The Holocene

http://hol.sagepub.com

High-resolution alkenone sea surface temperature variability on the North Icelandic Shelf: implications for Nordic Seas palaeoclimatic development during the Holocene

James A.P. Bendle and Antoni Rosell-Melé

The Holocene 2007; 17; 9
DOI: 10.1177/0959683607073269

High-resolution alkenone sea surface temperature variability on the North Icelandic Shelf: implications for Nordic Seas palaeoclimatic development during the Holocene

James A.P. Bendle[1]* and Antoni Rosell-Melé[2]

([1]Department of Geography, University of Durham, Durham DH1 3LE, UK; [2]CREA and Institut de Ciència i Tecnologia Ambientals, Universitat Autònona de Barcelona, 08193 Bellaterra, Catalonia)

Received 27 June 2006; revised manuscript accepted 23 August 2006

A HOLOCENE RESEARCH PAPER

Abstract: The palaeoceanography of the northern Icelandic Shelf for the Holocene period was reconstructed from alkenone indices measured in core JR51-GC35. This contains a continuous record of Holocene sedimentation spanning 0–10.2 cal. kyr BP with a resolution of $\sim$20 yr/cm. We have identified a general Holocene cooling trend that has superimposed millennial-scale oscillations of $>2°$C. Their timing is in close agreement with the timing of glacier advances in northern Iceland. For the later half of the Holocene, the alkenone-sea surface temperature (SST) record from JR51-GC35 correlates with proxy data for the strength of NADW formation recorded in cores south of Iceland. This is interpreted as evidence of a close connection existing between north Icelandic sea surface temperatures and the North Atlantic meridonal overturning circulation. The timing of the millennial-scale SST variability in our core off North Iceland is found to be out of phase, or anti-phased, with the SST variability of a record in the eastern Nordic Seas (MD952011). This suggests that the evolution of Holocene climate in the Nordic Seas was more complex than previously proposed; and it is likely to be caused by differential responses of the Irminger and Norwegian Currents and modulated by changes in atmospheric circulation analogous to the North Atlantic Oscillation.

Key words: Alkenones, UK37, SST, palaeoceanography, Iceland, North Atlantic, Nordic Seas, millennial, anti-phasing, high-resolution sediment core, North Atlantic Oscillation, NAO, MOC, marine–terrestrial correlations, Irminger Current, Norwegian Current, Holocene.

Introduction

The Holocene

Aside from a few historically documented anomalies, eg, the 'Little Ice Age' and the 'Mediaeval Warm Period', the Holocene was regarded, until fairly recently, as a period of climatic stability. However, palaeoclimatic and palaeoceanographic research over the last decade has suggested that Holocene climate – on a global and regional scale – has experienced higher instabilities than previously thought (Oppo, 1997). Abrupt millennial-scale Holocene climate changes are recognized in various proxy archives globally (see review by Mayewski *et al*., 2004). Significant variability in proxies for parameters such as temperature, ice rafting, deep water flow strength, aridity and prevailing winds can be recognized in the sediments of the North Atlantic Ocean (eg, Andrews *et al*., 1997; Bond *et al*., 1997, 1999; Bianchi and McCave, 1999; deMenocal *et al*., 2000b; Calvo *et al*., 2002; Oppo *et al*., 2003), ice cores from Greenland (O'Brien *et al*., 1995; Mayewski *et al*., 1997) and glacial moraine complexes in Iceland (eg, Stötter *et al*., 1999; Kirkbride and Dugmore, 2001; Mackintosh *et al*., 2002).

Declining Northern Hemisphere summer insolation during the Holocene (Berger, 1978) appears to have had a strong control on low-frequency Holocene climate development in the North Atlantic region (Bradley, 1990; Koç and Jansen, 1992, 1994; Andrews *et al*., 1997; Calvo *et al*., 2002; Andersen *et al*., 2004a,b). This may have induced changes in persistent states of

*Author for correspondence (e-mail: james.bendle@bristol.ac.uk)

  10.1177/0959683607073269

the atmospheric pressure system over the region (Harrison *et al*., 1992; Keigwin and Pickart, 1999; deMenocal *et al*., 2000b). Based on historical analogies from the period covered by instrumental data and general circulation model (GCM) experiments, Rimbu *et al*. (2003) have attributed regional variation in Holocene sea surface temperature trends to a long-term continuous weakening of a Northern Hemisphere atmospheric circulation pattern, similar in concept to that of the Arctic/North Atlantic Oscillation (NAO). As a consequence, temperature trends in northern Europe have been negative and positive in the eastern Mediterranean/Middle East. Sea surface conditions in the North Atlantic during the Holocene have also been linked to the migration of the Atlantic Intertropical Convergence Zone (ITCZ) (Haug *et al*., 2001), thus providing evidence for global teleconnections among regional Holocene climates (Haug *et al*., 2001).

Many elements of high-frequency (millennial to decadal) Holocene climatic change, are not fully understood. A pervasive 1500-yr periodicity throughout the Holocene has been proposed as the source of cold spells documented in different proxy records (Bond *et al*., 1997; Mayewski *et al*., 1997; Campbell *et al*., 1998; Bianchi and McCave, 1999). Some workers have argued that this variability has the same general characteristics as the millennial-scale climate fluctuations of the last glacial period, only with a subdued amplitude (Bond *et al*., 1997) and that the cycles may be forced by changes in solar activity (Bond *et al*., 2001). Other studies have suggested that there is a more prominent 900–1000- and 550-yr Holocene periodicity, both in some ice core and marine records (Grootes *et al*., 1993; Stuiver and Braziunas, 1993; Stuiver *et al*., 1995; Chapman and Shackleton, 2000). These shorter periodicities, in particular the 550-yr period, have also been linked with changes in the formation of deep-water masses and changes in solar activity (residual $\Delta^{14}C$) (Chapman and Shackleton, 2000).

Quantifying the variability of the Holocene climate is required to assess the natural versus human contribution to contemporary climatic change (eg, for the development of predictive climate models) and for understanding the role of the environment in shaping the rapid development of human societies, from the first Neolithic farmers (and their potential impact on atmospheric methane levels: Ruddiman and Thomson, 2001; eg, Ruddiman, 2003), through to industrialization. The human significance of Holocene climatic changes is emphasized by the coincidence of some inferred climatic changes with collapses of historical civilizations such as the Maya in central America (deMenocal *et al*., 2000a; deMenocal, 2001; Hodell *et al*., 2001; Haug *et al*., 2003), the Akkadian in Mesopotamia (Cullen *et al*., 2000) and the Norse in Greenland (Buckland *et al*., 1996).

Alkenone proxies in the Nordic Seas

The long-chain alkenones (aliphatic ketones with 37–40 carbons and 2–4 double bonds or unsaturations) are a suite of compounds that is almost ubiquitous in the sediments of the world's oceans. Their biological source is unicellular algae of the class Haptophyceae, the most common extant source being the abundant and cosmopolitan coccolithophorid *Emiliania huxleyi* (Volkman *et al*., 1980a,b). A close linkage between the relative abundance of the $C_{37:2}$ and $C_{37:3}$ alkenones (ie, those with 37 carbons and 2, 3 unsaturations) and the water temperature in which the algae grow has been confirmed by culture, surficial sediment and water column particulate organic matter (POM) studies (eg, Prahl and Wakeham, 1987; Prahl *et al*., 1988, 2000; Conte *et al*., 1992, 1994, 2001, 2006; Brassell, 1993; Sikes and Volkman, 1993; Conte and Eglinton, 1993; Rosell-Melé *et al*., 1995a; Sikes *et al*., 1997; Sonzogni *et al*., 1997; Ternois *et al*., 1997; Muller *et al*., 1998). Palaeoceanographers generally assume that the sedimentary alkenone signal reflects the annually averaged sea surface temperature (SST). This is based on the empirical relationship derived from alkenone distributions in large core-top data sets with ocean atlas surface (0–10 m) SSTs. It also provides the benefit of temporal and spatial averaging of all the factors that may influence alkenone systematics as well (see review by Herbert, 2001, and references therein). Alkenone ratios – once set biogeochemically by the algae – are not significantly altered by sedimentary degradation processes (eg, Prahl and Muehlhausen, 1989; Freeman and Wakeham, 1991; Conte *et al*., 1992; Madureira *et al*., 1995; Teece *et al*., 1998; Bendle *et al*., 2005).

The measure of the C_{37} alkenone unsaturation ratio was initially defined as (Brassell *et al*., 1986):

$$U_{37}^{k} = \frac{C_{37:2} - C_{37:4}}{C_{37:2} + C_{37:3} + C_{37:4}} \qquad (1)$$

The $C_{37:4}$ alkenone is often absent or not detectable in middle to low latitudes, and the ratio was simplified to (Prahl and Wakeham, 1987):

$$U_{37}^{k'} = \frac{C_{37:2}}{C_{37:2} + C_{37:3}} \qquad (2)$$

For the Nordic Seas it has been suggested that, based on extensive core-top data sets, the original U_{37}^{K} index gives more accurate predictions of SST down to 6°C (Rosell-Melé *et al*., 1995b; Rosell-Melé, 1998; Bendle and Rosell-Melé, 2004). In the Nordic Seas below water temperatures of $\sim 6°C$ there is increasing error and, coincidentally, the $C_{37:4}$ alkenone – rare in mid to low latitudes – becomes increasingly abundant (> 5%). Recent work has examined the geographical dependence of the alkenone–SST relationship in the Nordic Seas and suggests that the Icelandic Shelf (as well as at least the Norwegian Basin and Lofoten Basin) should yield reliable alkenone reconstructions of SST from recent (ie, Holocene) sediments (Bendle and Rosell-Melé, 2004). Furthermore, it appears that when the relative abundance of the $C_{37:4}$ alkenone ($\%C_{37:4}$) is below 5% in Nordic Seas sediments alkenone-SSTs are reliable (Rosell-Melé, 1998). At values of $\%C_{37:4}$ above 5% alkenone-SSTs have increasing errors. The $\%C_{37:4}$ parameter is also a marker for the influence of low salinity polar waters ($> \%C_{37:4} => $ influence of polar water types) (Bendle *et al*., 2005).

Physical setting

Core JR51GC-35 is located on the north Icelandic continental shelf in the Nordic Seas (Figure 1). This is a region of strong east–west hydrographic gradients, characterized by seasonal and spatial variations in the physical properties of the surface waters (temperature (SST) and salinity (SSS)), sea-ice distribution and deep water formation. Iceland is located in a position that is sensitive to interactions of the Atlantic source waters, advected by the Irminger (IC) and North Icelandic Irminger Currents (NIIC), and opposing cold Arctic and Polar waters advected by the East Icelandic (EIC) and East Greenland Currents (EGC) (Steffenson, 1962; Malmberg, 1985; Hopkins, 1991; Hansen and Østerhus, 2000) (Figure 1).

The site studied in this paper is today influenced by the warm IC and NIIC, and cooler EIC. A hydrographic transect of the shelf (see Figure 1C) made in July 1997 (Andrews *et al*.,

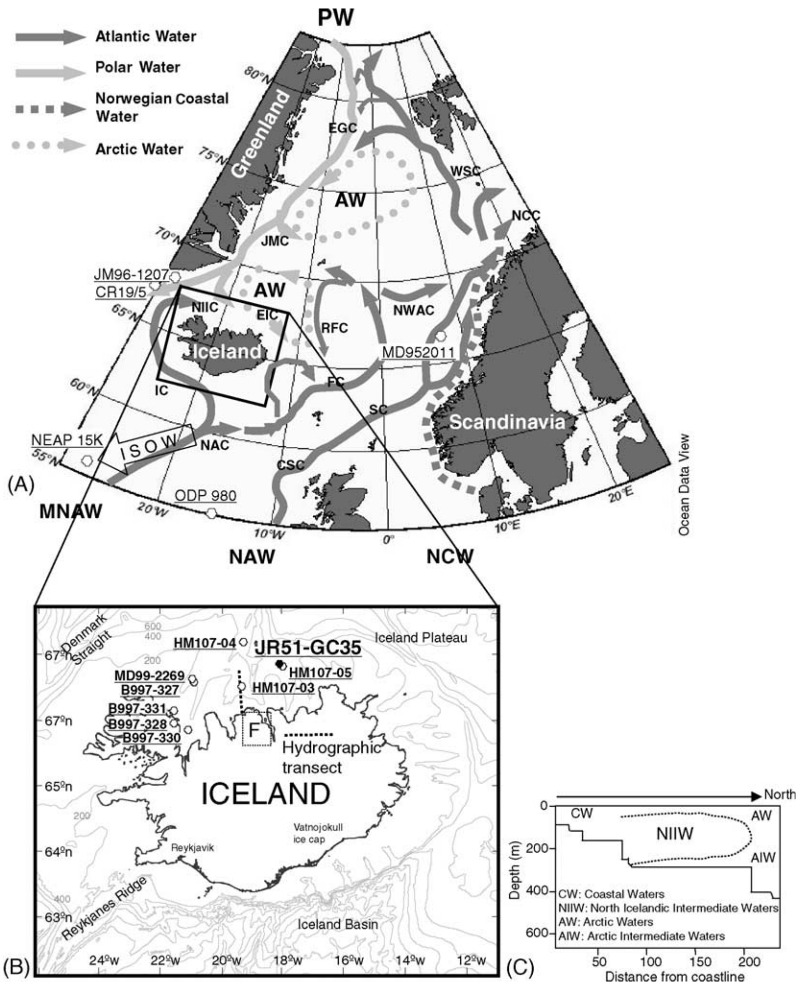

Figure 1 (A) Map of Nordic Seas illustrating core sites from some recent publications discussed in the text, and main features of the surface to near-surface circulation (grey solid and dashed arrows) and the path of the near bottom Iceland–Scotland overflow water (large arrow). (B) Location of JR51-GC35, regional bathymetry, and F marks the Trollaskagi fieldwork location of Guðmundsson (1997) for Holocene reconstructions of Neoglacial glacier advances – referred to in text and Figure 4. (C) Hydrographic transect of water masses across the North Icelandic shelf as inferred from CTD measurements in July 1997 (adapted from Andrews *et al.*, 2003). Abbreviations are as follows. Currents: EGC, East Greenland Current; EIC, East Icelandic Current; IC, Irminger Current; NAC, North Atlantic Current; NIIC, North Icelandic Irminger Current; RFC, Recirculated Faroe Current; SC, Shetland Current; WSC, West Spitsbergen Current; JMC, Jan Mayen Current; CW, Coastal Water. Water masses: AW, Arctic Water; MNAW, Modified North Atlantic Water; NAW, North Atlantic Water; PW, Polar Water; AIW, Arctic Intermediate Water. Sources: Hansen and Østerhus (2000); Johannessen (1986); Swift (1986)

