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The Baltic Sea inflow regime at the termination of the Medieval Climate Anomaly linked to North Atlantic circulation

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Abstract Baltic Sea water exchange is primarily governed by atmospheric forcing of the inflow of saline waters by strong westerly winds prevailing over the central North Atlantic and north-western Europe. Our sediment core study uses geochemical element records indicative of phytoplankton and cyanobacterial blooming as well as continent-derived mineral input for reconstructing hydrographic changes in the deeper Baltic Sea basins around AD 1200. An alkenone-based Sea Surface Temperature (SST) reconstruction for the relevant time span, AD 500–1500, is presented for another sediment core obtained from the shallow Isefjord located at the southern coast of the Kattegat at the entrance of the Baltic. At the termination of the Medieval Climate Anomaly at approximately AD 1200, the basin sediment facies and the geochemical records reveal an environmental change indicative of a marked decrease of inflow activity and marine productivity. This change coincides with a SST decrease and recently reported general fall in Kattegat sea level. A comparison with palaeo-climate data from the wider North Atlantic region demonstrates that this regime shift in Baltic Sea water exchange is linked to a large-scale change in ocean and atmosphere circulation from a dominating, positive North Atlantic Oscillation (NAO+) mode to more negative NAO conditions.

Keywords *Saline inflow • Marine productivity • Medieval Climate Anomaly • Sediment cores • Geochemistry • Baltic Sea*

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INTRODUCTION

As a landlocked sea in a humid, temperate climate, the brackish Baltic Sea is characterized by a positive water balance where precipitation and run-off exceed evaporation (Brogmus 1952; HELCOM 1986). This normally results in a surface outflow of less saline Baltic water through the Danish Belts and Sound towards the Kattegat and Skagerrak, while intermittent inflow of denser, saline water near the bottom (Fig. 1) contributes to maintaining the brackish conditions of the Baltic Sea. Water mass exchange between the Baltic and Skagerrak is thus primarily controlled by atmospheric circulation variability and related changes in precipitation (Matthäus, Schinke 1994, 1997). Previously, Wyrtki (1954) had found that a major inflow event in 1951 was related to a three-week period of strong, gale-force westerly winds. Later, Dickson (1973) pointed out that during the 20th century wind-controlled variations in the salinity of the northwest European shelf seas may have played an important role, but could not be the primary cause of a major inflow. Matthäus and Schinke (1994), who studied major Baltic inflow events between 1899 and 1976, confirmed that strong zonal circulation over the central North Atlantic and NW Europe is a crucial precondition for triggering a major Baltic inflow event. They also found that the timing of such events

