (Kankaanpää 1997, Vallius 1999).

The positive temperature correlation of *Acartia* spp., *T. longicornis* and *E. affinis* applies only for a certain period of the year, usually spring. There are two possible explanations for this relationship. In spring, these populations usually have their exponential growth phase and they consist to a large extent of copepodites. Probably, higher temperatures favour this exponential growth phase. Also, these three species all have resting (diapause) eggs (Mauchline, 1998) which sink to the sediment and can be buried for long periods. High spring temperature might induce the hatching of these resting eggs. The decreasing phase of these populations in summer and spring does not seem to be correlated with temperature. Johansson (1992) studying copepod

populations at the Swedish coast in the northern Baltic Proper concluded that the exponential growth phase of these copepod populations is regulated by temperature whereas the decline of the populations later in the year might be controlled by predation. In contrast to the smaller copepod species, long-term fluctuations of *P. elongatus* are positively correlated with salinity and do not show any statistically significant temperature relationship. Obviously, *P. elongatus* needs higher salinities than the other copepod species and this is reflected in its vertical distribution. The main parts of the population are found at much greater depths than those of *Arctia* spp., *E. affinis* and *T. longicornis* (Möllmann et al., 2000) which have higher salinities than the upper layer.

**Table 1: Correlations between long-term dynamics of zooplankton and temperature and salinity**

Species	T	S	Reference
<b>Swedish Bays</b>			
A. spp.	+ (May, NAO)		Hansson et al. MS
A. spp. (eutr)	+ (Mar, NAO)		Hansson et al. MS
E. affinis	+(May, NAO)		Hansson et al. MS
T. longicornis (eutr)	+ (Aug, NAO)		Hansson et al. MS
<b>Archipelago Sea</b>			
A. spp. cop.	+ + (Apr, SLP)		Vuorinen et al. 1998 Dippner et al., MSa
A. spp. ad.	+ (Jul, SLP)		Dippner et al., MSa
E. affinis cop.	+ (Jul, SLP)		Dippner et al., MSa
E. affinis ad.	+ (Jul, SLP)	-	Vuorinen et al. 1998 Dippner et al., MSa
L. macrurus cop.		-	Vuorinen et al. 1998
L. macrurus ad.		-	Vuorinen et al. 1998
C. hamatus. cop.	-	+	Vuorinen et al. 1998
C. hamatus ad.		+	Vuorinen et al. 1998
T. longicornis cop.		+	Vuorinen et al. 1998
B. longispina	+	-	Vuorinen et al. 1998
<b>Gulf of Riga</b>			
<i>P. elongatus</i>		+	Ojaveer et al. 1998
<b>Baltic Proper</b>			
A. spp.	+ (spring) + (spring)	- (summer)	Dippner et al., MSb Möllmann et al., MS
T. longicornis	+ (spring) + (spring)		Dippner et al., MSb Möllmann et al., MS
<i>P. elongatus</i>		+ (autumn)	Möllmann et al., MS
<i>E. nordmanni</i>	+ (spring)		Dippner et al., MSb
P. spp.	+ (spring)		Dippner et al., MSb

Dynamics of sprat and herring and of three of their most important food items, the copepods *Acartia* spp., *E. affinis* and *T. longicornis*, show a positive correlation with temperature. These results give strong support to the hypothesis that all these species are controlled by climate variation, namely fluctuations of the NAO. The most important dietary component of sprat, *P. elongatus*, is governed by salinity. As the climate dependence of Baltic Sea salinity is obscure, it is not clear whether *P. elongatus* is also controlled by climate variability. The trend of temperature and salinity over the last 20 years was that salinity has decreased due to reduced salt water intrusions from the North Sea and increased river run-off (Vuorinen et al. 1998) and temperature has increased as reflected by the predominantly positive state of the NAO index. Consequently, abundance of *P. elongatus* has declined over this period (Möllman et al. 2000; Ojaveer, 1998) and abundance of sprat (Ojaveer 1998) and the other copepod populations (Möllmann et al. 2000) has increased.

In coastal areas, river run-off certainly has a more direct impact on salinity than in the Baltic Proper. Consequently, copepod populations in the Finnish Archipelago Sea are also controlled by salinity fluctuations caused by river run-off which is forced by the NAO (Vuorinen et al. 1998). So, climate variability seems to force copepod populations in Finnish coastal areas through changes in temperature and salinity. Interestingly, Hänninen et al. (1999) recently also found that deep water salinities of the Baltic Sea respond to changes in total freshwater run-off with a time lag of about one year. They foresee the possibility to eventually predict population dynamics of copepods and their predators.

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