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Variability of the North Atlantic Current during the last 2000 years based on shelf bottom water and sea surface temperatures along an open ocean/shallow marine transect in western Europe

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Abstract: Marine localities on the west European shelf have been studied to reconstruct the nearshore palaeoceanography of the last two millennia. The sites form a transect from the Iberian margin northeastward via Scotland to western Norway and Iceland. Proxies used for palaeoclimatic reconstructions include stable isotopes, benthic and planktonic foraminifera, diatoms, dinoflagellates, as well as geochemical and sedimentological parameters. Major changes as well as long-term trends in oceanographic conditions are observed in the records, including a general cooling trend through much of the last millennium. There is a clear linkage between the atmospheric processes and the oceanic circulation, and the ocean temperature variability in the records can be correlated with the so-called ‘Mediaeval Warm Period’ and ‘Little Ice Age’. These oscillations are, however, by no means unique within the last two millennia. As an example, sea surface temperatures to the north of Iceland and on the Iberian margin were higher in the Roman Warm Period than at any time during the ‘Mediaeval Warm Period’. However, the palaeoceanographic record generally supports a distinct cooling at the transition between the ‘Mediaeval Warm Period’ and the ‘Little Ice Age’. While a number of records indicate a warming of coastal and shelf waters during the last 200 years, the twentieth century does not appear to be unusual when the proxy records spanning the last two millennia are examined.

Key words: North Atlantic Ocean, sea surface temperature, climate variability, palaeoceanography, North Atlantic Current, Holocene, HOLSMEER project.

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Introduction

This study aims to add information to, and improve understanding of, temporal and spatial palaeoceanographic varibility along the eastern part of the northern North Atlantic on a common timescale. The sites range from being proximal to the path of the North Atlantic Current to the southern boundary of the Arctic, providing an extensive overview of the coastal realms in northwestern and western Europe. The target of the project is an acquisition of reliably dated continuous climate records from the coastal realm covering the last two millennia.

One of the objectives of the HOLSMEER project (Late Holocene Shallow Marine Environments of Europe) (Scourse *et al.*, 2006, this issue) was to obtain data on the natural variability of the regional ocean circulation in order to understand processes governing the climate system of western Europe. For the documentation of temporal changes in water masses affecting European shelf environments during the last two millennia, marine sediment cores from shelf settings off North Iceland, Western Norway and Iberia, as well as Scotland have been studied (Figure 1).

Natural variability of the ocean circulation on millennial timescales has played a major role in the past global climate system. The termination of the last glacial cycle in the northern North Atlantic and the transition involving climate–ocean reorganization from the glacial ocean into the Holocene one is a well-documented example (Ruddiman, 1977; Ruddiman and McIntyre, 1981; Duplessy *et al.*, 1981; Bond *et al.*, 1992, 1993; Kroon *et al.*, 1997; Boessenkool *et al.*, 2001). Most studies indicate that this transition was associated with variability in the position and shape of the oceanographic Polar Front separating Atlantic and Arctic surface water masses.

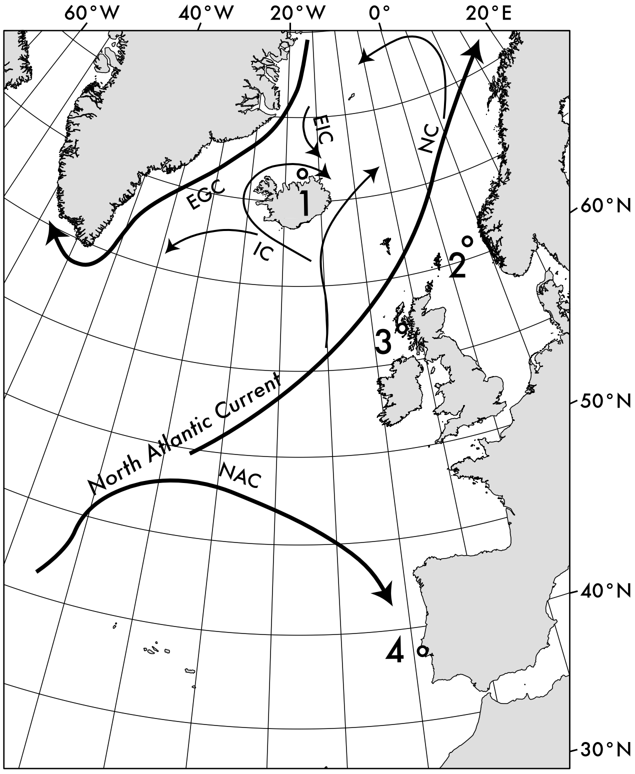

Figure 1 Location map and modern surface ocean circulation in the northern North Atlantic. 1, North Iceland shelf; 2, Norwegian margin (Norwegian Channel); 3, Scottish Sea Loch (Loch Sunart); 4, Iberian margin off Portugal (Tagus Prodelta). NAC, North Atlantic Current; NC, Norwegian Current; EGC, East Greenland Current; IC, Irminger Current; EIC, East Icelandic Current

For the Holocene, it has been suggested that climatic conditions related to the strength of the Atlantic's conveyor circulation have been modulated over a period of around 1500 years (Bond *et al.*, 1999). Major components of the ocean circulation in the region include the North Atlantic Current carrying warm, saline surface waters from low latitudes towards Europe, and the East Greenland Current outflow from the Arctic Ocean through the Fram Strait, carrying sea ice and cold, fresh surface waters into the Nordic Seas and the northern North Atlantic Ocean (Hansen and Østerhus, 2000). The role of the inflow of Arctic Water into the northern North Atlantic and the Nordic Seas was exemplified by so-called salinity anomalies that occurred during the latter half of the twentieth century (Malmberg, 1984; Dickson *et al.*, 1988; Belkin *et al.*, 1998). These events were characterized by lowered sea surface salinity and temperature, and increased sea ice in the Iceland Sea (Dickson *et al.*, 1988).

The strength of the North Atlantic Current is generally related to deep water formation in the Nordic Seas, which is again associated with southward overflow across the Greenland-Iceland-Faeroe-Scotland Ridge (Swift, 1986; Dickson *et al.*, 1996). The North Atlantic Current is expected to be strong during active deep water formation and weak during periods of freshening of the surface waters north and northeast of Iceland, ie, during periods with strong input of Polar Water from the East Greenland Current and the East Icelandic Current (Dickson *et al.*, 1996; Malmberg and Jónsson, 1997).

During the present interglacial, the Holocene (11 500 cal. yr BP to the present), relatively stable atmospheric conditions are indicated by one of the most important Northern Hemisphere climate data archives available, the Greenland ice core stable isotope record (Dansgaard *et al.*, 1971; Johnsen *et al.*, 1972, 1992; O'Brien *et al.*, 1995). Holocene variability, however, is recorded in the Greenland ice cores by several other geochemical parameters (Mayewski *et al.*, 1994). In a recent review of Holocene climate data archives, Mayewski *et al.* (2004) concluded that the Holocene climate has been highly variable on a millennial timescale, incorporating several rapid climate change events, with the early Holocene events being related to or influenced by the glacial world scenario because the Northern Hemisphere ice caps were still melting away.