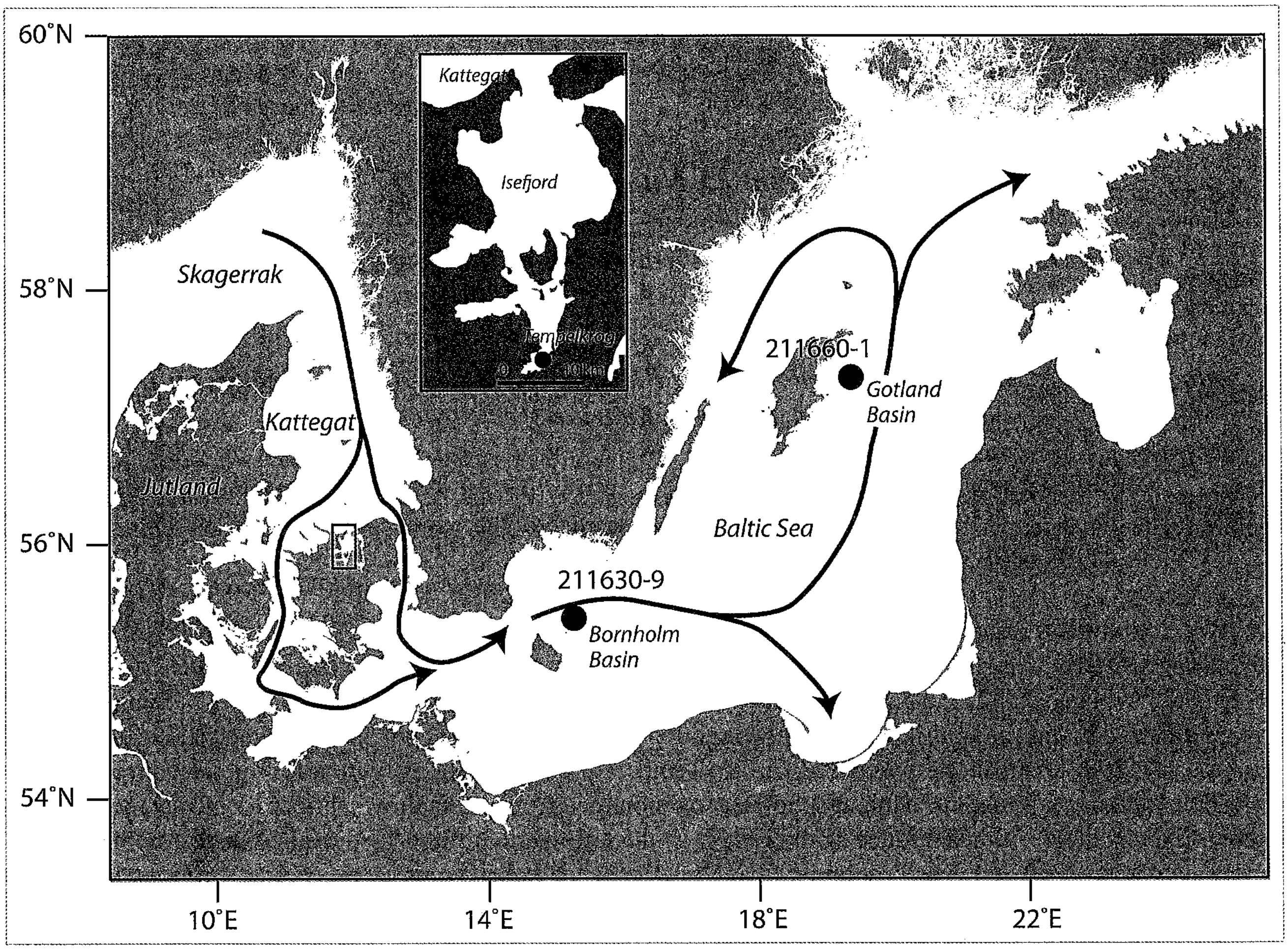

Fig. 1 Location of the sediment cores 211660–1 and 211630–9 in the Gotland and Bornholm basins, respectively, of the Baltic Sea. In addition, the small insert map shows the location of the sediment core retrieved from Tempelkrog, Isefjord, at the southern coast of the Kattegat. Arrows indicate the main pathway of the inflow of saline waters into the Baltic Sea basins (modified after Neumann *et al.* 1997, Fig. 1).

was not random, but confined to the period between August and April. As already observed by Dickson (1973), these events were associated with an increase in wind strength from westerly directions over several weeks. Stronger than average westerly winds over the middle latitudes of the North Atlantic are indicated by a positive index of the North Atlantic Oscillation (NAO; Hurrell, van Loon 1997). These conditions are characterized by low-pressure anomalies in the Iceland region and an anomalously strong subtropical high-pressure system, favouring mild and stormy winter weather with only limited sea ice formation in the Baltic. Under negative NAO conditions, atmospheric pressure over Scandinavia tends to be high, often leading to advection of cold Arctic air masses over the Baltic during the winter, which may result in extensive sea ice formation in the central and eastern part of the Baltic Sea (Koslowsky, Glaser 1999).

Periodic inflow of salt water into the Baltic is an important mechanism for renewal and ventilation of the Baltic deep water. However, during the periods in between these events, stagnation and strong stratification lead to increased hypoxia which in the sedimentary record of the deeper part of the Baltic is typically reflected by a biologically undisturbed laminated sediment sequence (Neumann *et al.* 1997; Andrén *et al.* 2000; Emeis *et al.* 2003). On geological time scales such sediment facies changes reveal distinct periodicities of 900 and 1500 years suggesting variations in palaeo-salinity that may be attributed to changes in large-scale wind forcing controlling the inflow of saline water masses into the Baltic basin (Harff *et al.* 2011). A more recent and very long stagnation period was observed after 1976, ending with an intense inflow event in 1993, which occurred during an episode of an unusually strong positive NAO (Neumann *et al.* 1997). Following a salt water intrusion the halocline rises, bringing nutrient-enriched water masses into the photic zone, favouring phytoplankton growth (Huckriede *et al.* 1995). It is thus obvious that the entire ecosystem of the Baltic Sea is strongly influenced by the atmospheric-controlled variations in deep- and surface water hydrography. Within this context it is important to note that cyanobacterial blooms often ascribed to anthropogenic eutrophication already occurred thousands of years before the increase of anthropogenic nutrient loading (Bianchi *et al.* 2000; Kunzendorf *et al.* 2001). Moreover, it is evident that these hydrographic changes and their impact on plankton blooming have also affected Baltic fish stocks that during medieval times contributed to the wealth of the northwest European Hanseatic League.

