# A 4500-year reconstruction of sea surface temperature variability at decadal time-scales off North Iceland

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Marie-Alexandrine Sicre [a,*], Ullah Ezat[a], Elwrick Guimbaut[a], Imane Dahhaoui[a], Pascal Yiou[a], Jón Eiríksson[b], Karen-Luise Knudsen[c], Eystein Jansen[d], Jean-Louis Turon[e]

(a) Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CNRS/CEA/UVSQ, Domaine du CNRS, Ave de la Terrasse, 91198 Gif-sur-Yvette, France, Phone: +33 1 69 82 43 34; Fax: +33 1 69 82 35 68; email: sicre@lsce.cnrs-gif.fr

(b) Earth Science Institute, University of Iceland, Askja, IS-101 Reykjavik, Iceland.

(c) Department of Earth Sciences, University of Aarhus, DK-8000 Aarhus C, Denmark.

(d) Bjerknes Centre for Climate Research, University of Bergen, Bergen, Norway.

(e) Département de Géologie et Océanographie, Université de Bordeaux I, Talence, France.

* corresponding author

**Abstract.** Marine paleo-records acquired at high temporal resolution provide critical data for testing numerical climate models and help to understand processes underlying ocean variability. This study presents a unique 4500-year reconstruction of sea surface temperature (SSTs) obtained from alkenones in the North Atlantic Polar Front area off North Iceland, at an average temporal resolution of 4-5 years. Spectral analysis of this signal shows dominant multidecadal oscillations (50-150 year period), which occurred with stronger amplitude between 2500-4200 years BP, hand in hand with distinct fluctuations of bottom currents indicated by paleomagnetic proxies. Contemporaneous large excursions of the Inter-tropical Convergence Zone (ITCZ) are also recorded by the distant Cariaco titanium time-series, suggesting a link with low latitude Atlantic climate. We speculate that the oscillations reflect changes of the Meridional Overturning Circulation (MOC) induced by increased ENSO activity.

**Keywords**: North Atlantic, Multidecadal variability, Meridional Overturning Circulation, Alkenone

## 1. Introduction

Climate in Europe is modulated by the northward transport of heat and moisture by the North Atlantic Current (NAC). Any change of this transport will impact on the winter temperature and precipitation patterns of northwestern European countries (Visbeck, 2002). Consequently, it is important to improve the understanding of the role of the ocean in broad-scale climate changes and the physical mechanisms underlying them, if we want to improve predictions. Advances in model performance and increased observational capacity have concurred to foster our comprehension of ocean variability over the past few decades to centuries. Yet, reliable quantification over longer time-scales remains a major challenge for climate research. Knowledge can be gained from palaeo-data but high-resolution and high-quality multi-proxy time series of the surface and deep ocean circulation need to be developed further. In the past few years, major efforts have been made to better describe marked changes of the past millennium, like the Medieval Warm Period (MWP) and the Little Ice Age (LIA) (Keigwin, 1996; Keigwin and Pickart, 1999; deMenocal et al., 2000; Eiríksson et al., 2006; Lund et al., 2006), or ocean circulation perturbed states such as the 8200 year melt water event (Ellison et al., 2006). Other studies have produced Holocene records at increasing temporal resolution to document the surface ocean variability, but few have achieved characteristic time-scales of the atmosphere/ocean coupling and the Meridional Overturning Circulation (MOC), i.e. decadal to centennial (Risebrobakken et al., 2003; Cronin et al., 2003; Cronin et al., 2005; Black et al., 2007; Sicre et al., 2008).

The MOC is affected by the North Atlantic Oscillation (NAO, winter index) (Latif et al., 2006), the dominant pattern of atmospheric variability in mid-latitudes North Atlantic (Hurrell, 1995). The NAO and associated wind fields alter the surface ocean buoyancy which in turn affect the convective activity of major regions of deep-water formation, i.e. the Labrador, Irminger and Greenland seas, as well as sea ice dynamics (Dickson et al., 1996). The northern North Atlantic is thus a key region for investigating MOC variability and its links to NAO within which shelf sediments off North Iceland represent an ideal sedimentary setting to undertake such studies. Owing to high sedimentation rates, North Icelandic sediments provide exceptional archives to capture surface ocean variability at decadal time-scales. Furthermore, the presence of well-known tephra layers from volcanic eruptions in Iceland allowed to develop an accurate tephrochronological age model, thus reducing uncertainties associated with radiocarbon dating of marine calcite.

