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Climate reconstruction of the MWP in the Baltic Sea area based on biogeochemical proxies from a sediment record

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Abstract A multi-proxy data set from a sediment core from the Central Gotland Basin shows an extreme peak in many variables in a depth of 70-80 cm. Dating suggests an age of 700-790 varve years (before 1950) which fits into the Medieval Warm Period (MWP) from 1100-1250 AD. The variables are used as regional climate proxies for the Baltic Sea to reconstruct the biological variability during this period, to specify the necessary climate condition for the biological response, and to reconstruct in detail the climate during the MWP in the Baltic Sea area. The reconstruction of the climate conditions from sediment proxies and other observations indicates two regime shifts during the MWP from cold winters and cool summers ~1150 to cold winters and hot summers for approximately 30 to 40 years followed by a period of warm winters and hot summers ~1190. Using various climate data sets from the 20th century, composites of high and low North Atlantic Oscillation (NAO) indices are constructed for winter and summer situations to understand the regional influence and response of the Baltic Sea to longer lasting regime shifts in climate.

Keywords *Central Baltic Sea, Medieval Warm Period, climate variability, NAO index.*

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INTRODUCTION

Climate variability arises from natural mechanisms unrelated to human's action. Depending on the specific question and time scale, instrumental, other indirect observation, and models are available for the reconstruction of climate variability. E.g., Ganopolski and Rahmstorf (2001) have shown that it is possible to simulate the Daansgaard-Oeschger and Heinrich events with a simple coupled climate model. The longest available instrumental record, based on the development of the thermometer of Samuel Reiher (1710), is the monthly mean central England temperature starting in 1659 (Manley 1953, 1974, Parker et al. 1992). This time series covers the Little Ice Age at the Maunder Minimum 1670-1710. To reconstruct climate variability before the middle of the 17th century, indirect observations, so-called "proxies" (Stokstad 2001), or other qualitative information documented in the literature on extreme events in weather and climate are necessary.

Pollen e.g. a proxy for shifts in vegetation patterns which reveal temperature and moisture, stable oxygen isotopes and other elemental ratios in corals serve as proxy for sea surface temperature (Hoefs 1987). Climate variability is contained in ice cores and marine sediments. In the latter, microfossil assemblages reveal nutrient status of the surface water temperature, and salinity, while stable isotope values additionally reveal more precisely temperatures, terrigenous vs. marine particle input (Westerhausen et al. 1993) or the occurrence of cyanobacteria blooms (Carpenter et al. 1997)

Besides indirect observations or climate proxies, other qualitatively written information on extreme events in weather and climate are useful for the reconstruction of climate variability (Lowe 1870, Brückner 1890, Hellmann 1904, Hennig 1904, Brooks 1949, Girgus and Strupczewski 1965). Such information has been compiled to reconstruct the decadal mean temperature in summer and winter during the past millennium in central Europe (Glaser 1995) or to reveal ice winter severity and North Atlantic Oscillation (NAO) for the last 500 years in the Baltic Sea (Koslowski and Glaser 1995, 1997).

Only few papers deal with regional scale, while most of the publications concerning the reconstruction of the climate variability in the past millennium consider global or northern hemisphere scale. In this paper, we focus on the Baltic Sea and on one of the strongest signals in climate variability in the past millennium: the Medieval Warm Period (MWP) from 1100-1250 AD. We will not only try to reconstruct the climate during the MWP but also define conditions for the regime shift before and after the actual MWP. It is known that in the Baltic Sea the variability of abundance and biomass of many zooplankton and benthic species are directly connected to climate variability (Dippner et al. 2000, 2001, Dippner and Ikauniece 2001). Climate variability forces not only the physical variability of the Baltic Sea such as mean sea level (Heyen et al. 1996) or the salinity and oxygen distribution (Zorita and Laine 2000), but also the variability in the biological system. These signals should be visible in sediment records. The questions are, how strong was the influence of the MWP if we consider a relatively small regional scale? Can we receive more detailed information on environmental setting during the MWP? What was the influence of the MWP on the Baltic Sea? By selection of more recent years that may represent typical situations for the MWP climate variables are supposed to be identified. A suite of published data from a sediment core in the Central Gotland Basin is additionally chosen to qualitatively specify the climatic conditions and to reconstruct in detail the climate during the MWP for the Baltic Sea area.

DATA

Baltic Sea sediment core

The upper 5.5 m from the Kastenlot core 211660-6 from the Central Gotland Basin have been analysed for different biogeochemical variables to infer changes in environmental settings during the last several thousand years (Litorina stage). The sediment dating from present to 3000 years ago is based on paleomagnetic variations in the inclination and declination compared to the paleosecular variation in annually laminated sediment from a Finnish lake with an absolute accuracy of better than ±50 years and a mean sedimentation rate through the upper 0.5 m of 1 mm/year (Kotilainen et al. 2000). Figures 1 to 3 show selected profiles of variables of the core, that were