2003) revealed that, starting from the mid-shelf area, Atlantic Water carried in the NIIC is submerged beneath colder, fresher Arctic Water carried by the EIC (Figure 1). The submerged remnant of the NIIC can be termed the Irminger Intermediate Water (IIW). Beneath the IIW, the temperatures of the AIW waters (Swift, 1986) decline with depth from 3.5°C to lower than 0°C >400 m depth. Lateral and vertical mixing as a result of the parallel flow of the NIIC and EIC and winter cooling leads to the formation of an intermediate-depth water mass (North Icelandic Winter Water, NIWW) in the Iceland sea, which disintegrates by spring or summer (Steffenson, 1962; Swift and Aagaard, 1981). This water mass contributes to the formation of deep waters in the Nordic seas, hence a mechanism exists whereby oceanographic and climatic changes on the Icelandic Shelf are linked ultimately to the meridonal overturning circulation (MOC). Changes in the MOC have been associated with dramatic modifications of northern European climate (eg, Dickson *et al.*, 1988; Sarnthein and Altenbach, 1995; Overpeck *et al.*, 1997).

The contemporary north continental shelf of Iceland is subject to extreme variations in hydrographic conditions that can lead to changes of 5°C averaged through the entire water column (Olafsson, 1999). The variability associated with Iceland's location proximal to the Arctic Front was demonstrated in the late 1960s by the Great Salinity Anomaly (GSA), triggered by an excursion of fresh water (sea ice) from the Arctic Ocean (Dickson *et al.*, 1988). This resulted in sharp decreases in both temperature and salinity at hydrographic stations on the North Icelandic Shelf, (Olafsson, 1999). The Icelandic continental shelf has many troughs characterized by high sedimentation rates of up to 2 m/cal. kyr (Andrews and Giraudeau, 2003). Given these attributes, the area has high potential for the identification of centennial- to millennial-scale climatic oscillations that occurred in the Holocene. This has been demonstrated by recent records from the Icelandic Shelf of variations in sediment physical properties (Andrews *et al.*, 2001b, 2002b, 2003; Eiríksson *et al.*, 2004), coccolithophore assemblages and isotopic data (Andrews and Giraudeau, 2003), benthic foraminiferal (Eiríksson *et al.*, 2000a) and diatom (Jiang *et al.*, 2002) assemblages. However, no alkenone proxy evidence (ie, $U^{K'}_{37}$ or U^{K}_{37}) of palaeo-SST or other biomarker evidence has yet been reported. Alkenone biomarkers should be particularly apposite for investigating palaeoceanographic changes on the North Icelandic Shelf. First, the alkenone indices may be used to reconstruct palaeo-SST, as long as values of $\%C_{37:4}$ are below the threshold of 5%

(Rosell-Melé, 1998). Second, prolonged influence by Arctic waters or a significant reduction in shelf SSSs by glacial or fluvial-runoff waters should be detected by fluctuations in the $\%C_{37:4}$ index to values above 5% (Rosell-Melé, 1998; Bendle *et al.*, 2005).

Materials and methods

Core JR51-GC35 was obtained on the 2000 Arctic Ice and Environmental Variability (ARCICE) cruise and was opened, described and subsampled on-board the RRS *James Clark Ross* (details are given in Table 1).

Biomarker analysis

All organic geochemical subsamples were kept frozen at $-20°C$ between subsampling and analytical work-up. Samples were freeze dried and ground, an internal standard added and extracted with dichloromethane/methanol at 70°C for 5 min using a MARS 5 microwave extractor (see Kornilova and Rosell-Melé, 2003, for details). The solvent extract was concentrated to dryness with a centrifugal evaporator or with nitrogen blow-down, and dried with Na_2SO_4. Sediment extracts were fractionated by High Performance Liquid Chromatography (HPLC). This was performed using a system consisting of a Thermo Hypersil column (50 mm × 4.6 mm) packed with Lichospher Si100 5 µm silica, and a Thermo Hypersil guard column. Fractions were collected using a Foxy Jr automatic collector. The solvent program was adapted from Schulz *et al.* (2000). Four fractions were collected in test tubes by eluting at 1 ml/min with: 1.4 ml hexane (aliphatic and cyclic alkanes), 3.5 ml hexane/dichloromethane (aliphatic ketones), 2.25 ml dichloromethane (cyclic ketones), 2.25 ml acetone (sterols, alcohols and other polar components). The first two fractions were combined, dried under nitrogen and derivatized using bis-trimethylsilyl-trifluoroacetamide (BSTFA) prior to gas chromatographic analysis.

In high-latitude environments, alkenone sedimentary concentrations can be very low, and the alkenone signal may be further diluted because of the greater relative inputs of clastic material from continental shelf environments. Gas chromatography-chemical ionisation-mass spectrometry (GC-CI-MS) has a greater sensitivity for the analysis of alkenones than using a flame ionization detector (Rosell-Melé *et al.*, 1995a). The higher selectivity of the former also allows a greater confidence in measuring alkenone within-class distributions, particularly $\%C_{37:4}$ (Bendle, 2003), and was the preferred instrumental method to quantify the alkenone indices in this study. GC-CI-MS was performed using a Varian 3400 gas chromatograph (GC) directly coupled to a Finnigan MAT TSQ 700 triple stage quadrupole mass spectrometer, using ammonia chemical ionization (Rosell-Melé *et al.*, 1995b). The GC was fitted with a temperature programmable injector operated in 'high performance' non-vaporizing mode, held at 80°C during injection then rapidly heated from 80 to 300°C at 200°C/min. Separation of the analytes was achieved using a 50 m, 0.32 mm i.d. fused silica column, with 0.12 µm CPSIL5-CB film thickness (Chrompack). The oven temperature programme was: 200–300°C at 6°C/min with no initial hold time and a final isothermal period of 10 min. Hydrogen was employed as a carrier gas with a head pressure of 8 psi. Operating conditions for the mass spectrometer were optimized for sensitivity with respect to the C_{37} methyl alkenones. Chemical ionization was achieved using high purity ammonia (BOC micrographic grade). Specific ions, corresponding to the $[M+NH_4]^+$ species of the analytes were monitored.

Procedural and analytical reproducibility was determined for the analyses with a homogeneous 'sediment standard' (analysed once for every ten samples to be validated). The overall average reproducibility by GC-CI-MS was 0.02 to measure U^K_{37}, giving an alkenone-SST error (2σ) of $\pm 0.63°C$ using the Rosell-Melé *et al.* (1995b) (annual) calibration. For $U^{K'}_{37}$ the reproducibility was 0.017, giving an alkenone-SST error (2σ) of $\pm 0.51°C$ using the Prahl and Wakeham (1987) calibration. For $\%C_{37:4}$ the reproducibility (2σ) was ± 0.79.

Chronology

AMS ^{14}C dating of either molluscs or benthic foraminifera was used to establish the chronology for JR51-GC35 (AMS ^{14}C sample details are given in Table 2). The lithostratigraphic log (with dated horizons indicated) and age–depth diagram is illustrated in Figure 2. Foraminifera are the most commonly used source of carbon for AMS ^{14}C dating in Atlantic marine cores. Foraminifera were present in most subsamples, however the total weight retrieved by dry picking often fell below the amount recommended (> 10 mg) by the dating laboratory for a precise AMS ^{14}C date. Therefore, as an alternative to foraminifera, mollusca (bivalves, gastropods) were utilized where possible (individually or in combination), to obtain sufficient weight of carbon for dating. Molluscs were identified by Dr H.A. Ten Hove and Dr. R. Moolenbeek at the Zoological museum, University of Amsterdam. At the NERC radiocarbon facility (East Kilbride, UK) all samples were hydrolysed to CO_2 with 85% ortho-phosphoric acid at 25°C. The gas was converted to graphite by FE/Zn reduction. Samples were sent to the NSF-University of Arizona AMS facility for analysis. We apply the modern reservoir age (ΔR) value of 400 yr (Andersen *et al.*, 1989) as a correction for all AMS ^{14}C dates. Andrews *et al.* (2002a) constrained (by AMS ^{14}C dates) the Saksunarvatn (10 180 ± 60 cal. yr BP) tephra layer in a number of marine cores from the NW Icelandic Shelf, and previous workers have applied a 400-yr correction to north Icelandic Shelf, marine core AMS ^{14}C dates as old as 14 100 ± 140 ^{14}C yr BP (Eiríksson *et al.*, 2000a). However, we note that recent work, correlating ^{14}C dated tephras in North Icelandic Shelf marine sediment cores and terrestrial reference sections, demonstrates significant temporal deviations of ΔR over the last 4500 years, by up to 450 yr more than the standard model ocean (Larsen *et al.*, 2002; Eiríksson *et al.*, 2004). This highlights that North Icelandic Shelf marine sediment core age models using the standard 400 yr ΔR correction may err on the side of being several hundred ^{14}C yr too old, with a high degree of temporal variation. The corrected AMS ^{14}C dates were converted to

Table 1 Collection details for JR51-GC35

Core name	Cruise (platform)	Coring system	Date obtained	Coordinates	Water depth	Sample thickness	Sampling frequency	Sample dry weight
JR51-GC35	JR51 (RRS *James Clark Ross*)	Gravity	26/8/00	66°59′96N 17°57′66W	420 m	1 cm	4 cm	~2 g

Table 2 Radiocarbon dates in cores JR51-GC35 from the North Icelandic Shelf

Core	Depth below surface (cm)	Laboratory code	Material and weight (mg)	^{14}C age (yr BP $\pm 1\sigma$)	Reservoir corrected age (yr BP $\pm 1\sigma$)	Calibrated age (yr BP $\pm 2\sigma$)	$\delta^{13}C_{PDB}$‰ ($\pm$0.1)
JR51-GC35	0–1	AA-46847	Mixed benthic forams (9)	473±36	73±36	70 (217–0)	–1.5 *
	54–55	AA-53112	Unknown bivalve mollusc fragments (11.3)	1417±65	1017±65	948 (1100–832)	–7.9
	112–113	AA-53113	Gastropod mollusc fragment *Buccinid?* (and mixed forams) (15.2)	2621±58	2221±58	2310 (2424–2146)	1.4
	168	AA-53114	Scaphopod mollusc *Dentalium entails* (30.2)	3706±59	3306±59	3620 (3783–3462)	0.7
	214–215	AA-53115	Mixed benthic forams (9.2)	4612±70	4212±70	4826 (4980–4634)	–1.2
	276–277	AA-53116	Bivalve molluscs *Thyasira* cf *sarsi* (11.2)	5541±44	5141±44	5910 (5997–5852)	–5.1
	334	AA-53117	Gastropod mollusc *Opisthobranch* fragments (35.8)	6537±45	6137±45	7021 (7172–6918)	–0.9
	384	AA-53118	Scaphopod mollusc *Dentalium entails* (35)	8286±50	7886±50	8828 (8946–8628)	0.2
	420–421.5	AA-53119	Mixed benthic forams (9.9)	9041±51	8641±51	9700 (9842–9156)	–1.8
	449–451	AA-46848	Mixed benthic forams (10)	9403±58	9003±58	10128 (10555–9810)	–2.2

*Estimated $\delta^{13}C$.

calendar ages using the CALIB 5.0 program (Stuiver and Reimer, 1993).

Age models and stratigraphy

JR51-GC35 consisted of one massive sediment unit of consistent colour, occasionally cut by thin horizons of coarser material, probably tephra layers or small-scale mass movements, such as contourites (Dr Colm Ó Cofaigh, personal communication, 2000) (see Figure 2). Physical properties, such as wet bulk density, showed little deviation down-core (see Figure 2). In the top part of the core (0–54 cm) the age–depth relationship is characterized by a sedimentation rate of 62 cm/cal. kyr, below this (54–451 cm), the sedimentation rate is 43 cm/cal. kyr and the age–depth relationship is remarkably linear (Figure 2). Thus, we use two linear regressions to derive the age-model (0–54.5 cm = (depth + 3.8)/0.061; > 54.5 cm = (depth – 15.71)/0.043). The core covers a portion of the Holocene from 0–10.1 cal. kyr BP. The sedimentation rates are sufficiently high so that we expect no significant attenuation of centennial–millennial scale data by bioturbation (Anderson, 2001; Bard, 2001). This, in addition to the consistent spacing of dated horizons, suggests that JR51-GC35 is suitable for the analysis of centennial–millennial scale variability in the Holocene.