## 2. Materials and Methods

### 2.1 Core location and oceanographic setting

The MD99-2275 core (66°33N; 17°42W, 440m water depth) analyzed in this study was retrieved on the North Icelandic shelf (Fig. 1) during the 1999 North Atlantic IMAGES cruise on the R/V *Marion Dufresne*. Because the top of the core was lost during normal coring operation, due to over-penetration of the Calypso corer, a box-core (BO5-2006-GBC-03C; 66°33.18N; 17°42.04W) was retrieved in 2006 (Millennium project, R/V *Bjarni Sæmundson* B05-2006 cruise) to recover the missing portion of Recent sediment. The sedimentation rate over the Holocene averages 250 cm/1000 years. The MD99-2275 was continuously sampled at 1-centimeter sampling step corresponding to a temporal resolution of 2-5 years, thus allowing resolving temperature changes at sub-decadal temporal resolution.

As can been seen from Fig. 1, the coring site is located close to the marine Polar Pront, in a climatically sensitive area where two important components of the North Atlantic circulation mixes, i.e. the warmer and saltier waters of the Irminger Current (IC), a branch of the NAC, and the cold and low-salinity southward flowing waters of the East Greenland Current (EGC) (Østerhus et al., 2005). The surface hydrology is also affected by sea ice and drifting ice exported from the Arctic Ocean and East Greenland.

### 2.2. Age model

Because of the proximity of volcanic tephra sources, precise age model can be constructed for the marine sediments avoiding bias from variable radiocarbon reservoir ages (cf. Larsen et al., 2002; Eiríksson et al., 2004). The tephrochronological age model developed for the MD99-2275 core is described in details by Eiríksson et al. (2004). The list of tephra layers used to build the age model over the past 4500 years is given in Table 1. The age control for box-core B05-2006-GBC03C (abbreviated as GBC-03C) is based on $^{210}Pb$ and $^{137}Cs$ measurements. Ages are expressed in years Before Present (BP; with 0 year BP = 1950 years AD) for the MD99-2275 core, and years AD for the GBC-03C core.

## 2.3. Alkenone determination

SSTs were estimated from the alkenone unsaturation index, $U^{K'}_{37}$, which is now a well-established tool in paleoceanography (Conte et al., 2006), using the widely applied calibration of Prahl et al. (1988). Chemical analyses were performed following the procedure described by Ternois et al. (1996). Briefly, lipids were extracted from 1.5 g of freeze-dried sediments in a mixture of $CH_3OH$:$CH_2Cl_2$ (1:2 v/v) in an ultra-sonic bath for 15 minutes. Samples were then centrifuged at 1000 rpm for 15 minutes and the supernatants containing the lipids, recovered and transferred in a pear-shaped flask. This operation was repeated twice. The three combined extracts were then evaporated to dryness using a rotary evaporator and a water bath at 50°C. The total extracts were transferred into a 4 mL vial using $CH_2Cl_2$ and evaporated to dryness under a $N_2$ stream. Alkenones were isolated from the total lipid extract by silica-gel chromatography using 5% desactivated silica-gel stored in hexane and an elution sequence of increasing polarity. The isolated alkenone fraction was then analyzed by gas chromatography on a Varian 3400 CX Series gas chromatograph. The oven was temperature programmed from 100°C to 300°C at a rate of 20°C/min. The temperature injector was set at 250°C and of the Flame Ionization Detector (FID) at 320°C. We used a 50 m long capillary fused silica column CPSil-5CB, with a 0.32 mm internal diameter and 0.25 µm film thickness.

## 3. Results

Water column studies, based on sediment traps and hydrocasts, have shown that alkenones in polar oceans are mainly produced in summer (Sikes et al., 1997; Ternois et al., 1998; Sicre et al., 2002). This implies that the SST reconstruction off North Iceland likely reflect summer conditions. As shown in Fig. 2, the North Icelandic SSTs over the last 4500 years vary from ~11 to ~6°C with strong high frequency variability. The 10-point running mean (red curve in Fig. 2) shows a clear warming between ~4200 yr BP and ~2500 yr BP, followed by a cooling towards present, except for a 3-4 century duration warmer interval which includes the MWP. This climatic anomaly is distinguished by a stepwise increase of 1-1.5°C around 1000 yr BP and an abrupt decline at ~600 yr BP, marking the onset of a cold period which encompasses the LIA.

The temporal characteristics of the SST signal were quantified by a continuous wavelet analysis (using Morlet wavelet). Spectral power was also computed with a multi-taper method (e.g. Ghil et al., 2002) to estimate the statistical significance of frequency peaks. Results of these calculations indicate significant variability at multidecadal (50-150 years) and to a lesser extent at bidecadal (20-25 years) time-scales, which are discussed in the next sections (Fig. 3).

SSTs reconstructed over the last 70 years from the GBC-03C box-core vary from 7.5 to 11°C and also depict short-term oscillations (Fig.4b). These values are consistent with the recent compilation of in-situ data produced by Hanna et al. (2006), reporting that since 1874, July and August SSTs measured from the nearby Grimsey island have varied between 6.7°C and 9°C (see Table 3 in Hanna et al., 2006). However, the latter values are averages over 20-25 year time periods, and higher frequency measurements indicate that summer month SSTs at Grimsey have occasionally reached 11°C.

