Decadal variability of sea surface temperatures off North Iceland over the last 2000 yrs

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Abstract

Ocean variability at decadal time-scales remains poorly described partly because of the scarcity of high temporal resolution marine records. Here, we present a reconstruction of Sea Surface Temperatures (SSTs) over the past two millennia at unprecedented temporal resolution (2 to 5 years), from a marine core located off North Iceland. Alkenone paleothermometry was used to infer SST variability, and tephrochronology to built the age model. Spectral analyses of the SST signal indicate intermittent 20-25 year oscillations, with periods of strong and weak power, that are likely reflecting the ocean response to wind forcing, presumably the North Atlantic Oscillation (NAO). Warmer SSTs and paleo-magnetic proxy data, between 1000 and 1350 year A.D., overlapping the Medieval Warm Period (MWP), suggest enhanced heat transport across the Denmark Strait by the North Icelandic Irminger Current (NIIC) This is in contrast with the subsequent period, which includes the Little Ice Age (LIA), showing continuous cooling towards the 20th century. Reduced NIIC flow through the Denmark Strait likely resulting from higher freshwater and sea ice export from the Arctic would account for the observed colder conditions.

Keywords. Decadal variability; Sea Surface Temperature; North Atlantic; Alkenones; Medieval Warm Period; Little Ice Age; Iceland

1. Introduction

Understanding ocean variability and how much of it is due to ocean-atmosphere interactions or internal dynamics is a key issue of climate research. In the past decade, numerous studies have focused on the detection of decadal to century time-scale variability in observations and model simulations in order to identify patterns of natural ocean variability in the North Atlantic (Kushnir, 1994; Schlesinger and Ramankutty, 1994; Delworth et al., 1993; 1997; Kaplan et al., 1998, Delworth and Mann, 2000), but the shortness of observational time series prevented from investigating suitably multidecadal variability. Longer duration records resolving ocean variability at the highest possible resolution are thus crucial to improve knowledge of the physical mechanisms with time constants that are those of the ocean/atmospheric coupling and the meridional overturning circulation (MOC). Yet, paleoceanographic proxy records reaching subdecadal resolution and extending back over several centuries to millennia are still sorely lacking, mainly because of the difficulty to obtain undisturbed high sedimentation rate and well-dated marine sediments. In this paper, we present a unique 2000 year long Sea Surface Temperature (SST) record obtained at unprecedented temporal resolution (2-5 years) off North Iceland (MD99-2275 core: 66°33N; 17°42W, 470m, average sedimentation rate 250 cm/1000 years). This site is located in the sub-polar frontal zone, where overlying waters are influenced by the cold and low-salinity waters of the East Greenland Current (EGC) and the Icelandic Current (IC) both flowing southwards, mixing with the warmer and saltier waters of the North Icelandic Irminger Current (NIIC), a branch of the North Atlantic Drift surrounding Iceland by the West (Østerhus et al., 2005) (Figure 1 insert). This region is also highly sensitive to the North Atlantic Oscillation (NAO), the dominant large scale extratropical atmospheric forcing in the Atlantic sector (Hurrell, 1995). Owing to these features, the MD99-2275 core offers the opportunity to capture ocean circulation changes at decadal-scales and investigate their link with NAO.

2. Methods

SSTs were estimated using alkenones, which are well established as a valuable tool in paleoceanography (Conte et al., 2006). This biomarker series is biosynthesized by the ubiquitous marine algae *Emiliania huxleyi* growing in the ocean surface waters. It has been shown by Prahl and Wakeham (1987) that the unsaturation index of the C37 alkenones, UK'37 (C37:2/(C37:2 + C37:3)), is linked to SSTs. UK'37 values were determined along the MD99-2275 core and

