Environmental changes in the central Baltic Sea during the past 1000 years: inferences from sedimentary records, hydrography and climate

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Abstract

Short sediment cores from the eastern Gotland Basin were investigated using a multi-proxy approach in order to reconstruct the environmental conditions of the area during the past 1000 years. Sediment data and facies were discussed in relation to hydrographic features (salinity, oxygen) and climate change. During the medieval warm period (MWP), from about 900 to 1250 AD, the hydrographic and environmental conditions were similar to those of the present time (modern warm period, since about 1850): a temporally stable halocline, caused by regular saline water inflows from the North Sea, prevents vertical mixing and leads to bottom water anoxia and the deposition of laminated, organic-rich sapropels. During the period from about 1250 to 1850, referred to as the cold phase (including the Little

Ice Age), the environmental conditions of the central Baltic Sea were distinctly different: the lower salinity, resulting from reduced North Sea water inflows, allowed vertical convection of the water column and long-term stable ventilation of the sea bed (oxic stage). Both the productivity of the planktonic ecosystem as well as the preservation of organic matter in the sediments improved during the warm periods. The anthropogenic impact can be identified within the recent laminated sequence by a temporal reconstruction of pollutant deposition. Our findings imply a climate-change driven shift in the environmental conditions and the ecosystem of the Baltic from the north to the south and back to the north.

1. Introduction

Any evaluation of human impact on the Baltic Sea environment as well as the possible ecological effects of future global warming has to be based on knowledge of the natural conditions and natural changes during the past (Andrén et al. 2000, Elmgren 2001, MacKenzie et al. 2002). The discussion of natural backgrounds, especially with respect to eutrophication, pollution, climate change and natural variability vs. anthropogenic impact has revived in recent times.

Direct, reliable hydrographic measurements in the Baltic Proper stretch back for 100 to 150 years (Fonselius & Valderrama 2003, Matthäus 2006). Meteorological observations and other available sources around the Baltic Sea have been used for climate and environmental reconstruction for the past 200 years (Omstedt et al. 2004). Finally, investigations of sedimentary deposits, especially in the undisturbed and continuous sequences of the central Baltic basins, are still one of the most important tools for assessing the natural history of the sea.

The general Quaternary and Holocene geological development of the Baltic Sea has been studied in recent decades (Ignatius et al. 1981, Eronen 1988). Multidisciplinary investigations of long and short sediment cores from the Gotland Basin were performed within the framework of the international GOBEX and BASYS projects during the 1990s. The major results of these projects, with the emphasis on paleoenvironmental reconstruction, are summarised in a special issue of the journal *Baltica* (Grigelis (ed.) 2001).

Nevertheless, there is a need to understand connections between climate change, ecosystem response and anthropogenic effects, especially with respect to past centuries. The results contribute new information and ideas in response to some relevant questions: Has historical climate change affected the hydrographic conditions of the Baltic Sea? What does this mean in the context of halocline, bottom-water anoxia and sediment formation? Are these environmental conditions important for nutrient cycles, ecosystem shifts and the deposition of anthropogenic pollutants?

2. Study area

The Gotland Basin, situated in the central Baltic Sea, is a key area for studying geological and historical processes: there are sites with sedimentary profiles showing almost undisturbed and continuous records over the past few thousand years. Previous studies have shown that a drawback of long-coring devices is that the very soft and fluid uppermost part of the sediment column is usually lost. Thus, for detailed investigations of the younger history, including the human impact of recent decades and centuries, a special surface, short-core sampling technique is necessary (Barnett et al. 1984); this method was used in the present study. In 2003 and 2004, two cruises on r/v 'Prof. A. Penck' were made to the eastern Gotland Basin. The sampling station grid (Figure 1) was designed to cover the area below 150 m water depth down to the maximum depth of the basin – c. 240 m. In total,