The HOLSMEER project addresses important questions related to the background levels of natural climate variability versus modern industrialization-induced global warming, and the combination of many sites, multiple proxies and high temporal resolution adds to the value of the project for understanding the ocean–atmosphere interaction in the region.

The North Iceland HOLSMEER sites were chosen because they are located at the Polar Front boundary between warm and cold surface water masses, recording changes in temperature, salinity and sea ice, whereas the Norwegian, Scottish and Iberian sites reflect variability in the surface temperature related to the physical properties of the North Atlantic Current, the strength of the global thermohaline circulation and atmospheric and oceanic circulation variability.

A number of micropalaeontological, chemical and sedimentological proxies were studied along an open ocean transect extending from the Iberian margin to Scotland, western Norway and Iceland. Comparing the various proxies within a site and between sites is, however, not always straightforward because, although the sites are located at shallow-water localities, some of the proxies reflect surface parameters while others are related to bottom conditions. This depth variability adds to seasonal variability, which also has to be taken into account. Seasonality is quite pronounced at the North Iceland shelf with Atlantic Water dominating the water column during summer and autumn, while Arctic waters, cooling and vertical mixing dominate the water column during the winter months, to create a new water mass (Stefánsson, 1962; Hurdle, 1986; Johannesen *et al.*, 1994). On the Scottish west coast, the development of seasonal stratification of the water column is initiated in April/May and normally breaks down in October.

Seasonality is also quite marked at the Iberian margin, with southward flow of surface currents and more enhanced upwelling during summer months while the winter months are characterized by a northward flow of surface currents (Fiúza, 1983). The Portuguese HOLSMEER site is furthermore influenced by fluvial runoff during winter months (Trigo *et al.*, 2002; Abrantes *et al.*, 2005).

Sites and research methods

Site information and core material

Iberian margin

The surface water masses found along the Portuguese margin mainly originate from the North Atlantic Current, being affected by narrow, warm, northward-flowing currents during the autumn and winter and by the southward-flowing cool Portugal Current during summers (Fiúza, 1983). The surface waters of the Portuguese margin are also affected by freshwater runoff and seasonal upwelling. These water masses constitute the surface mixed layer down to the thermocline at about 70–110 m (Schönfeld, 1997). The water depth at the coring sites is close to the thermocline depth. Below the thermocline, the interval down to 600 m is occupied by the North Atlantic Central Water (NACW). This water mass plays an important role in the summer upwelling, which is an important feature of the present-day oceanography along the Iberian margin. During periods of persistent northerly winds, the surface mixed layer along the coast is displaced westward by the Coriolis force, being compensated by upwelling of cool, nutrient-rich NACW water. The present-day oceanographic conditions along the Iberian margin are thus sensitive to the wind regime and to precipitation and runoff from the Tagus. According to Abrantes *et al.* (2005), the modern sea surface temperature values range from 15.5°C (winter) to 19.5°C (summer).

Samples from the Iberian margin were obtained on two oceanographic cruises, RV *Discovery* 249, and the PALEO1 on the RV *Poseidon* (Lebreiro *et al.,* 2006, this issue). A composite sequence is used from intervals of piston core D13902 (600 cm long), gravity core PO287-26-3G (305.5 cm) and box core PO287-26-1B (33 cm) retrieved from the southern part of the Tagus Prodelta at 90 and 96 m water depth (Figure 1). Data from the intervals 18–150 cm of core PO287-26-3G and 240–400 cm of core D13902 were included, together with the entire box core. The chronology for the composite sequence is based on calibrated radiocarbon dates and using data from the age model presented by Abrantes *et al.* (2005), modified by Bartels-Jónsdóttir *et al.* (2006). Results presented here include stable isotope analyses as well as alkenone biomarker analyses for the calculation of sea surface temperatures on the basis of the UK' 37 index.

West Scotland margin

Samples from the northwest British margin were obtained from Loch Sunart, a sea loch (fjord) on the west coast of Scotland (GC023, 56°40.324′N, 5°50.328′W). Stable isotope data have been obtained from the benthic environment of the main sedimentary basin of the sea loch, which maintains a connection with the open shelf through frequent deep-water renewal events across a deep (> 30 m) rock sill (Gillibrand *et al.*, 2002, 2005). The age model for the core is based on radiocarbon dating of marine bivalved molluscs (eg, Cage, 2005), but the record post AD 1100 is either missing or disturbed by coring processes. Summer bottom water temperatures in the loch have been estimated using a benthic foraminiferal transfer function approach modified after Sejrup *et al.* (2004; Cage, 2005). The Loch Sunart basin, despite its restricted coastal location, is strongly influenced by exchange with coastal water. It therefore provides a site of exceptionally high sediment accumulation (up to 0.5 cm/yr) and provides proxy records that reflect both variability in the physical properties (primarily temperature) of the North Atlantic and the strength of westerlies in the region. The latter, which is an important forcing mechanism in fjordic hydrography, is very closely coupled to the predominant mode of atmospheric forcing at this latitude, namely the North Atlantic Oscillation (eg, Ruprecht *et al.*, 2002; Trigo *et al.*, 2002).

Norwegian margin

The main water masses in the Norwegian Channel are the Atlantic Water and Norwegian Coastal Current waters. The continuation of the North Atlantic Current, the Norwegian Current transports warm, saline water into the southeastern Nordic Seas along the Norwegian continental margin. A branch of the Norwegian Current flows into the Norwegian Channel, following the western slope of the channel towards the south (Furnes *et al.*, 1986), and is the main route for the import of Atlantic Water (7.5–9.0°C, salinity > 35 psu) into the North Sea. The other major current in the Norwegian Channel is the Norwegian Coastal Current (NCC; temperature 3–18°C, salinity < 34.7 psu) that flows along the Norwegian coast (data retrieved 28 June 2006 from http://www.imr.no). During wintertime, the NCC is expressed in a well-defined wedge-shaped water mass that reaches down to 150 m water depth at the Norwegian coast, whereas during summertime large sea surface lateral extensions westwards onto the North Sea plateau are observed as result of the wind stress forcing (Furnes *et al.,* 1986).

From the Norwegian Channel two cores (Figure 1), the box core HM115-16TBC (60°51.991′N, 03°43.955′E, water depth 338 m, length 38 cm) and the gravity core HM115-16GC (60°52′N, 03°44′E, water depth 345, length 475 cm) have been investigated for content of organic walled dinoflagellates, benthic and planktonic foraminiferal faunas and stable isotopes (D. Klitgaard-Kristensen, H.P. Sejrup, M. Smelror, H.J.B. Birks and H. Haflidason, unpublished data, 2004). The two cores have been combined into one record by using dating (AMS ^{14}C and ^{210}Pb) and foraminiferal fauna.

The majority of the faunal and floral species in the stratigraphic record are found to be associated with Atlantic Water based on previous investigations of the content of these in surface sediment samples (Sejrup *et al.*, 1981; Quale and van Weering, 1985; Rochon *et al.*, 1998; Klitgaard-Kristensen *et al.*, 2001), hence interpreted to reflect past variability of the Atlantic Water. In order to capture temperature changes in the Atlantic Water, the results from the benthic stable isotope record are also included. This approach has recently been used on records from western Norwegian fjord basin (Mikalsen *et al.*, 2001; Sejrup *et al.*, 2001; Klitgaard-Kristensen *et al.,* 2004).