In the present study the authors will focus on changes in the Baltic Sea inflow regime at the termination of the Medieval (warm) Climate Anomaly (MCA) and link these changes to large-scale North Atlantic atmosphere and ocean circulation as documented by other studies. For this purpose geochemical data from two sediment cores retrieved from the Gotland and Bornholm basins will be used, supplemented by alkenone-based surface water temperature data from Isefjord, a Danish fjord at the southern coast of the Kattegat (Fig. 1). This reconstruction may have relevance for the assessment of possible future changes in the inflow regime of the Baltic as a consequence of a change in the wind field over Scandinavia (e.g. Pryor *et al.* 2012) under a global warming scenario.

MATERIAL AND SEDIMENT CORE SETTING

The two cores analysed for geochemistry were retrieved from two of the deeper basins of the Baltic Sea, i.e. the Bornholm and Gotland Basin (see Fig. 1). The cores were obtained within the framework of the BASYS project funded by the EU during the period 1998–2001 (Winterhalter 2001). Core 211660–1 was collected from the central part of the Gotland Basin (57.28° N : 20.12° E) at a water depth of 241 m, while the location of core 211630-9 is in the Bornholm Basin (55.38° N : 15.40° E) where local water depth is 93 m. Both cores have previously been subject to geochemical studies by Kunzendorf and Larsen (2002, 2009), who also report on the chronology. For details of the chronology of core 211660-1, the reader is further referred to Andrén *et al.* (2000) and Kotilainen *et al.* (2000).

The Gotland Basin represents one of the deepest areas of the Baltic Sea, with maximum water depths in excess of 200 m occurring in the north-eastern part of the basin from where the core was taken. Several studies (Winterhalter 1992; Sviridov *et al.* 1997; Emelyanov 2001) have demonstrated that the sediments in the deep Gotland Basin are much more heterogeneous than previously assumed, which can be ascribed to bottom current activity related to the occasional flow of dense, saline water masses into the basin. Maximum water depth in the Bornholm Basin is close to 100 m. The sediment accumulation patterns in the basin display strong variations that can be attributed to specific pathways followed by the dense bottom currents associated with major saltwater inflows (Christoffersen *et al.* 2007). The halocline in this basin is somewhat shallower, i.e. at c. 60 m, compared to the Gotland Basin, where the halocline is found at 70–80 m water depth. The core from Isefjord for which sea surface temperatures are presented was retrieved from a water depth of about 5 m in the relatively shallow Tempelkrog embayment (55.40° N : 11.49° E) in the inner part of the fjord (see Fig. 1). Isefjord is an estuary located at the southern Kattegat coast extending inland over a distance of about 36 km. It has a large central basin and is separated from the Kattegat by a threshold which does, however, still allow an inflow of saline Kattegat water towards the innermost parts of the fjord (Rasmussen 1973). The core chronology has previously been presented by Olsen *et al.* (2009).

ANALYTICAL PROCEDURES

The dating of the analysed cores has been described in detail in several former publications referred to above. The chemical analyses of cores 211660–1 and 211630–9 were based on a modified energy-disperse X-ray fluorescence (EDX) technique using radioisotopes for characteristic X-ray excitation. The system was equipped with a Si(Li) detector with a sample changer having a capacity of 48 samples as previously described by Kunzendorf (1979). Using two different radioisotope sources, the duration of the measurements of each sample was one hour. In addition, in order to evaluate the complex X-ray spectra, a conventional least-squares fitting unit, AXIL, was used. The results were calibrated with standards of 28 internationally recommended geological reference samples. The precision of the analyses was assessed from repeated measurement of international rock standards to be better than 5%. Although a wide spectrum of major and trace elements was measured over the length of the entire cores, in the present study authors focus on the element Cu and Mo (Gotland Basin core 211660–1) and K (Bornholm Basin core 211630–9) over the period of the last 2500 years.

