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A dinoflagellate cyst record of Holocene climate and hydrological changes along the southeastern Swedish Baltic coast

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Abstract

A high-resolution, well-dated dinoflagellate cyst record from a lagoon of the southeastern Swedish Baltic Sea reveals climate and hydrological changes during the Holocene. Marine dinoflagellate cysts occurred initially at about 8600 cal yr BP, indicating the onset of the Littorina transgression in the southeastern Swedish lowland associated with global sea level rise, and thus the opening of the Danish straits. Both the species diversity and the total accumulation rates of dinoflagellate cysts continued to increase by 7000 cal yr BP and then decreased progressively. This pattern reveals the first-order change in local sea level as a function of ice-volume-equivalent sea level rise versus isostatic land uplift. Superimposed upon this local sea level trend, well-defined fluctuations of the total accumulation rates of dinoflagellate cysts occurred on quasi-1000- and 500-yr frequency bands particularly between 7500 and 4000 cal yr BP, when the connection between the Baltic basin and the North Atlantic was broader. A close correlation of the total accumulation rates of dinoflagellate cysts with GISP2 ice core sea-salt ions suggests that fluctuations of Baltic surface conditions during the middle Holocene might have been regulated by quasi-periodic variations of the prevailing southwesterly winds, most likely through a system similar to the dipole oscillation of the modern North Atlantic atmosphere.

Keywords: Holocene; Baltic Sea; Dinoflagellate cysts; Littorina transgression; Climate changes; North Atlantic storminess

Introduction

Glacio-chemical measurements on Greenland ice cores reveal that the North Atlantic area has experienced millennial-scale changes in storminess (O'Brien et al., 1995), accompanied by periods of repeated cooling during the late glacial and Holocene as marked by episodic southward advection of polar drift ice (Bond et al., 1997). Persistent storm activities not only shaped the northwestern European coasts in the form of widespread beach-ridge progradations and dune buildings (Clemmensen et al., 2001; Wilson, 2002; Orford et al., 2003), but also exerted a great impact on coastal hydrology and ecology (Nordberg et al., 2000; Stenseth et al., 2002). Both observations and modeling (Orvik et al., 2001; Schrum, 2001; Lehmann et al., 2002) indicate that climate and hydrological conditions in the Baltic Sea are closely related to variations of the prevailing southwesterly winds (Fig. 1A), which are known to be a manifestation of the North Atlantic Oscillation (NAO) (Jacobi and Beckmann, 1999). Therefore, reconstructions of past hydrological conditions in the Baltic Sea are particularly important for understanding paleo-atmospheric dynamics in the North Atlantic realm.

The brackish-water conditions in the landlocked Baltic basin are primarily maintained by the wind-driven water exchange with the North Sea as well as river discharge (Hanninen et al., 2000; Winsor et al., 2001; Gustafsson and Westman, 2002). Spatial variations of these two processes lead to a distinct salinity gradient between the Kattegat Sea and the Gulf of Bothnia (Fonselius and Valderrama, 2003). In the deep basins, a permanent halocline is present, separating the surface water mass from the dense, oxygen-depleted, and stagnant deep-water column. The deep water can be occasionally renewed by inflows of saline water in late autumn or winter, when a prolonged period of strong easterly winds is followed by stormy southwesterly winds as a low pressure develops over the North Sea (Lass and

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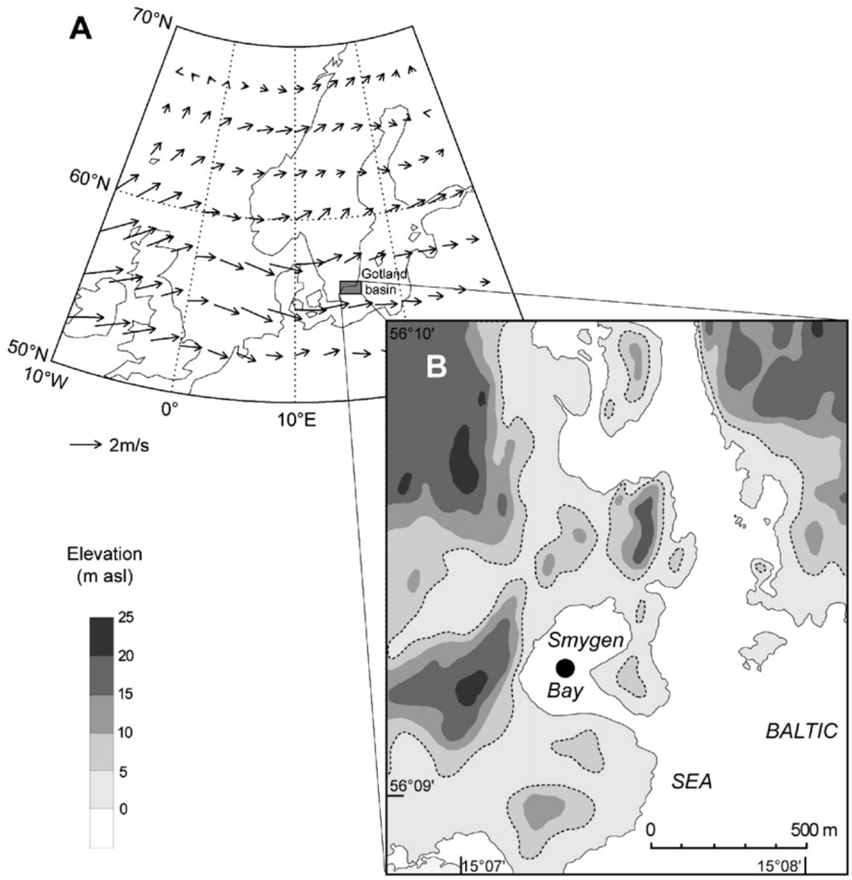

