A 100-year long record of alkenone-derived SST changes by Southeast Greenland

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1. Introduction

In the early part of this century, the Greenland Ice Sheet (GIS) experienced a marked increase in net mass loss (Rignot and Kanagaratnam, 2006; van den Broeke et al., 2009), stimulating research for better understanding how such future glacier changes will affect global sea level rise. In Southeast Greenland, outlet glaciers thinned, accelerated and retreated between 2003 and 2005 (Howat et al., 2007, 2008; Moon and Joughin, 2008; Stearns and Hamilton, 2007; Luckman et al., 2006, Rignot and Kanagaratnam, 2006), and it was suggested that concurrent rising temperatures of subsurface ocean currents may have triggered the onset of this acceleration (Nick et al., 2009; Straneo et al., 2010, 2011, 2012; Murray et al., 2010). Likewise, the early 2000s thinning, retreating and doubling of flow velocity of the Jakobshavn Isbrae in West Greenland has been linked to a pulse of warm waters in the West Greenland Current (WGC) propagating up the West Greenland coast and entering Disko Bay in 1997 (Holland et al., 2008). The exact processes involved in ocean-forced destabilization of outlet glaciers is still not well understood, but it is believed that rapid submarine melting of calving faces is an important mechanism for glacier calving (Rignot and Jacobs, 2002; Rignot et al., 2010) and that changes in North Atlantic ocean heat transport may decrease the support from the buttressing ice mélangé in front of the glacier margin (Vieli and Nick, 2011).

Ice sheet mass changes of the GIS have only been estimated for the past 20–30 years using satellite data. Likewise, the observational SST record on the continental shelf around Greenland is sparse in space and time, and hydrographic surveys in the near-shore and fjord waters virtually absent prior to 2008 (cf. Straneo et al., 2010; Murray et al., 2010). Therefore, in order to establish a more firm causal relationship between ocean variability and glacier dynamical changes we need to explore longer timescales, which requires the use of proxy records (Andresen et al., 2011, 2012).

In this paper, we present a 100-year long SST time-series based on the C27 alkenone from a sediment core retrieved in Sermilik Fjord. Alkenone biomarkers in the open ocean waters are mainly
produced by the prymnesiophytae, *Emiliania huxleyi*, growing in the photic zone (Volkman 2000). The unsaturation index of the $C_{37}$ alkenones ($U_{37}^K$) in marine waters has been shown to be highly correlated to water temperature on a global scale (Prah et al., 1988; Conte et al., 2006). We argue that alkenone SSTs derived from the fjord core are indicative largely of property changes of surface waters occurring just outside of Sermilik Fjord. This conclusion is supported by comparing our results to oceanographic data obtained from the broader shelf region. Finally, we discuss the link between ocean variability and glacier dynamical changes on longer timescales by comparing alkenone SSTs with a proxy record of Helheim Glacier calving.

2. Setting

Sermilik Fjord is ca. 80 km long with a width varying between 7 and 13 km. The bathymetry documents a U-shaped fjord with steep side walls and depths of 920 m at the mouth and 600 m at the northern end of the fjord extending approximately in a north-south direction (Schjøth et al., 2012). The northern end of the fjord branches into three fjords each containing ice-calving glaciers. The westernmost glacier – the Helheim Glacier – is a fast flowing glacier and the third most prolific exporter of icebergs in Greenland (Rignot and Kanagaratnam, 2006). The two northern glaciers, Midgaard and Fenris Glaciers are far less ice productive compared to Helheim (Mernild et al., 2010).

According to MODIS satellite images for the past few years (http://ocean.dmi.dk/arctic/modis.php), open water conditions occur frequently in the fjord throughout the winter as fjord-ice is broken, likely due to strong currents and storms. A marked ice-mélange, with inter-annually varying extension, is situated in front of the Helheim Glacier.