North Icelandic shelf

The North Icelandic shelf is within the boundary between Atlantic Water, which is brought to the area by the relatively warm, high-salinity Irminger Current on the one hand, and cold, low-salinity surface water of the East Icelandic Current (Polar Water) on the other (Figure 1). The East Icelandic Current is partly derived from the East Greenland Current (Polar Water) and partly from the Norwegian Atlantic Current (Atlantic Water) (Stefánsson, 1962; Swift, 1986; Johannesen *et al.*, 1994; Malmberg and Jónsson, 1997; Hansen and Østerhus, 2000). At present the Norwegian Sea Deep Water (NSDW) replaces the mixed surface-water masses at about 3–400 m depth off North Iceland. During periods of strong overflow in the Denmark Strait and across the Iceland-Faeroe Ridge, the cold deep water masses (NSDW) may be expected to influence the deepest topographic basins north of Iceland (Eiríksson *et al.*, 2000). The modern summer sea surface temperature in the study area is relatively constant, generally around 6–7°C, while the winter sea surface temperature is around 1–3°C (Jiang *et al.*, 2002).

On the North Icelandic shelf, dinoflagellate cyst data were obtained from core MD992271 (66°30.07′N; 19°30.33′W, water depth 345 m) and stable isotope, diatom and sedimentological data from core MD992275 (66°33.10′N, 17°41.98′W, water depth 410 m, Figure 1), both obtained on the 1999 IMAGES cruise. Age models for both cores are based on tephrochronology (Larsen *et al.*, 2002; Eiríksson *et al.*, 2004).

Proxies and methods

Iberian margin

Oxygen isotope analyses were carried out at 1 cm intervals in all three Iberian margin cores. An average number of six specimens from the >250 μm fraction of the benthic species *Uvigerina* sp. 221 was used for each measurement. For the planktonic record, specimens of the planktonic foraminifera *Globigerina bulloides* were used. The laboratory procedures are described in Bartels-Jónsdóttir *et al.* (2006). The alkenone-based SST reconstruction from the Iberian margin is based on procedures described by Abrantes *et al.* (2005).

West Scotland margin

The age–depth model of core GC023 is primarily based upon ^{14}C-dated marine molluscs applying a regional marine reservoir age correction ($\triangle R = -26 \pm 14$ yr), which has been derived from a pre-bomb dating programme of museum collection material (Cage *et al.,* 2006). Despite some uncertainties regarding the dating of the second millennium AD in the GC023 record, we calculate an average sample resolution equivalent to 7 years. The epibenthic foraminifera *Cibicides lobatulus* was picked from the size-range 125–250 μm, and samples were analysed on a MAT251 with Kiel Device at the University of Bremen, Germany. Stable isotope measurements are reported on the VPDB scale, relative to the NBS-19 standard, with the following precision: $\delta^{18}O = 0.035 \pm 0.015‰$; $\delta^{13}C = 0.025 \pm 0.011‰$.

Norwegian margin

In the Norwegian margin record, the stable oxygen isotopes in benthic foraminifera have been measured on the benthic species *Uvigerina mediterranea*. Specimens (one to two individuals) were picked from the 0.125–1000 μm fraction. Stable isotope analyses were conducted at the mass spectrometry laboratory at Department of Earth Science, University of Bergen. Prior to analyses, drops of methanol were added to all samples, followed by ultrasound treatment for 1 min in methanol to remove the fine-grained particles. The methanol was removed using a syringe and the samples allowed to evaporate to dryness in a drying cabinet. The foraminifer shells were then loaded into individual reaction glasses, and each sample was reacted with three drops of H_3PO_4 using a MAT Carbo Kiel III automated preparation line. Isotope ratios were measured on a Finnigan MAT 251 mass spectrometer. The data are reported as $\delta^{18}O$ versus the Vee Pee Dee Belemnite (VPDB) standard after calibration with NBS-19 standard (Coplen, 1995). Analytical precision of the system as defined by replicate measurements of carbonate standards is ±0.07‰ for $\delta^{18}O$. The age model is based on ^{210}Pb and ^{137}Cs measurements and six radiocarbon AMS dates and yields a time resolution of 4–22 years for the last 2000 years (D. Klitgaard-Kristensen, H.P. Sejrup, M. Smelror, H.J.B. Birks and H. Haflidason, unpublished data, 2004).

North Icelandic shelf

Oxygen isotopes were measuered on the planktonic sinistrally coiled *Neogloboquadrina pachyderma* as well as on the benthic species *Islandiella norcrossi* (Cushman) from the 125–1000 μm fraction of each foraminiferal sample, when possible. The $\delta^{18}O$ values were measured on a Finnigan MAT 251 mass spectrometer at the Stable Isotope Laboratory, University of Bergen, following standard procedures (cf. Knudsen *et al.,* 2004a,b).

Foraminiferal content in the North Iceland shelf record was analysed in the 125–1000 μm sand fraction, and this grain size interval was also used for ice-rafted debris (IRD) analyses (for discussion of the origin of IRD, see Eiríksson *et al.*, 2004; Knudsen *et al.*, 2004b). The planktonic assemblages are dominated by sinistrally coiled *Neogloboquadrina pachyderma*. The percentages of this species are calculated relative to the total planktonic content. Carbonate content was determined by titration on a UIC coulometer, and the sortable silt grain size parameter was calculated from results from a Malvern Mastersizer.

A modern diatom–environmental variable data set from around Iceland (Jiang *et al.*, 2001, 2002) covers areas with sufficient environmental gradients for the deduction of quantitative relationships between diatom species and environmental variables. A Monte Carlo permutation test with forward selection shows that diatom distribution in the area is primarily controlled by summer and winter sea surface temperatures (SSTs, SSTw). These variables are therefore suitable climatic parameters for quantitative reconstruction of palaeorecords based on diatoms in the region.

Diatom samples were extracted from 1 cm thick slices taken at 5 cm intervals from the uppermost 5.3 m of core MD992275. The mean sample resolution is less than 20 years. The CALIBRATE program was used to quantitatively reconstruct the SSTs and SSTw (Juggins and ter Braak, 1992; Jiang *et al.*, 2002). WA-PLS using six components was employed for quantitative reconstruction of the SSTs and WA-PLS using five components for the SSTw. Root mean squared errors of prediction based on the leave-one-out jackknifing ($RMSEP_{(Jack)}$) test are 0.98°C for the SSTs and 0.92°C for the SSTw (Juggins and ter Braak, 1992; Jiang *et al.*, 2002). For dinoflagellate cyst-based SST reconstructions on the North Icelandic shelf, the upper 300 cm of core MD992271 were subsampled at 5 cm intervals. Laboratory procedure for dinocyst analyses consists of repeated acidic treatments (cold HCl (10%) and HF (32–40%)) and sieving at 10 and 118 μm (cf. Marret *et al.*, 2004). Oxidation was avoided as it has been demonstrated that sensitive dinocyst taxa may disappear during the treatment (cf. Marret, 1993). A tablet of exotic marker spores (*Lycopodium clavatum*) was added at the beginning of the procedure for calculating the concentration of dinocysts. The remaining material was mounted in glycerine gel coloured with safranin for light microscopic observation.