Figure 1. Map showing the meteorological and topographical settings of study area. (A) Mean summer surface winds over northwestern Europe (data from NOAA-CIRES Climate Diagnostics Center, http://www.cdc.noaa.gov). (B) Terrain of the Smygen Bay and surrounding areas. Dashed lines indicate the 5-m contour, which approximately represents the Littorina transgression limit. Solid dot indicates the coring position.

Matthäus, 1996; Schinke and Matthäus, 1998). Anoxic conditions may occur if major inflows of saline and oxygen-rich water are absent in these deep basins (Zorita and Laine, 2000). The surface water are more sensitive to regional atmospheric activities (Ekman, 1998; Andersson, 2002), particularly to the prevailing southwesterly winds (Plag and Tsimplis, 1999), which in turn lead to a sea-level gradient between the Kattegat Sea and the Gulf of Bothnia (Ekman, 1996).

Although the southwesterly winds are both ecologically and hydrologically important to the Baltic Sea, their long-term variability is not known. Most of the existing paleoclimate records were retrieved from deep depositional basins, such as the Gotland Basin (Huckriede et al., 1995; Sohlenius et al., 1996; Andrén et al., 2000a; Brenner, 2001a,b, 2005; Hofmann, 2001; Emeis et al., 2003), and the Bornholm deeps (Andrén et al., 2000b). Marginal basins of the Baltic Sea also hold the key to understanding postglacial environmental changes (e.g. Müller, 2001; Berglund et al., 2005; Yu et al., 2005). Moreover, compared with the euxinic deep basins, the marginal basins tend to be more sensitive to atmospheric forcing (Yu, 2003). Here we present a dinoflagellate cyst record to scrutinize the Holocene variability of Baltic nearshore climate and hydrology, by analyzing a sediment sequence recovered from a lagoon in southeastern Sweden (Fig. 1B). The stratigraphy and detailed magnetic, pollen, and macrofossil analyses as well as AMS ^{14}C dates of this core addressing postglacial sedimentary and vegetation histories have been published elsewhere (Yu et al., 2005).

Materials and methods

The Smygen Bay, southeastern Sweden (Fig. 1B), is a northwest extension of the Baltic Sea through a narrow sound with a granitic bedrock sill 1.0 m below present sea level. In the summer of 2001, the shallow seabed was cored from a raft, which had been anchored in the center of the bay where water depth was 1.4 m. An 11-m-long sediment sequence was recovered using a Russian peat sampler. The top 0.5 m sediments were not sampled because of very high water content. In the laboratory, the magnetic and sedimentary properties of the core were initially examined using the parameters of magnetic susceptibility, porosity, and dry bulk density.

The core was subsampled at 8 cm intervals. Total organic carbon (TOC) content was measured using a LECO RC-412 multiphase carbon analyzer. Aliquot samples of 1.5 cm^3 bulk sediments were processed for dinoflagellate cyst analyses following the guidelines of Rochon et al. (1999). The morphology and taxonomy of dinoflagellate cysts also follow Rochon et al. (1999). Prior to chemical treatments, five tablets of *Lycopodium* spores were added as marker grains. The samples were pretreated with 10% HCl acid to remove carbonates, and then soaked in 40% cold HF acid for 2 days until silicates were dissolved. To improve the concentration of microfossils, the samples were rinsed repeatedly with distilled water through a 10-μm mesh. The residues were dried overnight and mounted onto microscope slides with glycerine gel for identification and counting. Counting was completed when the entire slide has been examined. The raw counts and the occurrence frequency of *Lycopodium* spores were then used to calculate the dinoflagellate cyst concentrations, which were eventually converted to fluxes (cysts/cm^2 yr) by multiplying sedimentation rates. Stratigraphically constrained cluster analysis (Grimm, 1987) was applied on these flux data to identify the changes in dinoflagellate cyst assemblages.

Terrigenous plant macrofossils from selected levels were dated using accelerator mass spectrometry (AMS) equipment. AMS radiocarbon dates were calibrated using the INTCAL 98 tree-ring data set in the CALIB 4.2 program (Stuiver et al., 1998). The calibrated age was expressed as a range defined by the 2σ standard deviation of the corresponding radiocarbon date. For the details of the radiocarbon dates and calibrations, see Yu et al. (2005). An age-depth model for this core was constructed using the cubic-spline regression method (Heegaard et al., 2005), which was implemented in the statistics freeware *R* (R Development Core Team, 2005). The chronology is the same as that used in Yu et al. (2005), with the addition of a 95% confidence envelope.