The oceanographic conditions on the Southeast Greenland shelf are characterized by the East Greenland Current (EGC), which transports cold and fresh sea ice-laden surface waters derived from the Arctic Ocean and glacial melt water from East Greenland that has an inner near coastal branch, the East Greenland Coastal Current (EGCC) (Sutherland and Pickart, 2008) (Fig. 1). Off Southeast Greenland, this cold upper (~250 m) layer is underlain by warmer and saltier waters derived from the Irminger Current (IC) (Malinberg 1985, Murray et al., 2010), which is a branch of the North Atlantic Current. Deep troughs (300–800 m) transect the shallow shelf (100–200 m) and thereby allow not only the upper cold waters, but also the warm subsurface waters to circulate within the Sermilik Fjord, either through estuarine circulation (Murray et al., 2010) or shelf-driven exchange (Straneo et al., 2010). Hence, the hydrographic conditions in Sermilik Fjord are characterized by a two-layer stratification with warm (3.5–4 °C) IC-derived waters from a depth of 200–300 m and downwards overlain by ~1 to +1 °C cold Polar Waters advected by the EGCC-EGCC water mass system (Fig. 2). In summer, the uppermost 10–20 m are characterized by low-salinity waters from glacier runoff and the temperature can be up to several degrees Celsius due to solar heating (Straneo et al., 2010).

Interaction between the IC and EGCC over the shelf influences temperatures and the interface depth (i.e. the thermocline), potentially altering the amount of heat reaching the glacier margins and its ice-mélange in the fjord (Straneo et al., 2010, 2011; Sutherland et al., 2013).

3. Methods

Alkenone analysis was carried out on sediment core ER07 obtained from Sermilik fjord (Fig. 1B). This core was retrieved from 525 m water depth (66°00’59”N, 37°51’07”W) and dated by means of $^{210}$Pb chronology and analyzed for grain size composition using a Malvern laser sedigraph. The chronology was calculated using the Constant Rate of Supply (CRS)-model (Appleby and Oldfield, 1983) and calculations of the activities of unsupported $^{210}$Pb in the lower part of the cores were based on regression of activity versus accumulated mass depth in order to increase the robustness of the age models. Further details on methodologies behind ER07 $^{210}$Pb chronology and sedimentology are provided by Andresen et al. (2012). The upper 24 cm of ER07 was sampled continuously every 0.25 cm for alkenone determination leading to 43 levels to be analyzed (higher sampling density in the upper part of the core).

Alkenones were extracted from freeze-dried sediments using a dichloromethane/methanol mixture (2:1 v/v) and isolated from the total lipid extract by silicagel chromatography (Ternois et al., 1997). The purified fractions were then analyzed by gas chromatography using a Varian 3400CX gas chromatograph and a CPSil5 capillary column (50 m length, 0.32 i.d., and 0.25 μm film thickness) equipped with a FID detector and a septum programmable
in estuarine sediments of Chesapeake Bay reached up to 40% of the total C$_{37}$ alkenones at temperature above 25°C (Mercer et al., 2005). This result indicates that besides marine producers local haptophyceae contributed to the production of this compound.

U$_{37}^{C}$ values in Sermilik Fjord range from 0.31 to 0.47 (Fig. 4) contrasting with the lower values found in the coastal waters of Chesapeake Bay (0.118–0.313) (Mercer et al., 2005) and those found in a Norwegian fjord (Conte et al., 1994). Higher U$_{37}^{C}$ index in Sermilik fjord sediments therefore suggest a dominant marine alkenone source with only minor contribution of autochthonous haptophyceae in Sermilik fjord sediments. U$_{37}^{C}$ converted to SSTs using Prahl et al.’s calibration range between 8 and 12.5°C with a mean value of ca. 10°C (Fig. 4). For comparison, SSTs calculated from the calibration establish by Mercer et al. (2005) (U$_{37}^{C}$ = 0.0137–0.04) for coastal/estuarine settings leads to unrealistic values ranging from 26.8 to 38.9°C, from which we hypothesize that the marine calibration likely provide better SST estimates and useful indication of its variability. SSTs along the core vary but are generally higher during the late 1930s and show a broad increase since 2000. Marked minima are observed in the 1960s, 1980s and 1990s.