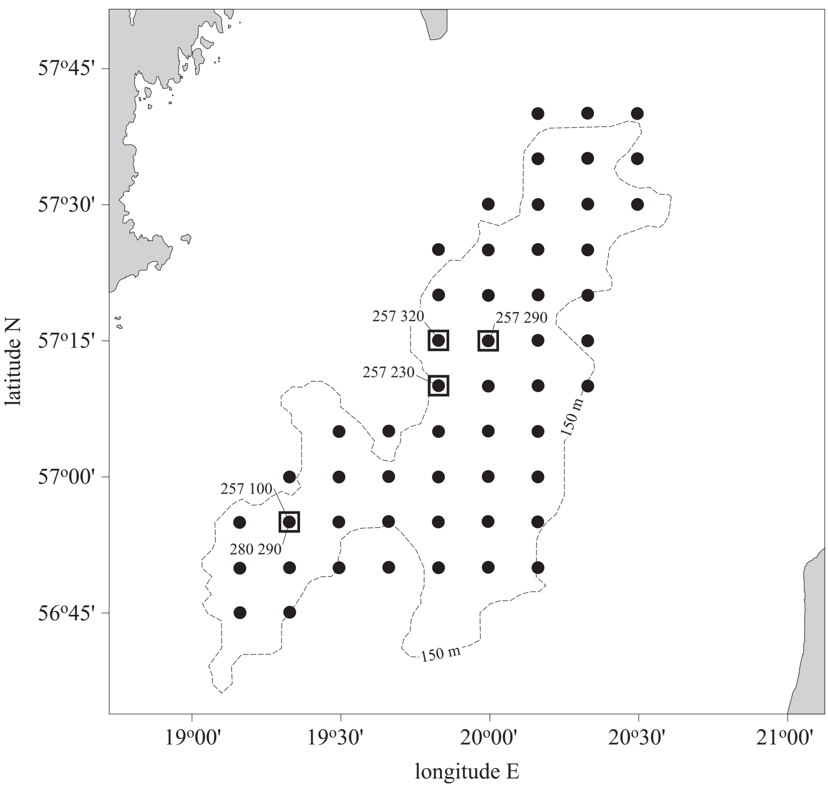

Figure 1. Study area in the eastern Gotland Basin, central Baltic Sea. The dots indicate the sampling stations of the 2003 and 2004 r/v 'Prof. A. Penck' cruises. The stations marked with squares show the locations and identification numbers of the sediment cores that are mentioned in the text and shown in the figures

short sediment cores (max length 60 cm) were obtained from more than 50 stations for various investigations: core description (structure, texture), sediment physical properties, grain size, inorganic and organic geochemistry, pore water analyses, isotope and age determination, and fossils. Selected results from this study have already been published by Hille et al. (2005, 2006). The present paper focuses mainly on the results of investigations of the following sediment cores: 257 100 and 280 290 (both cores at the same position 56°55′N; 19°20′E, water depth: 176 m), 257 230 (57°10′N; 19°50′E; WD: 234 m), 257 290 (57°15′N; 20°00′E; WD: 247 m) and 257 320 (57°15′N; 19°50′E; WD: 228 m). They were obtained with a multi-corer device, sliced into 1 or 2 cm discs, freeze-dried and analysed for selected parameters and proxies.

3. Methods

Sediment age was determined at the Gamma Dating Centre in Copenhagen, Denmark (^{210}Pb) and the Gliwice Radiocarbon Laboratory, Poland (^{14}C). All other measurements were done at the Institute of Baltic Sea Research in Warnemünde, Germany.

Dry bulk density (and water content) was determined after the freeze-drying of a given volume of fresh sample. Grain-size analyses were done on a laser-sizer (CILAS 1180-Quantachrome). Total carbon, organic carbon, inorganic carbon, nitrogen and sulphur were measured on dry samples with elemental analysers (EA 1110 CHN – CE-instruments; Multi EA 2000 CS – Analytik Jena).

Selected major and trace elements (Al, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Ni, P, Pb and Zn) were determined by ICP-ESA (Varian Liberty 200) following total digestion of the dry samples with a mixture of acids (HNO_3, $HClO_4$, HF) and a microwave oven (Mars Xpress 5 – CEM).

Hg analyses were performed on dry samples with a direct mercury analyser (DMA-80 – MLS GmbH). This method is based on the gold-trap technique and single element AAS detection.

The determination of biogenic silicate (opal) was done on silicate extractions from dry sediment samples treated with 1M NaOH for 40 min at 85°C. The solvents were measured for Si concentrations on an ICP-ESA instrument (Varian Liberty 200) and calculated for biogenic silicate. The method is a modified version of the analytical procedure described by Müller & Schneider (1993). Further details of biogenic silicate measurements in sediments are given by Conley (1998).

The δ^{13}C analyses of the organic carbon of the samples were done simultaneously with a 1108 Elemental Analyser (Carlo Erba-Fisons) connected to an isotope-ratio mass spectrometer (Finnigan Delta S) following pretreatment of the samples with 2M HCl for removal of inorganic carbon (Struck et al. 2000).

Lignin was analysed in lignin-derived phenols after CuO oxidation (Hedges & Ertel 1982). Prior to analysis by GC/MS (HP 6890; HP 5973) the samples were dissolved in acetonitrile and derivatised with BSTFA (bis-trimethylsilyl-trifluoroacetamide) for 1 h at room temperature. This fairly complicated method is described in detail by Miltner & Emeis (2001) and Miltner et al. (2005).

Quality control of all analyses was performed by comparison with standard samples (e.g., MESS, BCSS, ABSS, MBSS, BCR 142R, pure single components of lignin, SIBER – BSI standard 2003, etc.) and by successful participation in Quasimeme intercalibration exercises.