For the Tempelkrog core authors focus on the SST record for the time interval AD 500–1500. The alkenone analytical procedure for this interval involved samples from every 2 cm. About 0.5 g of freeze-dried sediment was extracted three times with a mixture of methanol/methylene chloride in an ultra sonic bath for 15 minutes. After that, these three extracts were combined and dried by evaporation. Alkenones were isolated from the resulting total lipid extract by silica-gel chromatography following the method of Ternois *et al.* (2000). Subsequently, the alkenone fraction was analysed using a Varian CX 3400 gas chromatograph. Finally, SSTs were calculated following the UK';37 index calibration by Prahl *et al.* (1988) confirmed for global application by the compilation of Conte *et al.* (2006). For open marine water environments, external T precision has been estimated to be ± 1° C (Conte *et al.* 2006).

RESULTS

The geochemical profiles from the Gotland Basin core 211660–1 and Bornholm Basin core 211630–9 covering the past 2500 years are shown in Fig. 2 and 3, respectively, whereas the SST reconstruction for the Isefjord (Tempelkrog) core covering the time span AD 500–1500 is presented in Fig. 4 The most significant feature of the Gotland Basin core (Fig. 2) is a peak of high Cu and Mo concentrations centered around AD 1000, followed by an abrupt drop towards low values at ca. AD 1200. These low concentrations are only slightly higher or comparable with values recorded in the period before about AD 400 (1600 yrs BP). The peak values are correlated with a distinctly laminated sediment facies. This laminated sediment facies has been found widespread in the deeper parts of the Baltic and has been dated to span the period ca. AD 750–1200 (Zillén *et al.* 2008). The latter authors report other laminated sediment intervals to cover the Holocene Thermal Maximum and the period after AD 1800. Fig. 3 displays a generally variable pattern of K concentrations with lower values prevailing notably over the period from c. 1200 to 800 years BP (AD 800–1200). Beginning at approx. AD 1230 the record displays persistently higher concentrations of this element. During the period AD 500 to AD 1500 the SST record from Isefjord shows relatively small fluctuations mainly confined to the 10–11°C range (Fig. 4). The record displays only one clear warming peak represented by a positive temperature anomaly of ca. 1.5° C dated to around AD 1100.

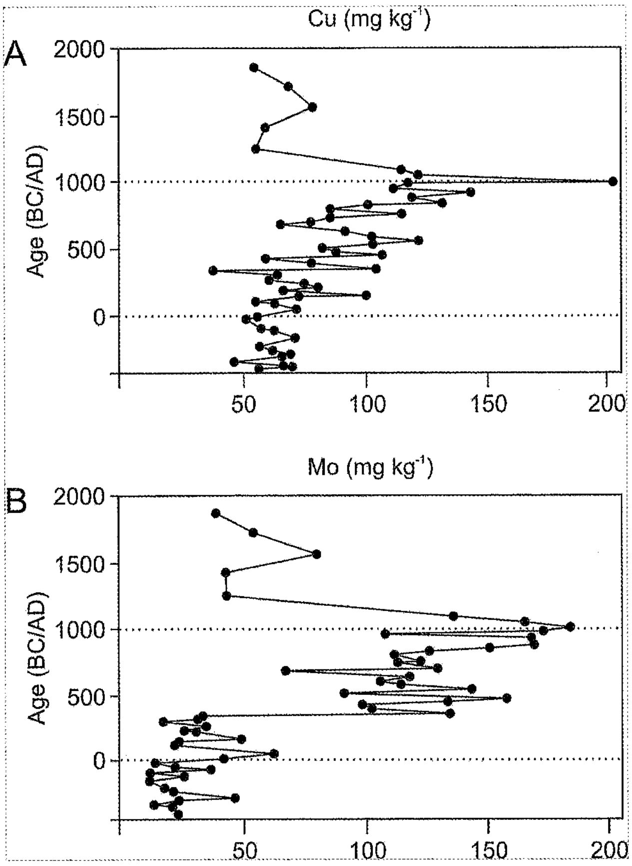

Fig. 2 Fluctuations of Cu and Mo concentration (mg/kg) in core 211660–1 from the Gotland Basin during the past 2500 years. The age model is from Andrén *et al.* (2000). Higher Cu and Mo values are indicative of phytoplankton and cyanobacterial blooming, respectively (Kunzendorf *et al.* 2001), and correlate with the organic carbon enriched, upper laminated (non-oxic) sediment sequence found in Gotland Basin sediment cores as illustrated by Zillén *et al.* 2008 (Fig. 6).