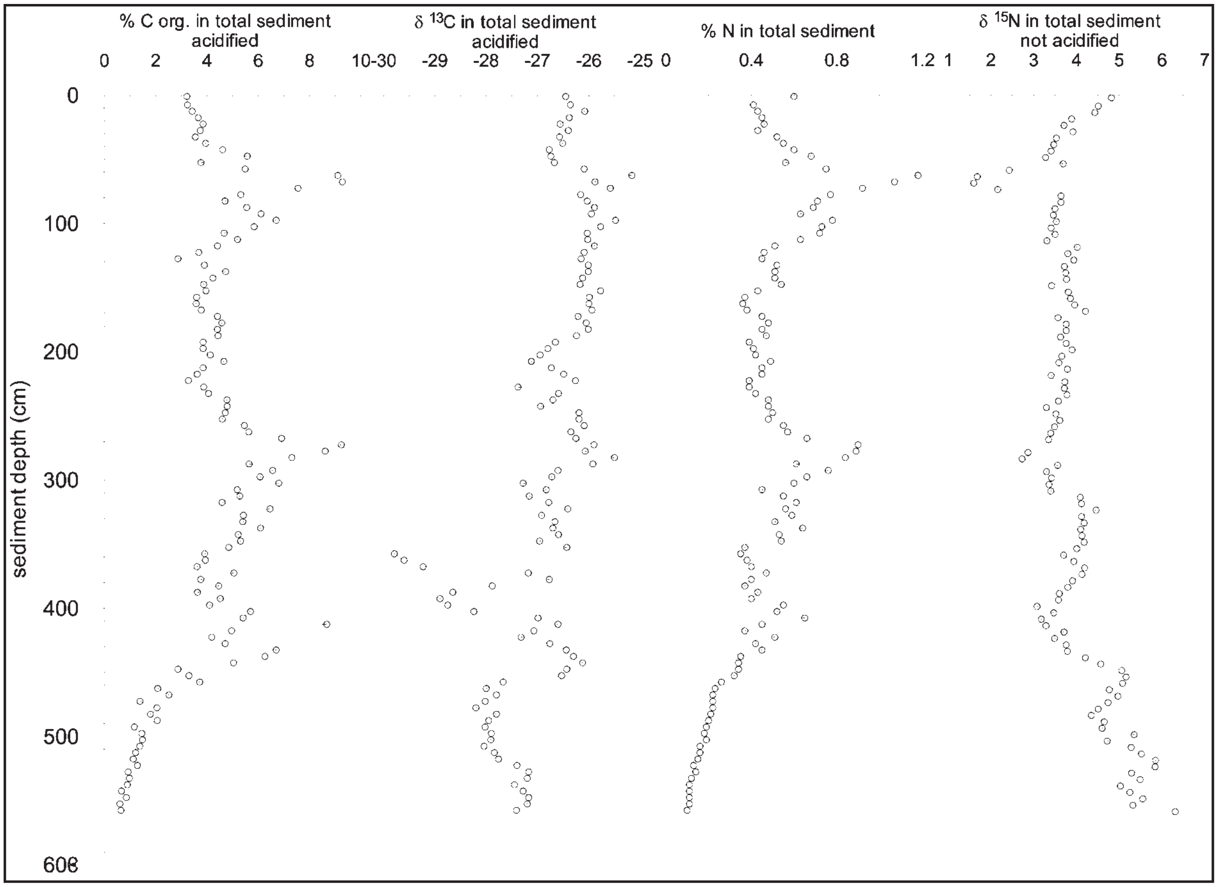

Fig. 1. Percent organic carbon, $\delta^{13}C$ in organic material in the sediment, % total nitrogen, and $\delta^{15}N$ in sediment against depth from sediment surface for core 211660-6 after Voss et al. (2001).

described elsewhere in detail (Nytoft and Larsen 2001, Kowalewska et al. 1998, Voss et al. 2001): percent organic carbon, $\delta^{13}C$ in organic material in sediment, % total nitrogen and $\delta^{15}N$ in sediment (Figure 1, Voss et al. 2001), percentages of grain sizes (<0.01 mm), pyrophaeophytin a, chlorophyll/chlorin a, chlorophyll b, chlorophyll c (Figure 2, Kowalewska et al. 1998), pine pollen, % *O. centrocarpum* with different spines <4 µm, 4-6 µm, and >6 µm (Figure 3, Brenner 2001) and organic compounds like hopanes and fernenes (Nytoft and Larsen 2001). The core shows extremely high peaks in several variables indicating good preservation conditions and high surface productivity, however, of different organisms in different times. A remarkable signal in this sediment core is a strong peak between 60 and 80 cm in different variables. Dating of the core suggests an age of 700-790 years before 1950 for this layer (Harff et al. 2001, Alvi and Winterhalter 2001, Andrén et al. 1999), that is app. 1160 to 1250 AD. The corresponding peak is subject of our interest and we try to reconstruct with a multi-proxy approach from various sediment proxies the biological and the climate variability during this period.

Organic nitrogen and carbon show the highest values of the whole core with 1.2% $N_{org.}$ and 10% $C_{org.}$ pointing to extremely high surface productivity and/or good preservation. The isotopic composition of nitrogen with values as low as 0.9‰ at 72 cm depth indicates almost pure nitrogen fixing cyanobacteria as organic matter source (Carpenter et al. 1997). All chlorines at that depth are high and have a concentration of slightly less than 400 µg/g. The peak chlorophyll c, however, is directly below the maximum of all other pigments and indicates the presence of diatoms at the time of sedimentation. This clearly indicates production and sedimentation of large amounts of relatively fresh organic matter from the surface waters (Kowalewska 2001). Some other variables like grain size and microfossil assemblages are not well resolved down core. Nevertheless, they can be used to support the interpretation of the peak identified by means of chlorines and stable isotope data. Six data points in the upper meter of the core were analysed for grain sizes (Repečka 2001), and around 60 cm depth a peak in percentage of grain size <0.001 mm, 0.005-0.001 mm, and a weak maximum in 0.01-0.005 mm was identified, while the coarse fraction was absent.

We assume that the Gotland Basin has higher sedimentation rates and calmer current conditions than the Northern Central Basin or the Bornholm Basin. Weak wind speed and low turbulent mixing were tentatively deduced from the grain size patterns. Twenty

