

Durham Research Online

Deposited in DRO:

11 May 2017

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Andresen, Camilla S. and Sicre, Marie-Alexandrine and Straneo, Fiammetta and Sutherland, David A. and Schmith, Torben and Hvid Ribergaard, Mads and Kuijpers, Antoon and Lloyd, Jerry M. (2013) 'A 100-year long record of alkenone-derived SST changes by Southeast Greenland.', *Continental shelf research.*, 71 . pp. 45-51.

Further information on publisher's website:

<https://doi.org/10.1016/j.csr.2013.10.003>

Publisher's copyright statement:

NOTICE: this is the author's version of a work that was accepted for publication in *Continental Shelf Research*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in *Continental Shelf Research*, 71, 1 December 2013, <https://doi.org/10.1016/j.csr.2013.10.003>

Additional information:

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

Highlights

- Alkenone analysis on sediment core from Sermilik Fjord, SE Greenland.
- Reconstruction of ocean surface temperature changes of the past 100 years.
- Alkenones advected and represent temperature changes on nearby shelf.
- Warm ocean c. 1940 concurs with increased calving from Helheim Glacier
- Similar to observation from Disko Bay and Jakobshavn Isbræ in West Greenland.

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

Camilla S. Andresen^{1*}, Marie-Alexandrine Sicre², Fiammetta Straneo³, David A. Sutherland⁴,
Torben Schmith⁵ Mads Hvid Ribergaard⁵, Antoon Kuijpers¹, Jerry M. Lloyd⁶

¹*Geological Survey of Denmark and Greenland, Department of Marine Geology and Glaciology,
Øster Voldgade 10, 1350 Copenhagen K, Denmark, csa@geus.dk*

²*Laboratoire des Sciences du Climat et de L'Environnement, Domaine du CNRS, Ave de la
Terrasse, 91198 Gif-sur-Yvette, Cedex, France*

³*Woods Hole Oceanographic Institution, Department of Physical Oceanography, Woods Hole, MA
02543, USA*

⁴*Department of Geological Sciences, University of Oregon, Eugene, Oregon, USA*

⁵*Danish Meteorological Institute, Centre for Ocean and Ice, Lyngbyvej 100, 2100 Copenhagen Ø,
Denmark*

⁶*Geography Department, University of Durham, South Road, Durham DH1 3LE, UK*

**corresponding author*

Abstract

Sediment core ER07 from Sermilik Fjord by Helheim Glacier in Southeast Greenland was analysed for alkenones to document sea surface temperature (SST) changes over the past 100 years. The alkenone SST values, ranging from 8 to 12°C, contrasts with colder values (0-4°C) obtained from recent hydrographic surveys inside the fjord. We suggest that advection of allochthonous alkenones produced in the warm Irminger Current waters circulating on the shelf likely accounts for this difference. The temperature range of the alkenone-derived record is similar to in situ observations of 8-11°C on the shelf just outside Sermilik Fjord, and its variability over the past 100 years resembles the constructed variability over the shelf using remote instrumental data. This suggests that oceanographic changes on the adjacent shelf are linked to regional changes of the Irminger Current and the East Greenland Current. The subsurface water heat content has previously been suggested as an important control on Greenland outlet glacier stability and underlined by an episode

1 of warm subsurface waters ~ 1940 concurrent with markedly increased calving and retreat of
2 Helheim Glacier. Our results therefore suggest that alkenone-derived SST time series from high-
3 sedimentation rate glacial fjords may provide a new approach for reconstruction of past changes of
4 shelf water properties and variability around Greenland.
5
6
7
8
9

10
11
12 **Key words:** Southeast Greenland, Sermilik Fjord, Helheim Glacier, alkenones, sea surface
13 temperature, ocean-cryosphere interaction, outlet glacier stability
14
15
16

17 **1. Introduction**

18
19
20 In the early part of this century, the Greenland Ice Sheet (GIS) experienced a marked increase in net
21 mass loss (Rignot and Kanagaratnam, 2006; van den Broeke et al., 2009), stimulating research for
22 better understanding how such future glacier changes will affect global sea level rise. In Southeast
23 Greenland, outlet glaciers thinned, accelerated and retreated between 2003 and 2005 (Howat et al.,
24 2007, 2008; Moon and Joughin, 2008; Stearns and Hamilton, 2007; Luckman et al., 2006, Rignot
25 and Kanagaratnam, 2006), and it was suggested that concurrent rising temperatures of subsurface
26 ocean currents may have triggered the onset of this acceleration (Nick et al., 2009; Straneo et al.,
27 2010; 2011, 2012; Murray et al., 2010). Likewise, the early 2000's thinning, retreating and doubling
28 of flow velocity of the Jakobshavn Isbræ in West Greenland has been linked to a pulse of warm
29 waters in the West Greenland Current (WGC) propagating up the West Greenland coast and
30 entering Disko Bay in 1997 (Holland et al., 2008). The exact processes involved in ocean-forced
31 destabilisation of outlet glaciers is still not well understood, but it is believed that rapid submarine
32 melting of calving faces is an important mechanism for glacier calving (Rignot et al., 2002, 2010)
33 and that changes in North Atlantic ocean heat transport may decrease the support from the
34 buttressing ice mélange in front of the glacier margin (Vielé and Nick, 2011).
35
36
37
38
39
40
41
42
43
44
45
46