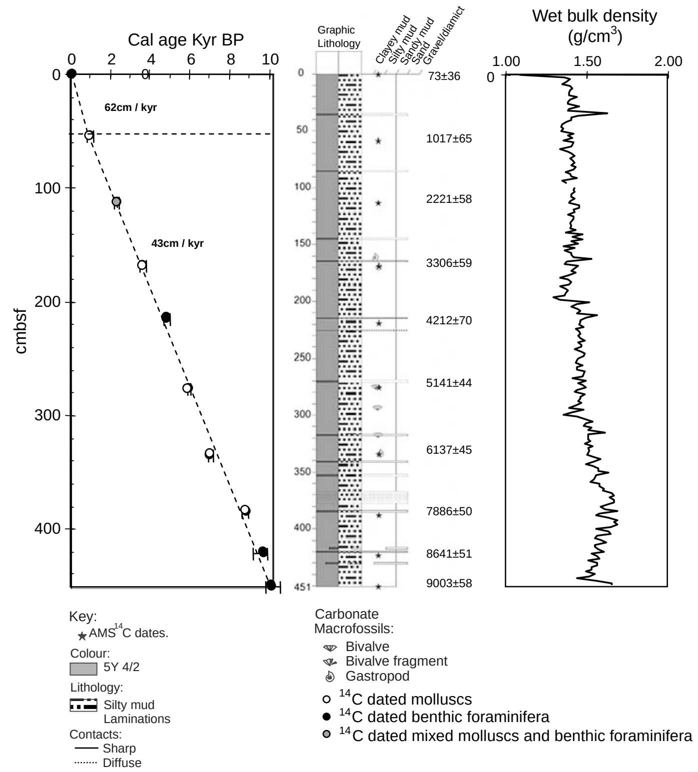

Figure 2 Calibrated radiocarbon dates plotted against depth, lithofacies log and selected wet bulk density in core JR51-GC35. Dates are fitted to two linear regressions (see text and Table 2)

Results

Alkenone stratigraphy

Alkenone concentrations were above the detection limits in 83% of the samples (97 of 116). There were 19 samples with alkenone concentrations too low for quantification, these were dispersed down core, except for three contiguous samples between 64 and 80 cm below the sediment surface (cmbsf) (1131–1505 cal. yr BP). Data for U^K_{37}, $U^{K\prime}_{37}$ and $\%C_{37:4}$ are plotted versus age in Figure 3 (for U^K_{37} and $U^{K\prime}_{37}$ unsmoothed data are shown with a superimposed three-point running average that highlights the millennial-scale events). Values of $\%C_{37:4}$, with the exception of one sample, are consistently below the 5% threshold (Rosell-Melé, 1998; Rosell-Melé and Comes, 1999; Bendle and Rosell-Melé, 2004), suggesting that, from the very start of the Holocene, there was persistent dominance of Atlantic source waters on the North Icelandic Shelf (at least during alkenone production seasons). The highest $\%C_{37:4}$ value (10%), in the Holocene, occurs at 8.9 cal. kyr BP. All other values (0–10.2 cal. kyr BP) recorded remain low (> 5%), therefore suggesting that the relationship of U^K_{37} to SST is consistently within the linear range (Rosell-Melé, 1998; Rosell-Melé and Comes, 1999; Bendle and Rosell-Melé, 2004). In Figure 3 U^K_{37} is converted to SST using the Rosell-Melé *et al*. (1995b) annual SST calibration that is constructed from an extensive data set of NE Atlantic and Nordic Seas core-tops. $U^{K\prime}_{37}$ is converted using the widely applied Muller *et al*. (1998) global core-top calibration. Except for the sample at 8.9 cal. kyr BP the U^K_{37} and $U^{K\prime}_{37}$ indices describe the same trend, but the Muller *et al*. (1998) calibration produces $U^{K\prime}_{37}$ – SSTs that are ~3°C warmer. For simplicity, in the remainder of this paper we discuss the U^K_{37}-SST data from the Rosell-Melé *et al*. (1995b) calibration. The mean temperature for the Holocene period is 7.7°C (s.d. 1.6°C), with extreme values recorded in individual samples of 12°C and 2°C. The SST record in JR51-GC35 features high-frequency centennial to millennial oscillations of a large amplitude (for an interglacial), typically between 1 and 3°C, superimposed on the overall cooling trend. The most prominent SST minima occur at < 0.2, 3, 4.9, 6.2, 8.9 cal. kyr BP (Figure 3).

Early Holocene glacial aftermath and thermal optimum (10 000–7400 cal. yr BP)

The period between 10 and 7.4 cal. kyr BP on the North Icelandic Shelf shows highly variable but in general ameliorated SSTs. During the early Holocene between 10 and 9 cal. kyr BP consistently high temperatures of ~10°C were recorded in JR51-GC35 (Figure 3). The early warm period was followed by a short cold episode between 9 and 8.7 cal. kyr BP, which saw the coldest temperature of 2°C (Figure 3). Furthermore, a coeval increase in the $\%C_{37:4}$ value, which jumps to 10%, is highly suggestive of a local increase in the influence of polar waters at the site (Bendle *et al*., 2005). U^K_{37}-SST temperatures warmed to 9°C by 8.5 cal. kyr BP and were relatively high (~8°C) to 7.3 cal. kyr BP.

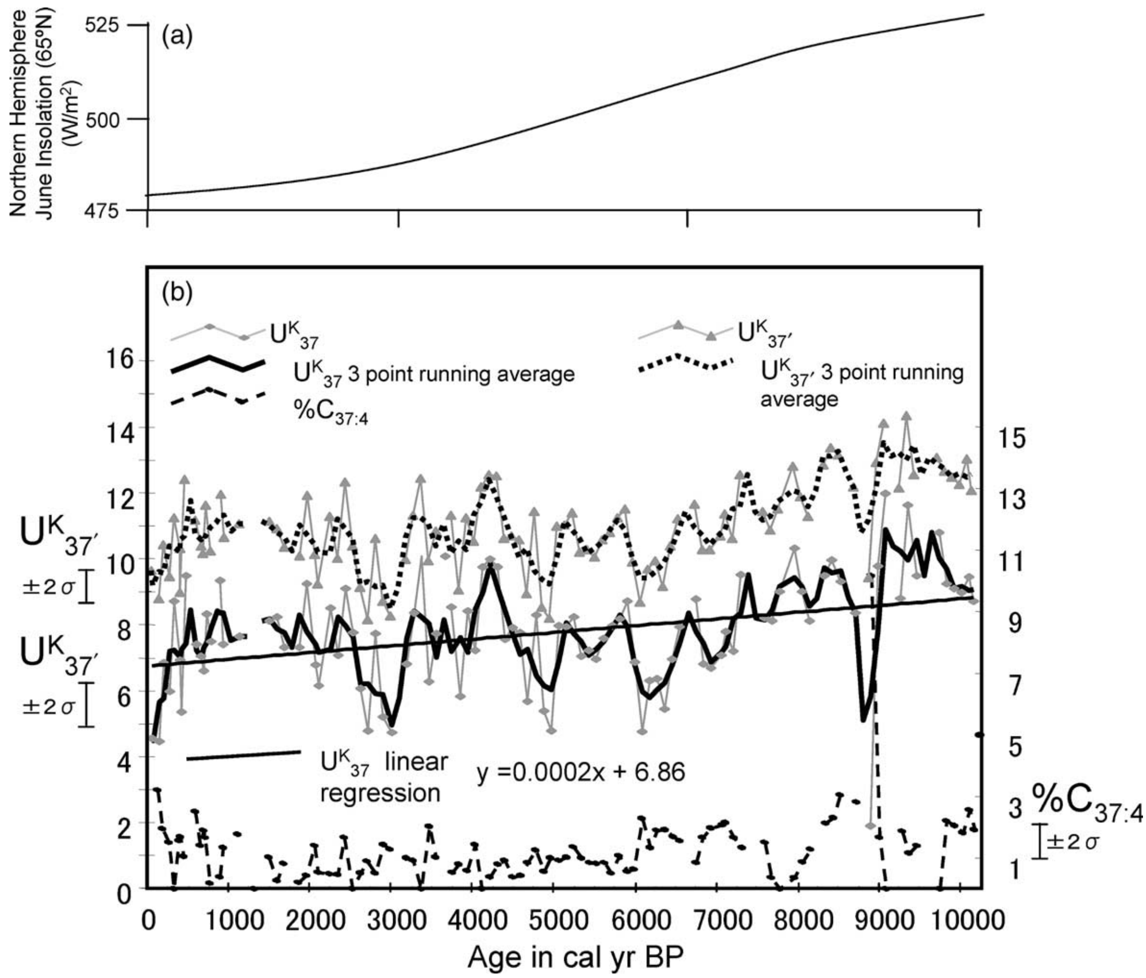

Figure 3 (a) Northern Hemisphere insolation (Berger, 1978) and (b) U^K_{37} and $U^{K\prime}_{37}$ estimated SSTs (using Rosell-Melé *et al*., 1995b and Muller *et al*., 1998 calibrations for U^K_{37} and $U^{K\prime}_{37}$, respectively) and $\%C_{37:4}$ plotted against calendar age for JR51-GC35. For U^K_{37} and $U^{K\prime}_{37}$ unsmoothed data are shown with a superimposed three-point running average which highlights the important millennial-scale events

Mid Holocene (7400–3200 cal. yr BP)

The U^K_{37}-SST record decreases from 9°C at 7.3 cal. kyr BP to 7°C at 7 cal. kyr BP, ameliorates to 8°C by 6.6 cal. kyr BP before decreasing into a major cooling of <6°C at 6.2 cal. kyr BP. The overall temperature drop from 7.4 to 6.2 cal. kyr BP is ~ 4°C. The SSTs recover to a warmer 8.3°C by 5.8 cal. kyr BP and remain relatively warm and stable (~ 7–8°C) until 5.1 cal. kyr BP. Following this there is another major mid-Holocene cooling during which U^K_{37}-SST dropped to 6°C by 5 cal. kyr BP. U^K_{37}-SSTs warm dramatically to 9.8°C at 4.2 cal. kyr BP, a warming of ~ 4°C – the same amplitude, but more rapid, than the cooling from 7.3 to 6.2 cal. kyr BP. U^K_{37}-SSTs then decrease to 7°C by 3.9 cal. kyr BP and are relatively mild (~ 7–8°C) until 3.2 cal. kyr BP.

Late Holocene (3200–80 cal. yr BP)

At 3.2 cal. kyr BP U^K_{37}-SSTs drop from <8°C to <5°C by 3 cal. kyr BP. The U^K_{37}-SSTs remain low (<6°C) until 2.6 cal. kyr BP and then ameliorate to 7.6°C by 2.5 cal. kyr BP. Then follows the most stable part of the Holocene from 2.5 to 0.3 cal. kyr BP where U^K_{37}-SSTs are generally between 7.3 and 8.3°C. In the youngest part of the record from 300 to 80 yr BP temperatures drop from 7 to 4.5°C.

Discussion

Holocene low-frequency trend

The U^K_{37}-SST record in JR51-GC35 contains a sustained cooling trend through the Holocene of -2.1°C (8.8 to 6.7°C, s.d. 1.6°C) from 10 200 to 80 cal. kyr BP (Figure 3). This overall trend is in step with the decreasing insolation (45 W/m^2 at 65°N) in the Northern Hemisphere (Berger, 1978) (Figure 3a), and supports the concept of a strong orbital influence on the climate evolution of the Holocene in the Nordic seas (Koç and Jansen, 1992, 1994; Andrews *et al.*, 1997; Andersen *et al.*, 2004b;). The data presented here are relevent in the context of recent work that has compared Holocene alkenone-SST trends in a number of cores from sites in the North Atlantic, Mediterranean Sea and northern Red Sea (Rimbu *et al.*, 2003) and Pacific (Kim *et al.*, 2004). This paper reports the first high-resolution Holocene U^K_{37}-SST data from the Icelandic Shelf, a key region with regard to any studies of Holocene changes in NAO type indices, because the NAO is defined by the surface atmospheric pressure difference between Iceland (Stykkisholmur) and the Azores. The data from this paper complement previously published records and strongly support the observations of negative Holocene SST trends in the northern Atlantic and thus a negative trend (weakening) in the AO/NAO index (Rimbu *et al.*, 2003).

High frequency variability and correlations

There have been numerous recent studies, employing various climate proxies, of Holocene high-frequency oceanographic changes in the northern North Atlantic, Nordic Seas and on the Iceland shelf. The timing of the coolings from a number of the most pertinent records and those in JR51-GC35 are summarized and compared in Figure 4.

Early-Holocene glacial aftermath and optimum (10 000–7300 cal. yr BP)

During the early Holocene the interpretation of SST proxies on high-latitude continental margins is inevitably complicated by the influence of the globally decaying large Northern Hemisphere ice sheets and potential local deglacial influences. Globally, following meltwater pulse (MWP) 1B eustatic sea level rose until ~ 7 cal. kyr BP (Fairbanks, 1989). Regionally, the isostatic recovery of Iceland during the deglaciation was rapid (Ingolfsson *et al.*, 1995) – by *c.*10 cal. kyr BP the modern relative sea level (RSL) was likely reached (Rundgren *et al.*, 1997). RSL then fell to 40–60 m below present during the early Holocene, based on fossil deltas, spits and littoral terraces (Thors and Boulton, 1991), before rising again in line with global sea levels (Fairbanks, 1989). Locally the NW Icelandic fjords were ice-free by 10.2 cal. kyr BP (Geirsdottir *et al.*, 2002), while deglaction of the northern Icelandic fjords progressed inland until as late as 9 cal. kyr BP (Kaldal and Vikingsson, 1990).