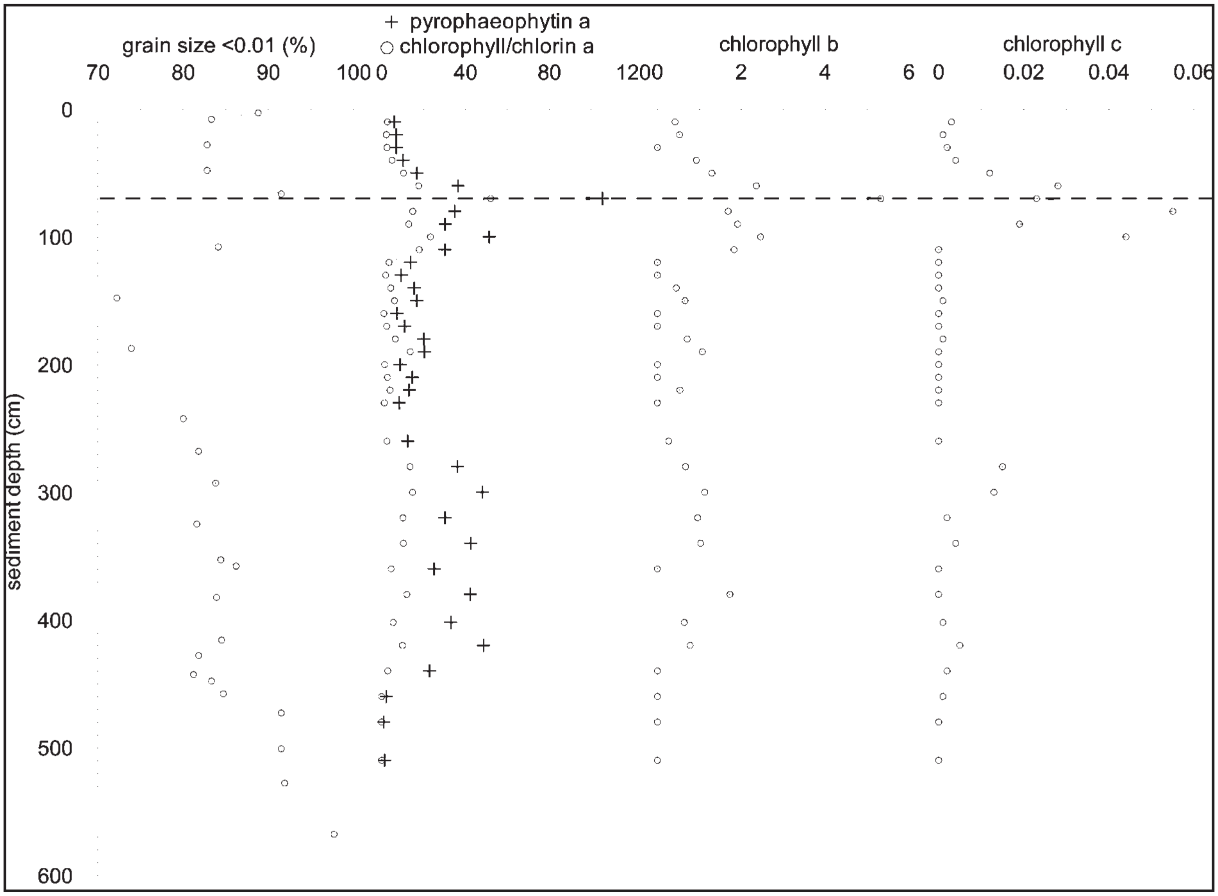

Fig. 2. Percent grain size (<0.01mm), pyrophaeophytin a, chlorophyll/chlorin a, chlorophyll b, chlorophyll c against depth from sediment surface for core 211660-6 after Kowalewska et al. (1998).

different microfossils were differentiated by Brenner (2001) in coarse resolution of just three values for the upper meter. The data set shows a peak at 78 cm sediment depth in spine length of *O. centrocarpum* (< 4 µm) indicating lower salinity. Alvi and Winterhalter (2001) showed peaks in Ca, Mn, and Si, but no signal in Fe, S, and Al. Kunzendorf et al. (2001) identified a peak in molybdenum, which they believe might serve as a proxy for cyanobacteria blooms. Further detailed analyses and descriptions of various brackish-marine taxa or freshwater taxa at this sampling position are given in Andrén et al. (2000a, 2000b). In addition, a peak at 70-80 cm depth appears in a number of organic compounds like malabaricatriene (MBT), fernene, and hopene (Nytoft and Larsen 2001). No absolute concentrations are given for these compounds but only relative values. The MBT has been analysed in anoxic sulphur rich sediments and is considered as a compound formed in specialised bacteria surviving highly anoxic sites (Nytoft and Larsen 2001). The fernene were thought to mirror input by terrestrial plants (ferns) before they were also detected in methanogenic sediments, so that their presence may reflect anoxic depositional conditions. The same is assumed for hopenes that are constituents of degradation products of membranes.

No peak appears at 70-80 cm in the following microfossils: *O. centrocarpum* with spine length of 4-6 mm, and >6 mm, in *L. machaerophorum*, *T. psilatum*, *Spiniferites* spp., *A. choantum*, *G. catenatum*, *Cymatiosphaera* spp., marine dinoflagellate cysts, freshwater dinoflagellate cysts. In addition, no peaks appear in taraxer-14-ene, a purely terrigenous product, and the hydrogen index (HI), both being rather evenly distributed along the core hinting towards a fairly constant terrestrial input. Copepod eggs, coccal green algae, and pine pollen show a peak at ~60 cm depth but no pronounced signal at ~70 cm depth. Table 1 displays selected regional climate proxies for the Baltic Sea in the sediment core, the possible biological causes, and the necessary climatic conditions for the biological response.

Taraxer-14-ene is purely of terrestrial origin and formed in higher plants (Ten Haven and Rullkötter 1988) as well as in pine pollen. The absence of both during this period indicates a climatic situation with weak river runoff, anomalously low precipitation, and low wind speed. This assumption is supported by the absence of cladoceran, freshwater dinoflagellates, and green algae. The cladoceran (remains) are dominant freshwater species. The green algae assemblage is dominated by Pediastrum, a freshwater algae. The absence of the