47 Ice sheet mass changes of the GIS have only been estimated for the past 20-30 years
48 using satellite data. Likewise, the observational SST record on the continental shelf around
49 Greenland is sparse in space and time, and hydrographic surveys in the near-shore and fjord waters
50 virtually absent prior to 2008 (cf. Straneo et al., 2010; Murray et al., 2010). Therefore, in order to
51 establish a more firm causal relationship between ocean variability and glacier dynamical changes
52 we need to explore longer timescales, which requires the use of proxy records (Andresen et al.,
53 2011, 2012).
54
55
56
57
58
59
60
61
62
63
64
65

1 In this paper, we present a 100-year long SST time-series based on the C₃₇ alkenone
2 from a sediment core retrieved in Sermilik Fjord. Alkenone biomarkers in the open ocean waters are
3 mainly produced by the prymnesiophytae, *Emiliania huxleyi*, growing in the photic zone (Volkman
4 et al., 2000). The unsaturation index of the C₃₇ alkenones (U_{37^K}) in marine waters has been shown to
5 be highly correlated to water temperature on a global scale (Prahl et al., 1988; Conte et al., 2006).
6 We argue that alkenone SSTs derived from the fjord core are indicative largely of property changes
7 of surface waters occurring just outside of Sermilik Fjord. This conclusion is supported by
8 comparing our results to oceanographic data obtained from the broader shelf region. Finally, we
9 discuss the link between ocean variability and glacier dynamical changes on longer timescales by
10 comparing alkenone SSTs with a proxy record of Helheim Glacier calving.
11
12
13
14
15
16
17
18
19
20

21 **2. Setting**

22 Sermilik Fjord is c. 80 km long with a width varying between 7 and 13 km. The
23 bathymetry documents a U-shaped fjord with steep side walls and depths of 920 m at the mouth and
24 600 m at the northern end of the fjord extending approximately in a north-south direction (Schjøth
25 et al., 2012). The northern end of the fjord branches into three fjords each containing ice-calving
26 glaciers. The westernmost glacier – the Helheim Glacier – is a fast flowing glacier and the third
27 most prolific exporter of icebergs in Greenland (Rignot and Kanagaratnam, 2006). The two
28 northern glaciers, Midgaard and Fenris Glaciers are far less ice productive compared to Helheim
29 (Mernild et al., 2010).
30
31
32
33
34
35
36
37

38 According to MODIS satellite images for the past few years
39 (<http://ocean.dmi.dk/arctic/modis.php>), open water conditions occur frequently in the fjord
40 throughout the winter as fjord-ice is broken, likely due to strong currents and storms. A marked ice-
41 mélange, with inter-annually varying extension, is situated in front of the Helheim Glacier.
42
43
44

45 The oceanographic conditions on the Southeast Greenland shelf are characterized by
46 the East Greenland Current (EGC), which transports cold and fresh sea ice-laden surface waters
47 derived from the Arctic Ocean and glacial melt water from East Greenland that has an inner near
48 coastal branch, the East Greenland Coastal Current (EGCC) (Sutherland and Pickart, 2008) (Fig. 1).
49 Off Southeast Greenland, this cold upper (< 250 m) layer is underlain by warmer and saltier waters
50 derived from the Irminger Current (IC) (Malmberg 1985, Murray et al., 2010), which is a branch of
51 the North Atlantic Current. Deep troughs (300-800 m) transect the shallow shelf (100-200 m) and
52 thereby allow not only the upper cold waters, but also the warm subsurface waters to circulate
53
54
55
56
57
58
59
60
61
62
63
64
65

1 within the Sermilik Fjord, either through estuarine circulation (Murray et al., 2010) or shelf-driven
2 exchange (Straneo et al., 2010). Hence, the hydrographic conditions in Sermilik Fjord are
3 characterized by a two-layer stratification with warm (3.5 to 4°C) IC-derived waters from a depth of
4 200-300 m and downwards overlain by -1 to +1°C cold Polar Waters advected by the EGC-EGCC
5 water mass system (Fig. 2). In summer, the uppermost 10-20 m are characterised by low-salinity
6 waters from glacier runoff and the temperature can be up to several °C due to solar heating (Straneo
7 et al., 2010).

8
9
10
11
12
13
14 Interaction between the IC and EGC/EGCC over the shelf influences temperatures and
15 the interface depth (i.e. the thermocline), potentially altering the amount of heat reaching the glacier
16 margins and its ice-mélange in the fjord (Straneo et al., 2010, 2011; Sutherland et al., 2013).

20 21 **3. Methods**

22 Alkenone analysis was carried out on sediment core ER07 obtained from Sermilik fjord (Fig. 1B).
23 This core was retrieved from 525 m water depth (66°00'59"N, 37°51'07"W) and dated by means of
24 ²¹⁰Pb chronology and analysed for grain size composition using a Malvern laser sedigraph. The
25 chronology was calculated using the CRS-model (Constant Rate of Supply (Appleby and Oldfield,
26 1978) and calculations of the activities of unsupported ²¹⁰Pb in the lower part of the cores were
27 based on regression of activity versus accumulated mass depth in order to increase the robustness of
28 the age models. Further details on methodologies behind ER07 ²¹⁰Pb chronology and sedimentology
29 are provided in Andresen et al. (2012). The upper 24 cm of ER07 was sampled continuously every
30 ½ cm for alkenone determination leading to 43 levels to be analysed (higher sampling density in the
31 upper part of the core).