Reconstructions of sea surface parameters were obtained from the modern analogue technique, adapted from Guiot and Goeury (1996) with the current $N = 940$ dinocyst data base (see de Vernal *et al.*, 2005). Validation of the modern data set with the WOA01 (Conkright *et al.,* 2002) hydrographical data gives a degree of accuracy as follows: ±1.31°C and ±1.93°C for winter and summer sea surface temperatures (SSTs) respectively, and ±2.94 psu and ±3.00 psu for winter and summer salinity, respectively. On the whole, the degree of accuracy of estimates is of the same magnitude as the standard deviations around the average for modern SSTs, salinity or sea-ice cover (see also Rochon *et al.*, 1998; de Vernal and Hillaire-Marcel, 2000).

Results

Iberian margin

Alkenones

On the Iberian Atlantic margin, the alkenone record of the Tagus Prodelta (Figure 2A) shows a relatively stable sea surface temperature from AD 0 to around AD 900, with a slight cooling of 0.5°C in the second and third centuries AD, recovering at AD 500–600. A distinct cooling trend begins after about AD 900, and the sea surface temperature apparently becomes more unstable at the same time. However, the time resolution of the record is considerably lower before AD 900 than after, possibly obscuring early fluctuations. The temperature of the last 500 years of the record fluctuates around 16°C, which corresponds to a temperature drop of 1.5°C compared with the first millennium of the record. A sharp cooling is observed during the fourteenth century, with the temperature rising moderately again towards AD 1450.

Sustained periods of sea surface temperatures over 17°C are not observed on the Iberian margin after AD 1000. This is most probably related to advection of colder subpolar surface waters from the north and possibly increased upwelling. As other sedimentary parameters reveal increased sedimentation of terrigenous material during the same period, this shift towards colder sea surface temperatures (SST) and increased precipitation on the western Iberian peninsula points to a change in the dominant features of the atmospheric circulation above the North Atlantic.

Planktonic stable isotopes

The planktonic oxygen isotope record of the Iberian margin (Figure 2B) shows a considerable variability through the last 2000 years. Instrumental data show that interannual variability in salinity (0.1 psu) is much smaller than variability in temperature (*c.* 4°C) in the Tagus Prodelta (Abrantes *et al.*, 2005; Terese Moita, personal communication, 2006). Thus, most of the fluctuations in the oxygen isotopes are probably related to variability in the temperature and only partly to variations in the salinity of the surface waters. However, persistent periods of increased precipitation over the Iberian peninsula resulting from strengthened westerlies across the Atlantic presumably also contribute to a decrease in the planktonic isotopic values.

Relatively light isotope values are found in the beginning of the record and between around AD 400 and 1400. Heavier isotope values parallel the alkenone SST cooling trend from the fourteenth century into the eighteenth century. This would be consistent with strengthening of the cool southward-flowing Portugal Coastal Current and/or enhanced upwelling during this time interval (Bartels-Jónsdóttir *et al.*, 2006). A clear trend towards lighter values is seen in the planktonic oxygen isotope record from the eighteenth century to the present day. Light value peaks are observed at around 100 BC, AD 150, AD 800, AD 1400 and in the latter half of the twentieth century.

Benthic stable isotopes

The bottom water conditions of the Tagus Prodelta are expected to be strongly influenced by the surface oceanography because of the shallow water depth of only 90 m, and the record is suggested to be influenced mainly by temperature, but to some extent also by salinity changes. The benthic $\delta^{18}O$ values show considerably less variability than the planktonic ones (Figure 2C). At the beginning of the record, benthic isotope values are relatively high, corresponding to temperatures fluctuating around 13.2°C, assuming a constant salinity (Bartels-Jónsdóttir *et al.*, 2006), with a distinct but short, particularly heavy interval centred around AD 200. This is followed by a slight decrease around AD 400. The benthic isotopic values then remained relatively light until around AD 1300 (650 cal. BP, Figure 2C). Shortly before AD 1300, a trend towards heavier values sets in, and the values remain high until the eighteenth century. Since AD 1800, the benthic oxygen isotope values have been relatively light.

A possible explanation for the heavy benthic isotopic values during the period AD 1450 to 1750 in the Tagus Prodelta may be the enhancement and maintenance of the cool Portuguese Coastal Current transporting cold subpolar waters to the Iberian margin. This is in agreement with a study by deMenocal *et al.* (2000), who recorded lower temperatures during the so-called 'Little Ice Age' (LIA) off NW Africa and proposed both a stronger Eastern Boundary Current and/or an enhancment of upwelling during the LIA. The benthic stable isotope record shows clearly that during the last 100 years the bottom temperature was higher, by almost 2°C, than at any time during the last *c.* 2000 years.

West Scotland margin

Benthic stable isotopes

Using a benthic foraminiferal summer bottom water temperature transfer function (modified after Sejrup *et al.*, 2004), we have confirmed that long-term changes in benthic foraminiferal $\delta^{18}O$ trace the temperature history of bottom water in Loch Sunart (Cage, 2005). Benthic foraminiferal $\delta^{18}O$ records summer bottom water temperature in the range 10–13°C throughout the first millennium AD. During this time, temperatures were typically 2°C warmer than the present day, and there is a cooling trend in bottom water temperature since around AD 900 (Figure 2D). Benthic foraminiferal $\delta^{13}C$ data suggest that the exchange between basin water and coastal waters has changed over this same time interval, a mechanism that could have been driven by enhanced westerlies.

Numerical modelling experiments of Loch Sunart circulation (Gillibrand *et al.*, 2005) investigated the forcing mechanisms at play during two recent extremes of the NAO. The results suggest that main basin salinity remains extremely stable in response to both the strength of westerlies and freshwater forcing driven by changing pattern of precipitation. We are therefore confident that the benthic $\delta^{18}O$ records reflect changing coastal temperature, but these may be complicated in shelf environments by the timing of seasonally triggered reproduction and growth in foraminifera (eg, Scourse *et al.*, 2004). Our data suggest that coastal temperatures over the last 2000 years are repeatedly influenced by a high frequency (multidecadal) 1–2°C variability that overprints a longer-term (centennial) climate signal, the most pronounced expression of which is a cooling trend at around AD 900.