5. Discussion

5.1. Sedimentation regime in the fjord

A large number of sediment core studies from other East Greenland fjords; Kangerlussuaq (Svendsen et al., 1996; Smith and Andrews, 2000; Smith et al., 2002), Nansen Fjord (Smith and Andrews, 2000; Smith et al., 2002; Jennings and Weiner, 1996; Jennings et al., 2001) and Scoresby Sund (Dowdeswell et al., 1993, 1994; O’Cofaigh et al., 2001), also situated by marine-terminating glaciers, describe in details the characteristic sediment lithofacies and the glacial processes involved in their formation. This information has been used to study the sediment cores from Sermilik Fjord. The massive diamicton facies, with abundant pebbles in cores from the mid-part of the fjord, have been interpreted as resulting from iceberg delivery of heterogeneous debris under the assumption that sand grains are too large to be carried in suspension by the melt water plume. Calving variability of Helheim Glacier for the past 120 years has been reconstructed in a previous study (Andresen et al., 2012) by averaging three $^{210}$Pb dated records, including ER07, of sand deposition (amount of sand deposited per year) taken from the mid-region of the fjord. The general conclusions from this study, thus taking into account changes in sand deposition in all three cores, are that iceberg discharge was markedly higher in the 1930s and 2000–2005 (Fig. 5F).

The occurrence of microfossils (foraminifera and diatoms) is low in the mid-fjord cores, most likely because harsh environmental conditions in the fjord waters restrict biological productivity. Limited light penetration due to sea ice and icebergs and high loads of sediments in the turbid, fresh and cold surface waters will likely decrease the photosynthetic activity of phytoplankton inhabiting these fjord waters.

4. Results

Core ER07 is massive diamiction facies and contains on average 20% sand in the 63–1000 μm fraction, 45% silt and 35% clay (Fig. 3A). The upper 24 cm represent the last 100 years according to $^{210}$Pb chronology (Fig. 3B and C). The time resolution is on average 2.5 years per sample and age uncertainties are in the order of ± 2 to 6 years.

The C$_{37}$ alkenone distribution is dominated by C$_{37}$:4 in Sermilik fjord sediments representing on average 65% of the total C$_{37}$ alkenones, which is quite unusual for open ocean waters even cold and low salinity ones. However, C$_{37}$:4 have been reported in cold ocean surface waters of the North Atlantic and Nordic Seas (Sicre et al., 2002) yet at lower abundances (up to 35%). Percent of C$_{37}$:4 in estuarine sediments of Chesapeake Bay reached up to 40% of the
thus allowing warm ‘detrital’ alkenones to enter the fjord and settle to the bottom floor. Several studies involving modern datasets already highlighted potential biases introduced by lateral advection of alkenones by strong surface ocean currents (Conte et al., 2006; Rühleman and Butzin, 2006; Mollenhauer et al., 2006). Sediments of the last glacial period from the Southern Indian Ocean revealed offsets between alkenone and foraminiferal transfer function SSTs due to advective transport of ‘warm’ alkenones by the Agulhas retroreflection to the core site (Sicre et al., 2005). A similar phenomenon related to Irminger Sea Water transport by the East- and West Greenland Current system has been reported in the north eastern Labrador Sea during the last deglacial period by Knutz et al. (2011).

Our hypothesis is supported by a recent analysis of data from the Southeast Greenland shelf derived from deep diving seals tagged with satellite relay depth loggers equipped with temperature sensors (Sutherland et al., 2013). These data show that the water column in connection with the deep trough just outside Sermilik Fjord (Box 1 in Fig. 1B) is often characterized by 8–11 °C warm water with no vertical variation during summer and fall (Fig. 2), and it was suggested that this warm water originates from the Irminger Current flowing along the continental slope. Indeed the temperature range derived from the seal data is similar to that recorded by alkenones deposited inside Sermilik Fjord. This supports the notion that the alkenones are mostly from outside the fjord and that they are indicative of water temperatures on the shelf region outside Sermilik Fjord and to a lesser degree also further upstream of the warmer waters of the IC. This conclusion is supported by Sutherland et al.’s (2013) observation that the region just outside Sermilik Fjord is a frontal region between warm surface IC and cold surface EGC. In such a region an associated enhanced vertical turbulent supply of nutrients (Gawarkiewicz and Chapman (1992)) would sustain primary production, including prymnosiphytes, as also observed by more northerly frontal regions of the Denmark Strait (Thordardottir 1977; Knudsen and Eiriksson, 2002). Increased biological production in this area is also supported by the high concentration of seal dives recorded with respect to neighboring regions (Sutherland et al., 2013). Considering the temperature values of the upper waters inside the fjord (≤ 4 °C; Fig. 2), local production is unlikely to have contributed significantly to sedimentary alkenone and it is therefore most probable that alkenone distributions reflect advection of subsurface waters into the fjord.