32
33
34 Alkenones were extracted from freeze-dried sediments using a
35 dichloromethane/methanol mixture (2:1 v/v) and isolated from the total lipid extract by silicagel
36 chromatography (Ternois et al., 1999). The purified fractions were then analysed by gas
37 chromatography using a Varian 3400CX gas chromatograph and a CPSi15 capillary column (50m
38 length, 0.3 2i.d., 0.25 µm film thickness) equipped with a FID detector and a septum programmable
39 injector (SPI). Helium was used as a carrier gas. The C₃₇ alkenone distribution comprises C_{37:3}, C_{37:2}
40 and C_{37:4} as expected from cold and low salinity waters of the Northern Hemisphere. While C_{37:4}
41 notably is absent in Southern ocean polar waters (Ternois et al., 1998), its presence in high
42 abundances has been reported in the Nordic Seas (Sicre et al., 2002 ; Bendle et al., 2005), the Baltic
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 Sea (Shulz et al., 2011) and more recently in Greenland lakes (D'Andrea et al., 2011) suggesting a
2 production that might be linked to species other than *E. huxleyi*.
3

4
5 However, the compilation of open-ocean water samples of Sikes and Sicre (2002)
6 showed that at cold temperatures, even when $C_{37:4}$ is abundant, the use of $U_{37}^K (C_{37:2} - C_{37:4}) / (C_{37:2}$
7 $+ C_{37:3} + C_{37:4})$ instead of $U_{37}^K (C_{37:2}) / (C_{37:2} + C_{37:3})$ does not improve SST estimates and we
8 therefore use the U_{37}^K index to calculate temperatures. In coastal regions such as estuarine or fjords,
9 where other species presumably contribute to alkenone production and where $C_{37:4}$ is abundant even
10 at elevated T, local calibration are needed for both indexes.
11
12
13
14
15
16
17
18

19 **4. Results**

20
21 Core ER07 is massive diamiction facies and contains on average 20 % sand in the 63-1000 μm
22 fraction, 45 % silt and 35 % clay (Fig. 3A). The upper 24 cm represent the last 100 years according
23 to ^{210}Pb chronology (Fig. 3B-C). The time resolution is on average 2.5 years per sample and age
24 uncertainties are in the order of +/- 2-6 years.
25
26
27

28 The C_{37} alkenone distribution is dominated by $C_{37:4}$ in Sermilik Fjord sediments
29 representing on average 65% of the total C_{37} alkenones, which is quite unusual for open ocean
30 waters even cold and low salinity ones. However, $C_{37:4}$ have been reported in cold ocean surface
31 waters of the North Atlantic and Nordic Seas (Sicre et al., 2002) yet at lower abundances (up to
32 35%). Percent of $C_{37:4}$ in estuarine sediments of Chesapeake Bay reached up to 40% of the total C_{37}
33 alkenones at temperature above 25°C (Mercer et al., 2005). This result indicates that besides marine
34 producers local haptophyceae contributed to the production of this compound.
35
36
37
38
39
40

41 U_{37}^K values in Sermilik Fjord range from 0.31 to 0.47 (Fig. 4) contrasting with the
42 lower values found in the coastal waters of Chesapeake Bay (0.118 to 0.313) (Mercer et al., 2005)
43 and those found in a Norwegian fjord (Conte et al. (1994). Higher U_{37}^K index in Sermilik fjord
44 sediments therefore suggest a dominant marine alkenone source with only minor contribution of
45 autochthonous haptophyceae in Sermilik fjord sediments. U_{37}^K converted to SSTs using Prahl et al.'s
46 calibration range between 8 and 12.5°C with a mean value of c. 10°C (Fig. 4). For comparison,
47 SSTs calculated from the calibration establish by Mercer et al. (2005) ($U_{37}^K = 0.013T - 0.04$) for
48 coastal/estuarine settings leads to unrealistic values ranging from 26.8 to 38.9°C, from which we
49 hypothesize that the marine calibration likely provide better SST estimates and useful indication of
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 its variability. SSTs along the core vary but are generally higher during the late 1930s and show a
2 broad increase since 2000. Marked minima are observed in the 1960s, 1980s and 1990s.
3
4
5

6 **5. Discussion**

7 **5.1 Sedimentation regime in the fjord**

8
9
10 A large number of sediment core studies from other East Greenland fjords; Kangerlussuaq (Syvitski
11 et al., 1996; Smith & Andrews 2000), Nansen Fjord (Smith and Andrews 2000; Jennings and
12 Weiner, 1996; Jennings et al., 2001) and Scoresbysund (Dowdeswell et al., 1993, 1994a; Ó Cofaigh
13 & Dowdeswell 2001), also situated by marine-terminating glaciers, describe in details the
14 characteristic sediment lithofacies and the glacial processes involved in their formation. This
15 information has been used to study the sediment cores from Sermilik Fjord. The massive diamicton
16 facies, with abundant pebbles in cores from the mid-part of the fjord, have been interpreted as
17 resulting from iceberg delivery of heterogeneous debris under the assumption that sand grains are
18 too large to be carried in suspension by the melt water plume. Calving variability of Helheim
19 Glacier for the past 120 years has been reconstructed in a previous study (Andresen et al., 2012) by
20 averaging three ²¹⁰Pb dated records, including ER07, of sand deposition (amount of sand deposited
21 per year) taken from the mid-region of the fjord. The general conclusions from this study, thus
22 taking into account changes in sand deposition in all three cores, are that iceberg discharge was
23 markedly higher in the 1930s and 2000-2005 (Fig 5F).
24
25
26
27
28
29
30
31
32
33
34
35

36 The occurrence of microfossils (foraminifera and diatoms) is low in the mid-fjord
37 cores, most likely because harsh environmental conditions in the fjord waters restrict biological
38 productivity. Limited light penetration due to sea ice and icebergs and high loads of sediments in
39 the turbid, fresh and cold surface waters will likely decrease the photosynthetic activity of
40 phytoplankton inhabiting these fjord waters.
41
42
43
44
45
46
47
48

