Biogeosciences Discuss., 9, 14053–14089, 2012
www.biogeosciences-discuss.net/9/14053/2012/
doi:10.5194/bgd-9-14053-2012

Biogeosciences Discussions

The Little Ice Age: evidence from a sediment record in Gullmar Fjord, Swedish west coast

I. Polovodova Asteman[1], K. Nordberg[1], and H. L. Filipsson[2]

[1]Department of Earth Sciences, University of Gothenburg, P.O. Box 460, 405 30, Sweden
[2]Department of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden

Received: 28 August 2012 – Accepted: 2 October 2012 – Published: 15 October 2012

Correspondence to: I. Polovodova Asteman (irina.polovodova@gvc.gu.se)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We discuss the climatic and environmental changes during the last millennium in NE Europe based on a ca. 8-m long high-resolved and well-dated marine sediment record from the deepest basin of Gullmar Fjord (SW Sweden). According to the ^{210}Pb- and ^{14}C-datings, the record includes the period of the late Holocene characterised by anomalously cold summers and well known as the Little Ice Age (LIA). Using benthic foraminiferal stratigraphy, lithology, bulk sediment geochemistry and stable carbon isotopes we reconstruct various phases of this cold period, identify its timing in the study area and discuss the land-sea interactions occurring during that time. The onset of the LIA is indicated by an increase in cold-water foraminiferal species *Adercotryma glomerata* at ~ 1350 AD. The first phase of the LIA was characterised by a stormy but milder climate, which is indicated by a presence of *Nonionella iridea*. Maximum abundances of this species are likely to mirror a short and abrupt warming event at ~ 1600 AD. It is likely that due to land use changes in the second part of the LIA there was an increased input of terrestrial organic matter to the fjord, which is indicated by lighter δ^{13}C values and an increase of detritivorous and omnivorous species as *Textularia earlandi* and *Eggerelloides scaber*. The climate deterioration during the climax of the LIA (1675–1704 AD), as suggested by the agglutinated species, caused some carbonate dissolution, variations in primary productivity and a decline of *N. iridea* dependant on fresh phytodetritus. It is also assumed that an increase of *Hyalinea balthica* could be indicative of climate warming trends at 1600–1743 and 1813–1940 AD.

1 Introduction

A number of proxy-based reconstructions show that over the last millennium several intervals with anomalously cold summers were characteristic of the period, well-known as the Little Ice Age or LIA (among others: Hughes and Diaz, 1994; Fricke et al., 1995; Bianchi and McCave, 1999; McDermott et al., 2001; Nordli, 2001; Xoplaki et al., 2005;

Lund et al., 2006; Leijonhufvud et al., 2010; Trouet et al., 2009; review in Ljungqvist, 2009, 2010; Cage and Austin, 2010; Sicre et al., 2011). The LIA was associated with a widespread expansion and subsequent fluctuation of glaciers in the Arctic and alpine regions at lower latitudes, which happened in response to climatic changes at ~ AD 1300–1850 (Porter, 1986; Miller et al., 2012). This climatic deterioration coincided with reduced solar activity (Mauquoy et al., 2002), regular decline in summer insolation as Earth moved steadily farther from the sun during the Northern Hemisphere summer (Wanner et al., 2011), increased volcanism (Miller et al., 2012) and weakening of the North Atlantic Oscillation after its strongly positive state during the Medieval Warm Period (Trouet et al., 2009). Some studies also associated the cooling with a decreased volume transport of the Gulf Stream (Lund et al., 2006).

There is growing evidence that the Little Ice Age occurred throughout the Northern Hemisphere (Moberg et al., 2005; Ljungqvist, 2009, 2010) and is distinctly seen as taking place during the last three to four centuries with a termination at ~ 1900 AD (Grove, 2001). Other studies, however, mentioned that the LIA started earlier, somewhere between ~ 1300 and 1400 AD (Fricke et al., 1995; Mauquoy et al., 2002; Moberg et al., 2005; Cage and Austin, 2010; Ljungqvist, 2010; Miller et al., 2012). The period 1675–1710 AD has been identified as the coldest phase (climax) of the LIA (Lamb, 1983), which was preceded by an abrupt and rather short-lived warming at 1540–1610 AD, according to a proxy-based reconstruction from the Scottish fjords (Cage and Austin, 2010).

The high-resolution fjord sediment records produce archives, which contain information about variations in marine, terrestrial and atmospheric environments (Howe et al., 2010) and therefore allow studying the air-ocean-land interactions in a great detail. The Skagerrak region with its fjords is a key area for investigation of such complex interactions: it acts as a main depositional basin for the North Sea; it is highly influenced by the North Atlantic Oscillation, a dominant pattern of atmospheric circulation over the North Atlantic; and it has been classified as a coastal area with a high cumulative human impact (Halpern et al., 2008). From the few marine records containing the Little

BGD
9, 14053–14089, 2012

Ice Age in the Skagerrak and attempting to link the air-ocean or land-sea interactions, the greatest interest in terms of high-resolution LIA stratigraphy represent studies of Hass (1996, 1997), Brückner and Mackensen (2006) and Erbs-Hansen et al. (2011) (Fig. 1). Some of the previous studies, however, included ^{14}C dating obtained from the mixed benthic foraminiferal faunas and therefore may potentially contain some chronological bias. This paper represents the first well-dated and high-resolved study of the Little Ice Age in the sedimentary archives from the Scandinavian coast. It aims to reconstruct environmental conditions during the LIA and contribute to a better understanding of the climate variations during the last millennium in the Northern Europe. Using lithology, bulk sediment geochemistry, benthic foraminifera and carbon stable isotopes we intend to reconstruct the various phases of this cold period; to identify its timing (onset, climax and termination) in the study area and to correlate our marine data with terrestrial records.

2 Study area

Gullmar Fjord is one of several silled fjords situated in the middle part of the Bohuslän province on the Swedish west coast (Fig. 1a, b). It is one of the most well studied fjords in the world. Over the last ca. 40 yr many studies were performed in the fjord regarding its hydrography (e.g. Rydberg, 1977; Björk and Nordberg, 2003; Arneborg, 2004; Arneborg et al., 2004; Erlandsson et al., 2006), and primary productivity (Lindahl and Hernroth, 1983; Schöllhorn and Graneli, 1996; Lindahl et al., 1998; Belgrano et al., 1999). Due to negligible tidal activity and high sedimentation rates (0.7–1.4 $cm\,yr^{-1}$: Filipsson and Nordberg, 2004) Gullmar Fjord is a high-resolution environmental archive acting as a large sedimentary trap (Filipsson and Nordberg, 2010). This resulted in numerous investigations, which were performed on sedimentary records from the fjord basin, including pollen, dinoflagellate cysts and benthic foraminifera as proxies of environmental changes during the Holocene and recent past (Fries, 1951; Qvale et al., 1984; Nordberg et al., 2000, 2009; Godhe et al., 2001; Gustafsson and Nordberg, 2001;

BGD
9, 14053–14089, 2012

Godhe and McQuoid, 2003; Filipsson et al., 2004; Filipsson and Nordberg, 2004, 2010; Harland et al., 2006; Risgaard-Petersen et al., 2006; Polovodova et al., 2011).

The Gullmar fjord has a sill area at a depth of 42 m and a maximum basin depth of 120 m. The water masses are stratified with respect to salinity and density into four layers (Fig. 1c). At the surface occurs a first thin layer (< 1 m) of river water from Örekilsälven, which does not influence the hydrography of the fjord in any significant way (Arneborg, 2004). The residence times for the second and third layers are 20–38 days and 29–60 days, respectively (Arneborg, 2004), whereas the deepest layer has a residence time of approximately one year (Nordberg et al., 2000; Erlandsson et al., 2006). The long residence time of the deep water and high oxygen consumption rates in the fjord provide a likelihood of hypoxia ($< 2\,\mathrm{ml\,O_2\,l^{-1}}$) in the basin (Inall and Gillibrand, 2010). Indeed, during the 20th century oxygen consumption in the fjord increased from $0.21\,\mathrm{ml\,O_2\,l^{-1}\,month^{-1}}$ (1950–1970) to about $0.35\,\mathrm{ml\,O_2\,l^{-1}\,month^{-1}}$ (1970s and the early 1980s) and to about $0.41\,\mathrm{ml\,O_2\,l^{-1}\,month^{-1}}$ from 1989 onward (Erlandsson et al., 2006). Given that concentration of dissolved oxygen during a bottom water renewal usually ranges between ~ 4 and $8\,\mathrm{ml\,O_2\,l^{-1}}$ (Filipsson and Nordberg, 2004) and the residence time of bottom water is 1 yr, the annual consumption rates may therefore remove all the oxygen before the next successive bottom water renewal takes place. After 1973, however, the timing of the renewal of the basin water in Gullmar Fjord occurs approximately 20 days later compared to the period prior to 1973, which is suggested to be a result of climate variations triggered by North Atlantic Oscillation (NAO) (Erlandsson et al., 2006). Therefore, annual stagnation periods and temporary hypoxic events, characteristic features in Gullmar Fjord, became significantly stronger during the second part of the 20th century (Filipsson and Nordberg, 2004; Nordberg et al., 2009 and references therein) but likely were less frequent/severe during the Medieval Warm Period (Polovodova et al., 2011).

BGD
9, 14053–14089, 2012

3 Methods

This study is based on three sediment cores: GA113-2Aa, 9004 and G113-091, which were all taken at 116 m water depth in Gullmar Fjord (58° 17.57′ N, 11° 23.06′ E) (Fig. 1). The cores 9004 (731-cm-long) and G113-091 (195-cm-long) were sampled with a piston corer during the expeditions of the R/V *Svanic* and R/V *Skagerrak* in 1990 and 2009, respectively. The core GA113-2Aa (60-cm-long) was taken with a Gemini corer aboard of the R/V *Skagerrak* in 1999. Together cores GA113-2Aa and 9004 represented a continuous sediment record with a small gap in-between due to difficulties with the piston corer methodology in relatively soft sediments. In order to find out the size of the gap, core G113-091 was used.