5.3. Assessing alkenone SSTs

In order to evaluate the alkenone SSTs as reflecting SST variability outside Sermilik Fjord, they are compared with the Shelf Index established by Andresen et al. (2012) (Fig. 5D). Even though this data set is generated by data from regions relatively remote from Sermilik Fjord, they still belong to the same regional front system and should thus display the same temporal variability.

The Shelf Index was previously proposed (Andresen et al., 2012) to describe the oceanographic variability in Sermilik Fjord and the nearby shelf accounting for the combined variability of the presence of Irminger Water and Polar Waters. We briefly summarize it here. Variability in the IC was reconstructed using a time series from 1876 to 2007 of annual mean SSTs in an area south of Iceland, where the IC Waters upstream Greenland occupy a layer of several hundred meters extending to the surface (Fig. 5A).
Periods of increased IC temperatures have been associated with a thickening of the Atlantic water layer (Våge et al., 2011). The Storis Index given by Schmith and Hansen (2005) and updated, 2000–2007, by Andresen et al. (2012) is used as a proxy for Polar Waters. It is defined as the amount of multi-year sea ice that exits the Arctic Ocean via Fram Strait, around Cape Farewell and onto the SW Greenland shelf (Fig. 5B) and is available for the period 1820–2007. It has been defined as the northernmost position on the southwest coast, relative to Cape Farewell, of Sermilik Fjord sediment records. A significant cross-correlation has been found between the Storis Index and the volume transport of sea-ice through Fram Strait derived from an ocean model (Schmith and Hansen, 2005). We use the Storis Index as a proxy for the Polar Water transport within the EGC assuming that the sea-ice export is correlated with the fresh water export through Fram Strait (Andresen et al., 2012). These Atlantic and Polar water records were subsequently normalized (by subtracting the mean and dividing by the standard deviation) and a Shelf Index was obtained by subtracting the resultant EGC Current index from the IC Water index. By doing so the two water masses are assumed weighted 1:1 in the Shelf Index in absence of information indicating different weighting of either water mass. A positive (negative) Shelf Index implies increased (decreased) influence of Irminger Water and decreased (increased) influence from the EGC on the shelf.

The Shelf Index was previously assessed by comparison with repeat hydrographic surveys from Fylla Bank off Southwest Greenland (Andresen et al., 2012, Fig. 5C). The Fylla Bank surveys were performed for the 1950–2010 period (Ribergaard, 2011) and extended back to 1876 (Ribergaard et al., 2008) using surface water temperature anomaly data (Smed, 1978). Even though these measurements are from the south-western side of Greenland, the continuity of the East and West Greenland Currents around Cape Farewell suggests that variability at Fylla Bank is also representative of the variability upstream by the southeast Greenland shelf and in the polar frontal zone (Bacon et al., 2008). The Shelf Index is statistically significant correlated with the Fylla Bank data (Andresen et al., 2012).

Similarities are observed between the alkenone-derived SST (Fig. 5E), the Shelf Index (Fig. 5D) and the Fylla Bank SSTs (Fig. 5C). Episodes with relatively warm conditions are recognized in the late 1930s and after 2000, as well as minor warming in the mid-1970s (red regions). During these warm periods, alkenone SSTs are slightly higher than those just outside the fjord emphasizing enhanced contribution of warmer IC waters which in summer can reach 11–12 °C. The Great Salinity anomalies (GSAs), which occurred in the mid-1960/70s, 1980s and 1990s are all recognized as cooling episodes in both the alkenone SSTs, the Shelf Index and the Fylla Bank data (blue stipled lines in Fig. 5). These were episodes with an increased amount of multi-year pack ice exported from the Arctic Ocean via the EGC. The episode in the mid-1960/70s was a more severe kind of a GSA, where the fresh surface water anomaly reached the northern coast of Iceland and was further transported with the WGC to the Labrador Sea and Newfoundland (Belkin, 2004). We investigated the link between the alkenone-derived SSTs and the Shelf Index more statistically rigorously. Interannual variations are strongly damped in the proxy-based alkenone derived SST, and therefore we low-pass filtered the Shelf Index with a five year moving average so that the two series would get similar spectral characteristics. We then calculated their detrended correlation coefficient as 0.34. The two-sided 90% confidence band on this value was estimated by block-bootstrapping (Wilks, 1997) and we obtained the limits –0.04 and 0.56. Varying the block length between 5 and 15 years did not significantly change this.