49 **5.2 SST variability offshore Southeast Greenland**

50 The temperatures calculated from C_{37:3} and C_{37:2} relative abundances in ER07 sediments are found
51 to be up to 8°C higher than the maximum summer temperatures observed in the upper 100 m of the
52 fjord water column (<4°C, Fig. 2 and Straneo et al. 2010; 2011), suggesting that alkenones
53 deposited in the fjord sediments are not primarily produced in the fjord. To account for this large
54 offset, we hypothesize lateral advection of detrital alkenones from the Irminger warmer waters
55
56
57
58
59
60
61
62
63
64
65

1 flowing from outside the fjord. This mechanism is consistent with the finding that Sermilik fjord
2 waters are quickly and continuously replenished through a wind-driven exchange with the shelf
3 (Straneo et al., 2010) thus allowing warm ‘detrital’ alkenones to enter the fjord and settle to the
4 bottom floor. Several studies involving modern datasets already highlighted potential biases
5 introduced by lateral advection of alkenones by strong surface ocean currents (Conte et al., 2006;
6 Rühleman and Butzin, 2006; Mollenhauer et al., 2006). Sediments of the last glacial period from the
7 Southern Indian Ocean revealed offsets between alkenone and foraminiferal transfer function SSTs
8 due to advective transport of ‘warm’ alkenones by the Agulhas retroflexion to the core site (Sicre et
9 al., 2005). A similar phenomenon related to Irminger Sea Water transport by the East- and West
10 Greenland Current system has been reported in the north eastern Labrador Sea during the last
11 deglacial period by Knutz et al. (2011).

21 Our hypothesis is supported by a recent analysis of data from the Southeast Greenland
22 shelf derived from deep diving seals tagged with satellite relay depths loggers equipped with
23 temperature sensors (Sutherland et al., 2013). These data show that the water column in connection
24 with the deep trough just outside Sermilik Fjord (Box 1 in Fig. 1B) is often characterized by 8-11°C
25 warm water with no vertical variation during summer and fall (Fig. 2), and it was suggested that this
26 warm water originates from the Irminger Current flowing along the continental slope. Indeed the
27 temperature range derived from the seal data is similar to that recorded by alkenones deposited
28 inside Sermilik Fjord. This supports the notion that the alkenones are mostly from outside the fjord
29 and that they are indicative of water temperatures on the shelf region outside Sermilik Fjord and to
30 a lesser degree also further upstream of the warmer waters of the IC. This conclusion is supported
31 by Sutherland et al.’s (2013) observation that the region just outside Sermilik Fjord is a frontal
32 region between warm surface IC and cold surface EGC. In such a region an associated enhanced
33 vertical turbulent supply of nutrients (Gawarkiewicz, 1992) would sustain primary production,
34 including prymnosiphytae, as also observed by more northerly frontal regions of the Denmark Strait
35 (Thordardottir 1977; Knudsen and Eiríksson, 2002). Increased biological production in this area is
36 also supported by the high concentration of seal dives recorded with respect to neighboring regions
37 (Sutherland et al., 2013). Considering the temperature values of the upper waters inside the fjord
38 (<4°C; Fig 2), local production is unlikely to have contributed significantly to sedimentary alkenone
39 and it is therefore most probable that alkenone distributions reflect advection of subsurface waters
40 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 (Schmith and Hansen, 2005 and updated 2000-2007 in 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 Storis exported through Fram Strait based on ice charts from the Danish Meteorological Institute (Valeur, 1976). 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 normalised (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

1 these measurements are from the south-western side of Greenland, the continuity of the East and
2 West Greenland Currents around Cape Farewell suggests that variability at Fylla Bank is also
3 representative of the variability upstream by the southeast Greenland shelf and in the polar frontal
4 zone (Bacon et al., 2008). The Shelf Index is statistically significant correlated with the Fylla Bank
5 data (Andresen et al. 2012).
6
7
8
9

10 Similarities are observed between the alkenone-derived SST (Fig. 5E), the Shelf Index
11 (Fig. 5D) and the Fylla Bank SSTs (Fig. 5C). Episodes with relatively warm conditions are
12 recognised in the late 1930s and after 2000, as well as minor warming in the mid-1970s (red
13 regions). During these warm periods, alkenone SSTs are slightly higher than those just outside the
14 fjord emphasizing enhanced contribution of warmer IC waters which in summer can reach 11-12°C.
15 The Great Salinity anomalies (GSAs), which occurred in the mid-1960/70s, 1980s and 1990s are all
16 recognised as cooling episodes in both the alkenone SSTs, the Shelf index and the Fylla Bank data
17 (blue stiped lines in Fig. 5). These were episodes with an increased amount of multi-year pack ice
18 exported from the Arctic Ocean via the EGC. The episode in the mid-1960/70s was a more severe
19 kind of a GSA, where the fresh surface water anomaly reached the northern coast of Iceland and
20 was further transported with the WGC to the Labrador Sea and Newfoundland (Belkin, 2004).
21
22
23
24
25
26
27
28
29

30 We investigated the link between the alkenone-derived SSTs and the Shelf Index more
31 statistically rigorously. Interannual variations are strongly damped in the proxy-based alkenone
32 derived SST, and therefore we low-pass filtered the Shelf Index with a five year moving average so
33 that the two series would get similar spectral characteristics. We then calculated their detrended
34 correlation coefficient as 0.34. The two-sided 90% confidence band on this value was estimated by
35 block-bootstrapping (Wilks, 1997) and we obtained the limits -0.04 and 0.56. Varying the block
36 length between 5 and 15 years did not significantly change this.
37
38
39
40
41
42