In the laboratory, all cores were split in two halves. One of the halves was saved for dinoflagellate cyst analysis (for the cores G113-091 and 9004 – to be presented elsewhere; for core GA113-2A see Harland et al., 2006). The other half was used for foraminiferal and geochemical studies. Twelve mollusc shells (Table 1, Fig. 2) were found in life position in cores G113-091 and 9004 and were subjected to radiometric ^{14}C AMS dating. The shells were dated at the Ångström laboratory (Uppsala University, Sweden) using the marine model calibration curve (Reimer et al., 2004; Bronk Ramsey, 2005). The half-life used is 5568 yr, and the margin of error is 1σ. Ages are normalized to δ^{13}C of −25 ‰ according to Stuiver and Polach (1977), and a correction corresponding to δ^{13}C = 0 ‰ (not measured) versus PDB has been applied. Based on the latest complementary datings radiocarbon dates were corrected using a reservoir age of 500 yr ($\Delta R = 0$) (Nordberg and Possnert, unpubl. data; Polovodova et al., 2011). For dating of core GA113Aa and details regarding the ^{210}Pb dating method, see Filipsson and Nordberg (2004) and Nordberg et al. (2001), respectively.

Prior to foraminiferal studies, core 9004 was sliced into 1 cm intervals down to a depth of 28 cm and thereafter into 2 cm intervals. Core G113-091 was cut into 1 cm slices until 19 cm, and thereafter 2 cm slices were taken. The same preparation technique was used for all samples: they were weighed, freeze-dried and their water content was

BGD
9, 14053–14089, 2012

determined. The measurements of organic carbon (C_{org}), total nitrogen (TN) in the bulk sediment and stable carbon isotopes on tests of benthic foraminifer *Cassidulina laevigata* were performed for the cores GA113-2Aa and 9004. All organic carbon samples from the core GA113-2Aa were analysed at University of Gothenburg (Sweden) using a Carlo Erba NA 1500 CHN analyser. Samples from the core 9004 were run at Bremen University (Germany) using a Vario EL III CHN analyser. In core G113-091 we ran $\delta^{13}C$ measurements on tests of *C. laevigata* and conducted a benthic foraminiferal analysis in order to determine the gap between the cores GA113-2Aa and 9004. All $\delta^{13}C$ measurements were run at the Department of Geosciences, University of Bremen using a Finnigan Mat 251 mass spectrometer equipped with an automatic carbonate preparation device.

All foraminiferal samples were washed over 63 µm and 1 mm sieves and treated with sodiumdiphosphate ($Na_2P_2O_7$), where necessary, in order to disintegrate sediment aggregates. In order to obtain a rough estimate of the sand content, the size fractions > 63 µm were dried at 50 °C and weighed. The foraminifera-rich samples were split and at least 300 specimens were counted in each sample from the dried > 63 µm fraction. Inner organic linings were counted separately. Planktonic individuals were counted but not identified at the species level. The partially destroyed foraminiferal tests lacking more than one chamber were counted separately in order to get a rough estimate of shell loss/carbonate dissolution. In total, 262 samples were analysed for foraminiferal fauna, here we report 72 samples. Both relative (%) and absolute abundances (ind. g^{-1} dry sed.) for the benthic species were determined. Faunal diversity is estimated as Fisher α-diversity (Murray, 2006), whereas species number represents the total amount of species recovered per sample. In order to distinguish the foraminiferal units with different species dominance we performed a simple CABFAC factor analysis with Varimax rotation using the software PAST, University of Oslo (Hammer et al., 2001). The analysis has been run on raw foraminiferal data with relative abundances > 5 %.

Results of C_{org} and $\delta^{13}C$ measurements from the cores GA113-2Aa and 9004 are given in Filipsson and Nordberg (2004, 2010). For the results on benthic foraminifera

BGD
9, 14053–14089, 2012

and dinoflagellate cysts analyses from the core GA113-2Aa see Filipsson and Nordberg (2004) and Harland et al. (2006), respectively. The part of the benthic foraminiferal record covering the Medieval Warm Period (core 9004: 350–500 cm) was previously published in Polovodova et al. (2011). In the current paper we concentrate upon the last 1000 yr of the high-resolution record with a special emphasis on the Little Ice Age.

4 Results

4.1 Chronology

The radiocarbon (AMS) dates suggest a time interval for core 9004 from at least 350 BC to ca. AD 1850–1900, and it comprises most of the well-known climatic periods: the Roman Warm Period (RWP), the Viking Age/Medieval Warm Period (MWP) and the Little Ice Age (LIA) (Filipsson and Nordberg, 2010). Radiocarbon AMS dates obtained for core 9004 between 410 and 750 cm indicate sedimentation rates of 2.8 mm yr^{-1} during the first 1250 yr, which then increases to 6.6 mm yr^{-1} up core around AD 1350–1500 (from 410 to 305 cm). From 305 cm and upwards, core sedimentation rate drops again to 3.1 mm yr^{-1}. The lower sedimentation rates in the deeper part of the core are regarded as an effect of sediment compaction. For the core G113-091 the only intact mollusc shell of *Nuculana pernula* yields an age of 1665±85 AD (Table 1; Fig. 2), which indicates that core represents the time interval from 2009 to the middle part of the Little Ice Age.

The ^{210}Pb analyses for core GA113-2Aa reveal a sedimentation rate of 7 mm yr^{-1} and represent the time interval between 1915 and 1999, which, therefore, encompasses the recent warming of the 1900s (Filipsson and Nordberg 2004, 2010).

BGD
9, 14053–14089, 2012

4.2 Geochemistry of bulk sediment

The organic carbon (C_{org}) data for the sediment cores GA113-2Aa and 9004 are presented in Filipsson and Nordberg (2010) and show a range from 0.6 to 3 % with 2 % as a long-term average.

The C/N ratio measurements are available only for core 9004 and therefore C/N data for the last 100 yr are missing. In core 9004 C/N ratio ranges from 5 to 10, indicating a organic matter of primarily marine origin (C/N ratio of 5–7: Redfield et al., 1963). The long-term average of the ratio is 8.3. Around 170 cm depth (ca. 1650 AD) a slight offset occurs in the C/N values, which divides the Little Ice Age into two periods: (1) before 1650 AD with C/N values higher than the long-term average and (2) after 1650 AD with C/N ratio below the average. Around 1900 AD, C/N ratio increases again and reaches 9.5 on top of the core.

4.3 Lithology

4.3.1 Core GA113-2Aa

The sediment column in general was olive-green-grey and contained mainly organic-rich silt and clay. The sediment surface was light brown, which indicated oxic conditions. An increased amount (9 %) of sand-sized fraction (> 63 µm) was found between 51 and 43 cm (~ AD 1915). For more detailed lithology of a Gemini core GA113-2Aa see Filipsson and Nordberg (2004).

4.3.2 Core 9004

The sediments generally consisted of mud and clay of an olive-green-grey colour up to 369 cm depth. Around 369–367 cm, a prominent brown layer was found and contained plant remnants. A distinct light grey horizon of clay, silt and fine sand at 367–364 cm was interpreted as a turbidite related to a landslide (Polovodova et al., 2011). From 364 cm up core, grey colour gradually turned brownish to 350 cm. The brownish layer continued until 330 cm and included visible organic particles. After 330 cm up core, the brown colour faded away and sediments became olive-green-grey again.

The sand-sized fraction (> 63 µm) had a long-term average of 1.89 % for the whole record with a distinct maximum of 6.7 % at ca. AD 1200 (370 cm). Within depth interval 350–60 cm, indicative of the Little Ice Age (AD 1350–1900), the sand-sized fraction showed three different units (Figs. 4, 5). A first coarser unit at ca. AD 1350–1600 (350–190 cm) can be identified based on a high variability of sandy fraction. A second unit between AD 1600 and 1850 (190–100 cm) was characterized by less variability and finer sediment. A third unit at ca. AD 1850–1900 (100–60 cm) was also characterised by coarser sediment.

4.3.3 Core G113-091

In general, the sediment column consisted of dark-olive-grey mud (gyttja clay) with mottled (containing black dots) sections in places. However, there were some distinct changes in colour within the interval 185–129 cm. At 185–181 cm the generally dark-grey mud contained horizontal layers of darker sediment, which gradually faded away at 174 cm. An interval of a light-grey mud was encountered at a depth of 174–171 cm and had a distinctly lighter 5–6 mm-thick horizon in the middle. After this layer sediments became dark-grey again and stayed so until 152 cm. Another light horizon was found at 152–129 cm, after which and towards the core top sediments column had a dark-grey colour. The surface of the core G113-091 was oxidised and had a light-brown colour down to 5 cm. The redox-cline was encountered at a depth of 9–5 cm.

The sand-sized fraction showed two distinct maxima (5 and 3 %) at depths of 36 and 64 cm and had a long-term average of 0.9 %.

BGD
9, 14053–14089, 2012

4.4 Stable carbon isotopes

4.4.1 Cores GA113-2Aa and 9004: $\delta^{13}C$ record of the LIA (1350–1900 AD)

The full record of $\delta^{13}C$ values from the cores GA113-2Aa and 9004 covering the last ca. two millennia was discussed in detail by Filipsson and Nordberg (2010). In the current paper we concentrate on the part relevant to the Little Ice Age.

The average $\delta^{13}C$ value for the GA113-2Aa–9004 record is −0.65 ‰. The $\delta^{13}C$ record of the LIA begins around 1350 AD with less negative values than the long-term average (Fig. 3) and the heavier values persist until ca. 1500 AD. After that $\delta^{13}C$ values reach their minimum of −1.15 ‰ and have a distinctly more negative phase, which lasts until almost 1850 AD. Afterwards the trend of the $\delta^{13}C$ record changed again towards the less negative values, reached a maximum of −0.2 ‰ and remained less negative until the termination of the LIA.