4. Results and discussion

Figures 4, 5, 6, 7 (see pages 32–35) and Table 1 (p. 36) present selected results of our sediment core analyses (original data); they are discussed in the context of the specific topics and with reference to the available relevant literature. The key aspects in the discussion of the climate-change (and anthropogenic) driven responses of the ecosystem and sediment deposition are: the situation regarding nutrients, redox and salinity (Figure 4); the deposition of terrigenous organic matter (Figure 5); the accumulation of biogenic silicate reflecting autochthonous plankton production (Figure 6); the human impact on the environment during industrial times as represented by the discharge of pollutants into the Baltic Sea (Figure 7).

4.1. Sediment core structure, age model, climate change

The site of the sediment core (Figure 2 – right) from the south-western Gotland Basin is situated in a region of low average sedimentation rates (c. 0.5 mm yr^{-1} – Hille et al. 2006); nonetheless, it is a site that has obviously remained undisturbed, allowing 1000 years of history to be reflected in a 60 cm core of sediment. The core consists of three distinct sections: a dark, laminated horizon at the top, a light grey, homogeneous segment in the middle, and another dark, laminated horizon at the bottom.

^{210}Pb dating shows the age of the upper laminated mud segment in the core to be c. 100 to 120 years. The darkly coloured, laminated muddy sediments, often referred to as sapropels in the literature, contain very large amounts of organic matter ($>10\%$ C-org. in the Gotland Basin) and are indicative of anoxic conditions at the sea bed; there is no benthic macrofauna to disturb the sedimentation process. The occurrence and distribution of laminated mud in the recent, near-surface sediments of the central Baltic Sea have been adequately documented (Jonsson et al. 1990).

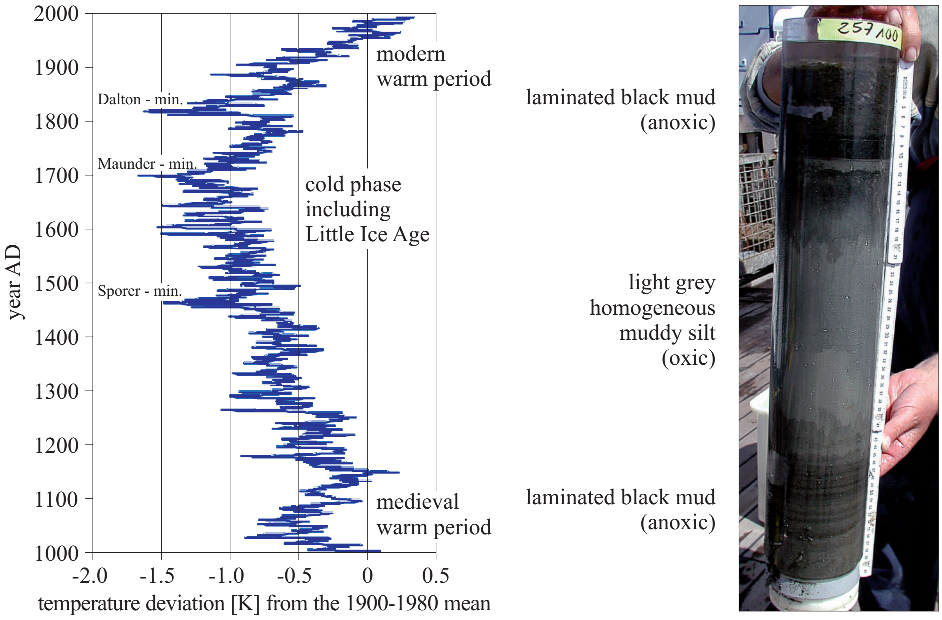

Figure 2. Climate change in the northern hemisphere during the past 1000 years represented by the temperature deviation (K) from the 1900–1980 mean (after Storch et al. 2004, left); photograph of core 257 100 (56°55′N; 19°20′E) from the Gotland Basin (right)

A few more available datings of short sediment cores from the Gotland Basin have confirmed that the thickness of these dark, laminated surface layers is a direct reflection of sedimentation rates (Kunzendorf et al. 1998, Vallius & Leivuori 2001, Christiansen et al. 2002). The period of time covered by the upper dark laminated layer in the Gotland Basin represents the past 100 to 150 years at most. The spatial distribution of recent sedimentation rates in the Gotland Basin is influenced by deep-water circulation patterns and corresponds to the total thickness of Holocene mud since the Littorina Transgression (Emelyanov 2001, Hille et al. 2006).

The light grey homogeneous horizon in the middle part of the core represents bioturbated muddy silt with a lower organic matter content (4–5% C-org.). This indicates that oxic conditions were prevalent at the sea bed during the time of its formation. Radioisotope dating of this layer is practically impossible: these sediments are too old for ^{210}Pb, and carbonate shell fossils of benthic fauna are extremely rare.