43 The effect of uncertainties in the age model on the correlation coefficient was also
44 considered. This was done by a Monte Carlo procedure where the age of each point in the record of
45 alkenone SSTs was perturbed according to the uncertainties in the dating (fig 3c). From this we
46 obtained a confidence band with limits 0.11 and 0.54. All this enable us to conclude with some
47 justification that we have a relationship on the longer time scales between alkenone-derived SSTs
48 and the Shelf Index.
49
50
51
52
53

54 Thus, comparison of the alkenone SSTs with the seal-derived SSTs and with the Shelf
55 Index suggests that alkenones from Sermilik Fjord sediment reflect mainly SST changes outside
56 Sermilik Fjord and to a lesser degree also further upstream of the warmer waters of the IC. Our
57
58
59
60
61
62
63
64
65

1 results thus show that the observed alkenone SSTs variability is linked, to a certain degree, with
2 shelf water property and variability caused by changes in the IC and EGC current systems.
3
4
5
6
7

8 **5.4 Comparing reconstructed ocean temperature with glacier changes in Greenland**

9

10 The correspondence between climatic and oceanographic changes and the variability in the
11 reconstructed changes in iceberg calving from Helheim Glacier was previously investigated
12 (Andresen et al., 2012a). However, due to a lack of data from local hydrographical surveys, the
13 calving record was compared with SST data from south of Iceland, the Storis Index and the Shelf
14 Index assuming that the heat content of the waters reaching the glacier and its mélange may be
15 linked to regional variability. It was found that on multi-decadal timescales, calving is linked with
16 synchronous changes in the Northern Irminger Sea SSTs. SSTs in this region reflect the Atlantic
17 Multi-decadal Oscillation (AMO), which is a multi-decadal mode of variability (oscillation of 65-70
18 years) occurring in the North Atlantic Ocean and is usually defined from patterns of SST
19 variability; i.e. a positive (negative) mode is characterized by relatively high (low) SSTs
20 (Schlesinger and Ramankutty, 1994). Furthermore, short-term (3-10 years) calving peaks were
21 coincident with short-term episodes of positive Shelf Index indicating that increased IC inflow
22 and/or warming along with decreased flow of Storis and EGC are associated with enhanced calving.
23
24
25
26
27
28
29
30
31
32
33

34 The alkenone SST data strengthens the link between oceanographic variability and
35 Helheim Glacier calving (Andresen et al., 2012) with a detrended correlation coefficient of 0.37 and
36 90% confidence band with limits 0.09 and 0.56. Also the limits of the confidence band associated
37 with uncertainties in the age model was estimated at 0.02 and 0.48 (see 5.3. for statistical method).
38
39
40

41 A new and interesting finding is that the alkenone SST data show a *record* peak in the
42 late 1930s at the culmination of the so-called Early 20th Century Warming (Wood and Overland,
43 2010) and that it is broadly concordant with a calving maximum in 1940 (Fig. 5E and F). The
44 upstream SSTs from south of Iceland do not show a *record* of high SST at this time – rather they
45 resemble the AMO pattern with generally high SSTs in 1925-1965 (Fig. 5A). A possible
46 explanation is that during the 1950s and 1960s the warm IC waters may have been mixed and
47 cooled more intensively by the EGC upon reaching Southeast Greenland than during the 1930s and
48 1940s, when sea ice was less abundant and the EGC weaker (Schmith and Hansen, 2005, Fig. 5B).
49 The same pattern of decreased ocean temperatures in the 1950-1960s is observed in West Greenland
50 (Lloyd et al., 2011, Fig. 5G). In this study, benthic foraminifera assemblage changes in sediment
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 cores obtained from Disko Bay by Jakobshavn Isbrae were used to reconstruct temperature
2 variability at 300 m water depth. According to aerial images, a relatively rapid retreat of the
3 Jakobshavn Isbrae glacier front occurred in 1930-1950, at the time of the subsurface water
4 temperature maximum in 1920-1945 (peak in 1940). The glacier subsequently attained a stable
5 position 1950-2000 and this stagnation was accompanied by a cold WGC in 1950-1980. Overall,
6 these proxy-based ocean water temperature reconstructions document a markedly warm peak in
7 subsurface water by West and surface water by Southeast Greenland in the late 1930s, possibly
8 caused by less mixing of cold EGC waters at this time. Proxy-based temperature reconstructions of
9 Greenland shelf waters detailing the past 100 years are restricted to the study presented here and the
10 data set from Jakobshavn (Lloyd et al. 2011), but on the basis of these we suggest a period of
11 markedly increased ocean heat content around 1940 impacted Greenland glacier stability to an
12 extent that was only matched after 2000.
13
14
15
16
17
18
19
20
21
22
23
24

25 **6. Conclusion**

26 The alkenone SST record obtained from core ER07 provides evidence of repeated mixing of warm
27 IC Water throughout the past 100 years into Sermilik Fjord. The temperature range of 8-12°C
28 suggests that alkenones were produced outside the fjord and in the IC, and that production in the
29 uppermost surface waters in the fjord was minor. The resemblance of alkenone SST variability with
30 the Shelf Index emphasizes the regional character of this signal and its link to IC and EGC
31 variability. Our results confirm previous finding on the important role of regional ocean forcing on
32 outlet glacier stability, particularly the marked calving episode of the late 1930s. They also provide
33 valuable information on the role of ocean and its heat content to Greenland Ice Sheet melting and
34 succeeding sea level rise and emphasize the need to better account for ocean/sea ice interactions in
35 modelling studies.
36
37
38
39
40
41
42
43
44