4.4.2 Core G113-091

The stable carbon isotope record for G113-091 shows a fairly good correlation with the $\delta^{13}C$ record derived from GA113-2Aa and 9004 down to a depth of ca. 90 cm (Fig. 3). Below 90 cm the G113-091 curve has a slight displacement of 0.2–0.4 ‰ from the GA113-2Aa and 9004 record. Nevertheless, the good correlation of both isotopic records until 90 cm indicates that there is no gap between the cores GA113-2Aa and 9004. This is also confirmed by analysis of the dominant foraminiferal species in both records (Fig. 3).

4.5 Foraminifera

4.5.1 350 BC–2001 AD

For foraminiferal data from the GA113-2Aa and 9004 record, we performed a factor analysis, which resulted in 4 factors, explaining as much as 89 % of variance (Table 2,

BGD
9, 14053–14089, 2012

Fig. 4). According to Klovan and Imbrie (1971), the minimum absolute factor value is a zero, which indicates that the variable contributes nothing to the factor. In our study eight foraminiferal species had high (> 1.0) absolute values of factor scores (Table 3, Fig. 4), which resulted in four foraminiferal assemblage units. Each foraminiferal unit was named after the most important species explaining each factor. Thus, Factor 1 (62 % of variance) corresponded to the *Nonionella iridea-Cassidulina laevigata* unit. Factor 2, which corresponded to *Stainforthia fusiformis* unit, accounted for 14 % of variance and also included species *Textularia earlandi*, *Bolivina pseudopunctata* and *Bulimina marginata*. The Factors 3 and 4 accounted for 7 and 5 % of variance and corresponded to units of *Adercotryma glomerata* and *Hyalinea balthica*, respectively. The fourth unit also included species *C. laevigata* and *T. earlandi*. The "*N. iridea-C. laevigata*" unit dominated the record during ca. 350 BC–1150 AD and 1350–1650 AD (Fig. 4). The *Adercotryma glomerata* unit interrupted its dominance at ~ 1300 AD. From ~ 1650 to 1900 AD the record alternated between foraminiferal units 3 and 4 (*A. glomerata* versus *H. balthica*). After 1900 AD, however, *Hyalinea balthica* unit dominated for ca. 80 yr and was replaced by unit 2 represented by *S. fusiformis* as the main species.

4.5.2 The Little Ice Age: 1350–1900 AD

In general, species composition of the benthic foraminiferal fauna during the Little Ice Age was characterized by three dominant (> 10 %) species: *A. glomerata*, *C. laevigata* and *H. balthica*, whereas *Eggerelloides scaber*, *Elphidium excavatum*, *N. iridea*, *S. fusiformis*, *Reophax subfusiformis* and *T. earlandi* were present as accessory species (< 10 %). Also, *Nonionella iridea* was a co-dominant species (20–30 %) during the first part of the Little Ice Age (ca. 1300–1650 AD).

Altogether 156 benthic foraminiferal species were found in the part of the record corresponding to the Little Ice Age. Among them 42 species had agglutinated tests and 113 species were calcareous. The Fisher α-diversity (Murray, 2006) varied between 6 and 20, with a mean of 13 (Fig. 5). The number of identified species or species richness varied between 68 and 29 with a mean of 43. The average of absolute foraminiferal

BGD
9, 14053–14089, 2012

abundances was 87 ind. g^{-1} of dry sediment, (14–208 ind. g^{-1}). The highest absolute abundances of foraminifera were encountered at 179 cm depth (ca. 1650 AD). The maximum abundances of planktonic foraminifera (13 %) were found at 155 and 137 cm (ca. 1750–1730-AD).

The absolute abundances showed rather lower values over the time period from ca. 1450 to 1600 AD (Fig. 5). At the same time there was a clear increase of the foraminifer *N. iridea*, which reached its highest abundances (30 % and 56 ind. g^{-1}) during the LIA at ∼ 1600 AD.

Both relative and absolute abundances showed a salient faunal change at 180 cm (ca. 1650 AD) when *N. iridea* became rare in the record. Around the same time *A. glomerata*, *E. excavatum*, *E. scaber*, *S. fusiformis* and *T. earlandi* increased. The foraminiferal absolute abundances showed high values from 1650 to 1850 AD with two minima at ca. 1630 and 1700 AD.

Hyalinea balthica became a prominent species in the record at ∼ 1650–1700 AD (Figs. 4, 5), but experienced several short declines until 1850 AD, after which its absolute abundance increased significantly. After 1850 AD there was also a significant increase in a portion of calcareous species, whereas some species such as *A. glomerata*, *C. laevigata*, *E. excavatum* and *E. scaber*, declined during that time.

In general, calcareous foraminiferal species dominated for the majority of the LIA. However during the second part of the LIA agglutinated species such as *A. glomerata*, *E. scaber* and *T. earlandi* became important components of the foraminiferal assemblages (Fig. 5).

BGD
9, 14053–14089, 2012

5 Discussion

5.1 Benthic foraminiferal record of the Little Ice Age

5.1.1 Abrupt faunal changes at ca. 1650 AD

In our record, during ca. 1300–1650 AD we observed increased scores of Factor 1 represented by *N. iridea* and *C. laevigata* (Fig. 4). This agrees with previous studies based on benthic foraminiferal stratigraphy from the Skagerrak (Hass, 1997; Erbs-Hansen et al., 2011), which reported high abundances of *C. laevigata* after 1450 AD and suggested an increased storminess, enhanced mixing of the water column and more fresh phytodetritus reaching the sea floor. Those studies however did not report any increase in *N. iridea*, which is probably due to use of the 100- and 125-µm fractions for foraminiferal analysis. A short and abrupt climate warming occurred at 1540–1610 AD as suggested by the benthic foraminiferal δ^{18}O record from the Scottish fjords (Cage and Austin, 2010). *Nonionella iridea* was previously reported as a species indicative of fresh phytodetritus pulses during the Medieval Warm Period (Polovodova et al., 2011). It is likely that this species responded positively to both the warming event (1540–1610 AD) and the increase of phytodetritus, and therefore may be considered as a proxy of climate warming during the LIA. The short warming event around AD 1600 is also seen in the foraminiferal δ^{18}O record based on core 9004 (to be published elsewhere). *Nonionella iridea* disappeared from the record after 1650 AD, which coincides with Maunder Minimum in solar activity between 1645–1715 AD (Mauquoy et al., 2002). The decreased bottom water temperatures due to an abrupt cooling in the second part of LIA could also contribute to dissolution of calcareous tests and favoured a proliferation of some agglutinated species (*Adercotryma glomerata*, *Textularia earlandi* and *Eggerelloides scaber*), which we will discuss below. The lower temperatures may have been one reason for the disappearance of *N. iridea*. This faunal change coincides with a unit characterised by less sand-sized fraction (Fig. 4), which implies calmer sedimentation or decreased bottom water currents (Hass, 1996). Theoretically,

BGD
9, 14053–14089, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

a less-energy sedimentation phase would favour more algae to settle on the sea floor. On the other hand, the period 1675–1710 AD has been known as the climax of the LIA (Lamb, 1983), which probably would be characterised by a shorter growing season of phytoplankton and therefore by less food available for fresh-phytodetritus feeders like *N. iridea*. Indeed, according to a tree-ring based climate reconstruction from the West-Central Sweden, the LIA was characterised by a cold climate phase with milder summers during 1350–1600 AD and colder summer conditions prevailed during 1600–1900 AD (Gunnarson et al., 2011).

5.1.2 Adercotryma glomerata, a proxy of climate deterioration

Brückner and Mackensen (2006) use benthic foraminiferal $\delta^{18}O$ to track a cold climate period in the Skagerrak and link this potentially to a decelerated thermohaline circulation until ca. 1630 AD. In addition, they suggest an enhanced circulation and warmer temperatures from ca. 1630 to 1870 AD. The latter is contradictory to our results, which show a decline and disappearance of the temperate species *N. iridea*. Also, according to the factor analysis, three repeated increases of *A. glomerata* unit correspond well with three periods of reduced solar activity (Fig. 4): the Wolf (1300–1380 AD), the Maunder (1645–1715 AD) and the Dalton (1790–1820 AD) minima (Eddy, 1976; Mauquoy et al., 2002). Reduced solar activity has been long time considered as one of important players causing climate cooling (e.g. Haigh, 1996; Shindell et al., 1999; Bond et al., 2001; Mauquoy et al., 2002). *Adercotryma glomerata* is an agglutinated species, which is often associated with cold waters ($< 4\,^{\circ}C$) and a wide salinity range (28–35) in the Labrador Sea, Canadian Arctic and Antarctic (Williamson et al., 1984). The Wolf sunspot minimum coincides with the onset of the Little Ice Age (Mauquoy et al., 2002), an abrupt ice-cap growth in the Arctic Canada between 1275 and 1300 AD (Miller et al., 2012) and an increase in drift ice off Iceland in the late 13th century, which caused the failure of Viking settlement on Greenland (Andrews et al., 2009). The climax of the Little Ice Age at ca. 1675/80–1710 AD, (Flohn, 1985; Lamb, 1983) is often associated with the Maunder minimum (Eddy, 1976). Therefore the appearance of *A. glomerata* in our

BGD
9, 14053–14089, 2012

record suggests that the intermediate Skagerrak water flowing into the fjord during the winter or early spring was colder than today, which supports the general idea of climate cooling after 1300 AD and then during ca. 1675–1700 AD.