During the early Holocene between 10 and 9 cal. kyr BP consistently high temperatures of ~ 10°C are recorded in JR51-GC35 (Figure 3). In the inner shelf (core B997-330, see Figure 1) during this period there were also relatively high numbers of warm water 'North Atlantic Drift' coccolithophore species (Andrews and Giraudeau, 2003; Giraudeau *et al.*, 2004) and more generally the δ^{18}O of foraminifera from a series of cores from the SW North Icelandic Shelf indicate the warmest Holocene SST conditions between 10 and 6 cal. kyr BP (Micaela Smith *et al.*, 2005). In contrast, Eiríksson *et al.* (2000b) have inferred – from benthic foraminifera assemblages – a cooling of the bottom waters of the outer shelf (cores HM107-4, -5; see Figure 1) during this period and have suggested that the palaeo-Irminger current did not reach the North Icelandic Shelf. We suggest that the coccolithophores and alkenones (produced in the mixed layer) record the climatic changes in the surface to near-surface Atlantic waters of the Irminger current, whereas the bottom-living benthic foraminfera (396 m and 458 m at sites HM107-4, -5) were influenced by intermediate and deep water masses. It appears that during periods of the Holocene, climatic trends of the surface to near-surface waters of the North Icelandic Shelf were highly divergent from changes in the deeper waters. A modern assay demonstrates the differential influences of water masses on the contemporary North Icelandic Shelf (see Figure 1C), which is influenced by the Atlantic type waters to ~ 300 m, greater depths come under the influence of the Arctic Intermediate Waters (Andrews *et al.*, 2003). In fact, previous work has found that the relationship on the North Icelandic Shelf between proxies of mixed layer origin and the information recorded by benthic foraminifera is not simple (Andrews and Giraudeau, 2003, Giraudeau *et al.*, 2004) and that the strength of the vertically integrated Irminger water flow ($\sim$ top 500 m of the water column) could be negatively correlated with the temperature of the uppermost surface waters (Giraudeau *et al.*, 2004). Diatom assemblages in core MD99-2269 (see Figure 1B) also provide evidence of very warm surface waters (August SST of up to 14°C) in the early Holocene (9.5–9 cal. kyr BP) on the North Icelandic Shelf (Andersen *et al.*, 2004a). However, the diatoms record a warming that starts later than that recorded by the alkenones (from 9 cal. kyr BP), and in fact indicates cool temperatures between 10 and 9.5 cal. kyr BP. Contrasts in the seasonality and integrated production depths of the diatoms, foraminifer and alkenones may account for the differences in the signal from these proxies at this time and during the Holocene.

The early warm period was followed by a short cold episode between 9 and 8.7 cal. kyr BP, which saw the coldest temperature of 2°C (Figure 4). Furthermore, a coeval increase in the %$C_{37:4}$ value, which jumps to 10%, is highly suggestive of a local increase in the influence of polar waters at the site (Figure 3) (Bendle *et al.*, 2005). A geographically widespread North Atlantic cooling event at ~ 8.9 cal. kyr BP has not been universally observed in the literature (Mayewski *et al.*, 2004).

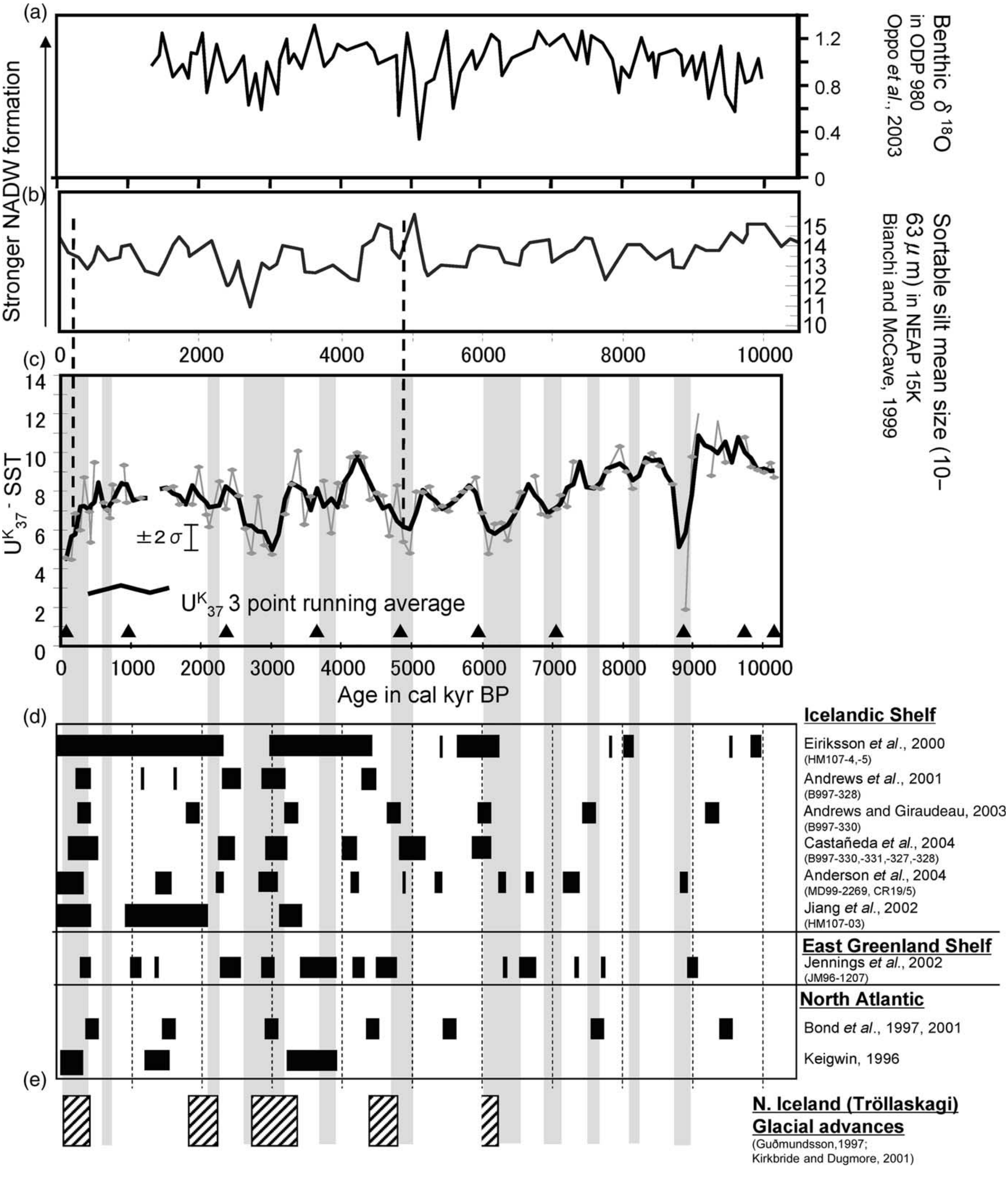

Figure 4 Comparison of U^{K}_{37}-SST from JR51-GC35 with Holocene palaeo-environmental records from North Atlantic and western Nordic Seas. (a) Oppo *et al.* (2003) record of benthic foraminferal (*Cibicidoides wullerstorfi*) $d^{13}C$, a proxy for the production of NADW and thus the strength of the MOC. (b) Bianchi and McCave (1999) record of the strength of Iceland–Scotland overflow water – another proxy for the strength the MOC (inferred from sortable silt mean size). (c) U^{K}_{37}-SSTs from the North Icelandic shelf (this paper), coolings are demarcated as grey areas, warmer periods as white. ▲ indicates the levels of the AMS ^{14}C dates. (d) Summary of inferred coolings (demarkated in black, superimposed on grey background of coolings in the JR51-GC35 UK37-SST record) derived from various marine cores from the North Iceland shelf (Andrews and Giraudeau, 2003, PCA of various sediment components; Andrews *et al.*, 2001a, $\%CaCO_3$; Eiríksson *et al.*, 2000b, IRD record; Castaneda *et al.*, 2004, $\delta^{18}O$ of foraminifera; Jiang *et al.*, 2002, diatom SSTs), East Greenland (Jennings *et al.*, 2002, IRD record), off Ireland (Bond *et al.*, 1997, IRD record) and on the Bermuda rise (Keigwin, 1996, $\%CaCO_3$ and $\delta^{18}O$), records are aligned by calendar age BP (not ^{14}C age). (e) Glacier advances in Northern Iceland (Guðmundsson, 1997; Kirkbride and Dugmore, 2001), the Tröllaskagi fieldwork region is indicated in Figure 1

However, evidence of a significant regional event in the western Nordic Seas is recorded by reduced diatom assemblage-derived August SSTs on the North Icelandic Shelf in core MD99-2269 (Andersen *et al*., 2004a), by a distinct peak in IRD in core JM96-1207 on the East Greenland shelf (Jennings *et al*., 2002) (see Figures 1 and 4).

U^{K}_{37}-SSTs warmed to 9°C by 8.5 cal. kyr BP and were relatively high (~8°C) to 7.3 cal. kyr BP in JR51-GC35. The general period of relatively warm temperatures during the early Holocene between *c*. 10 cal. kyr BP and 7 cal. kyr BP is sometimes referred to as the Holocene Climatic Optimum (HCO) and is found in numerous proxy records from the Nordic Seas (eg, Koç and Jansen, 1992; Koc *et al*., 1993; Andrews *et al*., 1997; Klitgaard-Kristensen *et al*., 1998; Andersen *et al*., 2004a; Kaufman *et al*., 2004) and is inferred on the North Icelandic Shelf in benthic foraminifera (Eiríksson *et al*., 2000a), coccolith data (Andersson *et al*., 2003; Giraudeau *et al*., 2004) and foraminiferal $\delta^{18}O$ (Castaneda *et al*., 2004; Micaela Smith *et al*., 2005) proxies.

The regional differences in the timing and duration of the HCO and the magnitude of surface variability may be partly due to differences in the climatic sensitivity of various proxies, but it is likely that a significant portion is due to a complex oceanic reaction to the insolation forcing. The HCO in the Nordic Seas occur almost 2000 years later than the Northern Hemisphere insolation maximum at 11 cal. kyr BP (Berger, 1978). Modelling suggests that this lag is a result of the Icelandic Low being located further north during the early Holocene than at present with westerly flow stronger than present (Harrison *et al*., 1992), because of the remnants of the Laurentide and Scandinavian ice sheets (Koç and Jansen, 1992; Koç *et al*., 1996). These effects could have caused the North Atlantic Drift to carry more warm water further north (Wanner *et al*., 2001), hence strengthening the IC and NIIC over the north Iceland shelf. North Iceland during the early Holocene Climate Optimum (HCO) is characterized by the establishment and stabilization of birch forests and high chironomid-inferred July temperatures between 9 and 7 cal. kyr BP (Caseldine *et al*., 2003).

The alkenone data record a relatively small cooling at 8.2 cal. kyr BP of 1°C. In the north Atlantic there is evidence for significantly widespread cooling at the 8.2 cal. kyr BP event as evidenced by, *inter alia*, colder temperatures in the Greenland GRIP $\delta^{18}O$ ice-core (Alley *et al*., 1997), ice rafting (Bond *et al*., 1997), strengthened atmospheric circulation over the North Atlantic and Siberia (Mayewski *et al*., 1997), mountain glacier advances in Scandinavia and lowered treeline limits in Sweden (Karlén and Kuylenstierna, 1996). The event was probably initiated by the catastrophic drainage of Laurentide ice-dammed lakes through the Hudson Strait (Barber *et al*., 1999). Rohling and Pälike (2005) have recently reviewed a large number of North Atlantic and global proxy records and have found that a short event (eg, ~100 yr in the GISP2 $\delta^{18}O$ record) at 8.2 cal. kyr BP is often superimposed on a broader cooling between ~8.6 to 8 cal. kyr BP. Moreover, Rohling and Pälike (2005) have found that the 8.2 cal. kyr BP event is most prominent in winter proxies and is less obvious in proxies that record a primarily summer-time climatic summer. The 8.2 cal. kyr BP event in the U^{K}_{37}-SST signal at JR51 GC-35 is not highly significant. This may be due to the alkenones being mostly produced in the summer and/or the transience of the event: making it vulnerable to attenuation in the marine record or not being fully captured by the sampling strategy. However, a cooling at around 8 cal. kyr BP is not a significant event in many other records from the N. Iceland shelf, including in the $\Delta^{18}O$ of benthic foraminfera (Castaneda et al., 2004) (see Figure 4). Temperature reconstructions based on chironomids from northwest Iceland indicate only a minor cooling at 8.2 cal. kyr BP (Caseldine et al., 2003). Also Icelandic glaciers – unlike those in Scandinavia (Nesje *et al*., 2001) – do not show an expansion at that time (Stötter et al., 1999). It appears that the impact of the 8.2 cal. kyr event, however significant in the Labrador Sea (Barber et al., 1999) and other North Atlantic records was diluted within the warm NIIC and hence had limited impact on terrestrial Iceland. This is confirmed by other recent multiproxy investigations "upstream" of the NIIC, within the North Atlantic Current NAC (59°N, 31°W) (Moros et al., 2004), and in the western subpolar North Atlantic between Hudson Strait and Cape Hatteras (Keigwin *et al*., 2005) which suggest that the impact of the 8.2 cal. kyr event was geographically restricted.