## 4. Discussion

### 4.1 Bidecadal variability

Bidecadal variability in the North Icelandic SST signal has been reported as the dominant oscillation mode over the last 2000 years, though expressing intermittently, while multidecadal oscillations were poorly characterized (Sicre et al., 2008). In this extended record, multidecadal excursions are more significant, in particular between 4200 and 2500 yr BP. Yet, the 20-25 yr period remains important. Interestingly, SSTs reconstructed over the last 70 years from the GBC-03C core show four major oscillations, each one of roughly 20-year duration (Fig. 4b). The first two cycles depict a slight cooling ending by a temperature minimum of 7.7°C, while the next two tend to warmer values, ~10.6°C, in 1996. The severe cooling of the late 1960s coincides with the Great Salinity Anomaly (GSA), a massive intrusion of Arctic polar waters and sea-ice. At that time, a high pressure anomaly had increased to a maximum over Greenland producing strong northerly winds over the Greenland and Iceland seas, thus intensifying the EGC and spreading drifting ice southward into the sub-polar Atlantic (Dickson et al., 1996). The concomitant northeast shift of the Icelandic low and storm activity northwest of Iceland were concurrent factors enhancing the inflow of Arctic waters. Conversely, in the following years the Icelandic low was centered over Iceland and South Greenland, and southerly winds were more frequent. According to the recent study of Logemann and Harms (2006), reduced northerly winds/enhanced southerly winds favor higher transport rates of Irminger Current across the Denmark Strait leading to positive SST anomalies of the North Iceland shelf waters, and could thus account for rising SSTs after the GSA.

Over the same time interval, the NAO index experienced a major decadal shift: values decrease from the 1930s to the late 1960s and then increase until the mid-1990s (Fig. 4a). A comparison between Figs. 4a and b suggests a link between decadal SST variations and decadal NAO variations. We hypothesize that the SST cooling from 1925 to 1968, and subsequent warming up to 1996, are induced by the low frequency NAO forcing. This finding also suggests that intermittent 20-25 year period oscillations along the MD99-2275 record, could reflect the ocean response to periods of sustained NAO, either in positive or negative phases. Bidecadal variability has also been reported in the Mg/Ca and oxygen isotopes records of ostracod shells of the Late Holocene estuarine sediments of Chesapeake Bay and attributed to NAO forcing by Cronin et al. (2005). In a recent study, Latif et al. (2006) have shown, using hydrographic data and model results, that low frequency variability of NAO can induce MOC changes through Labrador Sea convection, which lead us to conjecture that bidecadal SST variability off North Iceland could be MOC driven.

### 4.2. Multidecadal variabillity

Highly significant variance in the 50-150 year band dominates in the ~ 2500-4400 year BP time interval. Multidecadal variability has been identified in modelling studies (Delworth et al., 1993; Delworth and Greatbach, 2000) and also seems to be a robust feature in globally distributed instrumental and proxy records over several centuries (Schlesinger and Ramankutty, 1994; Kushnir, 1994; Kaplan et al., 1998). This mode of variability has been linked to the MOC internal variability, although the dominant period differs between models, i.e. centered on 50 years in Delworth et al. (1997) and of about 35 years in Timmermann et al. (1998). Recently, wavelet analysis of natural variability of the MOC simulated over 1600-year long by the HadCM3 identified maximum variance at time-scale of 10-30 years and predominantly of 70-200 years (Vellinga and Wu, 2004), a result that comes close to our data analysis.

The high-resolution titanium (Ti) record of the ODP 1002 core from the anoxic Cariaco Basin of the Southern Caribbean (10°42N, 65°10 W, 893 m) is of interest for comparison to our record. This low latitude climatic signal has been interpreted as a proxy of rainfall/fluvial input to the basin driven by the N-S movements of the

Intertropical Convergence Zone (ITCZ) (Haug et al., 2001). Lower %Ti values indicate drier conditions and a more southern position of the ITCZ, while higher %Ti occur during wet conditions, when the ITCZ is more northern. Comparison with our data points out that major shifts of the ITCZ are contemporaneous to the large variations of the magnetic parameters and multidecadal SST oscillations (Fig. 5). Episodes of coarser sediments, indicative of more vigorous bottom currents, coincide with a northerly position of the ITCZ, and a stronger phase of MOC. Indeed, enhanced transport by MOC creates a cross equatorial SST gradient which causes the displacement of the ITCZ to the North (Vellinga et al., 2001). This shift in turn generates a negative freshwater anomaly that propagates to high latitude sinking regions thus starting to reverse the process, i.e. to slowdown the MOC, completing a multidecadal oscillation. The large amplitude multidecadal SST fluctuations between 4200 and 2500 year BP could thus be MOC driven and reflect alteration of the hydrological cycle in the tropical Atlantic.