It seems that in general the "non-stormy" period of the LIA is characterised by increased abundance of agglutinated species – *A. glomerata*, *T. earlandi* and *E. scaber* (Fig. 5). Wollenburg and Kuhnt (2000) reported *A. glomerata* prevailing in low-energy environments characterised by lower carbon fluxes in the Arctic Ocean. This is consistent with our results, showing proliferation of *A. glomerata* during ca. 1600–1800 AD, which was characterised by a finer sediment interval, i.e. a lower amount of sand-sized fraction (Figs. 4, 5). *Textularia earlandi*, an omnivorous opportunist (Alve, 2010), is reported as a dominant faunal element in Canadian fjords at water depths ≥ 100 m (Schafer and Cole, 1988). *Eggerelloides scaber* is mentioned by Murray (2006) as a detritivorous shelf species, which demands salinity > 24 for most of the year and temperatures 1–20 °C. Therefore, proliferation of these agglutinated species might imply a change in quality of organic matter in Gullmar Fjord sediments during ca. 1600–1800 AD; however, it is likely that another important process came into play during the cold LIA. This process is likely the dissolution of calcareous tests due to lowering of calcium carbonate saturation state at lower bottom water temperatures. A useful parameter indicating carbonate dissolution of foraminifera is the number of inner organic linings (Murray and Alve, 1999; Steinsund and Hald, 1994), which in our record shows higher values after 1500 AD. Another important measure is the calcareous/agglutinated ratio, which usually decreases with dissolution of calcium carbonate (Steinsund and Hald, 1994). In Gullmar Fjord this ratio displays clearly lower values during the time interval ~ 1650–1850 AD. A number of corroded foraminiferal individuals indicated in Fig. 5 as shell loss shows a slightly different picture and increases during ca. 1420–1550 AD. However the shell loss variable includes both partially destroyed agglutinated foraminifera and corroded calcitic specimens. At the same time the generally low foraminiferal numbers during the period 1450–1600 AD may also result from partial carbonate dissolution. It is clear that carbonate dissolution due to the change in bottom

BGD
9, 14053–14089, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

water temperatures affects the benthic foraminiferal fauna and is a useful paleoenvironmental indicator. It is, however, plausible that degree of carbonate dissolution can be estimated as moderate, since together with agglutinated species we still find relatively high numbers of well preserved and shiny calcareous specimens and thin-shelled species like *N. iridea* and *S. fusiformis*.

5.1.3 Hyalinea balthica and amelioration of climate?

In general, based on the distribution of the main foraminiferal units, it appears that 1650 AD is a starting point for the establishment of new foraminiferal faunas in the fjord. This is a time when *H. balthica*, typical of the area during the 20th century, increases in Gullmar Fjord (Figs. 4, 5). *Hyalinea balthica* together with *B. marginata* and *A. glomerata* are reported in the recent fauna at Fladen Ground, N North Sea, between Scotland and Norway (Klitgaard Kristensen and Sejrup, 1996). Hass (1997) suggested that assemblages of *H. balthica* in the Skagerrak are indicative of "stagnant conditions", by which he probably meant less intense bottom water currents on the southern flank of the basin. Indeed, in some of his cores (I KAL), there was an increase in *H. balthica* during the calm phase of the LIA (ca. 1550–1750 AD). Our results are consistent with Hass's findings and in our record *H. balthica* peaks starting at around 1650 AD, then at ca. 1800 AD and finally at 1900 AD, after which it remains as a dominant species for about 80 yr. The dominance of *H. balthica* may also indicate a climate warming. According to reconstructions based on a start of the sailing season in Stockholm ports, there was a warming trend starting at ∼ 1600 AD until 1743 AD with subsequent cooling at 1743–1813 AD and a warming trend again from 1813 to 1940 AD (Leijonhufvud et al., 2010). This reconstruction, however, did not show any indication of the Maunder minimum.

BGD
9, 14053–14089, 2012

5.2 Land use changes during the LIA

From the C/N record of core 9004 (Fig. 4) it is rather difficult to distinguish the sources of organic matter (marine vs. terrigenous) since ratio fluctuates within purely "marine" values. It has been suggested that C/N ratio reflects organic matter sources inaccurately, since nitrogen is affected by organic matter diagenesis and biological controls (Thornton and McManus, 1994). Therefore, using C/N ratio for degraded organic matter (which is usually the case for long sediment cores) the marine or terrigenous sources may be hard to distinguish. Filipsson and Nordberg (2010) studied $\delta^{13}C$ on the tests from *C. laevigata* from the core 9004 and suggested that during the LIA changes in land use could contribute to the input of terrestrial carbon into the fjord. The terrestrial organic matter would change $\delta^{13}C$ towards lighter values, which is the case indeed from ca. 1500 to 1850 AD. From terrestrial records it is known that during 1500–1700 AD there were increased losses of topsoil and finer particles in Sweden due to changes in land use and irrigation (Dearing et al., 1990) and periods of a widespread deforestation in Scandinavian countries (Bradshaw et al., 2005; Kaplan et al., 2009). Based on the pollen data from the Gullmar Fjord, Fries (1951) showed an increase in non-arboreal pollen (NAP), which started at the end of the Medieval Warm Period and lasted until ca. 1650 AD (Fig. 4). This suggests an intensification of the land use including clearing of forests to increase croplands and pasture together with exploitation of timber for construction. Land use in Sweden and particularly Bohuslän most likely experienced a decline caused by outbreak of Black Death in ca. 1350 AD, which wiped out between a half and 2/3 of the population (Harrison, 2000) and resulted in large scale abandonment of farms together with a series of wars, which followed thereafter (Fig. 4). The same was suggested for the Central Europe (Büntgen et al., 2011). In addition, there were several productive herring periods in the Bohuslän and Norwegian fisheries (Cushing, 1982; Corten, 1999) after ca. 1550 AD. One of them, a so-called "The Great Herring Period" (Den Stora Sillperioden: 1748–1808 AD) resulted in the

BGD
9, 14053–14089, 2012

extensive production of fish oil, which required a lot of wood for boiling of herring guts and a substantial alteration of the landscape (Utterström, 1959; Byron, 1994).

5.3 Storminess signals in the sediment lithology?

The Little Ice Age has been generally regarded as a stormy period (Lamb, 1983; De Jong et al., 2007, 2009). Based on granulometric data from Skagerrak, Hass (1996) divided the LIA into three parts: intervals 1350–1550 and 1750–1900 AD, characterised by a stormy mode of sedimentation and an interval 1550–1750 AD, characterised by a "calmer" sediment deposition. Using two raised bogs in near coastal part of SW Sweden, Björck and Clemmensen (2004) also reported an increased aeolian sediment influx (ASI) caused by winter storminess at 1810–1820, 1650 and 1450–1550 AD. The increased aeolian activity occurred at transitional phases between the Roman Warm Period and the Dark Ages (starting ca. 100 AD), at termination of the Medieval Warm Period (1050–1200 AD) and during the coldest phase of the LIA (1550–1650 AD) (Clemmensen et al., 2009). The climax of the LIA also coincided with sand movement and dune formation in Denmark (Clarke and Rendell, 2009; Clemmensen et al., 2009), which is in contrast with a hypothesis of a "calmer sedimentation period" at 1550–1750 AD (Hass, 1996).

Due to a limited amount of the available sediment material, we could not perform a granulometric analysis to identify coarse silt (32–63 µm) and fine-sand (63–125 µm) fractions, used as proxies for storminess and strong bottom currents (Hass, 1996). Instead, we hypothesised that the sand-sized fraction (> 63 µm) may be used to some extent as a storminess signal. The occasionally increased amount of sand-sized fraction in the deepest basin may result from a turbulent flow causing erosion of the coarser material from the sill and slopes and its transport along the fjord during the water renewals. To investigate this further, we plotted the > 63-µm fraction against the frequency of geostrophic winds (Fig. 6), calculated from air pressure data (Alexandersson et al., 1998; Björk and Nordberg, 2003) and describing the regional wind direction during the storm events (Nilsson et al., 2004). As a result, the > 63-µm fraction and

BGD
9, 14053–14089, 2012

the number of storms show a relatively weak correlation with the exception of two sandy peaks at 1965 and 1915 AD as well as larger variability in the > 63-µm data set between 1870 and 1890 AD, which possibly correlates with periods of the higher storm and hurricane frequency (Fig. 6). The maximum sand-sized fraction reached at 1915 AD, given that a general uncertainty for ^{210}Pb CRS dating is 10–20 yr as suggested by Binford (1990), coincides with storms of 1921–1925 AD traced in Greenland ice by an elevated Na^+ content (Dawson et al., 2003). At the same time, the two strong hurricanes of January 2005 and 2007 (Iseborg, 1997; SMHI, 2009) are not visible in the sandy fraction records (Fig. 6). Generally the periods with increased variabililty of sandy fraction (1350–1600 and 1850–1900 AD), which may result from "stormy sedimentation" in Gullmar Fjord, coincide with the findings of Björck and Clemmensen (2004), Clarke and Rendell (2009) and Clemmensen et al. (2009), whereas the division into two stormy and one calm LIA phases generally agrees with the idea of Hass (1996).

An alternative or/and complementary explanation of increased sandy fraction in the record at the LIA onset and at ca. 1850 AD may be a sediment-laden sea ice. Omstedt and Chen (2001) and Omstedt et al. (2004) reported an increase of the maximum ice extent in the Skagerrak during the LIA. During the winter growing sea ice collects sediment from the near-shore areas of the fjord (Cossellu and Nordberg, 2010). These sediments are eventually transported to the deeper fjord areas by the offshore winds or high tides and may get deposited there during the spring thawing.

6 Conclusions

The Little Ice Age period is clearly seen in the benthic foraminiferal records from the deep basin of Gullmar Fjord. The onset of the LIA is indicated by an increase in cold-water species *Adercotryma glomerata*. The first phase of the LIA has been characterised by a stormy but milder climate, which is indicated by the presence of *Nonionella iridea*. Maximum abundances of this species are likely to mirror a short and abrupt warming event at ~ 1600 AD. It is likely that due to deforestation, extensive fishing and land use changes in the second part of the LIA, there was an increased input of terrestrial organic matter to the Gullmar Fjord, which is indicated by lighter $\delta^{13}C$ values and an increase of detritivorous and omnivorous foraminiferal species, such as *Textularia earlandi* and *Eggerelloides scaber*. At the same time, the general climate deterioration during the climax of the LIA (1675–1704 AD), as suggested by the increase of agglutinated species, may have caused some carbonate dissolution as well as variations in marine primary productivity, which therefore led to a decline of *N. iridea* dependant on fresh phytodetritus. We also suggest that an increase of *Hyalinea balthica* could be indicative of general climate warming at 1600–1743 and 1813–1940 AD.