Mid Holocene (7400–3200 cal. yr BP)

The U^{K}_{37}-SST record in JR51-GC35 decreases from 9°C at 7.3 cal. kyr BP to a major cooling of <6°C at 6.1 cal. kyr BP. A number of records from the North Icelandic Shelf infer a transition to cooler waters starting at around this time: from ~6.5 cal. kyr BP in the $\delta^{18}O$ of foraminifer from various SW north Icelandic cores (Micaela Smith *et al*., 2005); from 6.5 cal. kyr BP in coccolithophore (Giraudeau *et al*., 2004) and diatom assemblages from MD99-2269 (Andersen *et al*., 2004a); from 6.2 cal. kyr BP in the $\delta^{18}O$ of $CaCO_3$ from B997-330 (Castaneda *et al*., 2004); from *c*. 6 cal. kyr BP in benthic foraminifer assemblages and from 6.2 cal. kyr BP in IRD from HM107-04 and HM107-05 (Eiríksson *et al*., 2000a) (see Figure 1). Cooling on terrestrial Iceland has been inferred from *c*. 6 cal. kyr BP from glacial advances (Stötter *et al*., 1999; Kirkbride and Dugmore, 2001;) and Chrinomid assemblages (Caseldine *et al*., 2003). A major mid-Holocene cooling is well recognized within a broader Nordic Seas/North Atlantic context, with eg, cooler Norwegian Sea and N Atlantic SSTs (Calvo *et al*., 2002; Andersen *et al*., 2004a; Moros *et al*., 2004) cooler temperatures over Greenland (Dahl-Jensen *et al*., 1998), a deeper Icelandic Low and Siberian High (Mayewski *et al*., 1997), Scandinavian glacial advances (Karlén and Kuylenstierna, 1996) and increased iceberg rafting along the east Greenland coast (Williams *et al*., 1995; Andrews *et al*., 1997; Jennings *et al*., 2002). A possible cause of the mid-Holocene neoglacial cooling is that solar radiation decreased beyond a critical threshold leading to a change in the predominance of the atmospheric circulation pattern, (Koç and Jansen, 1994; Williams *et al*., 1995; Andrews *et al*., 1997; Jennings *et al*., 2002). The postglacial emergence of the Arctic Island Channels has also been invoked as a factor in the mid-Holocene, as a result of isostatic rebound the channels shallowed, changing the proportion of freshwater advected via the Fram Strait into the Nordic Seas (Williams *et al*., 1995).

The mid-Holocene U^{K}_{37}-SST record in JR51-GC35 is highly variable and does not describe a simple transition to a cooler late-Holocene regime. Superimposed on this overall cooling are several major recoveries in U^{K}_{37}-SST. The magnitude of these recoveries seems to be greater than anything previously inferred from other Holocene investigations on the North Icelandic Shelf. First, SSTs warm to 8.3°C by 5.8 cal. kyr BP, following which there is another major mid-Holocene cooling at 5 cal. kyr BP. This cooling is coeval with an abrupt cold event inferred from the $\delta^{18}O$ of foraminifer in B997-324, B997-347 and B997-330, and a reduction in carbonate content in the latter core (Andrews and Giraudeau, 2003; Castaneda *et al*., 2004; Micaela Smith *et al*., 2005) (Figures 1 and 4). On the East Greenland Shelf there is a major shift to increased IRD deposition starting at 5 cal. kyr BP (Jennings *et al*., 2002)

(Figure 1). However, in the diatom record from MD99-2269 only a minor reduction in SST is observed at 5 kyr BP (Andersen *et al.*, 2004a) (Figures 1 and 4). Another major recovery occurs at 4.2 cal. kyr BP and sees U^{K}_{37}-SSTs warm to 9.8°C and remain relatively mild (~7–8°C) until 3.2 cal. kyr BP. The significance of this phase is such that it can be considered a late mid-Holocene thermal optimum (LTO). A significant warming (*c.* 3°C) in diatom SSTs is also reported in MD99-2269 between 4.3 cal. kyr BP and 4 cal. kyr BP (Andersen *et al.*, 2004a) and on the inner North Icelandic Shelf from 4.6 to 3.8 cal. kyr BP in HM107-03 (Figure 1) (Jiang *et al.*, 2002), while lighter formaniferal δ^{18}O values infer a warming between 4.5 and 3.7 cal. kyr BP in B997-324 (Micaela Smith *et al.*, 2005) and centred at *c.* 3.7 cal. kyr BP in B997-330 (Castaneda *et al.*, 2004) (Figure 1).

Late Holocene (3200–80 cal. yr BP)

Following the mid-Holocene LTO (4.2–3.2 cal. kyr BP), there is a major cooling in U^{K}_{37}-SSTs (from > 8°C to < 5°C) from 3.2 to 2.6 cal. kyr BP. This is an event that appears to be well recognized in other proxies from the North Icelandic Shelf, including *C. lobatus* δ^{18}O values (Castaneda *et al.*, 2004) and diatom assemblages (Andersen *et al.*, 2004a) (Figure 4). Eiríksson *et al.* (2000a) also note that, prior to the eruption of Hekkla 3 (*c.* 3 cal. kyr) IRD flux increases, as do cold water benthic foraminifera on the North Icelandic Shelf. A major Holocene climate deterioration at *c.* 3 cal. kyr BP also appears to have wider geographical significance. There is an increase in IRD in the N. Atlantic (Bond *et al.*, 1997, 2001) and East Greenland Shelf (Jennings *et al.*, 2002). Also the Greenland ice core records suggest a deeper Icelandic Low and Siberian High (Mayewski *et al.*, 1997) from 3.2 to 2.8 cal. kyr BP.

At 2.6 cal. kyr BP U^{K}_{37}-SSTs ameliorate to 7.6°C. Then follows the most stable part of the Holocene, in our record, from 2.5 to 0.5 cal. kyr BP, where U^{K}_{37}-SSTs are generally between 7.3 and 8.3°C. Phases of relative warmth within this period on the North Icelandic Shelf have also been inferred from *C. lobatus* δ^{18}O values between 1.7 and 1 kyr BP in B997-330 (Castaneda *et al.*, 2004) and between 1.5 and 0.05 cal. kyr BP from diatom SSTs in MD99-2269 (Andersen *et al.*, 2004a). However, this warming is not noted by Eiríksson *et al.* (2000b) in benthic foraminifera nor by Jiang *et al.* (2002) in HM107-03 where a gradual cooling in diatom SSTs is inferred between 2.2 and 1 cal. kyr BP.

In the youngest part of the record from 340 yr to 80 cal. yr BP temperatures drop from 7 to 4.5°C. This latter event, which sees U^{K}_{37}-SSTs drop by 3.5°C, is coeval with the 'Little Ice Age' (LIA). Evidence of a climatic deterioration on the North Icelandic Shelf is also found in the δ^{18}O of benthic formanifera (Castaneda *et al.*, 2004) and in increases in cold/freshwater benthic foraminferal species (Andrews *et al.*, 2001). There is abundant historical documentary evidence for climatic deterioration during the 'Little Ice Age', such as Koch's index of the severity of sea ice incidence around Iceland, which shows a marked increase in the incidence of sea ice along the Icelandic coastline from 1520 to the mid-twentieth century (Koch, 1945; referenced in Grove, 1988). Moreover, there is abundant historical evidence for social hardship in Iceland during the LIA, with failed harvests, declining fish catches and an impoverished population retreating from the most severely affected areas in the north of the country (Grove, 1988).

Correlations with Icelandic glacial record

Such extreme changes in U^{K}_{37}-SST off north Iceland should have corresponding events in the Icelandic terrestrial record, because of the observed close coupling of north Icelandic marine conditions and terrestrial temperatures during the instrumental period (Kugelmann, 1989, 1991; Stötter, 1991). Figure 4d shows a summary of records of Holocene mountain glacier advances in the Tröllaskagi peninsula, northern Iceland (Figure 1) (Guðmundsson, 1997; Kirkbride and Dugmore, 2001), compared with the U^{K}_{37}-SST record from JR51-GC35. Evidence of climatic deteriorations coeval with some glacial advances have also been found in records of pollen assemblages and peat accumulation (eg, Caseldine and Hatton, 1994; Rundgren, 1998; Andrews *et al.*, 2001a). The glacier records show agreement with the U^{K}_{37}-SST data. During the early Holocene when we observe the generally highest temperature in JR51-GC35 there is no evidence of glacial re-advance. Subsequently advances at < 6, 4.7 and 3.5 cal. kyr BP show parallel changes with the major mid-Holocene troughs in U^{K}_{37}-SSTs. Moreover, the termination of the advances are coeval with the subsequent U^{K}_{37}-SST recoveries. Stötter *et al.* (1999) suggest that reductions in SSTs and increases in winter sea ice north of Iceland reduce the precipitation input to Icelandic glaciers. However, this negative effect on glacier mass balance is more than compensated for by a reduction in equilibrium line altitude (ELA), thus resulting in a net gain in ice mass and expansion of glaciers. The data from this paper appear to support this conceptual model for the response of Holocene glaciers at least for the northern Tröllaskagi peninusla.

Comparison with North Atlantic Deep Water proxies

When the U^{K}_{37}-SST record from JR51-GC35 and proxy data for the strength of the MOC in the North Atlantic are compared, a correlation is highlighted for the later half of the Holocene between 5000 and 100 cal. yr BP (dashed lines, Figure 4a, b). Variations in the δ^{13}C of *Cibicidoides wuellerstorfi* in ODP 980 (55°N, 15°W) reflect variations in the influence of North Atlantic Deep Water (Oppo *et al.*, 2003) at the site, and in core NEAP 15K (56°21.92′N, 27°48.68′W) near-bottom palaeocurrent speeds are recorded (Bianchi and McCave, 1999). The near-bottom current speeds at site NEAP 15K are a function of the strength of the Iceland–Scotland overflow water (ISOW), which transports North Atlantic Deep Water (NADW), an important component of the global MOC (Bianchi and McCave, 1999). The deep, dense, return flow of ISOW and formation of NADW partly counterbalances and maintains the poleward flux of warm saline Atlantic waters at the surface (Bianchi and McCave, 1999). The surface flow of the North Atlantic Current (NAC), feeds into the IC and NIIC, which dominates surface conditions at site JR51-GC35. Hence a mechanism exists that could explain a connection between the U^{K}_{37}- SST data on the North Icelandic Shelf and ISOW strength/NADW production. A probably much weaker, less direct, connection exists via the winter formation of the intermediate depth NIWW (Swift and Aagaard, 1981), which contributes to the formation of deep waters in the Nordic seas and ultimately the 'overspill' of the I-S ridge which feeds the ISOW. Prior to *c.* 5 cal. kyr BP the correlation is not so clear. The reasons for this are unknown, but it may be due to complicating factors in the early Holocene, such as a greater flux of meltwater to the northern North Atlantic in general (sea levels were rising at a sustained rate until *c.* 7 cal. kyr BP (Fairbanks, 1989)), or that a more persistent and northerly located Icelandic Low (NAO+) during the early Holocene drove a stronger surface IC and NIIC (Harrison *et al.*, 1992) that was not so sensitive to changes in the MOC. Also proxy records suggest that deep water ventilation was slower generally in the early Holocene (Veum *et al.*, 1992; Bianchi and McCave, 1999; Bauch *et al.*, 2001; Oppo *et al.*, 2003), and therefore may have had less influence on north Icelandic SSTs.

Comparison of North Iceland and Norwegian current

Eiríksson *et al.* (2000b) suggested that during the Lateglacial period some climatic events in western Europe were coeval with events of an apparently contradictory sign on the North Icelandic Shelf. Benthic foraminiferal assemblages suggest a strong (warm) pre-Bølling palaeo-Irminger Current on the North Icelandic Shelf. This contrasts with a particularly cold episode in the North Sea (Rochon *et al.*, 1998) and in the GRIP ice-core (Björk *et al.*, 1998). However, Eiríksson *et al.* (2000b) found no evidence of such discrepancies between the NIIC and other North Atlantic or Greenland records during the Holocene. This may have been due to the relative insensitivity of the benthic foraminiferal assemblages studied to lower amplitude Holocene changes. Moreover, the benthic foraminifera studied by Eiríksson *et al.* (2000b) responded to changes in water masses at 300–500 m depth on the shelf, rather than SSTs in the mixed layer.

In Figure 5 we compare changes in published Holocene alkenone-SSTs from MD952011, a high-resolution core (7 m Holocene section) from the Norwegian Sea (Calvo *et al.*, 2002) with the U^K_{37}-SST record from JR51-GC35 on the Icelandic Shelf. The comparison shows that there are some general similarities between the records. For example, they both record an overall decrease in mean SSTs during the Holocene, and a marked cooling event at ~9 cal. kyr BP. However, the records show some significant differences in the millennial-scale climate events between the NIIC and NC, especially between 7.5 and 2.5 cal. kyr BP. The most prominent example is the timing of the mid-Holocene thermal optimum. In MD952011 the mid-Holocene TO is a distinct phase between 6 and 8 cal. kyr BP (with the consistently highest SSTs between 6 and 7 cal. kyr BP). Calvo *et al.* (2002) suggest this is supported by data from diatom and foraminifera reconstructions in the eastern Nordic Seas (eg, Koç and Jansen, 1992; Koc *et al.*, 1993; Sarnthein *et al.*, 1995), by records of mountain glacier retreat in Norway (Nesje and Kvamme, 1991) and European pollen data (Huntley and Prentice, 1988). However, in the records from the western Nordic Seas, during the period 6–7 cal. kyr BP, there is a trough in the U^K_{37}-SSTs on the North Icelandic Shelf, an increase in ice-rafted detrital carbonate on the East Greenland Shelf (Jennings *et al.*, 2002) and glacier expansion in northern Iceland. In the Eastern Nordic Seas the TO terminates between 6 and 5 cal. kyr BP at the same time as U^K_{37}-SSTs are increasing on the North Icelandic Shelf and IRD is decreasing in East Greenland (Jennings *et al.*, 2002). Another example of anti-phasing is between 3.3 and 2.5 cal. kyr BP when there is a major cooling in JR51-GC35 on the North Icelandic Shelf and a warming of U^K_{37}-SSTs in MD952011 between 3.3 and 3 cal. kyr BP. Subsequently, between 3 and 2.5 cal. kyr BP as U^K_{37}-SSTs warm on the North Icelandic Shelf U^K_{37}-SSTs in the Norwegian Sea decline sharply.