45 **Acknowledgements**

46 This study has been supported by Geocenter Denmark in financial support to the SEDIMICE
47 project, the Danish Council for Independent Research | Nature and Universe (Grant no. 09-
48 064954/FNU) and the Danish Agency for Science, Technology and Innovation as part of the
49 Greenland Climate Research Centre. The alkenone data presented here have been produced within
50 the NAIV project supported by LEFE program of the Institut National des Sciences de l'Univers
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 (INSU) of the Centre national de la Recherche Scientifique. FS and DS were supported by NSF
2 funded projects. We are very grateful to our reviewers for their help in improving this manuscript.
3
4
5
6
7

8 **References**

9
10 Andresen, C.S., Nørgaard-Pedersen, N., Jensen, J. B., Larsen, B., 2010. Southeast Greenland ice-
11 sheet variability elucidated by shallow seismic survey and sediment coring in the Sermilik Fjord
12 near the Helheim Glacier in 2009. Geological Survey of Denmark and Greenland Bulletin 20, 83-
13 86.
14
15
16
17

18
19 Andresen, C. S., Straneo, F., Ribergaard, M. H., Bjørk, A. A., Andersen, T.J., Kuijpers, A.,
20 Nørgaard-Pedersen, N., Kjær, K. H., Schjøth, F., Weckström, K., Ahlstrøm, A. P., 2012. Rapid
21 response of Helheim Glacier in Greenland to climate variability over the past century. Nature
22 Geoscience 5, 37-41.
23
24
25
26
27

28 Appleby, P. G. and Oldfield, F. 1983. The assessment of ^{210}Pb data from sites with varying
29 sediment accumulation rates. Hydrobiologia 103, 29-35
30
31
32
33

34 Bacon, S., P.G. Myers, B. Rudels, and D.A. Sutherland (2008), Accessing the inaccessible:
35 buoyancy-driven coastal currents on the shelves of Greenland and eastern Canada. *Arctic-Subarctic*
36 *ocean fluxes: Defining the role of the Northern Seas in climate*. Eds. Dickson, Meincke, and
37 Rhines.
38
39
40
41
42

43 Belkin, I.M., 2004. Propagation of the “Great Salinity Anomaly” of the 1990s around the northern
44 North Atlantic. Geophysical Research Letters 31, L08306, doi:10.1029/2003GL019334.
45
46
47

48 Bendle, J., A. Rosell-Melé, and P. Ziveri., 2005. Variability of unusual distributions of alkenones in
49 the surface waters of the Nordic seas, *Paleoceanography*, 20, PA2001, doi:10.1029/2004PA001025.
50
51
52
53

54 Conkright, M. E., Locarnini, H. E., Garcia, T. D., O'Brien, T. P., Boyer, C. , Stephens, J., Antonov
55 I., 2002. World Ocean Database 2001, vol. 1, Introduction, edited by S. Levitus, NOAA Atlas
56 NESDIS 42, 167 pp., NOAA, Silver Spring, Md.
57
58
59
60
61
62
63
64
65

1
2
3 Conte, M. H., Thompson, A., Eglinton, G., 1994. Primary production of lipid biomarker compounds
4 by *Emiliania huxleyi*: Results from an experimental mesocosm study in fjords of southern Norway.
5 *Sarsia* 79, 319-331.
6
7

8
9
10 Conte, M. H., Sicre, M.-A., Rühlemann, C., Weber, J. C., Schulte, S., Schulz-Bull, D., Blanz, T.
11 2006. Global temperature calibration of the alkenone unsaturation index (UK'37) in surface waters
12 and comparison with surface sediments, *Geochem. Geophys. Geosyst.*, 7(2),
13 Doi:10.1029/2005GC001054, 2006.
14
15
16
17

18
19 D'andrea, J.W., Y. Huang, S.C. Fritz and N.J. Anderson, 2011. Abrupt Holocene climate change as
20 an important factor for human migration in West Greenland, *PNAS*, doi/10.1073/pnas.1101708108.
21
22

23
24 Dowdeswell, J.A., Whittington, R.J., Marienfeld, P., 1994. The origin of massive diamicton facies
25 by iceberg rafting and scouring, Scoresby Sund, East Greenland. *Sedimentology* 41, 21-35.
26
27
28

29
30 Dowdeswell, J.A., Villinger, H., Whittington, R.J., Marienfeld, P., 1993. Iceberg scouring in
31 Scoresby Sund and on the East Greenland continental shelf. *Marine Geology* 111, 37-53.
32
33
34

35 Dowdeswell, J.A., Whittington, R.J., Jennings, A.E., Andrews, J.T., Mackensen, A., Marienfeld, P.,
36 2000. An origin for laminated glaci-marine sediments through sea-ice build-up and suppressed
37 iceberg rafting. *Sedimentology* 47, 557-576.
38
39
40

41
42 Enfield, D.B., Mestas-Nunez, A.M. and Trimble, P.J. 2001. The Atlantic Multidecadal Oscillation
43 and its relationship to rainfall and river flows in the continental U.S.. *Geophys. Res. Lett.* 28, 2077-
44 2080.
45
46
47

48
49
50 Gawarkiewicz, G., and D. C. Chapman (1992). The role of stratification in the formation and
51 maintenance of shelf break fronts, *J. Phys. Oceanogr.*, 22, 753– 772, doi:10.1175/1520-
52 0485(1992)022<0753:TROSIT>2.0.CO;2.
53
54
55

56
57 Grimalt, J.O., Rullkötter J., Sicre M.-A., Harvey H.R., J.W. Farrington, Goni M., Sawada K. and
58 Summons R., Modifications of the C₃₇ Alkenone and Alkenoate Composition in the Water Column
59
60
61
62
63
64
65