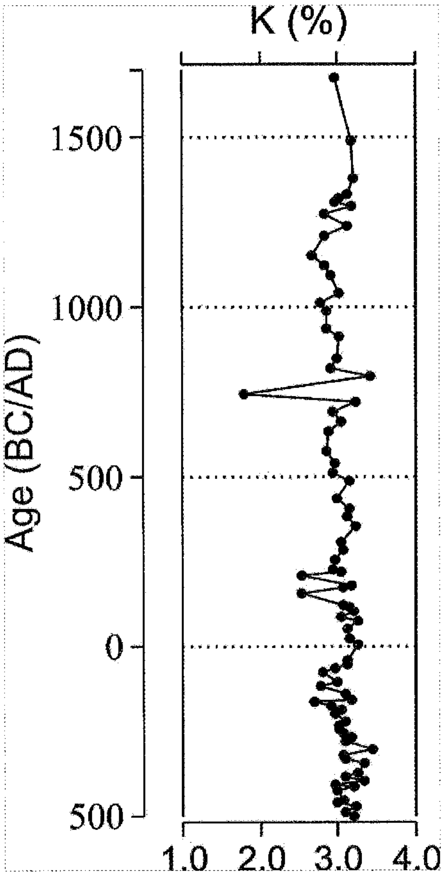

Fig. 3 Fluctuations of K concentration (%) in core 211630–9 from the Bornholm Basin during the past 2500 years. The age model is from Kunzendorf and Larsen (2009). Elevated K values are indicative of a relatively increased input of continent–derived detrital minerals, whereas low values point to an increased influx of marine matter. Lower K values during the MCA are associated with increased concentrations of Br (see Kunzendorf, Larsen 2009), an element indicating marine influence.

DISCUSSION

Baltic Sea inflow and marine productivity regime

The SST record from Isefjord (Fig. 4) shows maximum values after AD 1000 followed by a marked drop in temperature towards lower levels around AD 1200. At exactly the same time, average sea level in the northern Kattegat has been found to have fallen by about 0.35 m from a positive anomaly during the preceding period to a negative anomaly when compared to present day sea level (Hansen *et al.* 2011). This finding confirms results of previous studies by Christiansen *et al.* (1985), who reported a higher sea level at the Danish (Jutland) coast around AD 1100 followed by a low sea level around AD 1550, which has been further supported by beach ridge studies at Skagen Odde, northernmost Jutland (Tanner 1993). The instrumental data from the 20th century clearly demonstrate a higher sea level in the Kattegat under conditions of a prevailing NAO+ atmospheric

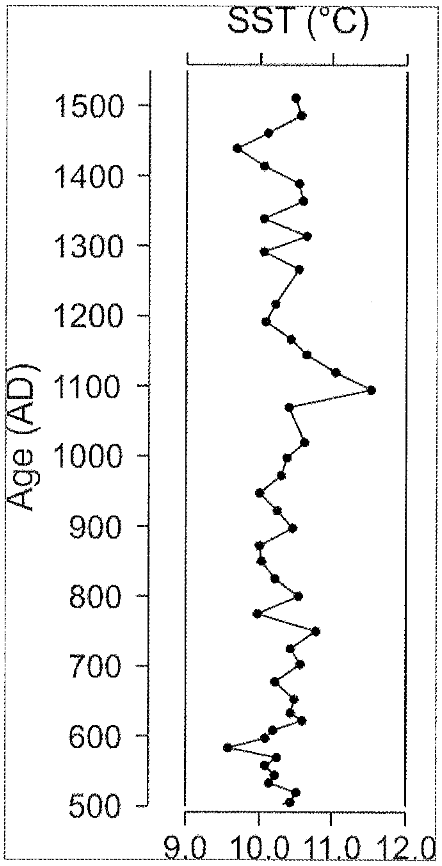

Fig. 4 Alkenone–based SST reconstruction for a shallow water core retrieved from Tempelkrog in the Isefjord, at the southern border of the Kattegat. Although the SST record of the entire core covers most of the Holocene, for the present study only the relevant time span between AD 500 and 1500 is presented. For comparison, mean annual SST values from the open, southern Kattegat during the second part of the 20th century generally range between 9.0 and 10.5° C (MacKenzie, Schiedek 2007; Madsen, Højerslev 2009).

circulation mode (Hansen *et al.* 2011). The timing of the medieval sea level change around AD 1200, which is coeval with the termination of laminated sediment deposition and Cu and Mo enrichment in Gotland Basin sediments coincides with the ending of the Medieval (warm) Climate Anomaly (MCA) and transition to the Little Ice Age (LIA), a period of below–average temperatures in Europe (Brazdil *et al.* 2005).