A non-uniform Holocene climatic development in the Nordic Seas has previously been highlighted by Andersen *et al.* (2004a), who observed that the gradient of diatom-SST cooling during the Holocene was greatest in the Norwegian Current and the gradient was less steep to the west on the Icelandic Shelf and shallowest further west on the East Greenland Shelf. Our comparison of two U^K_{37}-SST records from the west and east Nordic Seas confirms that the response of the ocean circulation within the Nordic Seas to decreasing Holocene insolation was complex. Furthermore, we show that this included millennial-scale anti-phased responses of the western (IC and NIIC) and eastern (NC) branches of Atlantic inflow to the Nordic Seas.

The mechanism for a differential response is not known. However, NAO-like changes in circulation may be key. Seasonal- to decadal-scale temperature dipoles in the North Atlantic region have been highlighted for the late Holocene, in comparisons of Greenland ice-core data with historical data sets, and have been suggested to be influenced by the NAO (Barlow *et al.*, 1997; Barlow, 2001;). Studies of instrumental data collected during the latter half of the twentieth century

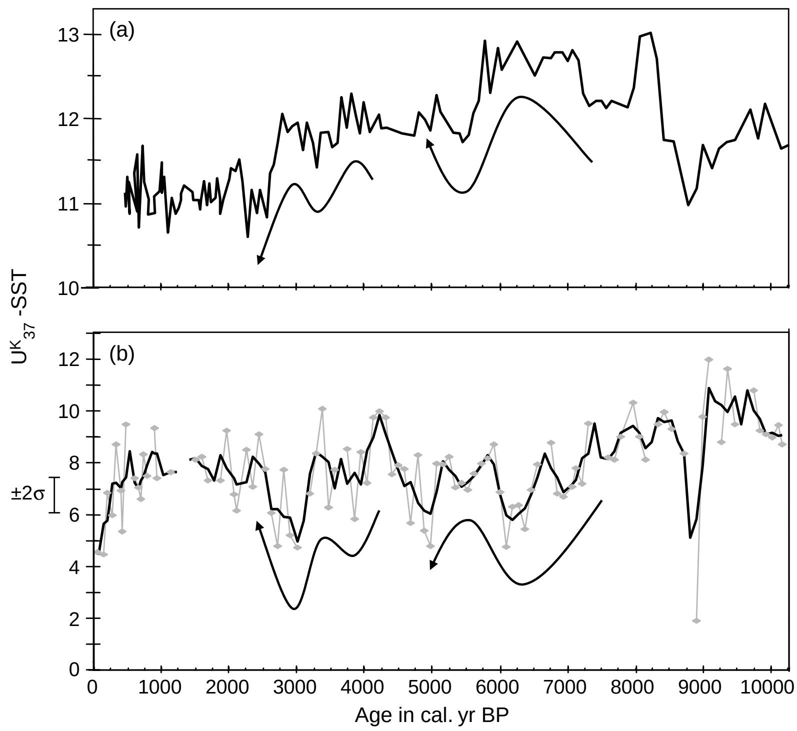

Figure 5 (a) U^K_{37}-SST values from the Norwegian Sea (MD952011: 66°58′N, 7°38′E) and (b) the North Icelandic Shelf (JR51-GC35: 66°59′N, 17°57′W) plotted against age in cal. yr BP

also provide insight. Alekseev *et al*. (2001) found a positive SST anomaly (+1°C) in the northern Norwegian Sea (73°N, 15°E) and the most negative anomaly (−1°C) in the seas to the north, east and south of Iceland for the 1980–1990 period. Blindheim *et al*. (2000) suggest that the instrumental data from 1950 onwards demonstrate that the oceanographic structure in the Nordic Seas is closely linked with the predominant wind system, which in turn is closely correlated with the NAO mode. This affects the westwards inflow of the Atlantic water in the Nordic seas and the speeds of the currents advecting Atlantic waters (Orvik *et al*., 2001). Blindheim *et al*. (2000) suggest that since the 1960s, conditions in the Norwegian Sea and Faeroe–Shetland area have shown little correlation with the conditions in the North Icelandic Shelf waters. Circulation of Atlantic water into the western Nordic Seas has reduced, while there has been a temperature rise in the narrowing Norwegian Atlantic Current (Blindheim *et al*., 2000). Most recently Flatau *et al*. (2003) suggest that NAO+ years are associated with intensification of subpolar westerlies in the Atlantic and northerlies along the Greenland coast, resulting in the intensification of the cyclonic circulation in the Irminger basin. This is associated with negative SST anomalies on the North Icelandic Shelf and northwest of Iceland to the East Greenland Shelf, but positive SST anomalies further north and to the east (including the Norwegian Sea). In general during a positive NAO phase the spatial structure of SSTs display anomalously high values in the eastern northern North Atlantic and anomalously low temperatures in the west (see review by Wanner *et al*., 2001, and references therein). However, further modelling work is needed to determine if such decadal-scale NAO-associated phenomena can be up-scaled to explain millennial-scale east–west anti-phasing in the Nordic Seas.

Conclusions

The record from the North Icelandic Shelf displays a Holocene cooling trend of 2.1°C (8.8 to 6.7°C) from 10 200 to 80 cal. yr BP. These data support published reports of negative Holocene SST anomalies in the northern North Atlantic towards the present. Contrasted with records of positive trends in the eastern Mediterranean and Middle East, this suggests a negative trend (weakening) in the AO/NAO index during the Holocene (Rimbu *et al*., 2003).

The SST oscillations in JR51-GC35 are of a large amplitude, with millennial-scale oscillations characterized by deviations of ~2°C. The millennial-scale oscillations in the JR51-GC35 U^K_{37}-SST, show some coeval events with a number of marine records of Holocene climate from the northern Iceland shelf and North Atlantic deep-sea cores. However, we do not see a close correlation with the widely referenced records of ice-rafting in the Nordic Seas (Bond *et al*., 1997, 2001) that have been correlated with changes in solar activity (Bond *et al*., 2001).

The U^K_{37}-SST record from JR51-GC35 shows close agreement with records of Holocene glacial advances from northern Iceland, with advances associated with the major mid-Holocene troughs in U^K_{37}-SSTs and the terminations with the subsequent U^K_{37}-SST recoveries.

There is a correlation for the later half of the Holocene between 5000 and 100 cal. yr BP between the U^K_{37}-SST record from JR51-GC35 and proxy data for the strength of NADW formation recorded in cores south of Iceland. We propose that this is evidence of a close connection between North Icelandic SSTs and the MOC in the late Holocene. The lack of a correlation in the early Holocene may be due to a greater flux of meltwater to the northern North Atlantic, a more persistent and northerly located Icelandic Low (NAO+) or a slower MOC.

A comparison of the U^K_{37}-SST in our core off North Iceland and a core from the eastern Nordic Seas (MD952011) shows that there are some general similarities in their overall variability. However, we find significant anti-phasing (superimposed on the general trend) in millennial-scale climate events between the eastern and western Nordic Seas, especially between 7.5 and 2.5 cal. kyr BP. Therefore, the data from this paper suggest that the response of the surface ocean circulation within the Nordic Seas on a millennial scale was more complex than previously suggested; characterized by differential responses of the Irminger/North Icelandic Irminger and Norwegian Currents.

Acknowledgements

The UK Natural Environmental Research Council (NERC) is thanked for a studentship to JB and for additional financial awards for AMS ^{14}C dates (NERC radiocarbon laboratory, East Kilbride) and use of the facilities at BOSCOR (Southampton Oceanography Centre) and the Organic Geochemistry Unit (School of Chemistry, University of Bristol). Many thanks to Dr Ian Bull and Dr Jim Carter who supervised analysis at Bristol, OGU. Thanks to Dr Steve Moreton of the NERC radiocarbon laboratory for advice on AMS ^{14}C sampling and analysis. Thanks to Harry A. ten Hove and Dr Rob Moolenbeek for identifying the mollusca picked for AMS ^{14}C dates (Zoological Museum, UVA, The Netherlands). Thanks to the scientific party and crew of the RRS *James Clark Ross* (cruise JR51), especially Neil Campbell (BGS) for the operation of the Gravity Corer and Cólm Ó Cofaigh for advice with lithostratigraphical logs. John T. Andrews and Alistair Dawson are thanked for providing constructive and insightful reviews.

References

Alekseev, G.V., Johannessen, O.M., Korablev, A.A., Ivanov, V.V. and **Kovalevsky, D.V.** 2001: Interannual variability in water masses in the Greenland Sea and adjacent areas. *Polar Research* 20, 201–08.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C. and **Clark, P.U.** 1997: Holocene climatic instability: a prominent widespread event 8200 years ago. *Geology* 25, 483–86.

Andersen, C., Koc, N. and **Moros, M.** 2004b: A highly unstable Holocene climate in the subpolar North Atlantic: evidence from diatoms. *Quaternary Science Reviews* 23, 2155–66.

Andersen, C., Koc, N., Jennings, A. and **Andrews, J.T.** 2004a: Nonuniform response of the major surface currents in the Nordic Seas to insolation forcing: implications for the Holocene climate variability. *Paleoceanography* 19, PA2003, doi:10.1029/2002PA000873.

Andersen, G.J., Hienemeier, J., Nielsen, H.L., Rud, N., Johnsen, S., Sveinbjörnsdóttir, Á.E. and **Hjartarson, Á.** 1989: AMS ^{14}C dating on the Fossvogur sediments, Iceland. *Radiocarbon* 37, 53–62.

Anderson, D.M. 2001: Attenuation of millennial-scale events by bioturbation in marine sediments. *Paleoceanography* 16, 352–57.

Andersson, C., Risebrobakken, B., Jansen, E. and **Dahl, S.O.** 2003: Late Holocene surface ocean conditions of the Norwegian Sea (Voring Plateau). *Paleoceanography* 18, 1044, doi:10.1029/2001PA000654.

Andrews, J.T. and **Giraudeau, J.** 2003: Multi-proxy records showing significant Holocene environmental variability: the inner N. Icelandic shelf (Húnaflói). *Quaternary Science Reviews* 22, 175–93.

Andrews, J.T., Smith, L.M., Preston, R., Cooper, T. and **Jennings, A.E.** 1997: Spatial and temporal patterns of iceberg rafting (IRD) along the East Greenland margin, ca. 68°N, over the last 14 cal. ka. *Journal of Quaternary Science* 12, 1–13.

Andrews, J.T., Caseldine, C., Weiner, N.J. and **Hatton, J.** 2001a: Late Holocene (ca. 4 ka) marine and terrestrial environmental change in Reykjarfjordur, north Iceland: climate and/or settlement? *Journal of Quaternary Science* 16, 133–43.

Andrews, J.T., Helgadóttir, G., Geirsdóttir, A. and **Jennings, A.E.** 2001b: Multicentury-scale records of carbonate (hydrographic?) variability on the northern Iceland margin over the last 5000 years. *Quaternary Research* 56, 199–206.

Andrews, J.T., Geirsdóttir, A., Hardardóttir, J., Principato, S., Gronvold, K., Kristjánsdóttir, G.B., Helgadóttir, G., Drexler, J. and **Sveinbjörnsdóttir, A.** 2002a: Distribution, sediment magnetism and geochemistry of the Saksunarvatn (10,180 +/− 60 cal. yr BP) tephra in marine, lake, and terrestrial sediments, northwest Iceland. *Journal of Quaternary Science* 17, 731–45.

Andrews, J.T., Hardardóttir, J., Geirsdóttir, A. and **Helgadóttir, G.** 2002b: Late Quaternary ice extent and glacial history from the Djúpáll trough, off Vestfirdir peninsula, north-west Iceland: a stacked 36 cal. Ky environmental record. *Polar Research* 21, 211–26.

Andrews, J.T., Hardardóttir, J., Stoner, J.S., Mann, M.E., Kristjánsdóttir, G.B. and **Koç, N.** 2003: Decadal to millennial-scale periodicities in North Iceland shelf sediments over the last 12000 cal yr: long-term North Atlantic oceanographic variability and solar forcing. *Earth and Planetary Science Letters* 210, 453–65.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Biodeau, G., McNeely, R., Southon, J., Morehead, M. D. and **Gagnon, J.-M.** 1999: Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–48.

Bard, E. 2001: Paleoceanographic implications of the difference in deep-sea sediment mixing between large and fine particles. *Paleoceanography* 16, 235–39.

Barlow, L.K. 2001: The time period AD 1400–1980 in central Greenland ice cores in relation to the North Atlantic sector. *Climatic Change* 48, 101–19.