The effect of uncertainties in the age model on the correlation coefficient was also considered. This was done by a Monte Carlo procedure where the age of each point in the record of alkenone SSTs was perturbed according to the uncertainties in the dating (Fig. 3c). From this we obtained a confidence band with limits 0.11 and 0.54. All this enable us to conclude with some justification that we have a relationship on the longer time scales between alkenone-derived SSTs and the Shelf Index.

Thus, comparison of the alkenone SSTs with the seal-derived SSTs and with the Shelf Index suggests that alkenones from Sermilik Fjord sediment reflect mainly SST changes outside Sermilik Fjord and to a lesser degree also further upstream of the warmer waters of the IC. Our results thus show that the observed alkenone SSTs variability is linked, to a certain degree, with shelf water property and variability caused by changes in the IC and EGC current systems.
5.4. Comparing reconstructed ocean temperature with glacier changes in Greenland

The correspondence between climatic and oceanographic changes and the variability in the reconstructed changes in iceberg calving from Helheim Glacier was previously investigated (Andresen et al., 2012). However, due to a lack of data from local hydrographical surveys, the calving record was compared with SST data from south of Iceland, the Storí Index and the Shelf Index assuming that the heat content of the waters reaching the glacier and its mélange may be linked to regional variability. It was found that on multi-decadal timescales, calving is linked with synchronous changes in the Northern Irmingen Sea SSTs. SSTs in this region reflect the Atlantic Multi-decadal Oscillation (AMO), which is a multi-decadal mode of variability (oscillation of 65–70 years) occurring in the North Atlantic Ocean and is usually defined from patterns of SST variability; i.e. a positive (negative) mode is characterized by relatively high (low) SSTs (Schlesinger and Ramankutty, 1994). Furthermore, short-term (3–10 years) calving peaks were coincident with short-term episodes of positive Shelf Index indicating that increased IC inflow and/or warming along with decreased flow of Storí and EGC are associated with enhanced calving.

The alkenone SST data strengthens the link between oceanographic variability and Helheim Glacier calving (Andresen et al., 2012) with a detrended correlation coefficient of 0.37 and 90% confidence band with limits 0.09 and 0.56. Also the limits of the confidence band associated with uncertainties in the age model were estimated at 0.02 and 0.48 (see Section 5.3 for the statistical method).

A new and interesting finding is that the alkenone SST data show a record peak in the late 1930s at the culmination of the so-called Early 20th Century Warming (Wood and Overland, 2010) and that it is broadly concordant with a calving maximum in 1940 (Fig. 5E and F). The upstream SSTs from south of Iceland do not show a record of high SST at this time – rather they resemble the AMO pattern with generally high SSTs in 1925–1965 (Fig. 5A). A possible explanation is that during the 1950s and 1960s the warm IC waters may have been mixed and cooled more intensively by the EGC upon reaching Southeast Greenland than during the 1930s and 1940s, when sea ice was less abundant and the EGC weaker (Schmith and Hansen, 2005; Fig. 5B). The same pattern of decreased ocean temperatures in the 1950–1960s is observed in West Greenland (Lloyd et al., 2011; Fig. 5G). In this study, benthic foraminifera assemblage changes in sediment cores obtained from Disko Bay by Jakobshavn Isbrae were used to reconstruct temperature variability at 300 m water depth. According to aerial Disko Bay by Jakobshavn Isbrae were used to reconstruct temperature variability at 300 m water depth. According to aerial

The temperature range of 8–12 °C suggests that alkenones were produced outside the fjord and in the IC, and that production in the uppermost surface waters in the fjord was minor. The resemblance of alkenone SST variability with the Shelf Index emphasizes the regional character of this signal and its link to IC and EGC variability. Our results confirm previous findings on the important role of the regional ocean forcing on outlet glacier stability, particularly the marked calving episode of the late 1930s. They also provide valuable information on the role of ocean and its heat content to Greenland Ice Sheet melting and succeeding sea level rise and emphasize the need to better account for ocean/sea ice interactions in modeling studies.

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