1 and Sediment: Possible Implications for Sea Surface Temperature Estimates in Paleoceanography.
2
3 *Geochemistry, Geophysics, Geosystems*, 2000GC000053, 2000.
4
5

6 Holland, D., Thomas, R., H., de Young, B., Ribergaard, M. H., Lyberth, B., 2008. Acceleration of
7 Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience* 1, 659-664.
8
9

10
11 Howat, I. M., Joughin, I., Scambos, T.A., 2007. Rapid changes in ice discharge from Greenland
12 Outlet Glaciers. *Science* 315, 1559-1561.
13
14

15
16
17 Howat, I. M., Smith, B. E., Joughin, I, Scambos T. A., 2008. Rates of southeast Greenland ice
18 volume loss from combined ICESAT and ASTER observations. *Geophys. Res. Lett.*, 35, L17505,
19 doi:10.1029/2008GL034496.
20
21
22

23
24
25 Jennings, A.E., Weiner, N.J., 1996. Environmental changes in eastern Greenland during the last
26 1300 years: evidence from foraminifera and lithofacies changes in Nansen Fjord, 68°N. *The*
27 *Holocene* 6 (2), 179–191.
28
29
30

31
32 Jennings, A. E. Knudsen, K. L., Hald, M, Hansen, C. V., Andrews, J. T., 2001. A mid-Holocene
33 shift in Arctic sea-ice variability on the East Greenland Shelf *The Holocene* 2002; 12; 49, DOI:
34 10.1191/0959683602hl519rp
35
36
37

38
39 Knudsen, K.L., Eiríksson J., 2002. Application of tephrochronology to the timing and correlation of
40 palaeoceanographic events recorded in Holocene and Late Glacial shelf sediments off North
41 Iceland. *Marine Geology* 191, 165-188.
42
43
44

45
46 Knutz, P. C., Sicre, M.-A., Ebbesen, H., Christiansen, S., Kuijpers A., 2011. Multiple-stage
47 deglacial retreat of the southern Greenland Ice Sheet linked with Irminger Current warm water
48 transport, *Paleoceanography* 26, PA3204, doi:10.1029/2010PA002053.
49
50
51

52
53
54 Luckman, A., Murray, T., de Lange, R., Hanna, E., 2006. Rapid and synchronous ice-dynamic
55 changes in East Greenland, *Geophys. Res. Lett.* 33, L03503, doi:10.1029/2005GL025428.
56
57
58
59
60
61
62
63
64
65

- 1 Lloyd, J.M., Moros, M., Perner, K., Telford, R., Kuijpers, A., Jansen, E., McCarthy, D, 2011. A 100
2 year record of ocean temperature control on the stability of Jakobshavn Isbrae, West Greenland.
3
4 Geology 39, 867-870.
5
6
7 Malmberg, S.-A. 1985. The water masses between Iceland and Greenland. J. Mar. Res. Inst. 9, 12-
8 140
9
10 Mercer, J.L., Zhao, M., Colman, S.M., 2005. Seasonal variations of alkenones and U^{K}_{37} in the
11 Chesapeake Bay water column. Estuarine, and Coastal and Shelf Sciences, 63, 675-682.
12
13
14
15
16 Mernild, S. H., Howat, I. M., Ahn, Y., Liston, G. E., Steffen, K., Jakobsen, B. H., Hasholt, B., Fog,
17 B., van As, D., 2010. Freshwater flux to Sermilik Fjord, SE Greenland. The Cryosphere, 4, 453-
18 465. www.the-cryosphere.net/4/453/2010/ doi:10.5194/tc-4-453-2010
19
20
21
22
23
24 Moon, T., Joughin I., 2008. Changes in ice front position on Greenland's outlet glaciers from 1992
25 to 2007. Journal of Geophysical Research-Earth Surface 113(F2), 10.
26
27
28
29
30
31 Mollenhauer, G., McManus, J.F., Benthien, A., Muller, P.J., Eglinton, T.I. 2006. Rapid lateral
32 particle transport in the Argentine Basin: molecular 14C and 230 Thxs evidence. Deep-Sea
33 Research I 53, 1224-1243.
34
35
36
37 Murray, T., Scharrer, K., James, T.D., Dye, S.R., Hanna, E., Booth, A.D., Selmes, N., Luckman, A.,
38 Hughes, A.L.C., Cook, S., Hybrechts, P., 2010. Ocean regulation hypothesis for glacier dynamics in
39 southeast Greenland and implications ice sheet mass change. J Geophys Res 115(F03026).
40 doi:10.1029/2009JF001522.
41
42
43
44
45
46 Nick, F. M., Vieli, A., Howat I.M., Joughin, I., 2009. Large-scale changes in Greenland outlet
47 glacier dynamics triggered at the terminus. Nature Geoscience doi:10.1038/ngeo394
48
49
50
51 Ó Cofaigh, C., Dowdeswell, J.A., Grobe, H., 2001. Holocene glacial marine sedimentation, inner
52 Scoresby Sund, East Greenland: the influence of fast-flowing ice sheet outlet glaciers. Marine
53 Geology 175, 103-129.
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Prah, F. G., Muehlhausen, L. A., Zahnle, D. L., 1988. Further evaluation of long-chain alkenones
2 as indicators of Paleoceanographic conditions, *Geochemica Cosmochimica Acta*, 52, 2303–2310.
3
4
5
6 Prah, F., Herbert, T., Brassell, S. C., Ohkouchi, N., Pagani, M., Repeta, D., Rosell-Melé, A. and
7 Sikes, E. 2000. Status of alkenone paleothermometer calibration: Report from Working Group 3.
8
9 *Geochem, Geophys. Geosys* 1, 2000GC000058
10
11
12
13 Ribergaard, M.H., 2011. Oceanographic Investigations off West Greenland 2010. NAFO Scientific
14 Council Documents 11/001.
15
16
17
18 Ribergaard, M.H., Olsen, S.M., and Mortensen, J., 2008. Oceanographic Investigations off West
19 Greenland 2007. NAFO Scientific Council Documents 08/003.
20
21
22
23
24 Rignot, E., and S. S. Jacobs, 2002. Rapid bottom melting widespread near Antarctic ice sheet
25 grounding lines. *Science* 296, 2020–2023.
26
27
28
29 Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland Ice Sheet.
30 *Science* 311(5763), 986–990.
31
32
33
34 Rignot E., Koppes, M., Velicogna I., 2010. Rapid submarine melting of the calving faces of West
35 Greenland glaciers. *Nature Geoscience* 3, 187–191.
36
37
38
39
40 Rühlemann, C., Butzin, M., 2006. Alkenone temperature anomalies in the Brazil-Malvinas
41 Confluence area caused by lateral advection of suspended particulate material, *Geochemistry
42 Geophysics Geosystems*, 7, Q10015, doi:10.1029/2006GC001251
43
44
45
46
47 Schlesinger, M. E., Ramankutty, N., 1994. An oscillation in the global climate system of period 65–
48 70 years. *Nature* 367, 723–726.
49
50
51
52
53 Schjøth, F., Andresen, C.S., 2010. From unknown sea bed morphology in the Sermilik Fjord,
54 Southeast Greenland to a bathymetric map based on more than 500.000 echo sounder and Chirp
55
56
57
58
59
60
61
62
63
64
65