Barlow, L.K., Rogers, J.C., Serreze, M.C. and **Barry, R.G.** 1997: Aspects of climate variability in the North Atlantic sector: discussion and relation to the Greenland Ice Sheet Project 2 high-resolution isotopic signal. *Journal Of Geophysical Research-Oceans* 102, 26 333–44.

Bauch, H.A., Erlenkeuser, H., Speielhagen, R.F., Struck, U., Matthiessen, J., Thiede, J. and **Heinemeier, J.** 2001: A multi-proxy reconstruction of the evolution of deep and surface waters in the subarctic Nordic seas over the last 30,000 yr. *Quaternary Science Reviews* 20, 659–78.

Bendle, J.A. 2003: Palaeoceanography of the Holocene and Late-Glacial N.E. Atlantic: development and application of biomarker proxies of environmental change. Unpublished Thesis, Geography, University of Durham.

Bendle, J.A. and **Rosell-Melé, A.** 2004: Distributions of UK37 and UK37′ in the surface waters and sediments of the Nordic Seas: implications for paleoceanography. *Geochemistry, Geophysics, Geosystems* 5, Q11013, doi:10.1029/2004GC000741.

Bendle, J.A., Rosell-Melé, A. and **Ziveri, P.** 2005: Variability of unusual distributions of alkenones in the surface waters of the Nordic seas. *Paleoceanography* 20, PA2001, doi:10.1029/2004PA 001025.

Berger, A.L. 1978: Long-term variations of caloric insolation resulting from the earth's orbital elements. *Quaternary Research* 9, 139–67.

Bianchi, G.G. and **McCave, N.** 1999: Holocene periodicity in the North Atlantic climate and deep-ocean flow south of Iceland. *Nature* 397, 515–17.

Björk, S., Walker, M.J.C., Cwynar, L., Johnsen, S., Knudsen, K.L., Lowe, J.J., Wohlfarth, B. and **INTIMATE_GROUP** 1998: An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *Journal of Quaternary Science* 13, 283–92.

Blindheim, J., Borovkov, V., Hansen, B., Malmberg, S.A., Turrell, W.R. and **Osterhus, S.** 2000: Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing. *Deep-Sea Research Part I–Oceanographic Research Papers* 47, 655–80.

Bond, G., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G. and **Johnson, S.** 1999: The North Atlantic's 1–2kyr climate rhythm: relation to Heinrich events, Dansgaard/Oeschger cycles and the Little Ice Age. In Clark, P.U., Webb, R.S. and Keigwin, L.D., editors, *Mechanisms of global climate change at millennial time scales.* American Geophysical Union, 35–58.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and **Bonani, G.** 2001: Persistent solar influence on north Atlantic climate during the Holocene. *Science* 294, 2130–36.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. and **Bonani, G.** 1997: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* 278, 1257–66.

Bradley, R.S. 1990: Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian high Arctic. *Quaternary Science Reviews* 9, 365–84.

Brassell, S.C. 1993: Application of biomarkers for delineating marine paleoclimatic fluctuations during the Pleistocene. In Engel, M.H. and Macko, S.A., editors, *Organic geochemisty: principles and applications.* Plenum Press, 699–738.

Brassell, S.C., Eglinton, G., Marlowe, I.T., Pflaumann, U. and **Sarnthein, M.** 1986: Molecular stratigraphy: a new tool for climatic assessment. *Nature* 320, 129–33.

Buckland, P.C., Amorosi, T., Barlow, L.K., Dugmore, A.J., Mayewski, P.A., McGovern, T.H., Ogilvie, A.E.J., Sadler, J.P. and **Skidmore, P.** 1996: Bioarchaeological and climatological evidence for the fate of Norse farmers in medieval Greenland. *Antiquity* 70, 88–96.

Calvo, E., Grimalt, J. and **Jansen, E.** 2002: High resolution UK37 sea surface temperature reconstruction in the Norwegian Sea during the Holocene. *Quaternary Science Reviews* 21, 1385–94.

Campbell, I.D., Campbell, C., Apps, M.J., Rutter, N.W. and **Bush, A.B.G.** 1998: Late Holocene ~1500 yr climatic periodicities and their implications. *Geology* 26, 471–73.

Caseldine, C. and **Hatton, J.** 1994: Interpretation of Holocene climatic change for the Eyjafjörður area of northern Iceland from pollen-analytical data: comments and preliminary results. In Stotter, J. and Wilhelm, F., editors, *Environmental change in Iceland.* Munchener Geogrephische Abhandlungen, 41–62.

Caseldine, C., Geirsdóttir, Á. and **Langdon, P.** 2003: Efstadalsvatn – a multi-proxy study of a Holocene lacustrine sequence from NW Iceland. *Journal of Paleolimnology* 30, 55–73.

Castaneda, I.S., Smith, L.M., Kristjánsdóttir, G.L. and **Andrews, J.T.** 2004: Temporal changes in Holocene delta O-18 records from the northwest and central North Iceland Shelf. *Journal of Quaternary Science* 19, 321–34.

Chapman, M.R. and **Shackleton, N.J.** 2000: Evidence of 550-year and 1000-year cyclicities in North Atlantic circulation patterns during the Holocene. *The Holocene* 10, 287–91.

Conte, M.H. and **Eglinton, G.** 1993: Alkenone and alkenoate distributions within the euphotic zone of the eastern North Atlantic: correlation and production temperature. *Deep-Sea Research I* 40, 1935–61.

Conte, M.H., Eglinton, G. and **Madureira, L.A.S.** 1992: Long-chain alkenones and alkyl alkenoates as palaeotemperature indicators: their production, flux and early sedimentary diagenesis in the Eastern North Atlantic. *Organic Geochemistry* 19, 287–98.

Conte, M.H., Thompson, A. and **Eglinton, G.** 1994: Primary production of lipid biomarker compounds by *Emiliania huxleyi*. Results from an experimental mesocosm study in fjords of southwestern Norway. *Sarsia* 79, 319–31.

Conte, M.H., Weber, J.C., King, L.L. and **Wakeham, S.G.** 2001: The alkenone temperature signal in western North Atlantic surface waters. *Geochimica et Cosmochimica Acta* 65, 4275–87.

Conte, M.H., Sicre, M.A., Ruhlemann, C., Weber, J.C., Schulte, S., Schulz-Bull, D. and **Blanz, T.** 2006: Global temperature calibration of the alkenone unsaturation index (U-37(K′)) in surface waters and comparison with surface sediments. *Geochemistry, Geophysics, Geosystems* 7, Art. No. Q02005 FEB 7 2006.

Cullen, H.M., deMenocal, P.B., Hemming, S., Hemming, G., Brown, F.H., Guilderson, T. and **Sirocko, F.** 2000: Climate change and the collapse of the Akkadian empire: evidence from the deep sea. *Geology* 28, 379–82.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnson, S.J., Hansen, A.W. and **Balling, N.** 1998: Past temperatures directly from the Greenland Ice Sheet. *Science* 282, 268–71.

deMenocal, P.B. 2001: Cultural responses to climate change during the Late Holocene. *Science* 292, 667–73.

deMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L. and **Yarusinsky, M.** 2000a: Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews* 19, 347–61.

deMenocal, P., Ortiz, J., Guilderson, T. and **Sarnthein, M.** 2000b: Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* 288, 2198–202.

Dickson, R.R., Meincke, J., Malmberg, S. and **Lee, A.** 1988: The 'Great Salinity Anomaly' in the Northern North Atlantic 1968–1982. *Progress in Oceanography* 20, 103–51.

Eiríksson, J., Knudsen, K.L., Haflidason, H. and **Heinemeier, J.** 2000a: Chronology of late Holocene climatic events in the northern North Atlantic based on AMS C-14 dates and tephra markers from the volcano Hekla, Iceland. *Journal of Quaternary Science* 15, 573–80.

Eiríksson, J., Knudsen, K.L., Haflidason, H. and **Henriksen, P.** 2000b: Late-glacial and Holocene palaeoceanography of the North Icelandic shelf. *Journal of Quaternary Science* 15, 23–42.

Eiríksson, J., Larsen, G., Knudsen, K.L., Heinemeier, J. and **Simonarson, L.A.** 2004: Marine reservoir age variability and water mass distribution in the Iceland Sea. *Quaternary Science Reviews* 23, 2247–68.

Fairbanks, F.G. 1989: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–42.

Flatau, M.K., Talley, L. and **Niiler, P.P.** 2003: The North Atlantic Oscillation, surface current velocities, and SST changes in the subpolar North Atlantic. *Journal of Climate* 16, 2355–69.

Freeman, K.H. and **Wakeham, S.G.** 1991: Variations in the distributions and isotopic compositions of alkenones in Black Sea particles and sediments. *Advances in Organic Geochemistry* 19, 277–85.

Geirsdóttir, A., Andrews, J.T., Ólafsdóttir, S., Helgadóttir, G. and **Hardardóttir, J.** 2002: A 36 Ky record of iceberg rafting and sedimentation from north-west Iceland. *Polar Research* 21, 291–98.

Giraudeau, J., Jennings, A.E. and **Andrews, J.T.** 2004: Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10,000 cal years: a view from the North Iceland shelf. *Quaternary Science Reviews* 23, 2127–39.

Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S.J. and **Jouzel, J.** 1993: Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* 366, 552–54.

Grove, J.M. 1988: *The Little Ice Age*. Methuen.

Guðmundsson, H.J. 1997: A review of the Holocene environmental history of Iceland. *Quaternary Science Reviews* 16, 81–92.

Hansen, B. and **Østerhus, S.** 2000: North Atlantic–Nordic Seas exchanges. *Progress in Oceanography* 45, 109–208.

Harrison, S.P., Prentice, I.C. and **Bartlein, P.J.** 1992: Influence of the insolation and glaciation on atmospheric circulation in the North Atlantic sector: implications of general circulation model experiments for the Late Quaternary climatology of Europe. *Quaternary Science Reviews* 11, 283–99.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C. and **Rohl, U.** 2001: Southward migration of the intertropical convergence zone through the Holocene. *Science* 293, 1304–08.

Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and **Aeschlimann, B.** 2003: Climate and the collapse of Maya civilization. *Science* 299, 1731–35.

Herbert, T.D. 2001: Review of alkenone calibrations (culture, water column, and sediments). *Geochemistry, Geophysics, Geosystems* 2, paper number 2000GC000055.

Hodell, D.A., Brenner, M., Curtis, J.H. and **Guilderson, T.** 2001: Solar forcing of drought frequency in the Maya lowlands. *Science* 292, 1367–70.

Hopkins, T.S. 1991: The GIN Sea: a synthesis of its physical oceanography and liturature review 1972–1985. *Earth Science Reviews* 30, 175–318.

Huntley, B. and **Prentice, C.P.** 1988: July temperatures in Europe from pollen data, 6000 years before present. *Science* 241, 687–90.

Ingólfsson, O., Norddahl, H. and **Haflidason, H.** 1995: Rapid isostatic rebound in southwestern Iceland at the end of the last glaciation. *Boreas* 24, 245–59.

Jennings, A.E., Knudsen, K.L., Hald, M., Hansen, C.V. and **Andrews, J.** 2002: A mid-Holocene shift in Arctic sea-ice variability on the East Greenland Shelf. *The Holocene* 12, 49–58.

Jiang, H., Seidenkrantz, M.-S., Knudsen, K.L. and **Eiríksson, J.** 2002: Late-Holocene summer sea-surface temperatures based on a diatom record from the north Icelandic shelf. *The Holocene* 12, 137–47.

Johannessen, O.M. 1986: Brief overview of the physical oceanography. In Hurdle, B.G., editor, *The Nordic seas*. Springer.

Kaldal, I. and **Vikingsson, S.** 1990: Early Holocene deglaciation in Central Iceland. *Jökull* 40, 51–66.

Karlén, W. and **Kuylenstierna, J.** 1996: On solar forcing of Holocene climate: evidence from Scandinavia. *The Holocene* 6, 359–65.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duvall, M.L., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.N., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliesner, B.L., Porinchu, D.F., Ruhland, K., Smol, J.P., Steig, E.J. and **Wolfe, B.B.** 2004: Holocene thermal maximum in the western Arctic (0–180 degrees W). *Quaternary Science Reviews* 23, 529–60.

Keigwin, L.D. 1996: The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* 274, 1504–08.

Keigwin, L.D. and **Pickart, RS.** 1999: Slope water current over the Laurentian Fan on interannual to millennial time scales. *Science* 286, 520–23.

Keigwin, L.D., Sachs, J.P., Rosenthal, Y. and **Boyle, E.A.** 2005: The 8200 year BP event in the slope water system, western subpolar North Atlantic. *Paleoceanography* 20, PA2003, doi:10.1029/2004PA001074.

Kim, J.H., Rimbu, N., Lorenz, S.J., Lohmann, G., Nam, S.I., Schouten, S., Ruhlemann, C. and **Schneider, R.R.** 2004: North Pacific and North Atlantic sea-surface temperature variability during the Holocene. *Quaternary Science Reviews* 23, 2141–54.

Kirkbride, M.P. and **Dugmore, A.J.** 2001: Timing and significance of mid-Holocene glacier advances in northern and central Iceland. *Journal of Quaternary Science* 16, 145–53.

Klitgaard-Kristensen, D., Rasmussen, T.L., Sejrup, H.P., Haflidason, H. and **Van Weering, T.C.E.** 1998: Rapid changes in the oceanic fronts in the Norwegian Sea during the last deglaciation: implications for the Younger Dryas cooling event. *Marine Geology* 152, 177–88.