Within this context it must be noted that marked temporal and regional differences have existed for both the MCA and LIA climate anomalies (Broecker 2001). As for the LIA, cooling appears to have been global, whereas the case for a global MCA is rather inconclusive. Our SST reconstruction from Isefjord (Fig. 4) confirms the existence of the MCA in north–western Europe, with maximum SST values having been reached around AD 1100. From long-term temperature and salinity instrumental records covering the entire 20th century (Madsen, Højerslev 2009) we can conclude that seasonally the most significant contribution to a positive SST anomaly is made during the months January to March. This is part of the (winter) season during which the NAO pattern is well developed, leading to mild or severe northwest European winters, depending on its positive or negative index, respectively. The reconstructed palaeo-SST values concentrated in the 10.0–10.5° C range are close to the mean annual temperatures (9.0 and 10.5° C) recorded in open Kattegat waters during most of the second part of the 20th century (MacKenzie, Schiedek 2007, Madsen, Højerslev 2009). The decrease from maximum SST values of near 11.5° C around AD 1100 to about 10.0° C at about AD 1200 corresponds well with the observed inter-annual temperature range between recent cold and warm years. This temperature difference most likely reflects a drop in West European mean air temperature in the order of 1.2–1.4° C after a maximum in the period AD 1000 – 1200 (Lamb 1965). The combination of a medieval sea level high stand in the Kattegat and eastern North Sea (Christiansen *et al.* 1985, Hansen *et al.* 2011) and a positive SST anomaly provides strong evidence for a well-developed (winter) NAO+ circulation mode favourable for the triggering of saline water inflows into the Baltic (e.g. Matthäus and Schinke 1994). A recent modelling study in agreement with observational data from the past 50 years confirms the NAO to control both annual mean SST and sea level in the eastern North Sea, with a positive NAO leading to higher SST and sea level (Narayan *et al.* 2012). The relationship between low-frequency (annually averaged) Baltic Sea salinity and oxygen concentration demonstrates a negative correlation for both the upper and deeper layers of the water column, i.e. higher salinities are correlated with lower oxygen concentrations (Zorita, Laine 2000). Frequent medieval hypoxia between ca. AD 750 and 1200 as indicated by sediment lamination (Leipe *et al.* 2008; Zillén *et al.* 2008) thus may point to enhanced inflow activity, which is confirmed by our geochemical record from the Bornholm Basin showing generally relatively low K concentrations, i.e. reduced input of continent–derived material, when compared with the following period after ca. AD 1230. During this medieval period the sediments in the Bornholm Basin show increased Br concentrations as reported by Kunzendorf and Larsen (2009), which is in support of a stronger marine influx.

High Cu and Mo concentrations in our Gotland Basin core are well correlated with the high organic carbon content of the predominantly non-oxic depositional environment during the MCA. However, as further outlined below, several other indicators still suggest that marine productivity patterns may have been different as well. For instance, Huckriede *et al.* (1995) report that increased bottom water salinity in the Gotland basin leads to halocline shallowing and associated availability of nutrients to the photic zone. This, in turn, will enhance (spring) plankton blooming and also favour the post-spring bloom availability of nutrients (e.g. P) for the development of cyanobacterial blooming in the summer months (e.g. Kahru *et al.* 1994). After the spring bloom, when nitrogen becomes the limiting nutrient, Mo isotope fractionation occurs by cyanobacterial assimilation in relation to nitrate utilization and N_2 fixation (Zerkle *et al.* 2011). In addition, the sediment Mo enrichment mechanism operates particularly during periods when bottom waters are anoxic, favouring the formation of thiomolybdate near the sediment-water interface (Adelson *et al.* 2001).