converted into SSTs by applying the most widely used calibration produced by Prahl et al. (1988) (T= (UK'37 – 0.039)/0.034). Alkenones were analyzed following the experimental procedure described in Ternois et al. (1996). Briefly, about 1.5 g freeze-dried sediments were extracted in an ultrasonic bath for 15 min using a mixture of methylene chloride/methanol (2:1; v/v). The samples were then centrifuged for 15 min at 2000 rpm and the supernatant recovered. This operation was repeated two times. The three extracts were combined, concentrated and fractionated into compound classes by silica gel chromatography. Alkenone isolation was performed on 5% deactivated silica gel and stored in glass vials at -18°C prior to gas chromatographic analyses. Alkenones were analyzed on a Varian Star 3400 CX gas chromatograph equipped a flame ionization detector (FID) and septum programmable injector (SPI), on a fused CP-Sil-5CB silica capillary column (50 m x 0.32 mm i.d., 0.25 μm film thickness, Chrompack). The oven temperature was programmed from 100°C to 300°C at 20°C min-1. The analytical precision obtained after repeated injections was calculated to be less than 0.01 unit ratio. Taking advantage of the proximity of major sources of volcanic tephras, reconstruction of an age model with the best possible accuracy was enabled by tephrachronology. Its detailed description can be found in Larsen et al. (2002) and Eiríksson et al. (2004). Eight well-identified tephra layers were used to constrain the age model up to 3000 yrs cal B.P. (Table 1). The tephra layers V 1717, V1477, and V 1410, Hekla 1300 and Hekla 1104 are historically dated, the Settlement layer is dated on the basis of correlations with Grip ice core, while Snæfellsjökull I and Hekla 3 are radiocarbon dated on terrestrial material from Iceland. Due to the overpenetration of the Calypso corer, the upper part of the core was lost during coring operation. The missing portion was estimated to cover the last half-century.

3. Results

Figure 1a shows the 2000-year long history of the North Icelandic SSTs plotted as a function of age in calendar years A.D., indicating the tephra age-control points. Earlier water column and sediment trap data have shown that in high latitude oceans, summer is the main season of alkenone production (Sikes et al., 1997; Ternois et al., 1998), thus implying that UK' 37 in the MD99-2275 core is recording summer conditions. The water column alkenone data acquired during the cruise are in agreement with this seasonal pattern (Sicre et al., 2002). Furthermore, the SST estimate of 9°C determined in the nearby surface sediment (box-core HM107-2798) is

consistent with the recent compilation produced by Hanna et al. (2006), reporting that since 1874, July and August SSTs measured at Grimsey island have varied between 6.7°C and 9°C (see Table 3 in Hanna et al., 2006). The close correspondence between the surface sediment SST value and the instrumental data suggests that alkenones are reliably recording summer SSTs and that potential bias from surface water advection can be ruled out (Conte et al., 2006; Sicre et al., 2005; 2006). Modern SST values also emphasize a significant warming over the past decades.

The North Icelandic SST curve reveals several remarkable features. First, SSTs depict a broad cooling trend towards present, steepening over the last 500 years, with values ranging from ~7 to ~10 °C. Second, prolonged warm or cool centennial intervals are recognizable among which are the known climatic periods such as the Medieval Warm Period (MWP), the Little Ice Age (LIA), but also the Roman Warm Period (RWP) and cooler Dark Ages. Third, SSTs exhibit unexpected large amplitude oscillations with peak-to-peak difference of 1-2°C. The temporal characteristics of this signal were quantified by Morlet wavelet analysis to provide information on how features of variability evolve with time. We also computed spectral power with the multi-taper method developed by Ghil et al. (2002) over the whole time series to estimate statistical significance of peaks (Figure 2). Results reveal a dominant variability around 20-25 year period with distinct strong and weak energy intervals, and some power in the multidecadal range that is poorly characterized. High energy at the 20-25 year band is more pronounced in the early (0-200 A.D) and late (1250-1950 A.D.) portion of the record, and notably during the LIA.