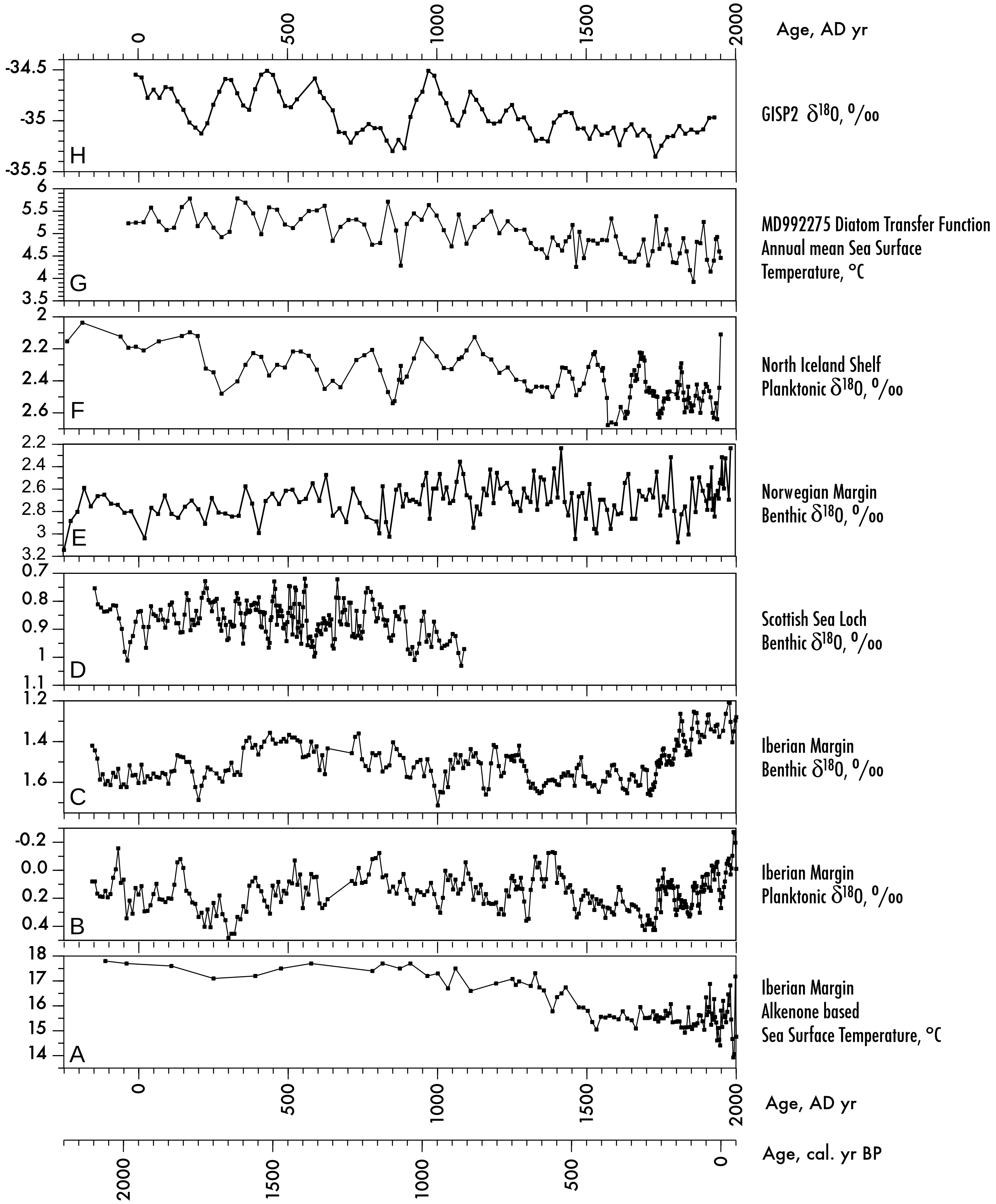

Figure 2 Palaeoceanographic parameters from open ocean shallow marine sites in western Europe. (A) Sea surface temperature record from the Iberian margin based on alkenones. (B) $\delta^{18}O$ record from the Iberian margin based on the planktonic foraminifera *Globigerina bulloides.* (C) $\delta^{18}O$ record from the Iberian margin based on the benthic foraminifera *Uvigerina* sp. 221. (D) Benthic foraminiferal $\delta^{18}O$ record from Loch Sunart based on *Cibicides lobatulus* (3 pt. running mean). (E) Norwegian margin $\delta^{18}O$ record based on the benthic foraminiferal species *Uvigerina mediterranea*. (F) North Iceland shelf record of $\delta^{18}O$ based on the planktonic foraminiferal species *Neogloboquadrina pachyderma* sinistral (3 pt. running mean). (G) Mean annual sea surface temperature record from the North Iceland shelf based on diatom transfer function. (H) Greenland ice core GISP2 oxygen isotope record (50 yr smoothing filter). Age scales in calibrated years BP for marine records, GISP2 ice years in the Greenland ice core. Age scales are given in years BC and AD as well as in years PB (before 1950)

Norwegian margin

Benthic stable isotopes

The benthic isotope record is interpreted to primarily reflect (annual) temperature changes in the inflowing Atlantic Water into the Northern North Sea. This follows from previous studies of oxygen isotope records of benthic foraminifera in cores presently underlying inflowing Atlantic Water in this region. These investigations inferred, based on the similarity between the proxy records and instrumental time series (annual temperature and salinity variations), that the isotope records mainly reflected temperature (Mikalsen *et al.,* 2001; Klitgaard-Kristensen *et al.,* 2004). If interpreted as temperature only, this means that a maximum amplitude of about 2°C is recorded (0.6‰) for the last two millennia. The long-term temperature development shows relatively low temperatures from AD 100 to 400, 600–900 and 1400–1900, whereas higher temperatures than average are seen from AD 400 to 600, 900–1400 and for the last 80 years (Figure 2E). These periods are, however, not only prolonged periods of high or low temperatures but also interrupted by shorter periods exhibiting warmer or colder conditions.

North Icelandic shelf

Planktonic stable isotopes

The planktonic oxygen isotope record from the North Icelandic shelf (Figure 2F) shows a variability of close to 2°C through the last 2000 years. There is an overall cooling trend through the entire period. The isotopic values are relatively low (around 2.1–2.2‰) until about AD 200, indicating a sustained warm surface ocean north of Iceland during the Roman Warm Period (RWP). A subsequent cooling in the time interval from AD 200 to 900 is indicated by generally heavier δ^{18}O values. The values are fluctuating, and distinct coolings are suggested by peak values around AD 300, 700 and 850. The isotopic values indicate a slight increase in temperature between AD 900 and 1100. Apparently, however, the surface waters during the interval corresponding to the 'Mediaeval Warm Period' (MWP) were not as warm as during the RWP. After AD 1100 there is clear evidence of a cooling trend, which continues through the remainder of the record. The isotopic values are particularly high after AD 1500. Short intervals of light isotopic values in this latter interval probably reflect periodic influx of low-salinity surface waters to the area. This indicates strengthening of the cold, fresh East Icelandic Current during the last few hundred years (Knudsen *et al.*, 2004b).

Diatoms

An annual mean sea surface temperature record based on diatom transfer function reconstructions is presented in Figure 2G. Temperature values range between 4 and 6°C. A long-term cooling trend characterizes the record as a whole. A cooling trend from AD 300 to 800 is followed by a relatively warm period from AD 800 to 1300. After a sharp temperature drop between AD 1250 and 1350, the last part of the record, from AD 1300 to 1950, is characterized by reconstructed temperature values that generally lie below 5°C. Within the period AD 1300 to 1950 the temperature trend is opposite to the one observed at the Norwegian margin site, with a general cooling.