Results

Stratigraphy and chronology

Stratigraphic descriptions of this core have been detailed in Yu et al. (2005). Here we summarize only the information needed for this paper. We also present new datasets addressing the magnetic and sedimentary properties of this core (Fig. 2). The sedimentary structure of the core above 10.2 m is very homogeneous, characterized by massive dark clayey fine-detritus gyttja with relatively low concentration of magnetic grains (Fig. 2A). Below this level, the lithologic boundaries are very sharp, clearly representing different stages of postglacial development of the Baltic basin (Yu et al., 2005). The uppermost sediments (above 2.5 m) were excluded from analyses because of the extremely high water content, as indicated by high porosities (>80%) and thus very low dry bulk densities (Figs. 2B and C).

A set of 10 AMS radiocarbon dates was obtained (Yu et al., 2005). The calibrated radiocarbon dates establish a calendar chronology from 11500 to 2500 yr BP for the undisturbed sediment sequence (Fig. 2D). This chronology agrees quite well with the timing of major Baltic stages (cf. Björck, 1995). The basal sediments are the Baltic Ice Lake gray clay. It is overlain by a thin dark-brown fine-detritus gyttja layer, which is dated to 11120 cal yr BP, corresponding to the brief Yoldia Sea phase of the Baltic Sea history. The light gray clayey gyttja, with higher magnetic susceptibility and dry bulk density (Fig. 2C), is assumed to have been deposited during the next Baltic stage–the Ancylus Lake phase, which in the basin was followed by a short period of isolation. The presence of brackish-water diatoms in extremely low abundances between 11.2 and 10.4 m implies a weak connection of this basin to the Baltic Sea (Yu et al., 2005), probably only during stormy seasons. Seagrass macrofossils occur continuously from 10.4 m (8600 cal yr BP) onward, indicating a full connection of the basin to the Baltic Sea as a result of global sea level rise (Yu et al., 2005).

Dinoflagellate cyst assemblages

Dinoflagellate cyst assemblages exhibit low species diversity along the core, and only six species were identified. This

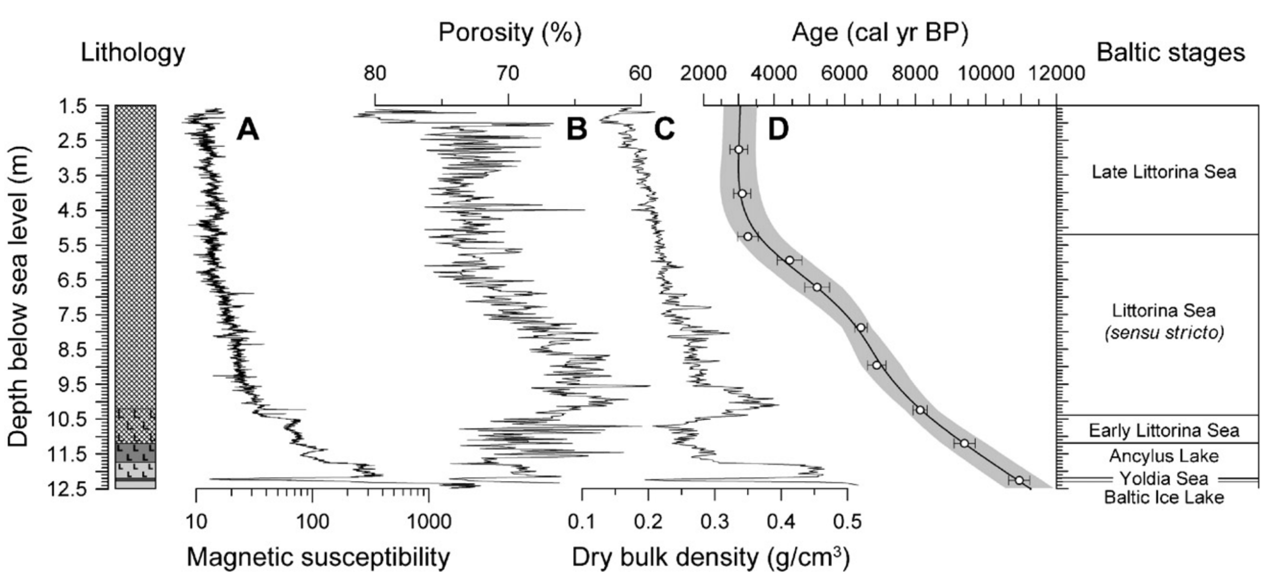

Figure 2. Core logs of magnetic and sedimentary properties (A–C) and age-depth model (D). The age-depth model is based on calibrated radiocarbon dates in Yu et al. (2005). The uncertainty envelope is defined by the 95% confidence level.

appears to be typical for a shallow-water bay (Matsuoka, 1994). Dinoflagellate cyst assemblages are dominated by Gonyaulacoids, such as *Operculodinium centrocarpum* sensu Wall et Dale 1966, *Spiniferites* spp., and *Lingulodinium machaerophorum* Deflandre and Cookson, 1955. Other species found in lower abundances are *Pyxidiniopsis psilata* Head 1994*, Alexandrium* spp., and *Ataxiodinium choane* Reid 1974. Changes in the cyst flux of individual species were plotted in Figure 3. Three dinoflagellate cyst assemblage zones can be divided numerically.