3. Discussion

3.1. Medieval Warm Period and Little Ice Age

A remarkable feature of the North Icelandic SST record is the abrupt increase of ~1-1.5°C occurring within a decade ~980 A.D., maybe imputable to the onset of the MWP. This sustained warm period, lasting for several centuries, ends by a sharp cooling ~1350 A.D., following a brief cold episode ~1250 A.D. The same pronounced centennial scale warming, though not exactly synchronous, has been documented by the distant records from the Sargasso Sea (Keigwin, 1996), the Eastern sub-tropical Atlantic (deMenocal et al., 2000) and estuarine sediments of Chesapeake bay (Cronin et al., 2005), confirming its widespread occurrence in the North Atlantic region. A rise in the titanium content in the tropical Atlantic Cariaco basin sediments at ~930

A.D. has also been reported, from which a northwards shift of the ITCZ and MOC change were inferred (Haug et al., 2001). Indeed, strong MOC generates a cross equatorial SST gradient that causes the ITCZ to move northward (Vellinga and Wu, 2004).

In order to investigate the links between the North Icelandic SSTs and ocean circulation changes, anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM) and volumic low field susceptibility (k) were measured along our core. In an earlier study, Rousse et al. (2006) have shown that, in core MD99-2275, the magnetic mineralogy is uniformly made of magnetites, allowing the use of the ARM/k or ARM/IRM ratios to deduce changes in the magnetite grain size, and ARM to trace changes in the concentration of fine grain magnetites. These parameters in core MD99-2275 were thus utilized to identify time spans of major ocean circulation changes at the site. Lower concentrations of fine-grained magnetites associated to coarser grains are indicative of stronger currents. The ARM/k or ARM/IRM plots, shown in Figure 1b, suggest a general slowdown tendency of the ocean circulation over the past 2000 years, but more vigorous bottom currents during most of the warmer period off North Iceland, between 1000-1300 A.D., likely reflecting enhanced NIIC inflow. The NIIC is one of the three branches of the North Atlantic Drift (NAD) entering the Greenland-Iceland-Norwegian seas (GINS) and the major heat source for the North Icelandic shelf waters (Østerhus et al., 2005). The NIIC transport rate and subsequent heat flux strongly control temperature changes North of Iceland. A higher NIIC flow rate through the Denmark Strait results in enhanced heat transport towards the North Icelandic shelf, while a lower flow causes SSTs to decrease. The basin-wide recognition of the MWP temperature anomaly in the North Atlantic basin and associated more northerly position of the ITCZ lead us to hypothesize a strengthening of the MOC.

This period contrasts with the cold SSTs and enhanced 20-25 cycles of the LIA. Large cooling of the surface waters can result from heat exchange at the surface ocean by vertical mixing under strong wind conditions. Several proxy record sources already suggested that during the LIA, latitudinal gradients would have been steeper and westerly winds more intense, which at a basin-scale, would result in larger heat loss to the atmosphere (Keigwin, 1996; Kreutz et al., 1997; Hendy et al., 2002). On a regional scale, observations combined to high-resolution modelling investigations have recently shown that the NIIC flow rate across the Denmark Strait is largely controlled by local wind fields (Logemann and Harms, 2006). NIIC northwards transport

increases when the northerly component of local winds blowing across the strait decreases, while it significantly reduces or suppresses when northerly winds reinforce the EGC. Under extreme conditions, the EGC broadens to reach the point to even block the NIIC passage across the Denmark Strait. This was presumably the case between 1685-1704 during the severe phase of the LIA, where lowest temperature values were found at the time of the Maunder sunspot minimum (1680-1730 A.D.) (Lamb, 1979). Icelandic records indicate that ice began to be more prominent after 1200 year A.D. and that no vessels could reach the East Greenland coast from 1476 to 1822 (Lamb, 1979). Wind forcing is thus an important parameter for the northwards heat transport by the NIIC as well as the southwards transport of polar waters and sea ice from the Arctic by the EGC, through the Denmark Strait. It is likely that persistent conditions of high EGC import of freshwater waters from the Arctic could have contributed to alter buoyancy and decrease deep-water formation in the GINS. Recent data from Lund et al. (2006) have shown reduced MOC transport across the Florida Strait, by about to 10%, during the LIA. The southern shift of the ITCZ over that period, as revealed by the Cariaco record, further supports this idea and lead us to hypothesize that lower MOC during the LIA would have been caused by the massive intrusion of freshwater and sea ice from the Arctic.