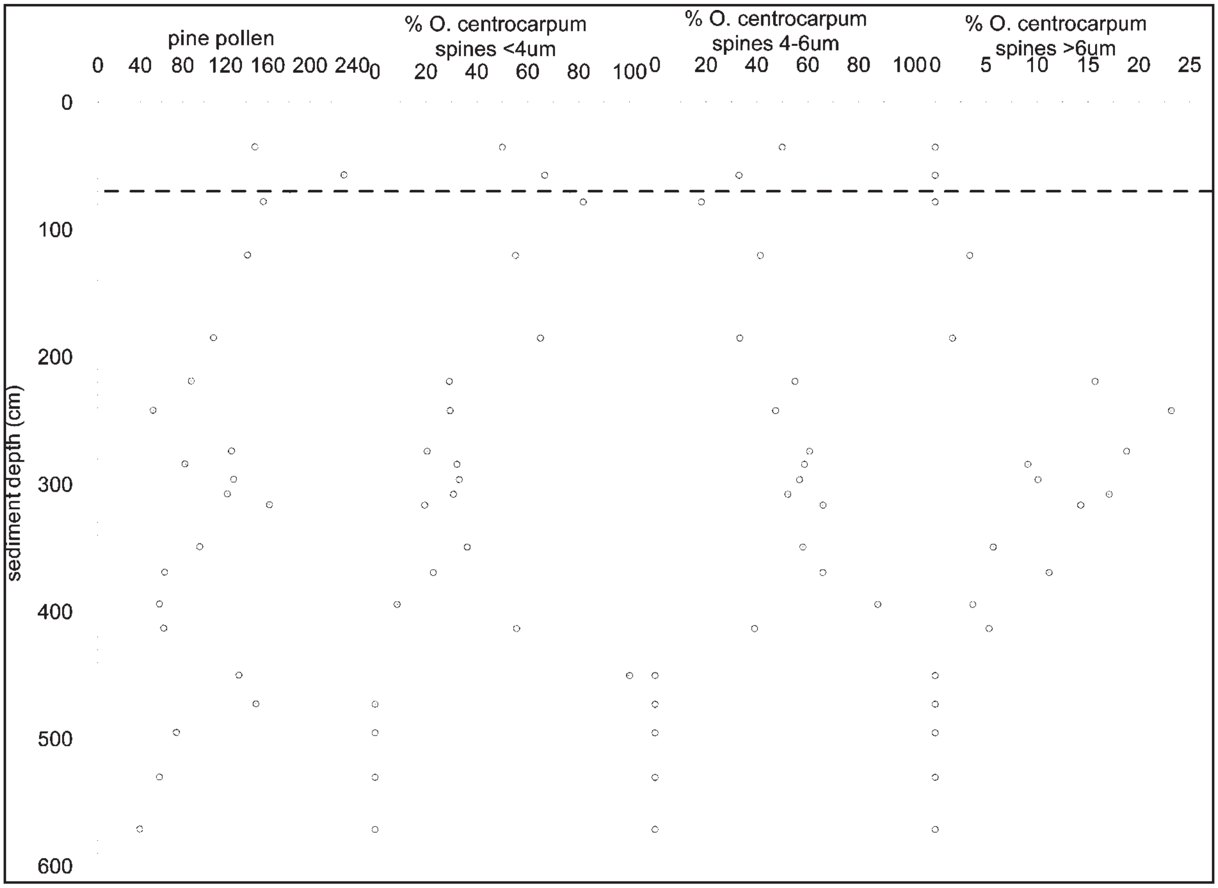

Fig. 3. Pine pollen and percent of *O. centrocarpum* with different spine length of <4 µm, 4-6 µm, and > 6 µm against depth from sediment surface for core 211660-6 after Brenner (2001).

Table 1. The regional climate proxies for the Baltic Sea in the sediment core, the biological interpretation and the necessary climatic conditions.

Sediment proxy	**Biological interpretation**	**Climate condition**
High chlorophyll- c	Strong diatom bloom	Cold winter
Low $\delta^{15}N$	Cyanobacteria bloom	Hot summer, low wind speed
No pine pollen		Calm winds, low river runoff, low precipitation
No taraxer-14-ene	Terrestric plants	Low river runoff, low precipitation
No cladocerans	Freshwater species	Low river runoff, low precipitation
No Pedastrium	Green freshwater algae	Low river runoff, low precipitation
High hop-22(29)-ene	High bacterial productivity	Hot summer
High TOC	High production and/or cyanobacteria bloom	Hot summer, low wind speed
Molybdenum	Cyanobacteria bloom	Hot summer, low wind speed
Fine grain size		Weak turbulent mixing, weak wind speed
Spine length *O. centrocarpum*		Salt water inflow into the Baltic Sea

three species may also be an indicator for low river runoff.

The pronounced peaks in % TOC and total nitrogen and inverse in the $\delta^{15}N$ indicate high biological production which can either be ascribed to high nutrient concentrations and high spring bloom sedimentation (Voss et al. 1996) or to an exceptionally dense bloom of cyanobacteria (Carpenter et al. 1997). Since high nutrient input can be excluded due to the low river runoff, the pattern is probably caused by a cyanobacteria bloom. Hopene is found in laminated sediments with high TOC. It is generally accepted that the accumulation of high cyanobacteria blooms appears during calm wind and hot summers. Therefore, in addition to low river runoff due to anomalously low precipitation, a climatic situation is required which is characterized by hot summers and low wind speeds. Additionally, low wind speeds might have fostered anoxia in deeper water layers, thus, enabling the release of Fe-III-phosphate, which is a prerequisite for cyanobacteria blooms.

The peak in chlorophyll-c indicates strong diatom blooms. This fits together with the peak in heterotrophic dinoflagellates, a group that feeds on other algae, mainly on diatoms. Since diatoms have a competitional advantage after cold winters (Fogg 1991, van Beusekom and Diel-Christiansen 1994, Wasmund et al. 1998), we propose a climatic situation with a longer lasting period of cold winters. After the peak the chlorophyll-c vanishes. Therefore, cold winters and cool summers must have existed before the appearance of the peak, followed by the "peak situation" with cold winters and warm summers, and then by a period of warm winters and hot summers after the peak.

Historical observations

Our qualitative reconstruction of the climate variability during the MWP in the Baltic Sea area is based on the historical observations of Hennig (1904), Hellmann (1904), and Girgus and Strupczewski (1965). The disadvantage of these observations is that only extreme events are documented, however, "normal" situations are not mentioned. That makes the reconstruction rather problematic.

Few typical examples of the historical observations are given here: 1114 AD was an extremely dry autumn in England and the River Thames was nearly dry. 1158 AD was an extremely hot summer with great aridity, therefore, the army of King Friedrich Barbarossa was able to cross all rivers in Italy, River Po included, without using boats or bridges. 1185 and 1186 AD were excellent wine years with many grapes and excellent quality and quantity. 1204 AD was an extremely cold winter with a lot of ice on the Baltic Sea; it was possible to walk from Germany to Denmark. In 1221 AD much rain fall and floods from spring through autumn were recorded in Poland; damage of many houses; complete crop failure; extreme famine; many villages were wiped out by death of starvation; followed by a cold winter.