Planktonic proxies and sedimentological parameters

The results of a multiproxy study of HOLSMEER site MD992275 on the North Iceland shelf are presented in Figure 3. The parameters all relate to the oceanography of the region, where the oceanographic Polar Front is located today. In the temperature reconstructions based on diatoms, consistently low sea surface temperatures, both summer and winter, appear to have prevailed since AD 1300 on the North Iceland shelf (Figure 3F, 3G). A sharp drop in sea surface temperature, observed between AD 1200 and 1400, coincides with an increase of the percentage of *Neogloboquadrina pachyderma* sinistral. This is probably an indication of a weakened Irminger Current and a concurrent southward shift of the Polar Front.

The decrease in planktonic isotope values after AD 1100 leads to generally heavy values after AD 1300 (Figure 2F). Intervals of light values within these last few hundred years coincide with cold periods reflected by the diatom record. This presumably reflects short-term incursions of relatively fresh surface waters with an Arctic component brought by the East Icelandic Current. Parts of the sixteenth century enjoyed relatively mild surface waters north of Iceland, terminated by sharp cooling at close to AD 1600 (Figure 2F, 3C, F, G). There is clearly a very close relationship between the carbonate content (Figure 3E) and the sea surface temperature record, with consistently low values after AD 1200. An increase is observed after AD 1900.

All these changes are interpreted to reflect variable strength of the Irminger Current, an interpretation that is supported by the sortable silt content. Sluggish bottom circulation is indicated by the sortable silt parameter at the base of the record, but the values between around AD 0 and AD 900 indicate the liveliest currents of the 2000 year record. A decreasing trend is then observed from AD 900 to 1900, with a slight increase towards the top after AD 1900. Percentages of the sinistrally coiled *Neogloboquadrina pachyderma* (Figure 3C) show that for sustained periods, arctic conditions have prevailed on the North Iceland shelf, with values exceeding 95%. The lowest percentages are observed after AD 1900 towards the top of the record, and between AD 300 and 450. The latter interval is also characterized by high reconstructed sea surface temperatures (diatom based), light planktonic δ^{18}O values, a slightly increased sortable silt mean, and a carbonate peak.

Generally, arctic conditions are indicated by the planktonic fauna at around AD 700 (Figure 3C), supported by low sea surface temperature and heavy planktonic δ^{18}O values (Figure 2F). This cold interval precedes the beginning of the MWP at AD 750 (Figure 4), the onset of which can be identified by increasing sea surface temperatures, rising carbonate content and sortable silt mean, as well as decreasing percentages of *Neogloboquadrina pachyderma* sinistral. The planktonic δ^{18}O record of the MWP starts with relatively light values around AD 750, but an interval with heavy values is observed around AD 900, followed by light values until AD 1250.

High percentages of *Neogloboquadrina pachyderma* sinistral characterize the interval AD 1350 to 1700 and the values fluctuate strongly between AD 1700 and 1900, with minima close to AD 1800 and 1900. A period of ice-rafting was also observed from just after AD 1300 until 1400, coinciding with the onset of the LIA (Eiríksson *et al.*, 2004; Knudsen *et al.*, 2004a). After a short-lived period of higher than average IRD flux in the early twentieth century, the values fall to background values at the top of the record.

Dinoflagellate record

A total of 26 taxa were identified, with three dominant taxa, ie, cysts of *Pentapharsodinium dalei*, *Operculodinium centrocarpum* and *Spiniferites ramosus.* The downcore variation of dinocyst spectra is suggested to indicate the relative influence of the Irminger Current and East Icelandic Current. Transfer function reconstructions, based on a modern data set from the Northern Hemisphere (de Vernal *et al.*, 2005), show an increasing trend in