Zone I (10.4–9.4 m; 8600–7500 cal yr BP). This zone is dominated by *O. centrocarpum*, which is the most opportunistic and ubiquitous species among dinoflagellates in a wide range of environments (de Vernal et al., 2001). This species occurred initially at about 8600 cal yr BP along with sea grass macrofossils, such as *Zannichellia palustris*, and *Zostera marina* (Yu et al., 2005), unambiguously indicating the transition from lacustrine to marine environments in this area, known as the Littorina transgression. Both the low species diversity and accumulation rates of dinoflagellate cysts may indicate a shallow and weak brackish-water condition. The low salinities also were revealed in diatom assemblages in neighboring areas as extremely high percentages of brackish-water species with a freshwater affinity (Berglund et al., 2005).

Zone II (9.4–5.5 m; 7500–4000 cal yr BP). This zone is marked by substantial increases in both the species diversity and accumulation rates of *O. centrocarpum* cysts, indicating that full marine conditions were established in the low-lying Swedish coast corresponding to the peak of the Littorina transgression. A significant increase of salinity was also observed in the deep depositional basins (Andrén et al., 2000a,b; Emeis et al., 2003). *O. centrocarpum* still dominated the dinoflagellate community. The second dominant species is *Spiniferites* spp., mainly including *S. belerius* Reid 1974*, S. lazus* Reid 1974, and *S. ramosus* (Ehrenberg 1838) Mantell 1854. These species prefer warm conditions, and are more common in neritic waters (Harland, 1983; Rochon et al., 1999). Today, these species occur mainly in open marine settings with more normal salinities along the North Atlantic coasts (de Vernal et al., 2001). Therefore, occurrences of these species in the Baltic Sea may indicate higher salinities and surface productivity, most likely related to the increasing penetrations of warm and saline water from the North Sea. This is consistent with the presence of *Lingulodinium machaerophorum,* a species requires more saline conditions (Lewis and Hallett, 1997) and higher nutrient level (Dale and Fjellsa, 1994; Brenner, 2005).

Zone III (5.5–1.5 m; 4000–2500 cal yr BP). Both the species diversity and accumulation rates of dinoflagellate cysts decreased substantially, indicating a regression in this bay as local sea level was lowered due to continued isostatic land uplift, which resulted in unfavorable conditions for the dinoflagellate community. Lowering of the local sea level also was indicated in the magnetic records as significant increases in fine-grained magnetic minerals (Yu et al., 2005). A minor rise of dinoflagellate cyst accumulation rates between 3000 and 2500 cal yr BP is primarily a manifestation of the episodic increase in sedimentation rates (Fig. 2D), most likely caused by enhanced human disturbance in the catchment during the Iron Age. The total accumulation rates of dinoflagellate cysts were less variable, implying a relatively protected sedimentary environment in this bay during the late Holocene.

Changes in the total accumulation rates of dinoflagellate cysts in the time and frequency domains

The trend of the temporal variations in total accumulation rates of dinoflagellate cysts (Fig. 4A) clearly shows the imprint of local sea level changes primarily as a function of ice-volume-equivalent sea level rise versus isostatic land uplift. For example, the total accumulation rates of dinoflagellate cysts exhibit progressive increases from 8600 cal yr BP onward, revealing a monotonic rise in local sea level known as the “Littorina transgression” that culminated at about 7000 cal yr BP in the circum-Baltic area (Berglund, 1971; Digerfeldt, 1975; Christensen, 1996; Brenner and Meemken, 2002; Miettinen, 2004). Accumulation rates decrease after 7000 cal yr BP, indicating a gradual lowering of the local sea level, which in turn led to a reduction of water exchange between the Baltic and the North Sea. Superimposed upon this general sea level pattern, small-scale fluctuations of the total accumulation rates of dinoflagellate cysts occurred particularly between 7500 and 4000 cal yr BP, when the connection between the Baltic and the North Sea was broader. Given a nearly constant sedimentation rate during this period (Fig. 2D), these small-scale fluctuations may indicate changes in salinity and/or productivity of the surface water.

Using the Morlet function as a base wavelet (Torrence and Compo, 1998), a continuous wavelet transform was performed on the total accumulation rates of dinoflagellate cysts to provide a spectral perspective on the changes in Holocene Baltic nearshore hydrological conditions. First, linear interpolation was used to produce an evenly spaced time series of the total accumulation rates of dinoflagellate cysts with a temporal resolution of 80 yr. This interpolation scheme was designed according to the average sampling resolution (i.e. ~80 yr) of the original time series. Therefore, no additional shorter cycle was introduced artificially into the new time series. The new data set was then normalized by subtracting the mean and dividing by the standard deviation. Note that the local sea level pattern, as defined by a 3-degree polynomial fit, was still kept (Fig. 4A). The significance of wavelet spectra above 90% confidence level was tested using a Chi-squared distribution of the theoretical spectra with respect to the red-noise background spectra. Wavelet transform indicates that, above the 90% confidence level, a quasi-1000- and a quasi-500-yr cycle prevailed between 7500 and 4000 cal yr BP (Fig. 4B), when the Baltic was widely connected to the North Sea. A quasi-300-yr cycle occurred intermittently during this period, and no cyclic pattern was found prior to 7500 and after 4000 cal yr BP,