All this information is merged in Table 2. Cold winters are marked (w-), warm winters (w+), cool summers (s-) and hot summers (s+). A cluster of years can be identified before ~1150 AD with cold winters and cool summers (w-s-), between ~1150-1190 AD of cold winters and hot summers (w-s+), followed by years with warm winters and hot summers (w+s+). The regime shifts thus identified (w-s-) ⇒ (w-s+) and

Table 2. Years fulfilling the (w-s-), (w-s+), and (w+s+) criterion between 1100-1250 AD.

(w-s-)	**(w-s+)**	**(w+s+)**
1125	1158	1186
1133	1159	1192
1143	1165	1194
1144	1170	1198
1147	1173	1227
1150	1176	1228
1154	1177	1236

(w-s+) ⇒ (w+s+) are around ~1150 and ~1190 AD respectively. They are identical with the reconstructed temperature of central Europe (Glaser 1995). We believe that these regime shifts are mirrored in climatic events producing the peak at 70 cm in the Gotland Sea. Crowley and Lowery (2000) have shown that the warming during the MWP was on a global scale of the same order as the warm periods in the 20th century. Hence, we try to reconstruct the climate during the MWP with climate data and composite analysis from recent decades when ample information is easily accessible.

Recent climate data

The following climate variables have been used for the reconstruction of the climate variability:

- Data of monthly mean sea level air pressure (SLP) anomalies on a 5°×5° grid from 1899-1996. These data were reanalysed in the National Center for Atmospheric Research (NCAR), Boulder (Trenberth and Paolino 1980). The selected area extended from 70°W to 15°E and from 30°N to 70°N.
- The North Atlantic Oscillation (NAO) index is defined as the difference between the normalized SLP anomalies during wintertime at Lisbon, Portugal and Stykkisholmur, Iceland. The SLP anomalies at each station were normalized by division of each seasonal pressure by the long-term mean (1864-1999) standard deviation (Hurrell 1995). Figure 4 shows the NAO winter index after Hurrell (1995). The thick line is the low-pass filtered time series.
- The global Comprehensive Ocean Atmosphere Data Set (COADS) Release 1 (1854-1979) and Release 1a (1980-1992) (Slutz et al. 1985, Woodruff et al. 1987). COADS contains on a 2°×2° grid monthly mean values of sea surface temperature (SST), air temperature, specific humidity, relative humidity, scalar wind speed, west-east and north-south component of the wind speed, and air pressure. In the Baltic Sea area, COADS is extremely sparse and infrequent in observations. Therefore, all points for Baltic Sea area, which have more than 80% observations, are selected and area averaged.
- Monthly runoff data for the whole Baltic Sea area for the period 1921 to 1993 consists of the data from 1921-1949 (Mikulski 1982) and the data compiled by the Swedish Meteorological and Hydrological Institute (SMHI) for 1950-1993. There are no in homogeneities between these two datasets (Bergström and Carlsson 1994).

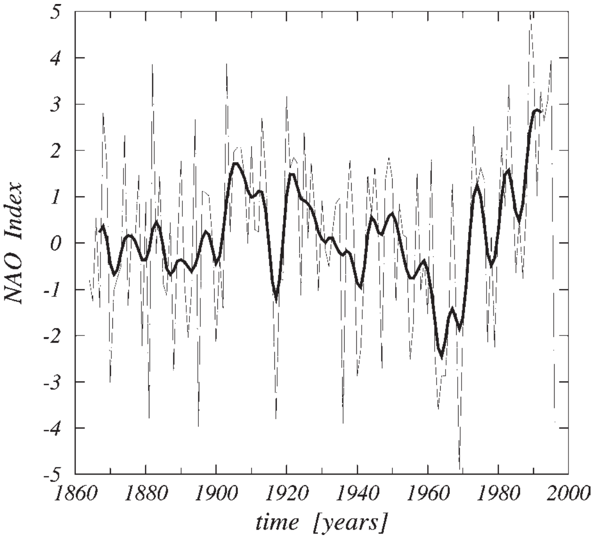

Fig. 4. North Atlantic Oscillation (NAO) winter index after Hurrell (1995). The thick line represents the low-pass filtered time series.

METHOD

The monthly mean NAO index and the SLP data set have been averaged over three month intervals. Winter (December-January-February, DJF) and summer (June-July-August, JJA) averages are used to construct composites for cold winters (w-), warm winters (w+), hot summers (s+) and cool summers (s-). From all DJF- and JJA-values larger in amount than one standard deviation, all years are selected that fulfil the criterion of the (w-s-), (w-s+) and (w+s+) composite. Table 3 displays all years selected for the composite analysis.

Table 3. Years fulfilling the (w-s-), (w-s+), and (w+s+) criterion for the construction of the composites in the data from the 20th century.

(w-s-)	(w-s+)	(w+s+)
1917	1941	1920
1956	1947	1925
1960	1955	1937
1963	1964	1973
1977	1969	1975
1987	1970	1983
		1989

These years are extracted and high and low NAO composites for the DJF- and JJA period are constructed. From SLP, SST, air temperature, scalar wind speed, west-east component and north-south component of the wind speed, and the total river runoff into the Baltic Sea monthly anomalies are constructed by subtracting the long term climatic mean. Thus, three composites for (w-s-), (w-s+) and (w+s+) are given by averaging the anomalies over the selected years (Table 3). To identify the transition from one period to the next, namely (w-s-) ⇒ (w-s+) and (w-s+) ⇒ (w+s+), also the differences of the composites are computed for the two regime shifts.