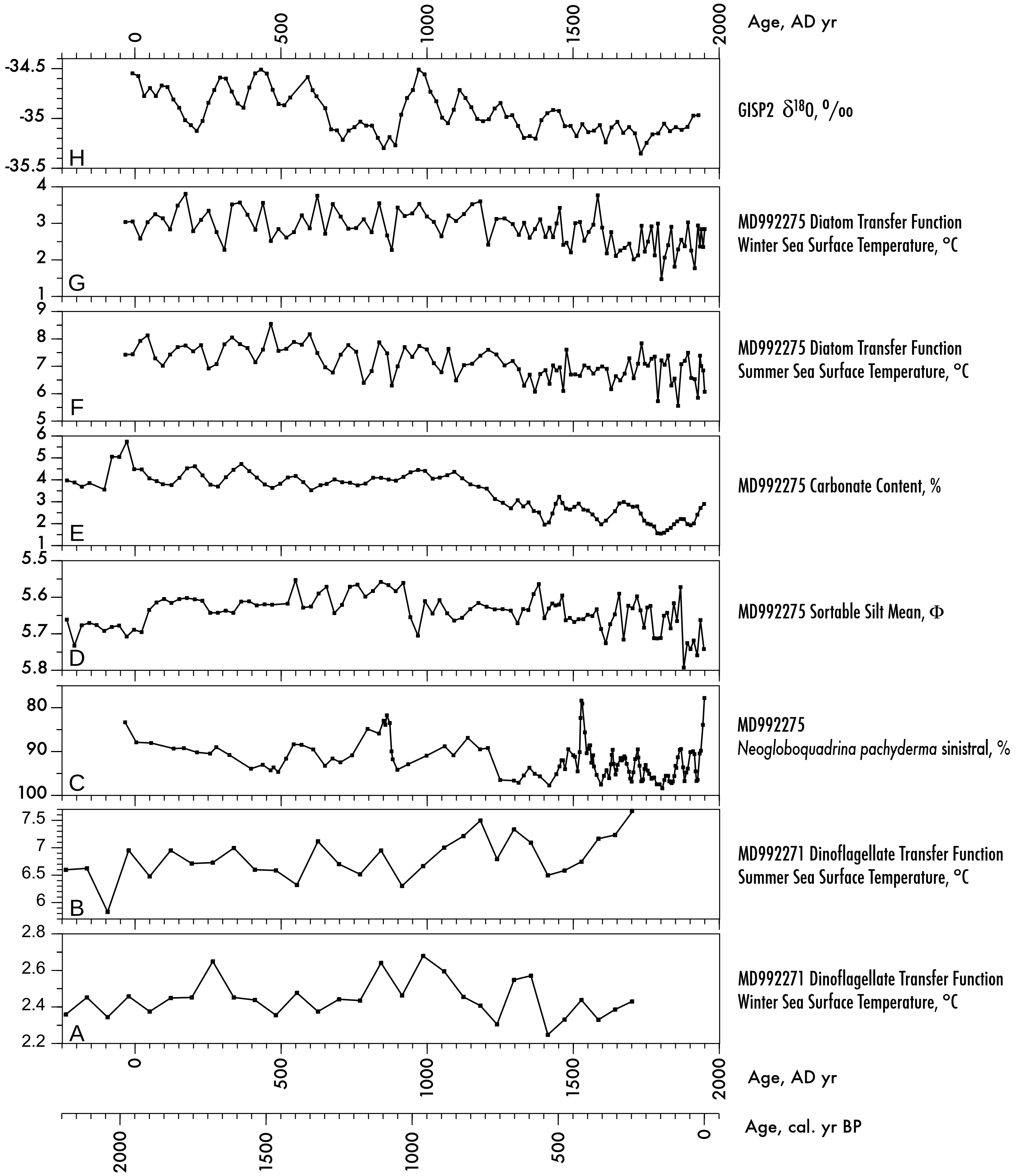

Figure 3 A record of palaeoceanographic proxies from the oceanographic Polar Front, North Iceland shelf. The Greenland ice core GISP oxygen isotope record is shown at the top. (A) Dinoflagellate cyst transfer function derived winter sea surface temperature record from core MD992271 on the North Iceland shelf. (B) Dinoflagellate cyst transfer function derived summer sea surface temperature record from core MD992271. (C) Percentages of the benthic foraminiferal species *Neogloboquadrina pachyderma* sinistral (3 pt. running mean). (D) Sortable silt (10–63 μm fraction) mean size in core MD992275 (3 pt. running mean). (E) Total carbonate content, weight percent, in core MD992275 (3 pt. running mean). (F) Summer sea surface temperature record from the North Iceland shelf based on diatom transfer function. (G) Winter sea surface temperature record from the North Iceland shelf based on diatom transfer function. (H) Greenland ice core GISP2 oxygen isotope record (50 yr smoothing). Age scales in calibrated years BP for marine records, GISP2 ice years in the Greenland ice core. Age scales are given in years BC and AD as well as in years PB (before 1950)

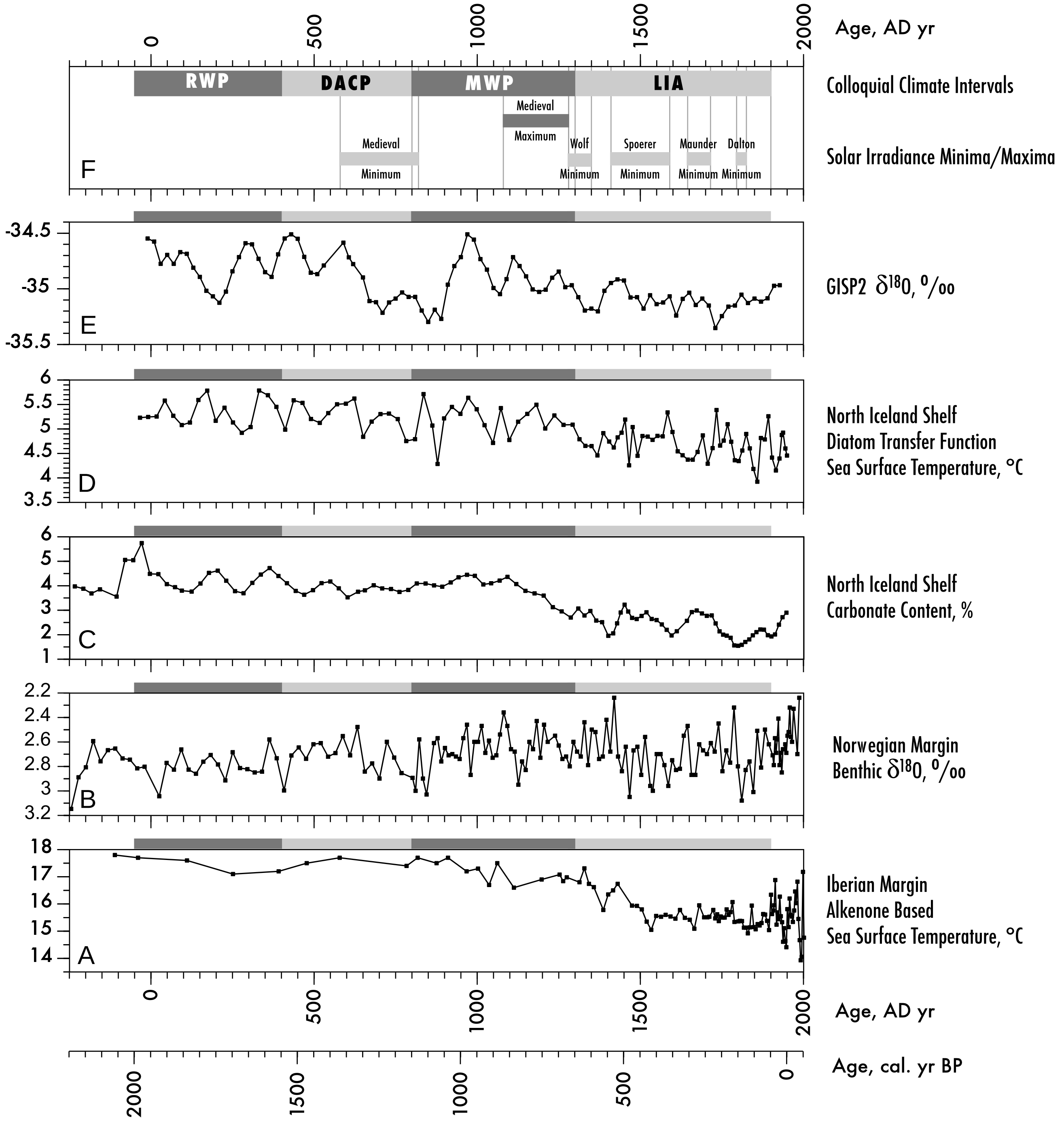

Figure 4 Selected oceanographic parameters for the last two millennia from shallow water open ocean sites in western Europe compared with a Greenland ice core record. (A) Sea surface temperature record from the Iberian margin based on alkenones. (B) Norwegian margin δ^{18}O measurements of the benthic foraminiferal species *Uvigerina mediterranea*. (C) Total carbonate content, weight percent, in core MD992275 (3 pt. running mean). (D) Mean annual sea surface temperature record from the North Iceland shelf based on diatom transfer function. (E) Greenland ice core GISP2 oxygen isotope record (50 yr smoothing filter). (F) Informal Holocene climate history terms are shown as shaded bars along the top of the panel (duplicated on the lower panels of each diagram; warm, dark; cool, light) including the Roman Warm Period (RWP, 50–400 BC), the Dark Ages Cold Period (DACP, AD 400–800), the 'Mediaeval Warm Period' (MWP, AD 800–1300) and the 'Little Ice Age' (LIA, AD 1300–1900). Solar irradiance minima and maxima are also shown on panel (F). Age scales in calibrated years BP for marine records, GISP2 ice years in the Greenland ice core. Age scales are given in years BC and AD as well as in years PB (before 1950)

summer SST whereas winter SST varies little, though with a general decrease since AD 1000 (Figure 3A, B).

Discussion

Atmospheric conditions in the northern North Atlantic region are commonly described with the North Atlantic Oscillation (NAO) winter index (Hurrell *et al.*, 2003), which is a measure of the pressure difference between the Iceland Low and the Azores High. A linkage between oceanic circulation and atmospheric processes is constituted by convective renewal of intermediate and deep waters in the Labrador Sea and the Nordic Seas, which leads to the formation and export of North Atlantic Deep Water; this plays a role in driving the global thermohaline circulation (Hurrell *et al.,* 2003). The winter convection at these sites is apparently linked to the NAO winter index on a decadal timescale (Dickson *et al.*, 1996). A linkage was clearly exemplified during salinity anomaly events during the latter half of the twentieth century. Instrumental temperature and salinity data through that time interval have been presented by Knudsen *et al.* (2004a) for a specific site off North Iceland.