Acknowledgements. The authors thank the crews of R/V *Svanic*; R/V *Skagerrak*, and personally Lennart Bornmalm and Ardo Robijn (University of Gothenburg) for help with sampling. Ardo Robijn also helped with picking of *C. laevigata* for isotope analysis; Monika Segl (University of Bremen, Germany) ran the stable isotope measurements; Asli Oflaz and Sofia Andersson helped with foraminiferal analysis, Göran Björk (University of Gothenburg) provided data on geostrophic winds calculated from air pressure measurements for the triangle Gothenburg-Lund-Oksøy, and Tim Gallagher (University of Michigan, USA) checked the paper for English grammar. We also would like to thank the Gothenburg University for a postdoctoral fellowship to IPA, the Lamm Foundation and the Swedish Research Council (VR) for funding to KN (621-2007-4369) and HLF (621-2005-4265 and 621-2011-5090). The full datasets discussed in this manuscript will be available online through the PANGAEA database.

References

Alve, E.: Benthic foraminiferal responses to absence of fresh phytodetritus: a two-year experiment, Mar. Micropaleontol., 76, 67–75, 2010.

Andrews, S. T., Belt, S., Olafsdottir, S., Massé, G., and Vare, L. L.: Sea ice and marine climate variability for NW Iceland/Denmark Strait over the last 2000 cal. yr. BP., The Holocene, 19, 775–784, 2009.

Arneborg, L.: Turnover times for the water above sill level in Gullmar Fjord, Cont. Shelf Res., 24, 443–460, 2004.

Arneborg, L., Erlandsson, C. P., Liljebladh, B., and Stigebrandt, A.: The rate of inflow and mixing during deep-water renewal in a sill fjord, Limnol. Oceanogr., 49, 768–777, 2004.
Belgrano, A., Lindahl, O., and Hernroth, B.: North Atlantic Oscillation primary productivity and toxic phytoplankton in the Gullmar Fjord, Sweden (1985–1996), Proc. Roy. Soc. B, 266, 425–430, 1999.
Bianchi, G. G. and McCave, I. N.: Holocene periodicity in North Atlantic climate and deep-ocean flow South of Iceland, Nature, 397, 515–517, 1999.
Binford, M. W.: Calculation and uncertainity analysis of ^{210}Pb dates for PIRLA project lake sediment cores, J. Paleolimnol., 3, 253–267, 1990.
Björck, S. and Clemmensen, L.: Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in Southern Scandinavia?, The Holocene, 14, 677–688, 2004.
Björk, J. and Nordberg, K.: Upwelling along the Swedish west coast during the 20th century, Cont. Shelf Res., 23, 1143–1159, 2003.
Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130–2136, 2001.
Bradshaw, E. G., Rasmussen, P., and Odgaard, B. V.: Mid- to late-Holocene land-use change and lake development at Dallund Sø, Denmark: synthesis of multiproxy data, linking land and lake, The Holocene, 15, 1152–1162, 2005.
Brückner, S. and Mackensen, A.: Deep-water renewal in the Skagerrak during the last 1200 years triggered by the North Atlantic Oscillation: evidence from benthic foraminiferal δ^{18}O, The Holocene, 16, 331–340, 2006.
Byron, R.: The maritime household in Northern Europe, Comp. Stud. Soc. Hist., 36, 271–292, 1994.
Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K. U., Wanner, H., Luterbacher, J., and Esper, J.: 2500 years of European climate variability and human susceptibility, Science, 331, 578–582, 2011.
Cage, A. G. and Austin, W. E. N.: Marine climate variability during the last millennium: the Loch Sunart record, Scotland, UK, Quaternary Sci. Rev., 29, 1633–1647, 2010.
Clarke, M. L. and Rendell, H. M.: The impact of North Atlantic storminess on Western European coasts: a review, Quaternary Int., 195, 31–41, 2009.

Clemmensen, L., Murray, A., Heinemeier, J., and De Jong, R.: The evolution of Holocene coastal dune fields, Jutland, Denmark: a record of climate change over the past 5000 years, Geomorphology, 105, 303–313, 2009.
Corten, A.: A proposed mechanism for the Bohuslän herring periods, ICES J. Mar. Sci., 56, 207–220, 1999.
Cossellu, M. and Nordberg, K.: Recent environmental changes and filamentous algal mats in shallow bays on the Swedish west coast – a result of climate change?, J. Sea Res., 63, 203–212, 2010.
Cushing, D. H.: Climate and Fisheries, Academic Press, London, 1982.
Dawson, A. G., Elliott, L., Mayewski, P., Lockett, P., Noone, S., Hickey, K., Holt, T., Wadhams, P., and Foster, I.: Late-holocene North Atlantic climate "seesaws", storminess changes and Greenland ice sheet (GISP2) paleoclimates, The Holocene, 13, 381–392, 2003.
Dearing, J. A., Alström, K., Bergman, A., Regnell, J., and Sandgreen, P.: Recent and long-term records of soil erosion from Southern Sweden, in: Soil Erosion on Agricultural Land, edited by: Boardman, J., Foster, I. D. L., and Dearing, J. A., Proceedings of a workshop sponsored by the British Geomorphological Research Group, Coventry, UK, January 1989, 173–191, 1990.
de Jong, R., Schoning, K., and Björck, S.: Increased aeolian activity during humidity shifts as recorded in a raised bog in south-west Sweden during the past 1700 years, Clim. Past, 3, 411–422, doi:10.5194/cp-3-411-2007, 2007.
de Jong, R., Hammarlund, D., and Nesje, A.: Late Holocene effective precipitation variations in the maritime regions of South-West Scandinavia, Quaternary Sci. Rev., 28, 54–64, 2009.
Eddy, J. A.: The Maunder minimum, Science, 192, 1189–1202, 1976.
Erbs-Hansen, D. R., Knudsen, K. L., Gary, A. C., Gyllencreutz, R., and Jansen, E.: Holocene climatic development in Skagerrak, Eastern North Atlantic: foraminiferal and stable isotope evidence, The Holocene, 22, 301–312, 2011.
Erlandsson, C. P., Stigebrandt, A., and Arneborg, L.: The sensitivity of minimum oxygen concentrations in a fjord to changes in biotic and abiotic external forcing, Limnol. Oceanogr., 51, 631–638, 2006.
Filipsson, H. L. and Nordberg, K.: Climate variations, an overlooked factor influencing the recent marine environment. An example from Gullmar Fjord, Sweden, illustrated by benthic foraminifera and hydrographic data, Estuaries, 27, 867–881, 2004a.

BGD
9, 14053–14089, 2012

The Little Ice Age in a sediment record from Gullmar Fjord

I. Polovodova Asteman et al.

Filipsson, H. L. and Nordberg, K: A 200-year environmental record of a low-oxygen fjord, Sweden, elucidated by benthic foraminifera, sediment characteristics and hydrographic data, J. Foramin. Res., 34, 277–293, 2004b.

Filipsson, H. L. and Nordberg, K: Variations in organic carbon flux and stagnation periods during the last 2400 years in a Skagerrak fjord basin, inferred from benthic foraminiferal δ^{13}C, in: Fjords: Depositional Systems and Archives, edited by: Howe, J. A., Austin, W. E. N., Forwick, M., Powell, R. D., and Paetzel, M., Geological Society Special Publication, Geological Society of London, London, UK, 261–270, 2010.

Fricke, H. C., O'Neil, J. R., and Lynnerup, N.: Oxygen-isotope composition of human tooth enamel from medieval greenland – linking climate and society, Geology, 23, 869–872, 1995.

Fries, M.: Pollenanalytiska vittnesbörd om senkvartär vegetationsutvekling, särskilt skoghistoria, i nord-västra Götaland/Pollenanalytical evidence about late Quaternary development of vegetation and particularly forests in the North-Western Götaland, PhD Thesis, University of Uppsala, Sweden, Acta Phytogeogr. Suecia, 29, 220 pp., 1951 (in Swedish).

Flohn, H.: Das Problem der Klimaveränderungen in Vergangenheit und Zukunft/The problem of past and future climate change, Wiss. Buchges., Darmstadt, 220 pp., 1985 (in German).

Godhe, A. and McQuoid, M. R.: Influence of benthic and pelagic environmental factors on the distribution of dinoflagellate cysts in surface sediments along the Swedish west coast, Aquat. Microb. Ecol., 32, 185–201, 2003.

Godhe, A., Noren, F., Kuylenstierna, M., Ekberg, C., and Karlson, B.: Relationship between planktonic dinoflagellate abundance, cysts recovered in sediment traps and environmental factors in the Gullmar Fjord, Sweden, J. Plankton Res., 23, 923–938, 2001.

Grove, J. M.: The initiation of the "Little Ice Age" in regions round the North Atlantic, Climatic Change, 48, 53–82, 2001.

Gunnarson, B. E., Linderholm, H. W., and Moberg, A.: Improving a tree-ring reconstruction from west-Central Scandinavia: 900 years of warm-season temperatures, Clim. Dynam., 36, 97–108, 2011.

Gustafsson, M. and Nordberg, K.: Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish West Coast, with comparisons to Hoglund's 1927 material, J. Foramin. Res., 31, 2–11, 2001.

Haigh, J. D.: The impact of solar variability on climate, Science, 272, 981–984, 1996.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K., S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P.,

BGD
9, 14053–14089, 2012
The Little Ice Age in a sediment record from Gullmar Fjord
I. Polovodova Asteman et al.