RESULTS

Figure 5 shows the long-term mean seasonality from COADS for the Baltic Sea area. The air temperature

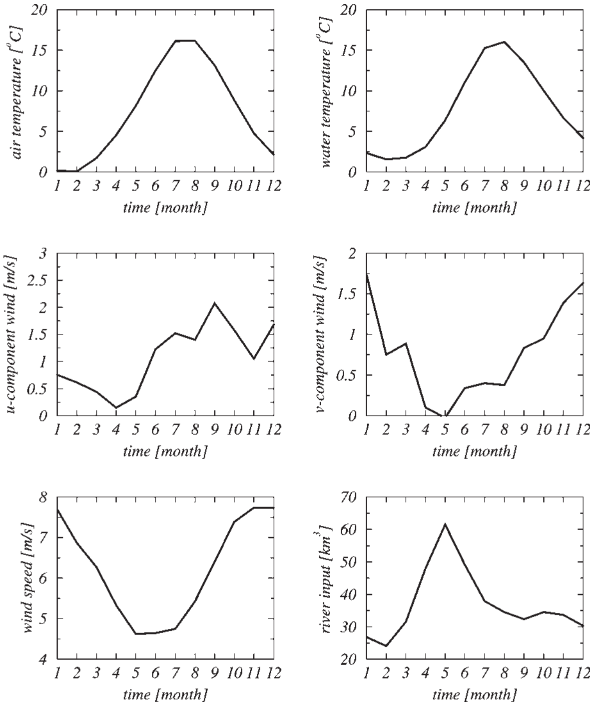

Fig. 5. Long-term seasonal means for the Baltic Sea area: air temperature *(top left)* and water temperature *(top right)*, u-component *(west-east, middle left)* and v-component *(north-south, middle right)* of wind, wind speed *(bottom left)* and total river input *(bottom right)* into the Baltic Sea.

varies between 0°C in winter and 16°C in summer, whereas the SST almost covers the range from 1.6°C in February to 16°C in August. The north-south (v-) component of the wind (positive sign indicates southerly wind) has the highest values during winter and shows calm wind situations from April to June. The west-east (u-) component of the wind (positive sign indicates westerly wind) has its maximum in autumn and weak westerlies from March to May. Both components are positive, indicating the typical climatological SW wind fields. The wind speed shows a climatic average of nearly 8 ms^{-1} from November to January and low wind speeds of 4-5 ms^{-1} from May to July. Finally, the climatic mean of total river input is in the order of 30-35 km^3 with a minimal runoff of 24 km^3 in February and a peak value of 61 km^3 in May.

The NAO is the only atmospheric mode that is robustly present in every month of the year. It is most pronounced in amplitude and areal coverage during winter and it accounts for more than one-third of the total variance of the SLP (Marshall et al. 2001). The atmospheric circulation patterns that are related to extreme situations are shown in the composites of high and low NAO index for winter and summer (Figure 6). Since composites are averages over extreme situations, the gradients in SLP fields might be much stronger than in "normal" climatic situations. The high NAO composite for SLP in winter shows the typical distribution of the Islandic low and the Azores high-

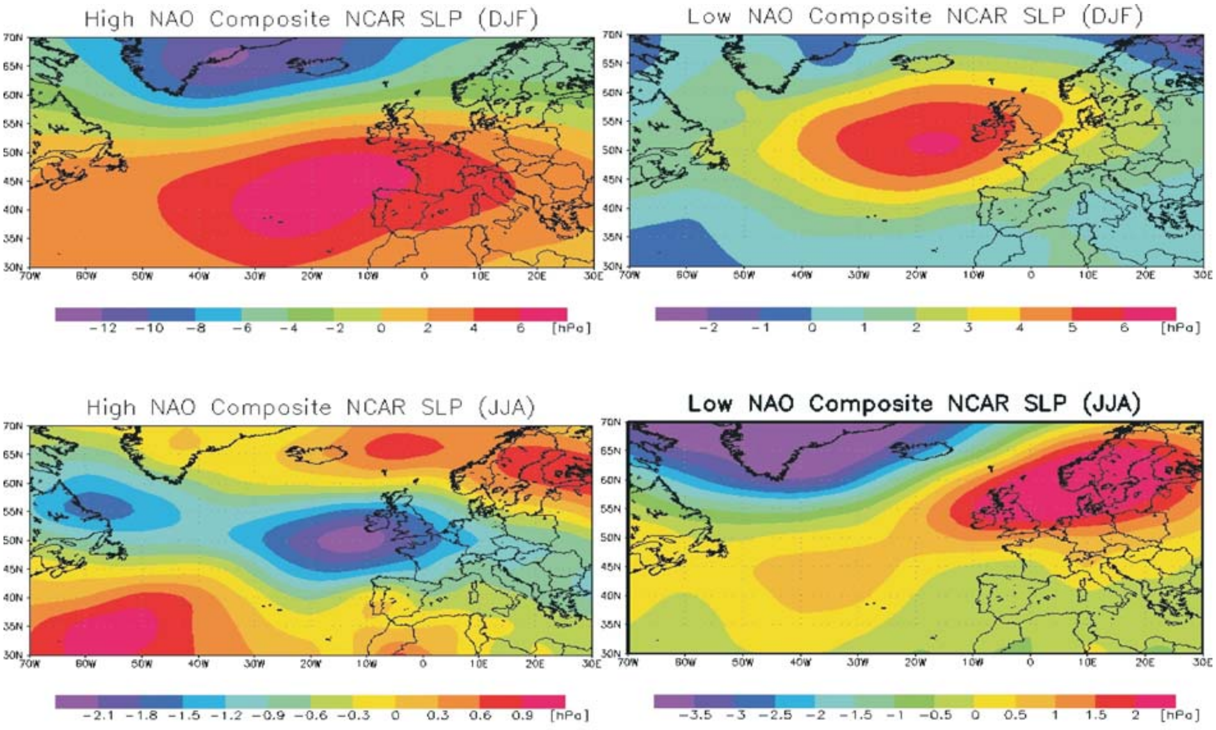

Fig. 6. *Top left:* high NAO composite for sea level pressure (SLP) in winter (DJF average). Contour interval (CI) = 1 hPa. *Top right:* low NAO composite for SLP in winter. CI = 1 hPa. *Bottom left:* high NAO composite for SLP in summer (JJA average). CI = 0.5 hPa. *Bottom right:* low NAO composite for SLP in summer. CI = 0.5 hPa.

pressure system with a difference of over 18 hPa between the centres of action. This circulation pattern is connected with strong westerly winds, transporting warm air masses to central Europe, and results in warmer than normal winters and higher than normal precipitation. The low NAO composite of SLP in winter is characterized by a huge ridge west of Ireland that might result in a blocking situation over the North Atlantic. The resulting atmospheric circulation transports warm air masses over the Gulf Stream to Greenland and cold polar air masses to central Europe causing extremely cold winters and anomalously low precipitation in Europe. The low NAO composite of SLP in summer shows a large high-pressure system over northern Europe. This pattern can have a persistency of many weeks and is connected with an atmospheric blocking situation, the so-called Ω-circulation. The blocking of the Fennoscandinavian high-pressure system results in warmer than normal summer situations with low wind speeds and nearly no precipitation. In contrast, the high NAO composite of SLP in summer is characterized by a broad band of troughs passing continuously over the North Atlantic. This circulation pattern affects colder than normal summer situation and extremely high precipitation. It should be mentioned that a positive NAO during wintertime is connected with warmer than normal winters in central Europe, whereas a positive NAO in summer results in cooler than normal summers, and vice versa.