3.2. Decadal variability

A near 20-year period has been found in various observation or proxy records such as the intensity of the winter zonal atmospheric circulation (Von Storch et al., 1993), the temperatures in central England (Folland, 1983; Plaut et al., 1995) and tree ring reconstructions (Mann et al., 1995; Cook et al., 1998), among others. These times series reproduce the lower frequencies evidenced in the NAO index spectrum, i.e. 24 and 8 years, suggesting a link between the short time scale variability of North Icelandic SSTs and NAO (Roger, 1984; Hurrell and Van Loon, 1997). However, multidecadal variability has been identified as the dominant mode of SST variability and linked to fluctuations of the MOC (Latif et al., 2004; Knight et al., 2005), while in our record such oscillations are poorly defined and less significant. A recent 1600-year simulation of the MOC variability by HadCM3 model (Third Hadley Center Coupled Ocean-Atmosphere General Circulation Model) has shown strong variance at time scales of 70-200 years and, intermittently, at 10-30 years (Vellinga and Wu, 2004). As opposed to the North Icelandic SST time series, centennial scale variability in this simulation was the dominant

oscillatory mode of internal MOC variability, a difference that could reflect the regional character of the North Icelandic SST time series and the predominant fingerprint of NAO forcing at this latitude. A high-resolution paleo-record documenting climate variability of the last millennia to which our data can be compared is from the mid-latitude Chesapeake Bay estuarine sediments, Eastern US (Cronin et al., 2005). Multi-taper analyses of the precipitation and temperature proxy records reconstructed at this site both indicate a strong variability around 40-80 year period in the early Holocene, shifting towards shorter 20-30 year period during the late Holocene (Cronin et al., 2005). Strong bi-decadal variability in the Chesapeake Bay time series is consistent with our data and further supports the idea of a link with NAO, and its stronger influence during the recent past. It is quite well-established that atmospheric processes drive North Atlantic SSTs at sub-decadal time scales. Atmospheric forcing produces perturbations that can be communicated by the main circulation and propagate in the North Atlantic within a few years. However, the exact link between NAO patterns, including the possible shift of its center of actions (Hilmer and Jung, 2000), and the ocean variability needs to be further explored within the instrumental period and paleo-records. Recent studies have shown that on decadal time scales, high NOA induces deeper convection in the Labrador Sea (Latif et al., 2006) and Irminger Sea (Pickart et al., 2003) and can therefore impact on the MOC variability (Latif et al., 2006). We speculate that during the LIA, NAO may have played a role by partly influencing the variation of sea ice and freshwater outflow from the Arctic, through the EGC.

4. Conclusion

This study demonstrates that shelf sediments can provide exceptional archives of the past climate and ocean circulation. The high-resolution North Icelandic SST time series reconstructed from alkenones has shown unexpected strong variability with bidecadal oscillations (20-25 years) comparable to those identified in the Late Holocene Chesapeake Bay sediments. These oscillations would primarily reflect the ocean response to NAO forcing. Colder conditions during the LIA could result from heat loss to the atmosphere due to stronger Westerly winds and/or a decline of the MOC as earlier suggested by Lund et al (2006). Enhanced export of freshwater and sea ice from the Arctic could have triggered a significant reduction of the deep-water formation, and subsequently of MOC, leading to severe LIA climate conditions. We speculate that NAO could have influenced the variations of the freshwater flow out of the Arctic. In contrast, during

the MWP, NIIC would have been stronger causing the observed 1.5°C warming off North Iceland. Future work on this core will focus on extending the reconstruction of SSTs to investigate the 3000-4000 years B.P. time interval where abrupt and large amplitude shifts of the ITCZ are seen in the Cariaco record, and on the 8200 year meltwater event.

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Figure Captions

Figure 1: (a) High resolution Sea surface temperature (in °C) derived from alkenone paleothermometry versus age A.D., over the last 2000 yr B.P. Temporal resolution of the blue curve is ranging from 2 to 5 years. The superimposed red curve is a 5 points running mean. Major known historical periods are reported. Back squares indicate tephra layers used to establish the age model. (b) The pink curve shows the ARM values and the dark blue curve plots the ARM/k ratio values (Rousse et al., 2006).