Perry, M. T., Selig, E. R., Spalding, M., Steneck, R., and Watson, R.: A global map of human impact on marine ecosystems, Science, 319, 948–952, 2008.
Hammer, Ø., Harper, D. A. T., and Ryan, P. D.: PAST: Paleontological Statistics Software Package for education and data analysis, Palaeontol. Electron., 4, 1–9, 2001.
Harland, R., Nordberg, K., and Filipsson, H. L.: Dinoflagellate cysts and hydrographical change in Gullmar Fjord, west coast of Sweden, Sci. Total Environ., 355, 204–231, 2006.
Harrison, D.: Stora Döden/The Black Death, Ordfront, Stockholm, 2000 (in Swedish).
Hass, H. C.: Northern Europe climate variations during late Holocene: evidence from marine Skagerrak, Palaeogeogr. Palaeoclim. Palaeoecol., 123, 121–145, 1996.
Hass, H. C.: The benthic foraminiferal response to late Holocene climate change over Northern Europe, in: Contributions to the Micropaleontology and Paleoceanography of the Northern North Atlantic, edited by: Hass, H. C. and Kaminski, M. A., Grzybowski Foundation Special Publication 5, Grzybowski Foundation, Krakow, Poland, 199–216, 1997
Howe, J. A., Austin, W. E. N., Forwick, W., Paetzel, M., Harland, R., Cage, A. G.: Fjord systems and archives: a review, in: Fjords: Depositional Systems and Archives, edited by: Howe, J. A., Austin, W. E. N., Forwick, M., Powell, R. D., and Paetzel, M., Geological Society Special Publication, Geological Society of London, London, UK, 261–270, 2010.
Hughes, M. K. and Diaz, H. F.: Was there a Medieval Warm Period, and if so, where and when?, Climatic Change, 26, 109–142, 1994.
Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N.: The prehistoric and preindustrial deforestation of Europe, Quaternary Sci. Rev., 28, 3016–3034, 2009.
Klitgaard Kristensen, D. and Sejrup, H. P.: Modern foraminiferal biofacies across the Northern North Sea, Sarsia, 81, 97–106, 1996.
Klovan, J. E. and Imbrie J.: An algorithm and FORTRAN-IV program for large scale Q-mode factor analysis and calculation of factor scores, Math. Geol., 3, 61–77, 1971.
Inall, M. E. and Gillibrand, P. A.: The physics of mid-latitude fjords: a review, in: Fjords: Depositional Systems and Archives, edited by: Howe, J. A., Austin, W. E. N., Forwick, M., Powell, R. D., and Paetzel, M., Geological Society Special Publication, Geological Society of London, London, UK, 17–33, 2010.
Iseborg, R.: Väder och oväder under 1900-talet/Weather and storms during the 20th century (in Swedish), Rabén Prisma, Stockholm, 223 pp., 1997.
Lamb, H. H.: Some studies of the Little Ice Age of recent centuries and its great storms, in: Climatic Changes on a Yearly to Millennial Basis: Geological, Historical and Instrumental

Records, edited by: Mörner, N. A. and Karlén, W., D. Reidel Publishing Company, Dordrecht, 1983.
Leijonhufvud, L., Wilson, R., Moberg, A., Soderberg, J., Retso, D., and Soderlind, U.: Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations, Climatic Change, 101, 109–141, 2010.
Lindahl, O. and Hernroth, L.: Phyto-zooplankton community in coastal waters of Western Sweden – an ecosystem off balance, Mar. Ecol.-Prog. Ser., 10, 119–126, 1983.
Lindahl, O., Belgrano, A., Davidsson, L., and Hernroth, B.: Primary production, climatic oscillations, and physico-chemical processes: the Gullmar Fjord time-series data set (1985–1996), ICES J. Mar. Sci., 55, 723–729, 1998.
Ljungqvist, F. C.: Temperature proxy records covering the last two millennia: a tabular and visual overview, Geogr. Ann. A, 91, 11–29, 2009.
Ljungqvist, F. C.: A regional approach to the Medieval Warm Period and the Little Ice Age, in: Climate Change and Variability, edited by: Simard, S. W. and Austin, M. E., Sciyo, Rijeka, Croatia, 486 pp., 2010.
Ljungman, A.: The Bohuslän sea fisheries and their future, Report of the commissioner for 1980, US Commission Fish Fisheries, Washington, USA, 89–98, 1883.
Lund, D. C., Lynch-Stieglitz, J., and Curry, W. B.: Gulf Stream density structure and transport during the past millennium, Nature, 444, 601–604, 2006.
Mauquoy, D., van Geel, B., Blaauw, M., and van der Plicht, J.: Evidence from northwest European bogs shows “Little Ice Age” climatic changes driven by variations in solar activity, The Holocene, 12, 1–6, 2002.
McDermott, F., Mattey, D. P., and Hawkesworth, C.: Centennial-scale holocene climate variability revealed by a high-resolution speleothem delta O-18 record from SW Ireland, Science, 294, 1328–1331, 2001.
Miller, G. H., Geirsdottir, A., Zhong, Y. F., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Bjornsson, H., and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys. Res. Lett., 39, L02708, doi:10.1029/2011GL050168, 2012.
Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., and Karlén, W.: Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, Nature, 433, 613–617, 2005.

Murray, J. W.: Ecology and Applications of Benthic Foraminifera, Cambridge University Press, Cambridge, 2006.
Nilsson, C., Stjernquist, I., Bärring, L., Schlyter, P., Jönsson, A. M., and Samuelsson, H.: Recorded storm damage in Swedish forests 1901–2000, Forest Ecol. Manage., 199, 165–173, 2004.
Nordberg, K., Gustafsson, M., and Krantz, A. L.: Decreasing oxygen concentrations in the Gullmar Fjord, Sweden, as confirmed by benthic foraminifera, and the possible association with NAO, J. Mar. Syst., 23, 303–316, 2000.
Nordberg, K., Filipsson, H. L., Linne, P., and Gustafsson, M.: Stable oxygen and carbon isotope information on the establishment of a new, opportunistic foraminiferal fauna in a Swedish Skagerrak fjord basin, in 1979/1980, Mar. Micropaleontol., 73, 117–128, 2009.
Nordli, P. O.: Reconstruction of nineteenth century summer temperatures in Norway by proxy data from farmers' diaries, Climatic Change, 48, 201–218, 2001.
Omstedt, A. and Chen, D.: Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea, J. Geophys. Res., 106, 4493–4500, 2001.
Omstedt, A., Pettersen, C., Rodhe, J., and Winsor, P.: Baltic Sea climate: 200 years of data on air temperature, sea level variations, ice cover, and atmospheric simulation, Clim. Res., 25, 205–216, 2004.
Polovodova, I., Nordberg, K., and Filipsson, H. L.: The benthic foraminiferal record of the Medieval Warm Period and the Recent Warming in the Gullmar Fjord, Swedish west coast, Mar. Micropaleontol., 81, 95–106, 2011.
Porter, S. C.: Pattern and Forcing of Northern-Hemisphere Glacier Variations during the Last Millennium, Quaternary Res., 26, 27–48, 1986.
Redfield, A. C., Ketchum, B. H., and Richards, F. A.: The influence of organisms on the composition of seawater, in: The Sea, edited by: Hill, M. N., Wiley, New York, 26–77, 1963.
Risgaard-Petersen, N., Langezaal, A. M., Ingvardsen, S., Schmid, M. C., Jetten, M. S. M., Op den Camp, H. J. M., Derksen, J. W. M., Pina-Ochoa, E., Eriksson, S. P., Nielsen, L. P., Revsbech, N. P., Cedhagen, T., and van der Zwaan, G. J.: Evidence for complete denitrification in a benthic foraminifer, Nature, 443, 93–96, 2006.
Rydberg, L.: Circulation in the Gullmaren – a silll fjord with externally maintained stratification, Inst. of Oceanography, Univ. of Gothenburg, Report no: 23 (mimeo), Gothenburg, 1977.
Qvale, G., Markussen, B., and Thiede, J.: Benthic foraminifers in fjords – response to water masses, Norsk Geol. Tidsskr., 64, 236–249, 1984.

BGD
9, 14053–14089, 2012

The Little Ice Age in a sediment record from Gullmar Fjord

I. Polovodova Asteman et al.

Schafer, C. T. and Cole, F. E.: Environmental associations of Baffin Island fjord agglutinated foraminifera, Abh. Geol. Bundesanst. 41, 307–323, 1988.
Schöllhorn, E. and Graneli, E.: Influence of different nitrogen to silica ratios and artificial mixing on the structure of a summer phytoplankton community from the Swedish west coast (Gullmar fjord), J. Sea Res., 35, 159–167, 1996.
Sicre, M. A., Hall, I. R., Mignot, J., Khodri, M., Ezat, U., Truong, M. X., Eiriksson, J., and Knudsen, K. L.: Sea surface temperature variability in the subpolar Atlantic over the last two millennia, Paleoceanography, 26, PA4218, doi:10.1029/2011PA002169, 2011
Shindell, D., Rind, D., Balachandran, N., Lean, J., and Lonergan, P.: Solar cycle variability, ozone, and climate, Science, 284, 305–308, 1999.
Steinsund, P. I. and Hald, M.: Recent calcium carbonate dissolution in the Barents Sea: paleoceanographic applications, Mar. Geol., 117, 303–316, 1994.
Swedish Meteorological and Hydrological Institute (SMHI): Jämförelse av stormarna 1902, 1969 och 2005/Comparison of storms 1902, 1969 and 2005 , available at: http://www.smhi.se/kunskapsbanken/meteorologi/jamforelse-av-stormarna-1902-1969-och-2005-1.5311, (last access: 11 October 2012), 2009 (in Swedish).
Thornton, S. F. and McManus, J.: Application of organic carbon and nitrogen stable isotope and C/N ratios as source indicators of organic matter provenance in estuarine systems: evidence from the Tay Estuary, Scotland, Estuar. Coast. Shelf. Sci., 38, 219–233, 1994.
Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C.: Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly, Science, 324, 78–80, 2009.
Utterström, G.: Migratory labor and the herring fisheries of Western Sweden in the 18th century, Scand. Econom. Hist. Rev., 7, 3–40, 1959.
Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P., and Jetel, M.: Structure and origin of Holocene cold events, Quaternary Sci. Rev., 30, 3109–3123, 2011.
Williamson, M. A., Keen, C. E., and Mudie, P. J.: Foraminiferal distribution on the continental margin off Nova Scotia, Mar. Micropaleontol., 9, 219–239, 1984.
Wollenburg, J. E. and Kuhnt, W.: The response of benthic foraminifers to carbon flux and primary production in the Arctic Ocean, Mar. Micropaleontol., 40, 189–231, 2000.
Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M., and Wanner, H.: European spring and autumn temperature variability and change of extremes over the last half millennium, Geophys. Res. Lett., 32, L15713, doi:10.1029/2005GL023424, 2005.