How do these patterns influence the Baltic Sea area? Figure 7 shows the various composites for cold winters and hot summers (w-s+). This climatic situation has been identified for the MWP between 1150 –1190 AD. The air temperature for this period is 2°C colder during wintertime and up to 1°C warmer in August compared to the long-term mean. This results in a decrease of SST of 1°C in April and a 1°C warmer SST in August. The composites of the wind anomalies show an easterly component of 3 ms^{-1} in February, which brings cold polar air masses to central Europe, whereas the negative values in both components in August indicate moderate northeasterly wind that is connected to the typical atmospheric blocking situation. The wind speed shows, compared to the long-term means, only a weak variability, however, the wind direction is completely different to the climatic mean. Except April, the total river input shows negative anomalies up to 8 km^3. Integrated over the whole year, the total river input is approximately 60 km^3 less than the long-term climatic mean.

In the following, two identified regime shifts are described. The first transition (w-s-) ⇒ (w-s+) around 1150 AD from cold winters and cool summers to cold winters and hot summers is constructed from the difference of the composites (w-s+) – (w-s-)

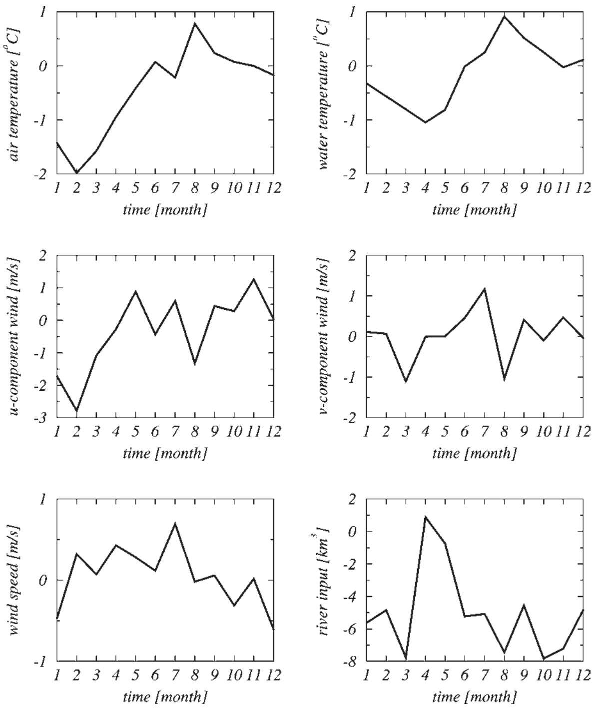

Fig. 7. Averaged anomalies for the (w-s+) composite for the Baltic Sea area: air temperature *(top left)* and water temperature *(top right)*, u-component *(west-east, middle left)* and v-component *(north-south, middle right)* of wind, wind speed *(bottom left)* and total river input *(bottom right)* into the Baltic Sea.

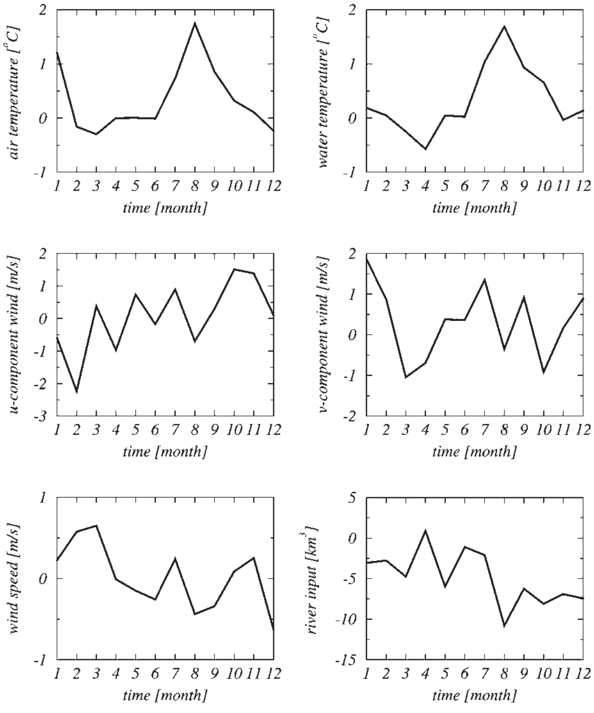

Fig. 8. Reconstructed regime shift (w-s-) ⇒ (w-s+) for the Baltic Sea area: air temperature *(top left)* and water temperature *(top right)*, u-component *(west-east, middle left)* and v-component *(north-south, middle right)* of wind, wind speed *(bottom left)* and total river input *(bottom right)* into the Baltic Sea.

(Figure 8). The air temperature and SST increase nearly by 2°C in August. The wind speed shows only weak variability, but the wind direction varies in the transition from southeasterly winds in winter over weak variability in spring, followed by northeasterly winds in summer and northwesterly winds in autumn. The total river input shows mainly negative anomalies, which are in the order of 60 km^3 integrated over the year. This is in the same range as the (w-s+) composite indicating that the (w-s-) composite which describes the period before 1150 AD, has weak anomalies and is very close to the long-term climatic mean.

The second regime shift (w-s+) ⇒ (w+s+) around 1190 AD. from cold winters and hot summers to warm winters and hot summers is constructed from the difference of the composites (w+s+) – (w-s+) (Figure 9). The air temperature increases over 4°C in January and February and the SST increases in the order of 1 to 2°C between January and May. Westerly winds increase by 3.5 ms^{-1} in January and February, which presumably results in higher precipitation in the Baltic Sea area. Therefore, the total river input increases between 9.5 to 13.6 km^3 for the period January to March.