The dark laminated horizon at the bottom of the core represents environmental conditions resembling those of the present day. This lower sapropel was bulk-sediment ^{14}C-dated to 900 AD or 1100 BP (Gliwice Radiocarbon Laboratory). Bearing in mind the problems affecting bulk sample carbon dating and also reservoir effects, this result confirmed that the lower sapropel layer has to be assigned to the medieval warm period (MWP). The existence of a MWP sapropel in Gotland Basin sediments was recently demonstrated by Dippner & Voss (2004) using data from a long sediment core from the deepest part of the Basin (Voss et al. 2001). The same core (211 660) was used by Harff et al. (2001) in their study of the physico-chemical stratigraphy of Holocene sediments in the Gotland Basin. Those authors correlated the changes (sequences) of dark and light horizons in different cores over larger distances throughout the basin, which clearly reflected the changes in oxic and anoxic conditions at the sea bed.

The sedimentary sequence of our short core obviously mirrors the climate change of the past 1000 years (Von Storch et al. 2004; Figure 2 – left). The warm periods correspond to the laminated sediments, indicating anoxic conditions, whereas the homogeneous light grey horizon belongs to the cold phase, including the so-called Little Ice Age, and represent oxic conditions at the sea bed.

4.2. Bottom water anoxia and salinity

The formation of long-term bottom water anoxia is determined by strong oxygen consumption during the mineralisation of organic matter, derived mainly from autochthonous dead phytoplankton, and by the existence of a stable halocline (pycnocline), which prevents vertical mixing of the water column and thus a supply of oxygen from above. Bearing in mind the general estuarine circulation pattern of the Baltic Sea, a shift from anoxic stages to regular ventilation of the bottom water (oxic stages) in the Gotland Deep can only be caused by two separate processes: 1) a decrease in salinity, which finally leads to the disappearance of the halocline and which allows vertical convection; 2) a regular and frequent supply of oxygen-rich saline bottom water from the North Sea (inflows).

Both of these different features are present today in the end-members of the salinity gradient in the Baltic Sea: one in the northern Bothnian Sea and Bay, the other in the western Belt Sea. Figure 3 gives two examples of hydrographic profiles, one for oxic and one for anoxic deep water conditions.

Strong inflow events reaching as far as the central Gotland Basin have been recorded in recent decades by hydrographic measurements and calculations (e.g., Matthäus & Franck 1992, Schinke & Matthäus 1998, Matthäus 2006) and are probably reflected by geochemical records (Mn-carbonates) in the laminated sediments of the Gotland Deep (Neumann et al. 1997).

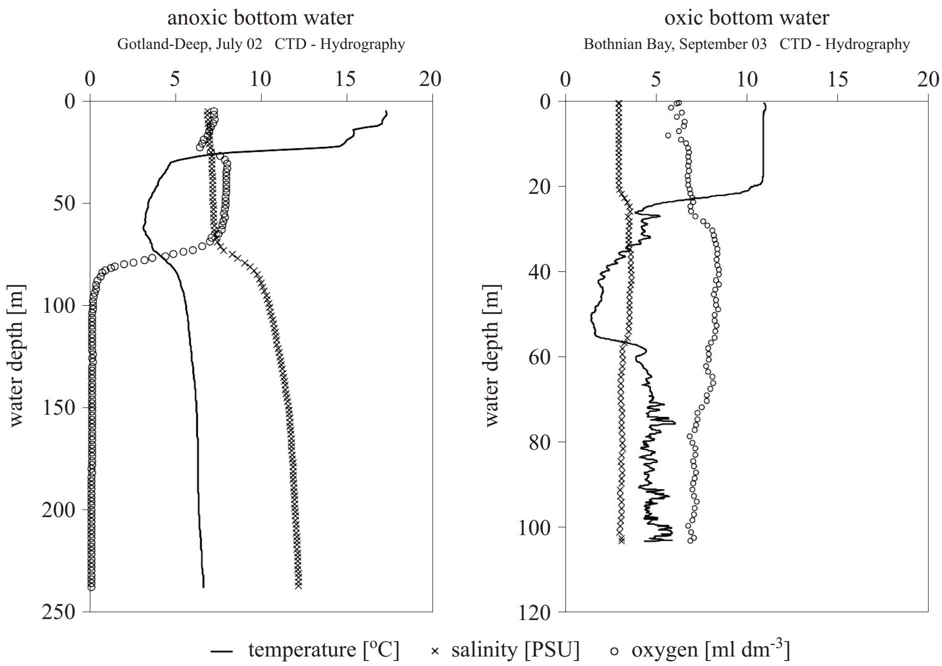

Figure 3. Temperature, salinity and oxygen profiles at two different stations in the Baltic Sea: left – in the Gotland Deep as an example of anoxic bottom water; right – in the Bothnian Bay as an example of oxic conditions at the sea bed