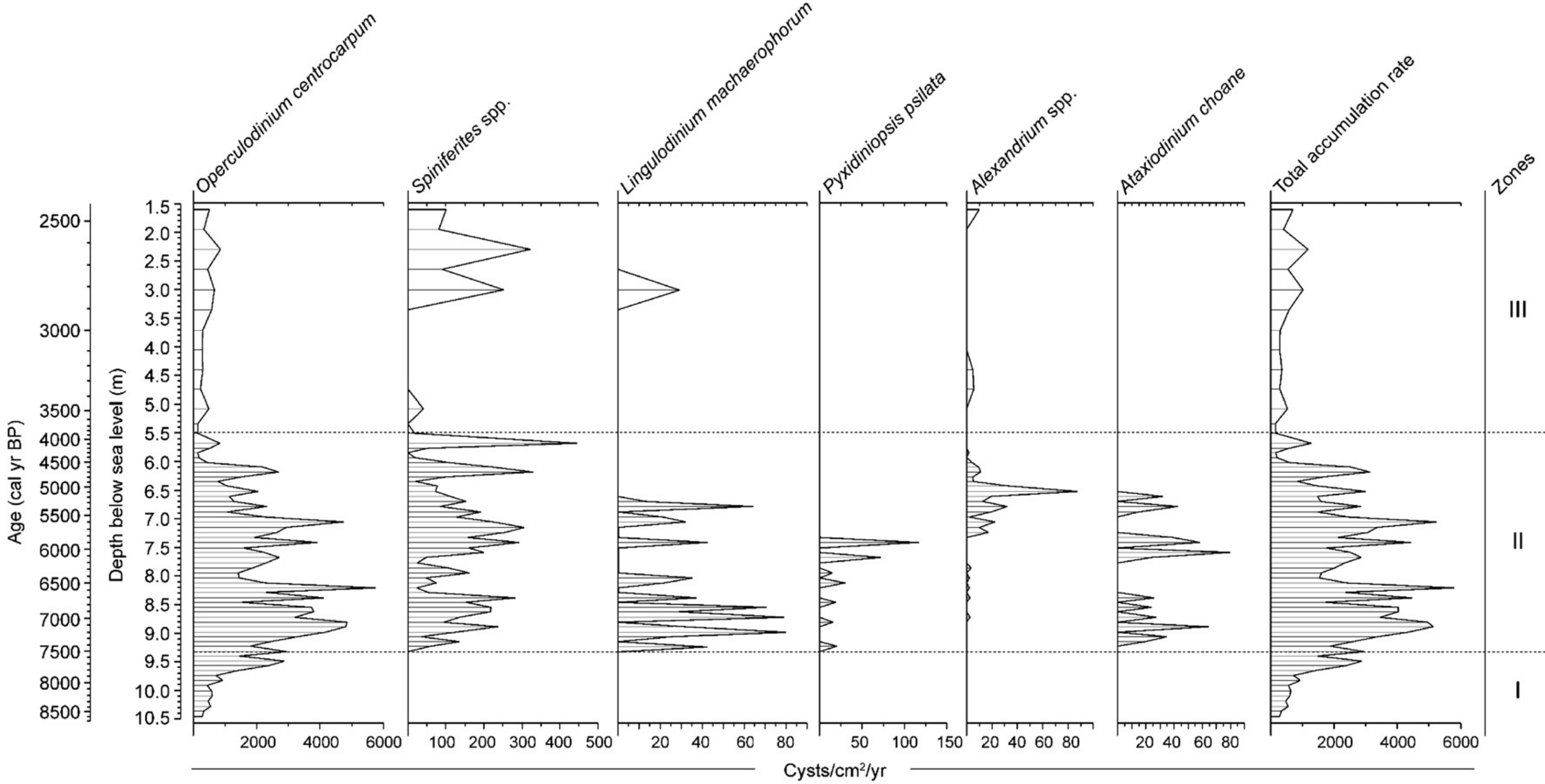

Figure 3. Diagram of accumulation rates of dinoflagellate cyst species in the Smygen Bay.