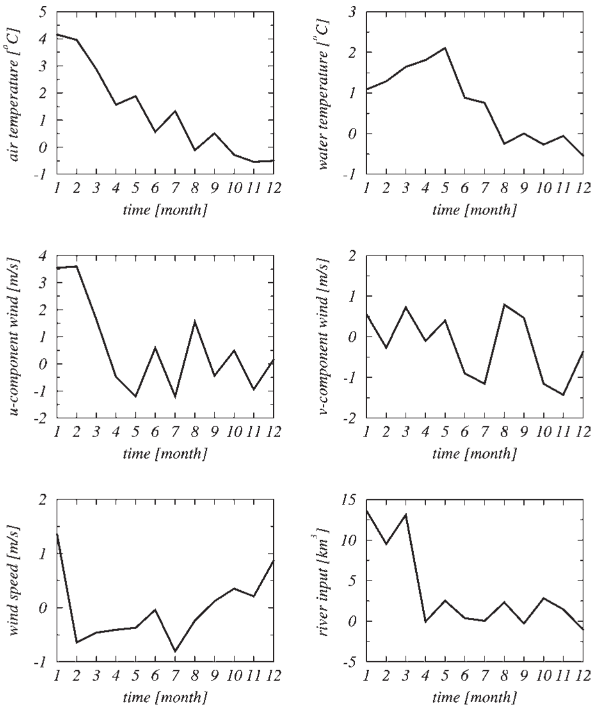

Fig. 9. Reconstructed regime shift (w-s+) ⇒ (w+s+) for the Baltic Sea area: air temperature *(top left)* and water temperature *(top right)*, u-component *(west-east, middle left)* and v-component *(north-south, middle right)* of wind, wind speed *(bottom left)* and total river input *(bottom right)* into the Baltic Sea.

DISCUSSION

Broecker (2001) argued that the MWP might be a global event. This is supported by Crowley (2000) and Crowley and Lowery (2000) who showed that the MWP was mainly driven by stronger than normal solar activity and no major volcanic activity for more than 80 years. Climate reconstruction of the MWP with tree ring records (Jones et al. 1998, Mann et al. 1999) shows a positive temperature anomaly in the order of 0.3°C for the northern hemisphere only. Glaser (1995) reconstructed an increase in decadal mean summer temperature of 0.9°C between 1150 and 1160 AD and an increase of 2°C in winter temperature around 1190 AD for central Europe. Our investigation shows an increase in the air temperature and SST in summer of 2°C for the Baltic Sea area starting around 1150 AD. The second regime shift around 1190 AD shows an increase in winter air temperature of 4°C and of 1–2°C in winter SST. Both results indicate that climate variability may have much stronger amplitudes on a regional scale such as the Baltic Sea area than on a global or northern hemisphere scale. Our results are supported by the careful analysis of Harff et al. (2001), who defined in the Baltic Sea a specific zone B5 that fits exactly into the MWP. They also propose high organic production and conservation, low influx of terrigenous material, and anoxic conditions for this layer.

Strong peaks in sediment variables created by changes in the biological system can be caused by sudden regime shifts followed by periods of extreme climatic settings. The biological regime shift during this period can be qualitatively compared to the 1930s and 1990s warm period in central Europe (Crowley and Lowery 2000). They showed that the warming during the MWP was in the same order of magnitude as the warm periods in the 20th century. The first regime shift results in a deficit of 60 km^3 per year in total river input into the Baltic Sea. If we consider the (w-s+) composite as longer lasting climate signal with a persistency of 40 years, we can integrate the 60 km^3 over the whole 40 years period. Dividing this loss in volume by the surface area of the Baltic Sea, the deficit in river input would equal a 6 m below normal mean sea level. Such a decrease is a prerequisite for major salt-water intrusion from the North Sea into the Baltic Sea (Matthäus and Schinke 1994). A strong salt-water inflow should give a signal in spine length of *O. centrocarpum* that is regarded as a proxy for salinity (Brenner 2001). However, no peaks exist in *O. centrocarpum* with longer spines, which might be due to long sampling interval. Another reason could be that major salt-water intrusions did not reach the sampling site in the Gotland Deep, since its location is too far in the north. A sediment core taken with a piston corer in the Bornholm Basin, closer to the Danish Straits than our sampling station (Andrén et al. 2000b) also shows a pronounced peak in %TOC, % nitrogen and various marine planktonic taxa in 70-80 cm depth. The appearance of marine planktonic taxa might indicate that a major salt-water inflow into the Baltic Sea has occurred.

The second regime shift results in much higher winter temperatures. A positive anomaly of 1° to 2°C in SST in winter leads to winter temperatures higher than 2.5°C which is exactly the temperature corresponding to the maximum density in the surface water of the Gotland Sea (7 psu salinity). Under "normal" conditions, SST in the central Baltic Sea is below 2.5°C during late winter, resulting in continuous vertical convection due to the warming in early spring by increasing solar radiation. The convection continues until the water body has a temperature above 2.5°C, after that the development of the thermocline starts. This spring convection is responsible for the transport of nutrients from deeper parts of the water column to the surface where they are available for phytoplankton growth. Periods of extreme warm winters with temperatures above 2.5°C suppress spring convection completely which results in lower than normal nutrient concentrations in the upper mixed layer. The result is a weaker spring bloom in the Baltic Sea, which is mirrored in chlorophyll c. In addition, the increase in river runoff due to higher precipitation can be identified in the increase of pine pollen and freshwater cladocerans.

Various authors argued that on short time scales the dynamic of the biological system reacts more pronounced to sudden events than to continuous changes (Lindeboom et al. 1995, Reise 1993). Our results suggest that the same is valid on decadal time scales. Sudden regime shifts in combination with longer lasting extreme climate conditions have a similar effect to the dynamic of the biological systems on decadal time scales as e.g. a single strong storm to the dynamics of phytoplankton in the thermocline or of epibenthos in shallow parts on short time scales.

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