However, these episodic inflows never lead to long-term ventilation of the basin because the consumption of oxygen in the deep water is faster than its supply by new inflow events (Feistel et al. 2006). The same paper describes the development of deep-water (and surface-water) salinity in the Gotland Basin since the late 1960s. This time series of measurements includes the strong stagnation period with decreasing salinity trends from the late 1970s to 1993, when a strong inflow event brought this trend to a close. These data are very useful for the discussion of a system switch from anoxic to oxic conditions in the central Baltic Sea. Theoretically, if the 1993 inflow event (and later ones) had not occurred, the decreasing (linear) trends of both bottom-water and surface-water salinities would meet in the 2030s at 5 PSU! Taking into account the salt residence times, calculated at c. 20–30 years (Feistel et al. 2006), a system change from an anoxic to an oxic deep-water environment in the central Baltic could easily take place during 100 years of reduced North Sea water inflow.

4.3. Palaeosalinity

To solve the problem of palaeosalinity in the Gotland Deep during the colder climate and oxic period between the sapropels of the warm periods, arguments supplied by suitable proxies are necessary. Of course, fossils, biomarkers, isotopes and other geochemical indicators have already been used to characterise the palaeoenvironmental conditions of the central Baltic Sea (Andrén et al. 2000, Voss et al. 2001, Nytoft & Larsen 2001, Emeis et al. 2003). But many of these indicators, analysed in long-core series, displayed distinct differences only between the major stages of the Baltic Sea's development during the Holocene (the Baltic Ice Lake, and the Yoldia, Ancylus and Littorina phases). It is more difficult to find evidence of more recent changes, especially within the post-Littorina mud series.

There are hardly any remains of benthic macrofauna (e.g., molluscs) in the younger Holocene sediments of the Gotland Deep, probably because the carbonate shells have dissolved. Microfossils were studied by Brenner (2001) and Hofmann (2001), for example, but there are no distinct signs of regular changes in salinity during the past 1000 years. In our core we found at least one species of agglutinated foraminifera (*Nodulina dentaliniformis*) within the light grey sediments of the cold climate phase. This species and the additional abundance of remains of the planktonic crustacean *Bosmina* are indicative of low salinities in the water column (Lutze 1965, Flößner 1972, Hermelin 1983, Hofmann 2001). These findings are in agreement with the results presented by Andrén et al. (2000) who, on the basis of diatom assemblages, postulates a reduced salinity during the colder climate phase. The extremely low abundance and species diversity of benthic fauna in the cold phase sediments strongly suggest a low salinity and resemble the recent situation in the northern Baltic Sea.

Benthic malacostracans (Crustacea) could be used to explain bioturbation under low salinity and oxic conditions. In particular, species from the genera *Pontoporeia*, *Bathyporeia* and *Saduria* are well known from the central to the northern Baltic Sea; in the zoological literature (Köhn & Gosselck 1989) they are often referred to as glacial relicts. Unfortunately, either the remains of these animals are very sparse, or else nobody has dealt with this group in the fossil sediments of the Baltic Sea. For example, we found *Saduria entomon*, a very mobile animal up to 7 cm in size, in some box-core sediment samples from the Gotland Basin. This species would easily be able to colonise the basin if it were ventilated for a longer period.

The relationship between salinity and δ^{13}C-isotope ratios of organic carbon in Baltic Sea surface sediments, derived by Emeis et al. (2003), supplies a good argument for the lower salinity during the cold phase in our core (Figure 4). Because the salinities calculated from the carbon isotopes reflect surface-water conditions (the organic matter is derived from the euphotic zone), a decrease in salinity below c. 5 PSU ($-26‰$ δ^{13}C) would support our hypothesis for the disappearance of the halocline.

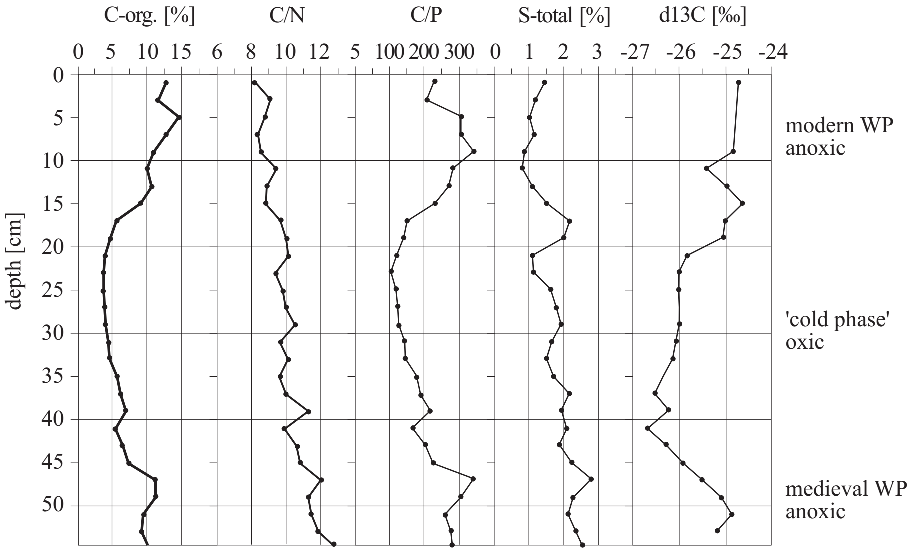

Figure 4. Sediment core 280 290 (3): profiles of selected geochemical parameters indicating the productivity, organic matter deposition and salinity development (d13C) for the three major historical stages of the Gotland Basin