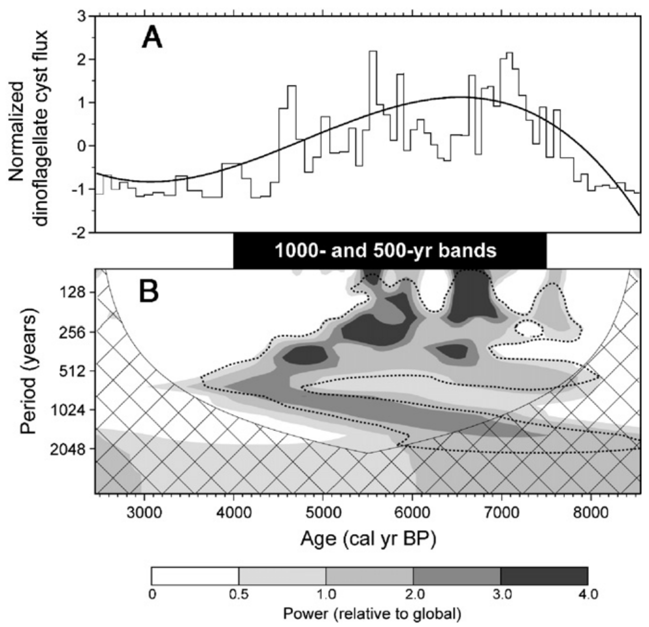

Figure 4. (A) Normalized time series of the total accumulation rates of dinoflagellate cysts. Heavy solid line is a 3-degree polynomial fit, which defines the pattern of local sea level changes. (B) Wavelet power spectra. The power has been scaled by the global wavelet spectra. Hatched area shows the cone of influence. Heavy dashed line is the 90% confidence level calculated using a red-noise background spectrum.

corresponding to the period of monotonic sea level rise and fall, respectively.

Discussion

Dinoflagellate cyst record and the timing of the Littorina transgression

Dinoflagellates are organic-walled, unicellular protists commonly occurring in marine and brackish-water settings (Rochon et al., 1999). The resting cysts produced within the motile theca are resistant to degradation in sediments and thus are the primary fossil remains. Therefore, changes in the assemblage of dinoflagellate cysts in sediment cores can provide valuable insight into past hydrological changes. Dinoflagellate cysts are common in the Baltic Sea sediments (Gundersen, 1988). Dinoflagellate cysts, along with other aquatic palynomorphs, have been used to infer paleoceanographical and paleographical changes of the Baltic basin following the growth and decay of the Scandinavia Ice Sheet during the last glacial/interglacial cycle (e.g. Brenner, 2001a,b, 2005; Head et al., 2005).

Our dinoflagellate cyst record unambiguously reveals the long-term trend of local sea level changes that are characterized by an initial rise and a subsequent fall. Our data indicate that first occurrences of marine dinoflagellate cysts along the southeastern Swedish coast were at about 8600 cal yr BP, almost synchronous as in the Kiel Bight area (Brenner and Meemken, 2002). This oceanic change marks the onset of the Littorina transgression in the Baltic basin as a result of global sea level rise and the opening of the Danish straits (Björck, 1995). Total accumulation rates of dinoflagellate cysts decreased substantially after 4000 cal yr BP, indicating the termination of the Littorina transgression in the Baltic basin as the isostatic land uplift outpaced global sea level rise. However, in the Gotland Basin (Fig. 1A), dinoflagellate cyst records reveal that marine conditions started at 7500 cal yr BP and terminated by ~3000 cal yr BP (Brenner, 2005). This ~1000 yr lag could be explained by the very slow vertical mixing rates of water column in the deep depositional basins. Water exchange between the Baltic and the North Sea is maintained by a circulation pattern similar to that in estuary settings (Döös et al., 2004): surface water flows out in the outlet area and saline water penetrates into the Baltic, sinks down to form deep water that then flow eastward into the Baltic proper. Such a circulation pattern might have not been fully established in the Baltic proper until 7500 cal yr BP, when the local sea level reached its maximum position.

Relationship between total dinoflagellate cyst accumulation rates and environmental variables

The modern distribution of dinoflagellate cysts in the world ocean and the statistical relationship with hydrological variables have been discussed by Harland (1983), Devillers and de Vernal (2000), de Vernal et al. (2001), and Marret and Zonneveld (2003). However, quantitative reconstructions of hydrological variables from fossil dinoflagellate cyst record using these relationships appear not to be applicable in the semi-enclosed Baltic Sea due to the low species diversity (Fig. 3). The most abundant dinoflagellate cyst type occurring in this bay is *Operculodinium centrocarpum*. This species has a relatively wide range of distribution, but it is often associated with the North Atlantic current along middle latitude coasts (Harland, 1983; de Vernal et al., 2001). The second dominant dinoflagellate cyst genera are *Spiniferites,* which includes several species such as *S. belerius, S. lazus*, and *S. ramosus*. These species tend to prefer warm surface water (Harland, 1983), as confirm by their continuous presence with maximum abundances during the major Littorina transgression phase.

Superimposed upon a general pattern of local sea level changes, the total accumulation rates of dinoflagellate cysts also exhibit well-defined fluctuations particularly between 7500 and 4000 cal yr BP (Fig. 4A). These small-scale fluctuations can be explained in many different ways in terms of short-term changes in sedimentation rates, salinity, temperature, ice cover, and productivity. However, given a nearly constant sedimentation rate during this period, periodical changes in the total accumulation rates of dinoflagellate cysts may reveal a linear response of surface productivity to regional atmospheric forcing through changing the upwelling of coastal water and thus the nutrient availability in surface water (Hanninen et al., 2000; Lehmann et al., 2002). This link is justified by a close correlation between the total accumulation rates of dinoflagellate cysts and organic carbon content between 7500 and 4000 cal yr BP (mode 1 in Fig. 5). Note that mode 2 showing an inverse relationship between the total accumulation rates of dinoflagellate cysts and organic carbon content represents an increased input of organic matter from the catchment as the