Koç, N. and **Jansen, E.** 1992: A high resolution diatom record of the last deglaciation from the SE Norwegian Sea: documentation of rapid climatic changes. *Paleoceanography* 7, 499–520.

—— 1994: Response of the high-latitude Northern Hemisphere to orbital climate forcing: evidence from the Nordic Seas. *Geology* 22, 523.

Koç, N., Jansen, E. and **Haflidason, H.** 1993: Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian Seas through the last 14 ka based on diatioms. *Quaternary Science Reviews* 12, 115–40.

Koç, N., Jansen, E., Hald, M. and **Laberyrie, L.** 1996: Late glacial–Holocene sea surface temperatures and gradients between the North Atlantic and the Norwegian Sea: implications for the Nordic heat pump. In Andrews, J.T. and Al, E., editors, *Late Quaternary palaeoceanography of the North Atlantic margins*.

Special Publication, Volume 111. Geological Society, Boulder, Colorado.

Koch, L. 1945: The East Greenland ice. *Meddelelser om Gronland* 130, 346.

Kornilova, O. and **Rosell-Melé, A.** 2003: Application of microwave-assisted extraction to the analysis of biomarker climate proxies in marine sediments. *Organic Geochemistry* 34, 1517–23.

Kugelmann, O. 1989: Gletschergeschichtliche Untersuchungen im Svarfaoardalur und Skioadalur, Trollaskagi, Nordisland. Diplomarbeit, Institut fur Geographie, Universitat Munchen (unpublished).

—— 1991: Dating recent glacier advances in the Svarfaoardalur-Skioadalur area of northern Iceland by means of a new lichen curve. In Maizels, J.K. and Caseldine, C., editors, *Environmental change in Iceland: past and present*. Kluwer, 203–17.

Larsen, G., Eiriksson, J., Knudsen, K.L. and **Heinemeier, J.** 2002: Correlation of late Holocene terrestrial and marine tephra markers, north Iceland: implications for reservoir age changes. *Polar Research* 21, 283–90.

Mackintosh, A.N., Dugmore, A.J. and **Hubbard, A.L.** 2002: Holocene climatic changes in Iceland: evidence from modelling glacier length fluctuations at Sólheimajökull. *Quaternary International* 91, 39–52.

Madureira, L.A.S., Conte, M.H. and **Eglinton, G.** 1995: Early diagenesis of lipid biomarker compounds in North Atlantic sediments. *Paleoceanography* 10, 627–42.

Malmberg, S.-A. 1985: The water masses between Iceland and Greenland. *Journal of the Marine Research Institute* 9, 127–40.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B. and **Prentice, M.** 1997: Major features and forcing of high-latitude Northern Hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. *Journal of Geophysical Research* 102, 26 345–66.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., Van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R. and **Steig, E.J.** 2004: Holocene climate variability. *Quaternary Research* 62, 243–55.

Micaela Smith, L., Andrews, J.T., Castaneda, I.S., Kristjánsdóttir, G.B., Jennings, A.E. and **Sveinbjörnsdóttir, A.E.** 2005: Temperature reconstructions for SW and N Iceland waters over the last 10 cal ka based on $\delta^{18}O$ records from planktic and benthic foraminifera. *Quaternary Science Reviews* 24, 1723–40.

Moros, M., Emeis, K., Risebrobakken, B., Snowball, I., Kuijpers, A., McManus, J. and **Jansen, E.** 2004: Sea surface temperatures and ice rafting in the Holocene North Atlantic: climate influences on northern Europe and Greenland. *Quaternary Science Reviews* 23, 2113–26.

Muller, P.J., Kirst, G., Ruhland, G., Von Storch, I. and **Rosell-Melé, A.** 1998: Calibration of the alkenone paleotemperature index UK37′ based on core-tops from the eastern South Atlantic and the global ocean (60 degrees N–60 degrees S). *Geochimica et Cosmochimica Acta* 62, 1757–72.

Nesje, A. and **Kvamme, M.** 1991: Holocene glacier and climate variations in western Norway: evidence for early Holocene glacier demise and multiple Neoglacial events. *Geology* 19, 610–12.

Nesje, A., Matthews, J.A., Dahl, S.O., Berrisford, M.S. and **Andersson, C.** 2001: Holocene glacier flucuations of Flatbreen and winter-precipitation changes in the Jostedalsbreen region, western Norway, based on glaciolacustrine sediment records. *The Holocene* 11, 267–80.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S. and **Whitlow, S.I.** 1995: Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* 270, 1962–64.

Ólafsson, J. 1999: Connections between oceanic conditions off N-Iceland, Lake Mývatn temperature, regional wind direction variability and the North Atlantic oscillation. *Rit Fiskideildar* 16, 41–57.

Oppo, D. 1997: Millennial climate oscillations. *Science* 278, 1244–46.

Oppo, D., McManus, J.F. and **Cullen, J.L.** 2003: Palaeo-oceanography: deepwater variability in the Holocene epoch. *Nature* 422, 277–78.

Orvik, K.A., Skagseth, O. and **Mork, M.** 2001: Atlantic inflow to the Nordic Seas: current structure and volume fluxes from moored current meters, VM-ADCP and SeaSoar-CTD observations, 1995–1999. *Deep-Sea Research Part I–Oceanographic Research Papers* 48, 937–57.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A. and **Zielinki, G.** 1997: Arctic environmental change of the last four centuries. *Science* 278, 1251–56.

Prahl, F., Herbert, T., Ohkouchi, N., Pagani, M., Repeta, D., Rosell-Mele, A. and **Sikes, E.** 2000: Status of alkenone paleothermometer calibration: report from Working Group 3. *Geochemistry, Geophysics, Geosystems* 1, paper number 2000GC000058.

Prahl, F.G. and **Muehlhausen, L.A.** 1989: An organic geochemical assessment of oceanographic conditions at Manop site C over the past 26,000 years. *Paleoceanography* 4, 495–510.

Prahl, F.G. and **Wakeham, S.G.** 1987: Calibration of unsaturation patterns in long-chain ketone compositions for paleotemperature assessment. *Nature* 330, 367–69.

Prahl, F.G., Muehlhausen, L.A. and **Zahnle, D.L.** 1988: Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions. *Geochimica et Cosmochimica Acta* 52, 2303–10.

Rimbu, N., Lohmann, G., Kim, J.H., Arz, H.W. and **Schneider, R.** 2003: Arctic/North Atlantic Oscillation signature in Holocene sea surface temperature trends as obtained from alkenone data. *Geophysical Research Letters* 30, art. no.1280.

Rochon, A., De Vernal, A., Sejrup, H.-P. and **Haflidason, H.** 1998: Palynological evidence of climate and oceanographic changes in the North Sea during the Last Deglaciation. *Quaternary Research* 49, 197–207.

Rohling, E.J. and **Pälike, H.** 2005: Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature* 434, 975–79.

Rosell-Melé, A. 1998: Interhemispheric appraisal of the value of alkenone indices as temperature and salinity proxies in high-latitude locations. *Paleoceanography* 13, 694–703.

Rosell-Melé, A. and **Comes, P.** 1999: Evidence for a warm Last Glacial Maximum in the Nordic Seas of an example of shortcomings in UK37′ and UK37 to estimate low sea surface temperature? *Paleoceanography* 14, 770–76.

Rosell-Melé, A., Carter, J., Parry, A. and **Eglinton, G.** 1995a: Novel procedure for the determination of the UK37 index in sediment samples. *Analytical Chemistry* 67, 1283–89.

Rosell-Melé, A., Eglinton, G., Pflaumann, U. and **Sarnthein, M.** 1995b: Atlantic core-top calibration of the UK^{37} index as a sea-surface palaeotemperature indicator. *Geochimica et Cosmochimica Acta* 59, 3099–107.

Ruddiman, W.F. 2003: The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* 61, 261–93.

Ruddiman, W.F. and **Thomson, J.S.** 2001: The case for human causes of increased atmospheric CH4. *Quaternary Science Reviews* 20, 1769–77.

Rundgren, M. 1998: Early-Holocene vegetation of northern Iceland: pollen and plant macrofossil evidence from the Skagi peninsula. *The Holocene* 8, 553–64.

Rundgren, M., Ingólfsson, O., Bjorck, S., Jiang, H. and **Haflidason, H.** 1997: Dynamic sea-level change during the last deglaciation of northern Iceland. *Boreas* 26, 201–15.

Sarnthein, M. and **Altenbach, A.V.** 1995: Late Quaternary changes in surface water and deep water masses of the Nordic Seas and north-eastern North Atlantic: a review. *Geologische Rundschau* 84, 89–107.

Sarnthein, M., Jansen, E., Weinelt, M., Arnold, M., Duplessy, J.C., Erlenkeuser, H., Flatoy, A., Johannessen, G., Johannessen, T., Jung, S., Koc, N., Labeyrie, L., Maslin, M., Pflaumann, U. and **Schulz, H.** 1995: Variations in Atlantic surface ocean paleoceanography, 50-

degrees–80-degrees N – a time-slice record of the last 30,000 years. *Paleoceanography* 10, 1063–94.

Schulz, H.M., Schoner, A. and **Emeis, K.C.** 2000: Long-chain alkenone patterns in the Baltic Sea – an ocean–freshwater transition. *Geochimica et Cosmochimica Acta* 64, 469–77.

Sikes, E.L. and **Volkman, J.K.** 1993: Calibration of alkenone unsaturation ratios (uk37) for paleotemperature estimation in cold polar waters. *Geochimica et Cosmochimica Acta* 57, 1883–89.

Sikes, E.L., Volkman, J.K., Robertson, L.G. and **Pichon, J.J.** 1997: Alkenones and alkenes in surface waters and sediments of the Southern Ocean: implications for paleotemperature estimation in polar regions. *Geochimica et Cosmochimica Acta* 61, 1495–505.

Sonzogni, C., Bard, E., Rostek, F., Lafont, A., Rosell-Melé, A. and **Eglinton, G.** 1997: Core-top calibration of the alkenone index versus sea surface temperature in the Indian Ocean. *Deep-Sea Research* 44, 1445–60.

Steffenson, U. 1962: *North Icelandic waters, volume 3*. Rit Fiskideildar III, Bind.

Stötter, J. 1991: Geomorphologishe und landschaftsgeschichtliche Untersuchungen im Svarfaoardalur-Skioadalur, Trollaskagi, N-Island. *Munchener Geographische Abhandlungen*, B9, 166.

Stötter, J., Wastl, M., Caseldine, C. and **Häberle, T.** 1999: Holocene palaeoclimatic reconstruction in northern Iceland: approaches and results. *Quaternary Science Reviews* 18, 457–74.

Stuiver, M. and **Braziunas, T.F.** 1993: Modeling atmospheric C-14 influences and C-14 ages of marine samples to 10,000 BC. *Radiocarbon* 35, 137–89.

Stuiver, M. and **Reimer, P.J.** 1993: Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35, 215–30.

Stuiver, M., Grootes, P.M. and **Braziunas, T.F.** 1995: The GISP2 delta-18O climate record of the past 16,500 years and the role of the Sun, ocean and volcanoes. *Quaternary Research* 44, 341–54.

Swift, J.H. 1986: The Arctic waters. In Hurdle, B.G., editor, *The Nordic seas*. Springer, 129–53.

Swift, J.H. and **Aagaard, K.** 1981: Seasonal transitions and water mass formation in the Iceland and Greenland seas. *Deep Sea Research Part I: Oceanographic Research Papers* 28A, 1107–29.

Teece, M.A., Getlife, J.M., Leftley, J.W., Parkes, R.J. and **Maxwell, J.R.** 1998: Microbial degradation of the marine prymnesiophyte *Emiliania huxleyi* under oxic and anoxic conditions as a model for early diagenesis: long chain alkadienes, alkenones and alkyl alkenoates. *Organic Geochemistry* 29, 863–80.

Ternois, Y., Sicre, M.A., Boireau, A., Conte, M.H. and **Eglinton, G.** 1997: Evaluation of long-chain alkenones as paleo-temperature indicators in the Mediterranean Sea. *Deep-Sea Research I* 44, 271–86.

Thors, K. and **Boulton, G.S.** 1991: Deltas, spits and littoral terraces associated with rising sea-level – Late Quaternary examples from Northern Iceland. *Marine Geology* 98, 99–112.

Veum, T., Jansen, E., Arnold, M., Beyer, I. and **Duplessy, J.-C.** 1992: Water mass exchange between the North Atlantic and the Norwegian Sea during the past 28,000 years. *Nature* 356, 783–85.

Volkman, J.K., Eglinton, G., Corner, E.D.S. and **Forsberg, T.E.V.** 1980a: Long-chain alkenes and alkenones in the marine coccolithophorid *Emiliania huxleyi*. *Phytochemistry* 19, 2619–22.

Volkman, J.K., Eglinton, G., Corner, E.D.S. and **Sargent, J.R.** 1980b: Novel unsaturated straight-chain C37-C39 methyl and ethyl ketones in marine sediments and coccolithophore *Emiliana huxleyi*. In Douglas, A.G. and Maxwell, J.R., editors, *Advances in organic geochemistry 1979*. Pergamon, 219–27.

Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B. and **Xoplaki, E.** 2001: North Atlantic Oscillation – concepts and studies. *Surveys in Geophysics* 22, 321–81.

Williams, K.M., Andrews, J.T., Weiner, N.J. and **Mudie, P.J.** 1995: Late Quaternary paleoceanography of the mid- to outer continental shelf, East Greenland. *Arctic and Alpine Research* 27, 352–63.