Even the curve of the total sulphur content in our sediment core (Figure 4) can be used to interpret palaeosalinity. Marine sulphate is reduced under anoxic conditions and fixed in the sediment mainly in the form of iron sulphides. Although this is a diagenetic process, penetrating the upper part of the sediment column to depths of a few cm, a trend parallel to the salinity changes, as indicated by the δ^{13}C curve in the lower part of the sediment core, is visible.

4.4. Further signals from marine and terrestrial end-members

The hypothesis of large-scale climate-driven shifts in the hydrography of the Baltic Sea was recently supported by Bock et al. (2005). Nd isotope signatures in dated iron-manganese crusts indicate a decrease in the marine and/or an increase in the freshwater end-member signals from the Scandinavian Shield during the Little Ice Age.

Moreover, analyses of lignin compounds (syringin/vanillin ratio) in our sediment cores, which can be used to characterise terrigenous organic matter from plants, indicate changes from a vegetation dominated by broadleaved woodland during the medieval and recent warm periods (sapropels) towards one with a greater proportion of coniferous forest in the cold-phase sediments (Figure 5). This could have been caused either by an extension or southward shift of the Scandinavian boreal coniferous forests during the cold period or

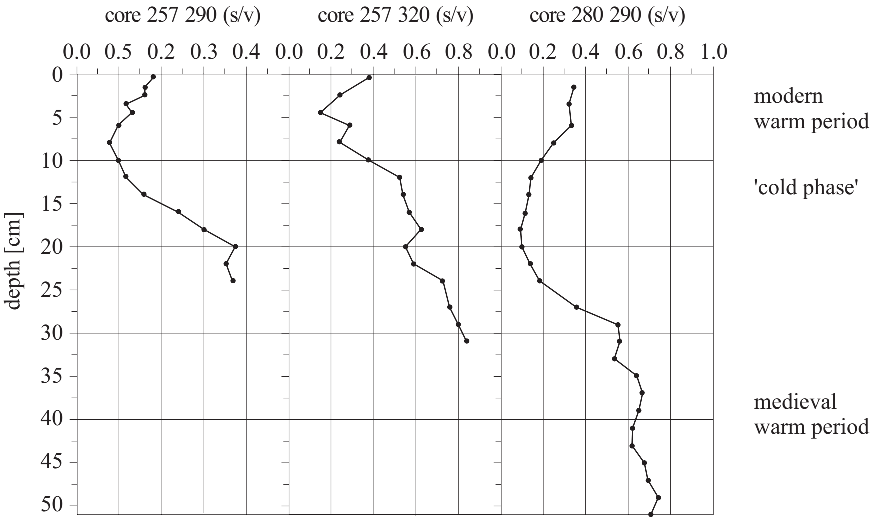

Figure 5. Sediment profiles of terrestrial plant biomarkers (lignin, syringin/vanillin ratio) in three different cores from the eastern Gotland Basin. The right-hand side of each column indicates the dominance of broadleaved woodland, the left-hand side the dominance of coniferous woodland in the composition of the ligneous material

by the increased impact of freshwater drainage from the Scandinavian Shield during that time, which fits the above-mentioned Nd-isotope signals well.

4.5. Nutrients and productivity

The change from oxic to anoxic conditions and vice versa in the deep water of the central Baltic Sea basins has important consequences for the nutrient situation and productivity of the system (Jonsson & Carman 1994, Emeis et al. 2000, Conley et al. 2005, Hille et al. 2005). Especially the enrichment of dissolved phosphate in anoxic deep waters may enhance the appearance and spread of cyanobacteria blooms in the surface waters of those areas. The cyanobacteria biomass undoubtedly constitutes the main part of the organic matter in recent sediments in the central Baltic Sea. Concentrations of more than 10% C-org. in the sediments and C-org. deposition rates of 10 to 20 g m^{-2} a^{-1} reflect this high productivity. Starting with the formation of the halocline and reduced vertical mixing, the spread of anoxic conditions from the sea bed has a positive feedback effect on biomass production in the surface water, after which there is intensified consumption of dissolved oxygen in the deep water. Such conditions have occurred naturally during all the periods represented by laminated sapropels in the Holocene sediments of the Gotland Basin. At least for the MWP sapropel, in the eastern Gotland Basin (Dippner & Voss 2004) and in long sediment cores from the western Gotland Basin (Bianchi et al. 2000) δ^{15}N-isotope values, biomarkers and other proxies were found to reflect cyanobacteria biomass deposition.