Table 1. Radiocarbon dating results based on 12 double mollusc shells recovered intact from the cores 9004 and G113-091.

Core	Core depth (cm)	Lab. ID	Species	^{14}C un-corrected ages (BP)	Error (±)	Corr f. reservoir age of 500 yr	Error (±)	Years AD corr. for atmos. ^{14}C	Years BP calendar yr
9004	98	Ua-24043	*Nuculana minuta*	710	35	210	35	1660 ± 100	340 ± 100
9004	136	Ua-35966	*Nuculana pernula*	675	25	175	25	1695 ± 75	305 ± 75
9004	164	Ua-23075	*Yoldiella lenticula*	800	40	300	40	1635 ± 105	365 ± 105
9004	265	Ua-35967	*Nucula* sp.	1025	30	525	30	1440 ± 60	560 ± 60
9004	312	Ua-35968	*Clamys septemradiatus*	1145	25	645	25	1357 ± 32	642 ± 32
9004	313	Ua-23000	*Abra nitida*	1305	45	805	45	1220 ± 100	780 ± 100
9004	371	Ua-35969	*Nucula tenuis*	1245	25	745	55	1305 ± 55	695 ± 55
9004	492	Ua-23001	*Abra nitida*	1640	45	1140	45	880 ± 110	1120 ± 110
9004	564	Ua-23002	*Nuculana minuta*	1925	40	1425	40	620 ± 100	1380 ± 100
9004	623	Ua-23003	*Thyasira flexuosa*	2155	45	1655	45	365 ± 135	1635 ± 135
9004	705	Ua-23004	*Thyasira flexuosa*	2415	45	1915	45	45 ± 225 BC	2045 ± 225
G113-091	145	Ua-39016	*Nuculana pernula*	717	30	217	30	1665 ± 85 AD	335 ± 85

BGD
9, 14053–14089, 2012

BGD
9, 14053–14089, 2012

Table 2. The factors, which resulted from a CABFAC factor analysis with varimax rotation performed on raw foraminiferal data for species contributing > 5% to the assemblages.

Factors	Eigenvalue	Variance (%)
1	125.29	62.02
2	28.985	14.35
3	14.338	7.1
4	10.389	5.14

Table 3. The varimax scores for factors 1–4. The bold numbers indicate foraminiferal species with high (> 1) absolute values of factor scores.

Foram. species	Factor 1	Factor 2	Factor 3	Factor 4
A. glomerata	−0.10768	−0.070154	**5.3381**	0.016301
A. planus	0.055213	0.021256	0.011319	−0.030299
B. pseudopunct.	−0.11202	**1.8777**	−0.05062	0.35149
B. marginata	0.34813	**1.478**	−0.4567	0.92736
C. laevigata	**2.3839**	−0.88175	0.97848	**1.7637**
C. reniforme	0.0077358	0.44531	0.066155	0.099771
Cribrost. sp.	0.038509	0.025065	0.27017	−0.089008
C. lobatulus	0.29699	0.088751	0.20022	0.11073
C. nitida	0.060098	0.028202	0.11089	−0.041738
E. scaber	−0.26005	0.064873	0.61528	0.246
E. excavatum	−0.082485	0.45029	0.42016	0.64108
E. incertum	−0.011122	0.20031	−0.067762	0.12595
Elph. sp.	0.1241	0.061917	−0.010176	0.006397
G. auriculata	0.076751	−0.025578	−0.059181	0.031602
G. turgida	0.025327	0.077637	0.09994	0.25327
H. baltica	0.14513	−0.47949	−0.49283	**4.9004**
L. goesi	0.13924	−0.16283	0.69875	0.076081
I. islandica	0.021199	−0.0138	0.0056691	0.024997
I. norcrossi	0.17626	−0.095165	−0.062956	0.17307
M. barleean.	0.46682	−0.089688	−0.022884	0.023435
M. subrot.	0.13755	−0.071081	0.06433	0.1651
N. labrad.	0.20474	0.41638	0.14557	0.54104
N. iridea	**4.905**	0.23259	−0.45699	−0.87469
P. osloensis	−0.058897	0.10956	0.161	0.27298
P. williams.	0.2882	0.021939	0.13268	0.0015362
Q. seminula	0.4742	−0.093081	0.18083	0.15535
Recurv. sp.	0.0027056	−0.01394	0.013286	0.0082206
R. subfusif.	0.65934	−0.2133	0.50517	0.082465
S. fusiformis	0.49417	**4.4902**	0.33699	−0.30734
T. tricarinata	0.41554	0.03763	0.34257	−0.21743
T. earlandi	−0.63152	**2.075**	0.10634	**1.3917**
V. media	0.082701	0.0097254	0.29911	−0.021164

BGD
9, 14053–14089, 2012

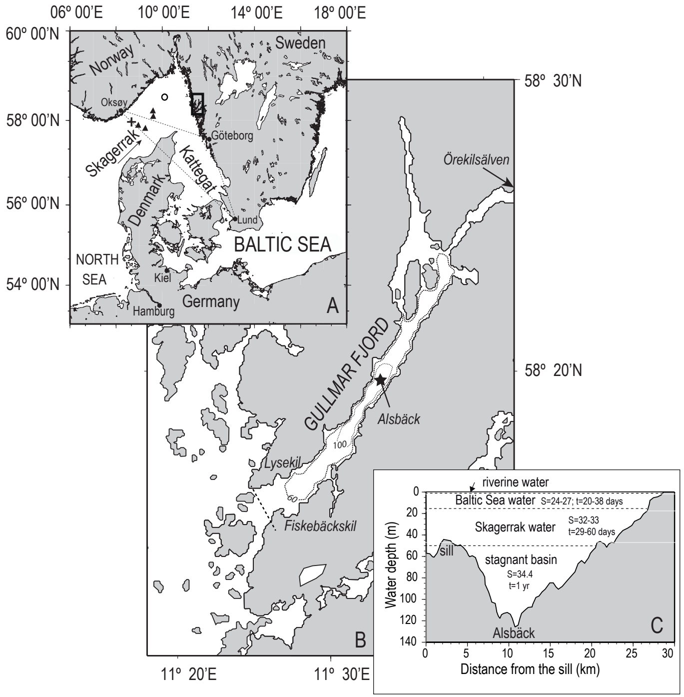

Fig. 1. Overview map of the study area. **(A)** A rectangle shows the location of Gullmar Fjord in the Skagerrak area; dashed-lines indicate triangle Göteborg-Lund-Oksøy, mentioned in the text; an empty circle and a plus show the positions of cores studied by Erbs-Hansen et al. (2011) and Brückner and Mackensen (2006), correspondingly; black triangles are positions of sediment cores studied by Hass (1997). **(B)** Overview of the Gullmar Fjord area; a star in the deepest basin (Alsbäck) indicates sampling site for cores GA113-2Aa, 9004 and GA113-091; a dashed line in the outer fjord indicates location of the sill. **(C)** Overview of water masses in the longitudinal profile of the Gullmar Fjord with indication of salinity (S) and residence times (t) typical for each water layer (Arneborg, 2004).

BGD

9, 14053–14089, 2012

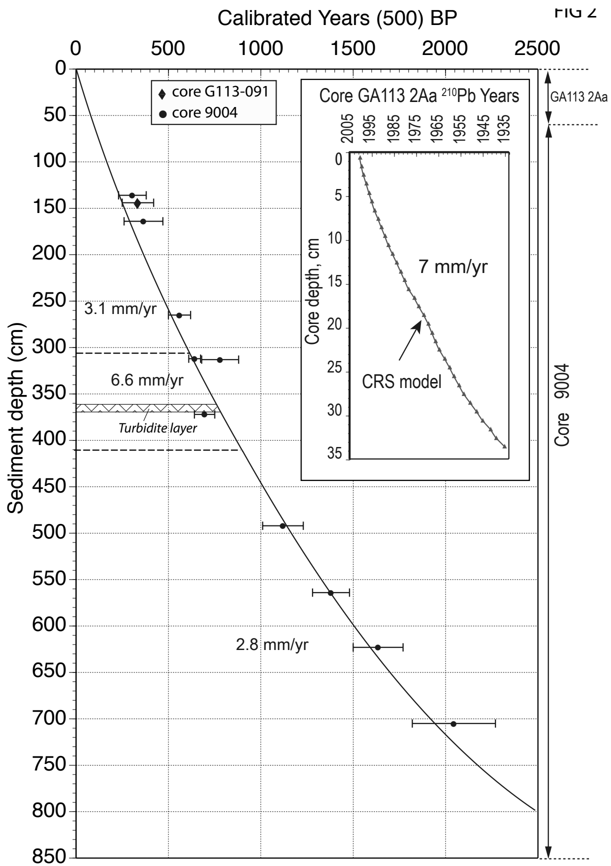

Fig. 2. Age model based on ^{210}Pb (core GA113-2Aa) and ^{14}C AMS datings (core 9004). For AMS dating a reservoir correction of 500 yr has been applied. Dashed lines at 357–371 cm indicate the primary position of a layer referred as landslide and turbidite and removed from the age model (Polovodova et al., 2011).