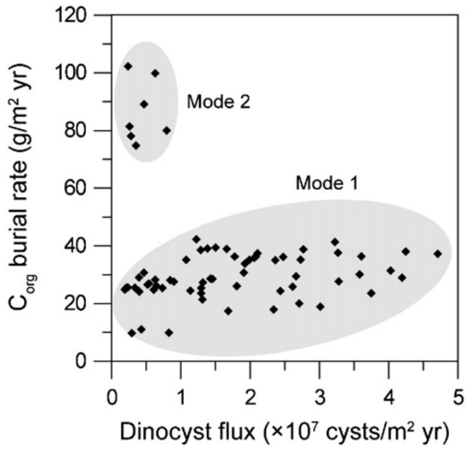

Figure 5. Relationship between the total accumulation rates of dinoflagellate cysts and organic carbon content. Mode 1: Littorina transgression phase (7500–4000 cal yr BP); Mode 2: post Littorina transgression phase.

local sea level was lowered after 4000 cal yr BP, which is indicated in the age-depth model as a rapid increase in sedimentation rate (Fig. 2D).

Short-term variability of Baltic nearshore hydrology and implications for regional atmospheric dynamics

Hydrographical conditions of the Baltic Sea are primarily governed by the prevailing wind pattern, particularly the southwesterly winds over the Danish straits (Plag and Tsimplis, 1999). Persistent southwesterly winds not only maintain a sea-level gradient in the Baltic (Andersson, 2002; Woolf et al., 2003), but also push massive warm and saline water into the Baltic basin, thereby raising the surface temperature and salinity of the Baltic Sea. A diminution of the southwesterly wind stress produces the opposite effect. Interannual variations of the southwesterly winds are governed by the NAO (Jacobi and Beckmann, 1999). However, the long-term behavior of the NAO is unknown due to lack of data, although tree ring-based reconstruction can extend the NAO indices back through the last 1500 yr (Glueck and Stockton, 2001; Luterbacher et al., 2002). High coherence between northern-Europe-gale frequency (Dawson et al., 2003) and GISP2 sea-salt ions suggests that the Greenland ice-core glacio-chemical records may provide a perspective on the long-term variations of the NAO-like atmospheric circulation pattern over the North