Another productivity proxy, biogenic opal, derived mainly from diatom skeletons, is also rich in laminated sapropels. Looking at the details of the C-org and biogenic opal (SiO_2) curves in the sediment cores (Figure 6), we can see that the opal maximum appears together with or even before the C-org maximum in the temporal development. Biogenic silicate decreases, but organic carbon remains at a high level or increases at a later stage. During the warm periods with higher-saline bottom water and the formation of anoxia, the planktonic ecosystem shifts from diatom-dominated to dinoflagellate- or cyanobacteria-dominated communities, in the same manner as the seasonal changes, but this time on a time scale of decades. This is in agreement with recent observations of phytoplankton trends in the Baltic Sea (Wasmund & Uhlig 2003).

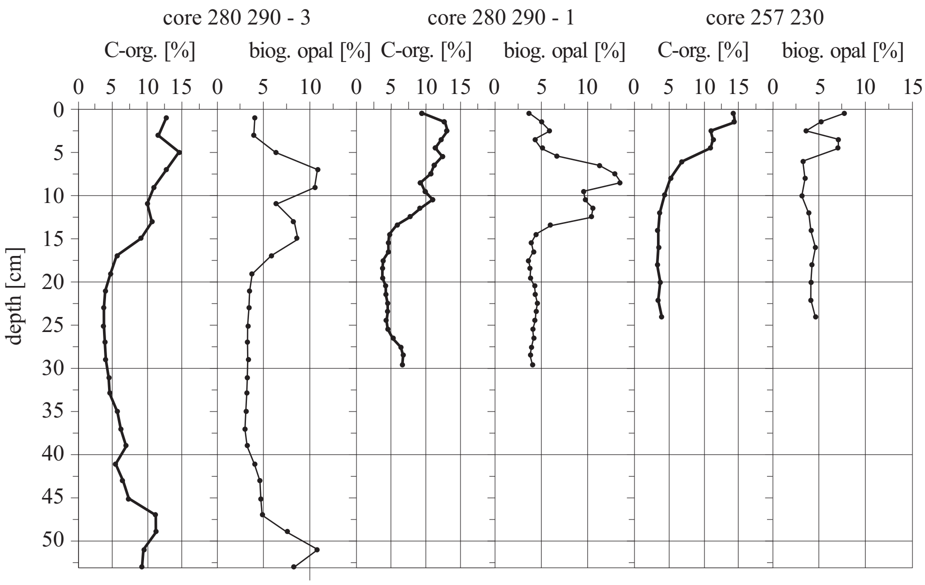

Figure 6. Vertical distribution of organic carbon and biogenic silicate (opal) in three different cores from the eastern Gotland Basin

During the whole modern anoxic phase, the plankton-community shift seems to have recurred two or three times. During the cold phase, when the bottom water was mainly oxic, conditions for the preservation of organic matter at the sediment surface were worse. High productivity in the euphotic zone may therefore not be reflected in the sediments. But the biogenic opal, the preservation of which is more or less independent of the redox state, indicates a lower productivity in the cold phase as well. During the cold phase, the salinity decrease induced changes in the zooplankton community: a decline in large neritic copepods and an increase in cladocerans (Vuorinen et al. 1998). The dominance of the anomopod zooplankter *Bosmina* points to phytoplankton with a low phosphorus content (Schulz & Sterner 1999).

4.6. The anthropogenic signal

The anthropogenic impact (eutrophication, pollution) in the wake of the industrialisation of northern and central Europe during the past 150 years can be reconstructed within the upper horizon of the laminated sediments of the Gotland Basin. The heavy metal and organic pollutant profiles mostly follow a typical trend: starting from natural backgrounds (or zero for most of the organic pollutants), increasing during the first half of the 20th century, reaching a maximum between the 1960s and 1980s, then decreasing towards the uppermost layer, representing the present (Figure 7). These patterns are in agreement with the findings of, e.g., Vallius & Leivuori (2001) and Vallius & Kunzendorf (2001) in the central basins of the Baltic Sea.