Figure 2: Results of spectral analyses of alkenone derived Sea Surface Temperature (SSTs) along the MD99-2275 core. We performed a continuous wavelet analysis of the data, using a Morlet wavelet. This analysis enables us to distinguish how the features of variability evolve with time. Spectral power was computed with a multi-taper method (Ghil et al., 2002) to estimate significance of peaks. Red noise tests were performed in order to assess the significance of the particular frequencies/periods present in the SST time series. The colored lines indicate the confidence interval for red noise tests.

Depth (in cm)	Age, (cal. BP)	Age, AD/BC (in AD/AC)	Marker horizons
101	230	1720	Veidivötn AD 1717
179	470	1480	Veidivötn AD 1477
209	540	1410	Veidivötn AD 1410
239	650	1300	Hekla AD 1300
275	850	1100	Hekla AD 1104
321	1080	870	Settlement Layer
460	1818	132	Snæfellsjökull I
687	2980	1030	Hekla 3

Table 1 : Depth in centimeters (cm), ages in year cal BP and in year AD of the tephra layers identified in core MD99-2275 used to build the age model.
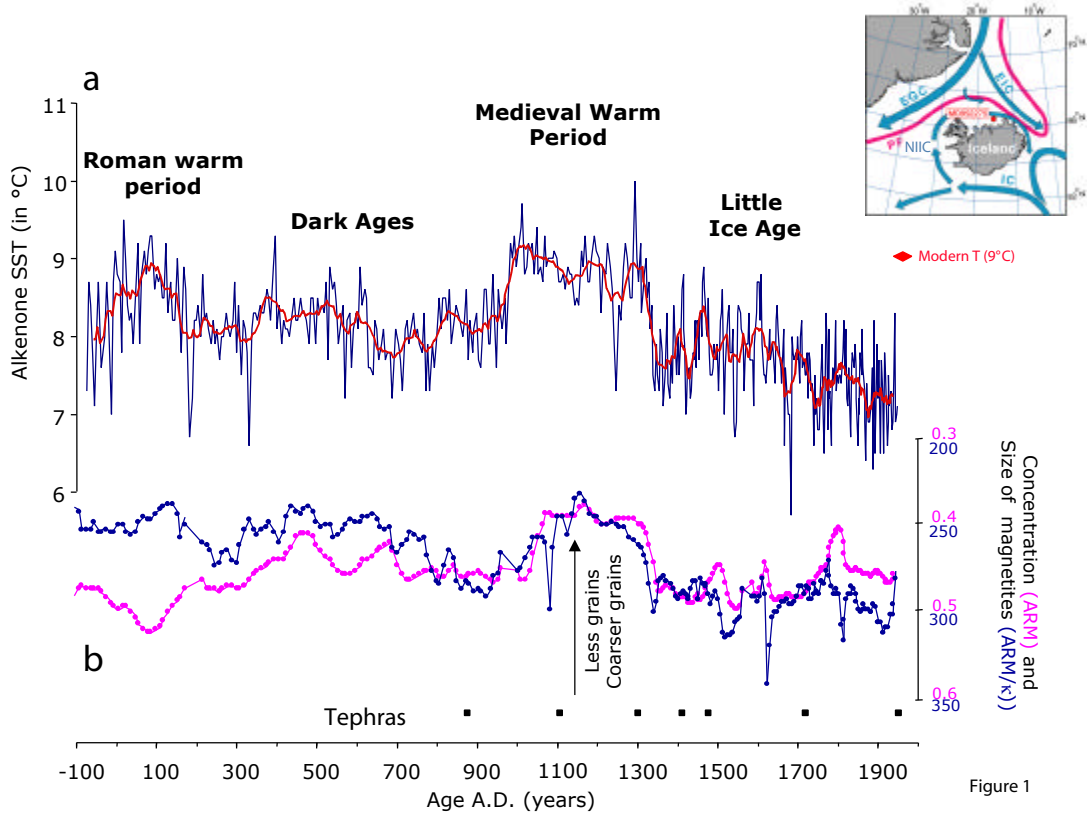
Figure 1

Figure 2

SST (1×2000)