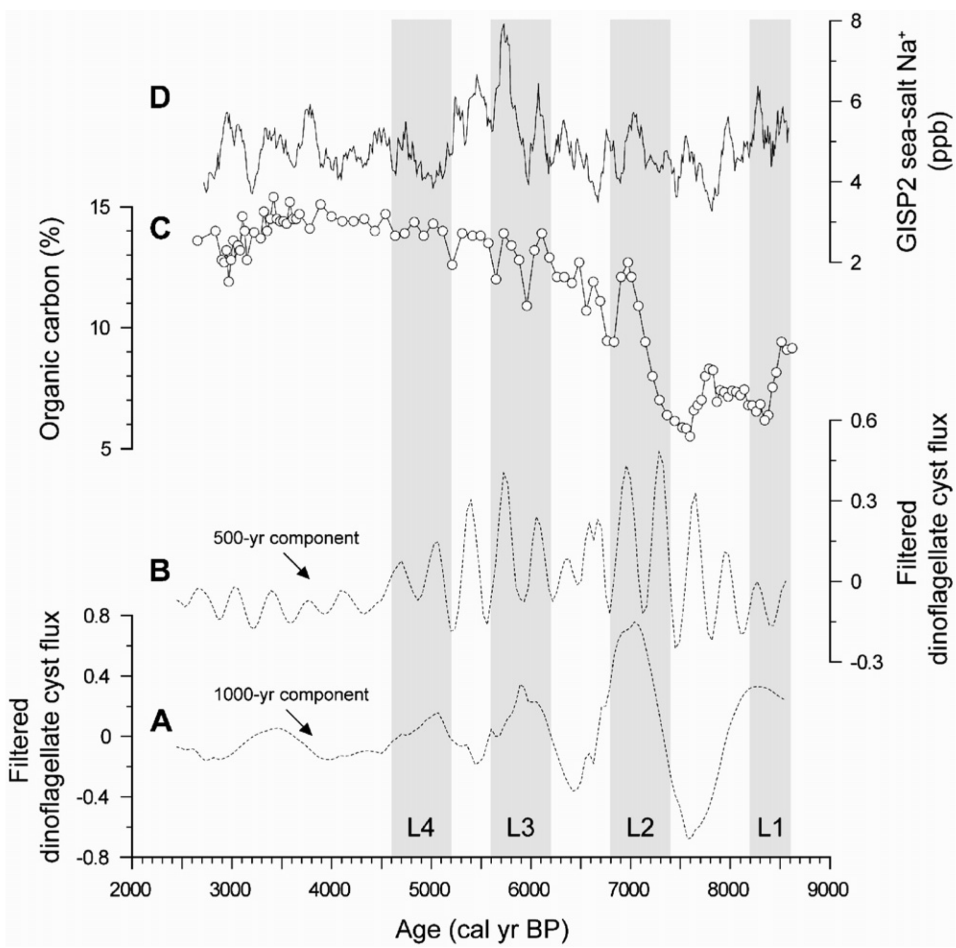

Figure 6. Comparison of the total accumulation rates of dinoflagellate cysts (A, B) with organic carbon content (C) and GISP2 ice core sea-salt Na^+ concentrations (D). Ice core data were smoothed using an 11-point moving average filter to show the variability at centennial time scales. The total accumulation rates of dinoflagellate cysts were smoothed using a bandpass filter centered at frequency bands of 0.001 cycle/yr (A) and 0.002 cycle/yr (B), respectively. Shaded bands numbered with L1–L4 denote the four Littorina transgression waves in southeastern Sweden (Berglund et al., 2005).

Atlantic sector (O'Brien et al., 1995; Mayewski et al., 1997; Fischer, 2001). Observed Baltic sea level fluctuations during the middle Holocene also exhibit a close correlation with GISP2 ice-core Na^+ concentrations, leading to a working hypothesis that changes in Baltic hydrological conditions also can be used as a measure of NAO-like atmospheric fluctuations over the North Atlantic realm (Yu, 2003).

We ascribe periodic changes in mid-Holocene Baltic surface conditions on the 1000- and 500-yr frequency bands to variations in the southwesterly winds at a longer time scale. To make a better visual correlation between our dinoflagellate cyst record and the GISP2 glacio-chemical record, the normalized total accumulation rates of dinoflagellate cysts were smoothed using a bandpass filter centered at frequency bands of 0.001 and 0.002 cycle/yr, respectively, equivalent to a 1000- and a 500-yr period. Peaks of the 1000-yr component occurred during 8600–8200,7400–6800, 6200–5600, and 5200–4600 cal yr BP (Fig. 6A), correlating to the four minor transgressions during the Littorina Sea phase (Berglund et al., 2005) that were presumably driven by millennial-scale variations of the prevailing southwesterly winds. Fluctuations of the 500-yr component (Fig. 6B) are generally in phase with organic carbon content (Fig. 6C) between 7500 and 4000 cal yr BP, revealing centennial-scale variations in surface productivity. Close correlation between the total accumulation rates of dinoflagellate cysts and GIPS2 ice-core Na^+ concentrations (Fig. 6D) on this frequency band existed between 7500 and 4000 cal yr BP, indicating that centennial-scale variations in Baltic surface productivity were associated with the wind-driven upwelling, when NAO-like fluctuations of the North Atlantic atmosphere prevailed during this period. The presence of a NAO-like atmospheric circulation pattern during the middle Holocene also can be supported by frequent south-westerly storm tracks and a deepened meridional pressure gradient over northwestern Europe (Hammarlund et al., 2002) as well as frequent floods in eastern North America (Brown et al., 1999; Brown et al., 2000; Noren et al., 2002), which were modulated by atmospheric activities that most resemble the positive phase of the modern NAO.

The Baltic surface conditions exhibited a cyclic pattern of variability at centennial time scales during the middle Holocene. These frequencies also characterized Holocene oceanic and atmospheric activities in the North Atlantic area (Stuiver and Braziunas, 1993; Ram and Stolz, 1999; Chapman and Shackleton, 2000; Andrews et al., 2003a,b) and probably reflect the regulation of centennial-scale storminess by solar forcing through sea-atmosphere interactions (Stuiver et al., 1995; Bond et al., 2001). The sinking of surface water and thus the formation of North Atlantic deep water releases potential heat, which may warm up the overlying atmosphere and affect pressure cells (Oppo et al., 2003), such as the Icelandic low, thereby inducing a NAO-like dipole oscillation (Rodwell et al., 1999).

Conclusions

A well-dated dinoflagellate cyst record from Smygen Bay reveals that the Littorina transgression occurred between 8600 and 4000 cal yr BP along the southeastern Swedish Baltic coast. Marine conditions were established in this area earlier than that in the Gotland Basin by about 1000 yr. This difference in timing may have resulted from a slow vertical mixing of water masses in the deep depositional basins. Given the nearshore nature of the bay, high sedimentation rates facilitate the reconstruction of past hydrological changes in this area at fine temporal resolution. Wavelet transforms on the time series of the total accumulation rates of dinoflagellate cysts reveal cyclic changes in surface conditions on ~1000- and ~500-yr frequency bands between 7500 and 4000 cal yr BP, when the connection of the Baltic with the North Sea was broader. The 1000-yr cycle represents millennial-scale fluctuations in local sea level, generally corresponding to the four minor transgressions during the Littorina Sea phase, presumably driven by long-term variations of the prevailing southwesterly winds. The 500-yr cycle is generally in phase with changes in organic carbon content, indicating centennial-scale variations in surface productivity. A close correlation of the total accumulation rates of dinoflagellate cysts with Greenland ice core sea-salt ions also existed during this period. This physical link is likely to be induced by NAO-like fluctuations of regional atmosphere at a longer time scale, which in turn governs the water exchanges between the Baltic and the North Sea as well as the upwelling of coastal waters.

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