BGD
9, 14053–14089, 2012

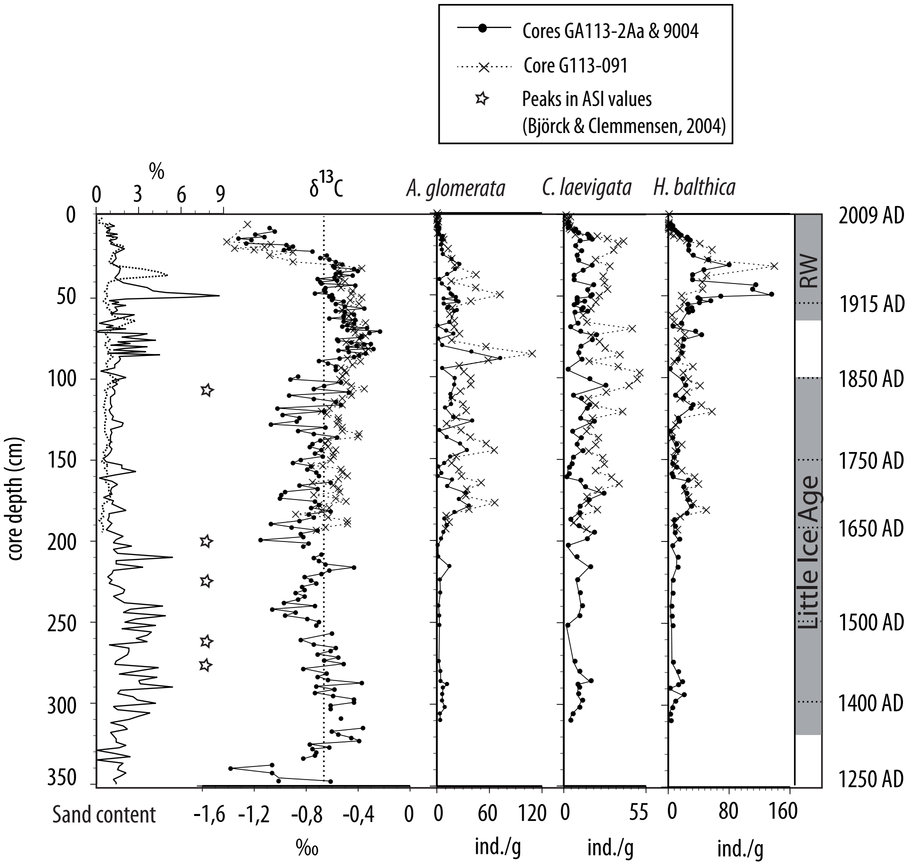

Fig. 3. Isotopic (‰) and foraminiferal (ind. g^{-1}) correlations between cores GA113-2Aa and 9004 and G113-091. The abbreviation RW indicates Recent Warming.

BGD

9, 14053–14089, 2012

The Little Ice Age in a sediment record from Gullmar Fjord

I. Polovodova Asteman et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

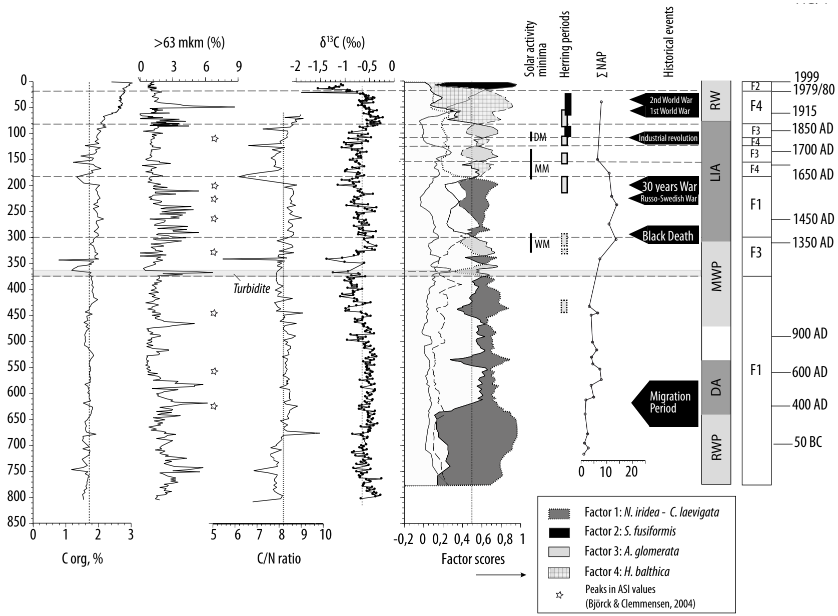

Fig. 4. Composite stratigraphy for the last 2000 yr from the sediment record GA113-2Aa and 9004, which includes the following sediment proxies: organic carbon (C_{org}), sandy sediment fraction (> 63 µm), C/N ratio; stable carbon isotopes (δ^{13}C) and main benthic foraminiferal units (factors) based on factor analysis. Stars indicate periods with increased aeolian sediment influx (ASI) from raised bogs in Halland (Southern Sweden), reconstructed by Björk and Clemmensen (2004), whereas thick vertical lines show periods of reduced solar activity, well known as Wolf (WM: 1300–1380 AD), Maunder (MM: 1645–1715 AD) and Dalton (DM: 1790–1820 AD) minima (Mauquoy et al., 2002). Gray and black rectangles indicate productive herring periods from the Bohuslän fishery (gray and gray with dotted frames) and from the Norwegian fishery (black) (Ljungman, 1883; Cushing, 1982). The thick dashed line with circles shows the total non-arboreal pollen (NAP; %) in the Gullmar Fjord, which is indicative of the land use intensification (Fries, 1951).

BGD
9, 14053–14089, 2012

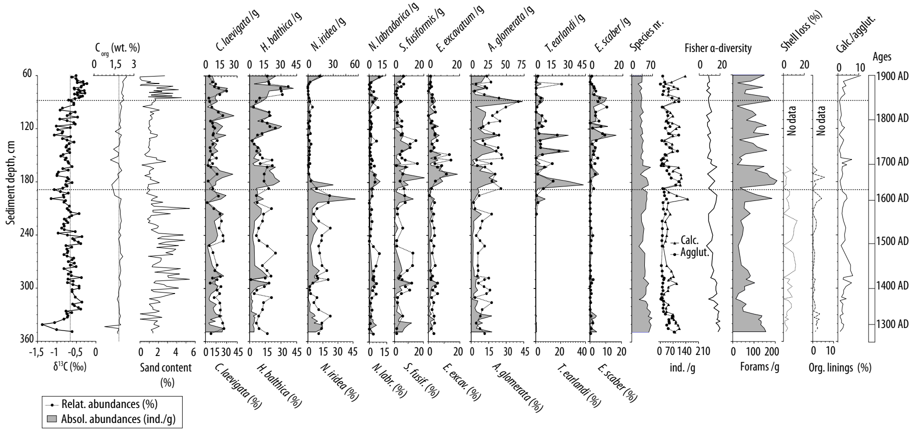

Fig. 5. Absolute and relative abundances of main foraminiferal species, together with some sediment proxies shown as enlargement for the Little Ice Age (LIA) period. Dashed lines indicate the main faunal changes at ca. 1650 and 1850 AD discussed in the text.

BGD

9, 14053–14089, 2012

The Little Ice Age in a sediment record from Gullmar Fjord

I. Polovodova Asteman et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

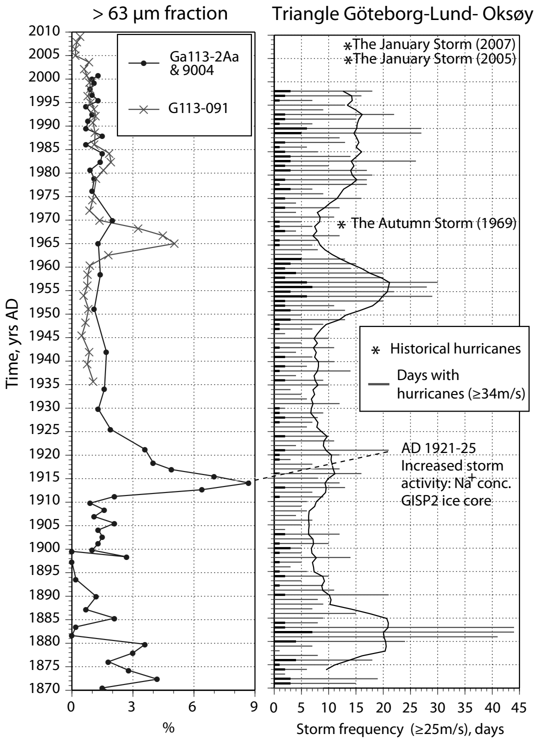

Fig. 6. Sand-sized fraction (> 63 µm) in cores GA113-2Aa and 9004 and G113-091 versus a number of geostrophic winds for triangle Gothenburg-Lund-Oksøy, calculated from air pressure data (Alexandersson et al., 1998; Björk and Nordberg, 2003). The thin grey columns indicate number of days with winds ≥ 25 m s^{-1} regarded as storms, whereas thick black columns show days with hurricanes (≥ 34 m s^{-1}). The black line indicates a 10-yr running mean for winds of speed ≥ 25 m s^{-1}. The asterisks show some of the historically documented hurricanes of ca. 40 m s^{-1}, which struck the west coast of Sweden: The Autumn Storm of 1969, and The January storms of 2005 and 2007 (Iseborg, 1997; SMHI, 2009).

BGD
9, 14053–14089, 2012

The Little Ice Age in a sediment record from Gullmar Fjord

I. Polovodova Asteman et al.