Studies in the Gulf of Finland have confirmed that cyanobacterial blooms can be triggered by the inflow of saline waters into the Baltic (Kahru *et al.* 2000). Thus, the high Cu and Mo concentrations cannot be excluded also to reflect enhanced nutrient availability and associated increased productivity and cyanobacterial blooming, for which the element Cu and Mo, respectively, are indicators (Kunzendorf *et al.* 2001). A different primary productivity pattern during the MCA is supported by studies of Brenner (2005), who reports a marked change in (dinoflagellate) plankton blooming in the Gotland Basin at ca. AD 1200. In addition, modern hydrographic changes in the North Sea area under a positive NAO circulation mode are reported to lead to higher nutrient levels in the inflowing saline water masses from the Kattegat and Skagerrak (Brückner 2008). Similar conditions under the MCA thus may have further contributed to an elevated nutrient and productivity level in the Baltic. Benthic foraminiferal fauna evidence from the deeper (312 m) part of the Skagerrak shows a change in Atlantic-derived water mass advection dated to ca. AD 1200 (Hebbeln *et al.* 2006), which must also have affected the properties of Baltic inflow waters. In a more general context, it may be interesting to speculate which role this apparent change in the Baltic Sea inflow regime and marine productivity pattern has played in the explosive development of Scania herring fishery around AD 1200, becoming an economic cornerstone of the Hanseatic League, an era which ended at the beginning of the LIA, ca. 200 years later.

Linkage to North Atlantic large-scale circulation

The proxy evidence for a more dominant NAO+ atmospheric circulation mode over the Baltic area prior to AD 1200 cannot be further verified without searching for similar indications from the wider North Atlantic region, where the NAO has major implications for regional climate and ocean-atmosphere interaction patterns. For instance, under a positive NAO index, in contrast to European climate, the winter climate of the Labrador Sea region displays marked negative temperature anomalies due to advection of cold, Polar air masses by prevailing strong north-westerly winds (e.g. Hanna and Cappelen 2003, Drinkwater *et al.* 2003). Proxy studies in the Labrador Sea and surroundings of Davis Strait have shown evidence for a lacking MCA warming signal in this region (Keigwin *et al.* 2003, Seidenkrantz *et al.* 2007). Geochemical records from west Greenland lake sediments demonstrate a major shift in atmospheric circulation dated at ca. AD 1200 (D'Andrea *et al.* 2011). This coincides with a major hydrographic change in the West Greenland Current (Seidenkrantz *et al.* 2007) and the re-appearance of sea ice on the north coast of Iceland, after it had not been observed for a period of almost 200 years (Ogilvie 1984). A reconstruction of Arctic sea ice variability documents a period of extensive sea ice between AD 1200 and 1450 (Kinnard *et al.* 2011).

Evidence for a worldwide change in atmospheric circulation dated at AD 1200 – 1250 is found both in the Southern Hemisphere (Mohtadi *et al.* 2007) and at northern (European) high latitudes (Bakke *et al.* 2008). A study by Trouet *et al.* (2009) based on a compilation of various proxy data demonstrated prevalence of the positive NAO mode during the MCA, which is in agreement with a similar study by Kuijpers *et al.* (2009) linking this North Atlantic atmospheric circulation pattern to changes in El Nino-Southern Oscillation boundary conditions. Thus, both ocean and atmosphere proxy information confirms the prevalence of strong westerly winds (NAO+) over the North Atlantic during the MCA, with a major regime shift to a more variable, or predominantly negative, NAO regime dated to about AD 1200. For the Baltic Sea this large-scale regime shift thus implies a marked decrease in inflow activity and presumably also a generally lower marine productivity level.

CONCLUSIONS

Sediment geochemical records from the Gotland and Bornholm basin document a significant change in Baltic Sea hydrographic conditions at ca. AD 1200. This is characterized by a shift from a very active inflow regime with widespread hypoxia to more ventilated bottom water conditions and decreased inflow activity, whereas several indications simultaneously point to a general decrease in nutrient availability and marine productivity. This also implies a reduction in cyanobacterial summer blooms after ca. AD 1200. The regime shift occurred after a period of positive SST anomalies recorded in southern Kattegat coastal waters (Isefjord) and generally higher sea level stand recorded in the northern Kattegat.

Comparison with proxy-records from the wider North Atlantic region confirms that the hydrographic regime shift in the Baltic Sea can be related to a general change in the dominating atmospheric circulation pattern from a more positive NAO mode during the MCA to a more frequently negative NAO pattern in the period after ca. AD 1200. Interestingly, this regime shift is coeval with the explosive development of Scania herring fishery, an era which ended at the beginning of the LIA, ca. 200 years later.

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