The MOC is sensitive to perturbation of the freshwater balance in the tropics because it influences the surface ocean density in the tropical Atlantic, which can then trigger climate variations at high latitudes (Vellinga and Wu, 2004). Today, there is a net export of freshwater from the tropical Atlantic to the Pacific Ocean through the atmosphere. According to Schmittner et al. (2000), this flux can be modified by ENSO (El Niño Southern Oscillation) and induce changes in the Atlantic MOC. During El Niño years, more freshwater is exported from the Atlantic to the Pacific, whereas this water export is decreased during La Niña years. Sensitivity experiments performed by Schmittner et al. (2000) using a coupled ocean-atmosphere model indicate that MOC is increased for larger export of freshwater out of the Atlantic and/or longer persistence of the perturbation, that is to say in a mean climate state shifted into stronger and/or more frequent ENSO.

To investigate further this hypothesis, our data were compared to the high-resolution record of storm-derived deposits from Laguna Pallcacocha (Ecuador), which provides a unique high-resolution description of El Niño events over 15,000 years (Rodbell et al., 1999). This record establishes that the periodicity of El Niño was >15 years in Late glacial to early Holocene. Modern El Niño periodicity of 2 to 8.5 years became most apparent after 5000 years, in particular between 5000 and 2500 yr BP when both strength and frequency increased (see Figure 5 in Rodbell et al., 1999). According to Haug et al. (2001), the large oscillations of the %Ti seen at the time of this marked increase of ENSO activity reveal a dynamical link between the two regions. Increased ENSO, by increasing the freshwater export from the Atlantic, would have generated salinity anomalies in the tropical Atlantic, thus affecting high latitudes sinking regions and subsequently the MOC and ITCZ dynamics. Adding our results to this scenario, we speculate that the multidecadal SST variability off North Iceland results from multidecadal MOC variability in response to increased ENSO activity.

## 5. Conclusions

We generated a unique 4500-year SSTs record obtained at 2 to 5-year temporal resolution for the high-latitude North Atlantic, in the oceanographic Polar Front area off North of Iceland, to explore ocean variability at decadal time-scale. Spectral analysis of this signal reveals two modes of strong variance, at bidecadal (20-25 year) and multidecadal (50-150 years) time-scales, with strong and weak phases along the record.

Low frequency NAO forcing is likely responsible for the bidecadal variability of SSTs. Larger amplitude multidecaldal oscillations between 4200 and 2500 year BP, clearly expressed in the SST and paleomagnetic proxy signals, are likely linked to MOC activity. Comparison with the distant high-resolution %Ti record from Cariaco Basin and the gray-scale of Pallcacocha sediments suggests a dynamic link between the hydrological cycle of the tropical Atlantic and the high latitude ocean variability, possibly triggered by ENSO. Enhanced frequency and strength of El Niño, by increasing the freshwater export flux from the Atlantic, could have led to multidecadal MOC oscillations during this time period. Overall, our results emphasize the importance of forcing frequency in triggering ocean perturbation.

## 6. Acknowledgements

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## Figure Captions

Fig. 1: Map showing the location and core sites used in this study: MD99-2275 (66°33N; 17°42W) and BO5-2006-GBC03C (66°33.18N; 17°42.04W). The main surface currents are indicated by the arrows (modified after Hurdle, 1986).

Fig. 2: Alkenone derived Sea surface temperature estimates (SSTs) over the past 4500 years, in the MD99-2275 core. The calibration established by Prahl et al. (1988) was used to convert $U^{K'}_{37}$ into SSTs. Black diamonds indicate tephra layers.

Fig. 3: Results of spectral analyses of alkenone derived sea surface semperature (SSTs) times series over the past 4500 years, in the MD99-2275 core. Continuous wavelet analysis of the data was performed using a Morlet wavelet. 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.

Fig. 4: Comparison of (a) the winter NAO index values smooth with a 10 year running mean and, (b) alkenone sea surface temperature (SSTs) from the box-core BCO5-2006-GBC-03C.

Fig. 5: Comparison of (a) sea surface temperatures derived from alkenone over the last 4500 yr BP from MD99-2275 core, (b) bulk titanium content of the Cariaco basin sediments from the ODP site 1002 (Haug et al., 2001), (c) the pink curve shows the ARM values and, (d) the dark blue curve plots the ARM/$\kappa$ ratio values from Rousse et al. (2006). Blue shades areas indicate time span of large fluctuations in the proxy records.

| 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 |
| 941 | 4200 | 2250 | Hekla 4 |
| 1552 | 7125 | 5175 | Hekla 5 |

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.