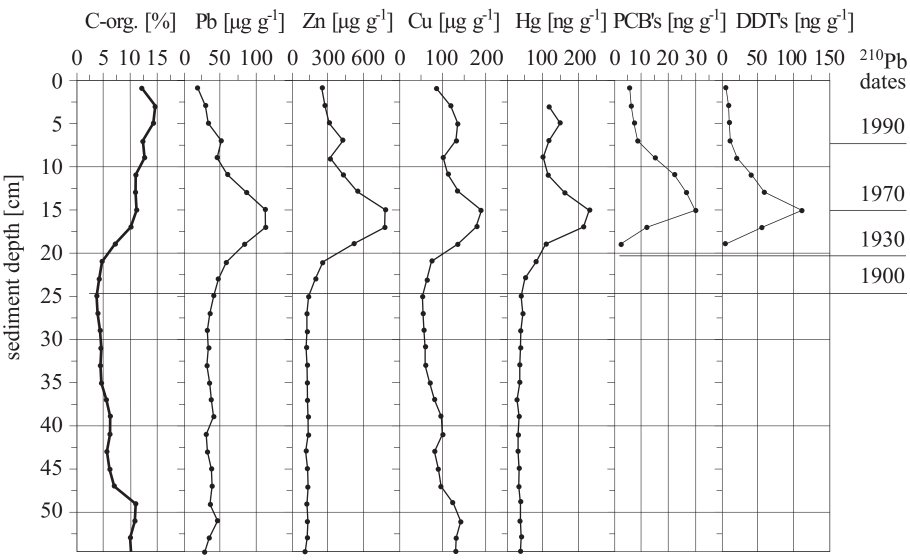

Figure 7. Vertical distribution of organic carbon, selected heavy metals and organic pollutants from anthropogenic sources in core 280 290 (2) from the eastern Gotland Basin. The age (years) of distinct horizons, based on ^{210}Pb dating, are given on the right-hand side of the figure

Table 1. Comparison of accumulation rates for different environmental conditions (time periods) represented in sediment core 280 290 from the Gotland Basin

	Deposition time	av. LSR	MAR	C-org	Al	P	Pb	Cu	Hg	PCBs	DDTs
	[~ years]	[mm a^{-1}]	[g m^{-2} a^{-1}]			[mg m^{-2} a^{-1}]			[μg m^{-2} a^{-1}]		
Fluffy layer	10	4.4	159	21.9	4.4	219	4.6	18.2	20.5	1.0	1.3
Modern warm period (industrial age)	100	2.0	116	13.3	4.4	113	9.2	16.7	18.2	2.7	6.8
	natural background values for oxic conditions										
Cold phase (incl. Little Ice Age)	600	0.4	81	3.7	3.1	67	2.9	6.1	2.9		
	natural background values for anoxic conditions										
Medieval warm period	300	0.6	96	10.1	3.4	85	3.5	12.8	3.8		

av. LSR = average linear sedimentation rate; MAR = total mass accumulation rate of dry sediment.

In contrast to pollutants, organic matter sedimentation has remained at a very high level. Even in the context of the natural eutrophication caused by anoxic deep water, readily comparable with the MWP sapropel, and also the ongoing degradation processes in the anoxic sediments, the additional effect of human-induced eutrophication is still apparent (Jonsson & Carman 1994, Struck et al. 2000, Christiansen et al. 2002).

Starting from the age model of the selected core and considering the physical properties and geochemical profiles of the sediment, mass accumulation rates of selected parameters were calculated (see Table 1). Now, for instance, the anthropogenic impact in the upper sapropel sediment can be evaluated against the background of natural oxic and natural anoxic environmental conditions. The accumulation rates of inorganic (terrestrial) sediments (represented by Al) have not changed very much. Increasing trends in sedimentation rates during recent decades in some areas of the Baltic Sea, due partly to the postulated increase of erosion processes in shallower areas (Jonsson & Carman 1994, Christiansen et al. 2002), cannot be confirmed for the deep Gotland Basin.

5. Conclusions

The presence of a long-term stable pycnocline (halocline) is a precondition for the formation of bottom-water anoxia and the deposition of undisturbed laminated sediments (sapropel). This state, typical of the medieval and modern warm periods, can only be attained with regular inflows of saline water. The supplies of dissolved oxygen in saline water inflow events are insufficient to transform the whole system into oxic environments at the sea bed for longer periods. The dominant positive mode of the North Atlantic Oscillation Index (NAO) is the characteristic climatic background for this scenario.

During the cold phase from about 1250 to 1850, which includes the period of the Little Ice Age, the dominant negative NAO caused a reduction in sea water inflows to the Baltic and allowed vertical convection of the water column in the central Baltic Sea and ventilation of the sea bed (oxic stage). One, probably underestimated, aspect of the reduction in North Sea water inflow into the Baltic in the context of climate change is the winter ice cover of the Baltic Sea. On the assumption that the ice cover during the winter months of the Little Ice Age was much more extensive than in the medieval and modern warm periods, the conditions for wind-driven barotropic inflows during this cold period must have been much less favourable.

The temporal changes to the environment of the central Baltic Sea can also be interpreted by a climate-change driven large-scale shift in the Baltic ecosystem from the north to the south and back to the north. For the

Baltic Proper this means that at least during the Little Ice Age between the medieval and modern warm periods, conditions were very similar to those recently recorded in the northern Baltic Sea (Bothnian Sea and Bay).

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