These salinity anomalies propagated along the subpolar gyre of the North Atlantic during negative phases of the NAO. Strong southward air flow east of Greenland resulting from the high-pressure field strengthens the East Greenland Current and its offshoot, the East Icelandic Current, transporting freshwater from the Arctic Ocean through the Fram Strait and into the Labrador Sea and the Nordic Seas. The Arctic Water, being channelled into the southern limb of the North Atlantic subpolar gyre, cools and reduces the salinity of the North Atlantic Current. Some of this influence may then be reflected by a southward shift of the divergence of the North Atlantic Current and carried towards the Iberian margin. During intervals of preferred negative state of the NAO, cooling and freshening of the surface waters may thus be expected to influence the region as a whole.

Selected environmental parameters that are considered to be climate related for each of the four study areas (Figure 1) are shown in Figure 4. In general, the parameters reflect annual mean temperature at the sea surface. Given the latitudinal variability from site to site, the range of proxies used and the age model uncertainties, it is not expected that detailed fluctuations should be replicated in these records. However, some common longer-term trends are observed. Informal terms traditionally used in discussing the upper Holocene atmospheric part of climate history include the Roman Warm Period (RWP, 50–400 BC), the Dark Ages Cold Period (DACP, AD 400–800), the ‘Mediaeval Warm Period’ (MWP, AD 800–1300) and the ‘Little Ice Age’ (LIA, AD 1300–1900). There is a continuing debate on the global significance of these climate intervals, which are clearly not well constrained in many records, and the boundaries between them are not strictly defined anywhere (for recent reviews see eg, Soon and Baliunas, 2003; Mayewski *et al.*, 2004; Goosse *et al.*, 2005).

In many environmental settings, coastal and shallow marine records are more prone to fluctuations in climate and are therefore more likely to exhibit greater variability in climatic reconstructions than observed in purely oceanic or terrestrial reconstructions This is due to the complex interaction of marine and terrestrial processes. To the advantage of such records, minor environmental changes are more likely to be preserved in the sedimentary record given high enough sedimentation rates.

The GISP2 δ^{18}O record, reflecting atmospheric conditions in the northern North Atlantic realm, shows a relatively clear cooling trend starting during the latter half of the RWP and extending to about AD 900, covering the DACP (Figure 4). A parallel trend is evident in the marine environment, reflected by the diatom-based SST reconstruction for the North Icelandic shelf, and the trend is also present in the total carbonate content, which reflects coccolith productivity (Andrews and Giraudeau, 2003). A very similar cooling trend is seen in the planktonic δ^{18}O record from the Norwegian margin (Berstad *et al.*, 2003). A cooling trend appears to be present in the Scottish sea loch benthic δ^{18}O record from *c.* AD 250 to 600 (Figure 2D). At the same time, the Iberian margin alkenone-based SST record is relatively warm but with slight cooling towards the end of the RWP.

The MWP is observed in the GISP2 δ^{18}O record with a clear atmospheric warming beginning at about AD 900. In the ocean, the alkenone-based Iberian margin record (Figure 4) does not show any change at the start of the MWP, nor do the benthic isotope data (Figure 2A, C). However, the alkenone-based SST values begin to fluctuate at AD 1000, and a slight cooling trend is seen after about AD 900. It is important to note that the alkenone-based SST record indicates higher temperatures during the RWP than in the MWP on the Iberian margin. On the other hand, planktonic isotopes at the Iberian margin site show a period of warm conditions at the start of the MWP, at AD 800, but the values remain at about the same level as during the RWP. In the Scottish sea loch record, the cooling trend extending well into the DACP is reversed and the MWP starts relatively warm, but this is followed by a distinct cooling trend for the remainder of the available record (Figure 2D). In the Norwegian margin and North Iceland shelf records there is a clear reversal of the cooling trend of the DACP towards the start of the MWP (Figure 2E, F, G).

Common to all the marine records shown in Figure 4 is a cooling trend setting in towards or at the end of the MWP, and an interval from AD 1300 to 1900 fluctuating around a lower temperature level than before. Generally, twentieth-century sea surface temperatures are not higher than those reconstructed for the MWP nor the RWP. However, a distinct temperature rise is evident towards modern values since the end of the LIA.

The configuration of the modern oceanic circulation in the northern North Atlantic suggests that the shallow marine realm from the Iberian margin to North Iceland (Figure 1) should respond coherently to variability of the heat transport of the North Atlantic Current. However, the surface currents may also be strongly affected by atmospheric processes, which in turn are most probably coupled to solar irradiance variability or maybe to volcanic forcing (cf. Crowley, 2000; Lean, 2002, Church *et al.,* 2005). Although it has been suggested that the North Iceland shelf SST record variability covaries with solar insolation (Jiang *et al.*, 2005), no simple relationship is evident between the solar minima/maxima and the marine HOLSMEER records seen in Figure 4. However, the Wolf Minimum coincides with the cooling trend at the transition towards the LIA, being preceded by the MWP maximum.

Summary and conclusions

Oceanic variability, spanning the last 2000 years, is recorded in HOLSMEER sites from the northern North Atlantic and has been correlated with atmospheric data from the Greenland ice cores. The atmospheric and marine records exhibit some common features, especially in the second millennium AD. With the available chronologies it is not possible to correlate short-term variations on a decadal timescale, but some parallel trends appear to be present. In summarizing the results, we use the atmospheric climate interval terms such as the Roman Warm Period (RWP), The Dark Age Cold Period (DACP), the ‘Mediaeval Warm Period’ (MWP) and the ‘Little Ice Age’ (LIA) in a chronological sense (cf. Figure 4). As a reference record, the GISP2 δ^{18}O record, shows a relatively cold latter part of the RWP with warming towards the end, and then a clear cooling trend throughout the DACP extending to about AD 900 (Figure 4). The onset of the MWP is fairly clear in the GISP2 δ^{18}O record, with a clear warming beginning at AD 900 followed by a cooling trend through the LIA extending into the eighteenth century. This is followed by warming continuing into the twentieth century.

A cooling trend towards the end of the RWP (about AD 200–300) followed by a warming trend close to the transition to the DACP (at about AD 400) is apparently a common feature of both the oceanic and the atmospheric records. The DACP is a period of generally decreasing temperatures. The Iberian margin temperature record (Figure 4) does not show any change at the start of the MWP, nor do the benthic isotope data (Figure 2). However, the alkenone-based SST values begin to fluctuate at AD 1000, and reduced upwelling and warm conditions are indicated by stable isotopes at the start of the MWP at AD 800. On the west coast of Scotland, the cooling trend is reversed and the MWP starts relatively warm, but this is followed by a distinct cooling trend for the remainder of the record. In the Norwegian margin and North Iceland shelf records, there is a clear reversal of the cooling trend of the DACP towards the start of the MWP.

All the records show an interval from AD 1300 to 1900 (coiniciding with the reported climatic event, the LIA) in which the climate fluctuates around the lowest temperature level seen within the past two millenia. A reversal of the cooling within the LIA is quite clear but not synchronous in many of the records, and it appears to be more distinct and to set in earlier in the southern sites. The twentieth century does not appear to be exceptional in terms of palaeoceanographic proxies for the last 2000 years. However, most of the records do indicate warming coastal and shelf waters during the last 200 years.

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