1 sub-bottom profiler measurements (abstract & poster). ESRI Europe, Middle East and Africa User
2 Conference. 26 – 28 october, 2010, ESRI Italia, Rome, Italy.
3

4
5
6 Schmith, T., Hansen, C., 2005. Fram Strait Ice Export during the Nineteenth and Twentieth
7 Centuries Reconstructed from a Multiyear Sea Ice Index from Southwestern Greenland. *Journal of*
8 *Climate* 16, 2782–2791 (2003).
9

10
11
12 Schulz, H.-M., A. Schöener, and K.C. Emeis, 2000. Long-chain alkenone patterns in the Baltic
13 Sea—an ocean-freshwater transition, *Geochimica et Cosmochimica Acta*, 64, 469–477.
14
15

16
17
18 Sicre, M.-A., Jacob, J., Ezat, U., Rouse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L.,
19 Jansen, E., Turon, J.-L., 2008. Decadal variability of sea surface temperatures off North Iceland
20 over the last 2000 years. *Earth and Planetary Science Letters* 268: 137-142.
21
22

23
24
25 Sicre M.-A., E. Bard, U. Ezat and F. Rostek, Alkenone distributions in the North Atlantic and
26 Nordic sea surface waters, *Geochemistry, Geophysics, Geosystems*, doi: 2001GC000159, 2002.
27
28

29
30
31 Sikes, E.L. and Sicre M.-A., The relationship of the tetra-unsaturated C₃₇ alkenone to salinity and
32 temperature: implication for paleo-studies, *Geochemistry, Geophysics, Geosystems*, doi:
33 2002GC000345, 2002.
34
35

36
37
38 Sicre, M.-A., Labeyrie L., Ezat, U. Duprat, J. Turon J-L, Schmidt S., Michel E. and Mazaud A.,
39 Southern Indian Ocean response to Northern Hemisphere Heinrich events. *Earth and Planetary*
40 *Science Letters* **240**, 724-731, doi: 10.1016, 2005.
41
42

43
44
45 Smed, J., 1978. Fluctuations in the temperature of the surface water in the areas of the northern
46 North Atlantic, 1876–1975. In: *Danish Meteorological Institute Climatological Papers*, **4**. p 205–
47 210.
48
49

50
51
52 Smith, L. M., Clark, A., Jennings, A. E. 2002. Accumulation in East Greenland Fjords and on the
53 continental shelves adjacent to the Denmark Strait over the last century based on ²¹⁰Pb
54 geochronology. *Arctic* 55, 109-122.
55
56
57
58
59
60
61
62
63
64
65

1
2
3 Stearns, L. A., Hamilton, G. S., 2007. Rapid volume loss from two East Greenland outlet glaciers
4 quantified using repeat stereo satellite imagery. *Geophys. Res. Lett.* 34, L05503,
5 doi:10.1029/2006GL028982 (2007).
6
7

8
9
10 Straneo, F., Hamilton, G. S., Sutherland, D. A., Stearns, L. A., Davidson, F., Hammill, M. O.,
11 Stenson, G. B., Rosing-Asvid, 2010. Rapid circulation of warm subtropical waters in a major
12 glacial fjord in East Greenland. *Nature Geoscience* 3, 182-186.
13
14

15
16
17 Straneo, F., R. Curry, D.A. Sutherland, G. Hamilton, C. Cenedese, K. Väge, L.A. Stearns, 2011:
18 Impact of fjord dynamics and subglacial discharge on the circulation near Helheim Glacier in
19 Greenland. *Nature Geoscience*, doi:10.1038/ngeo1109.
20
21

22
23
24 Straneo, F., D. A. Sutherland, D. Holland, C. Gladish, G. Hamilton, H. Johnson, E. Rignot, Y. Xu,
25 M. Koppes, 2012: Characteristics of ocean waters reaching Greenland's glaciers. *Annals of*
26 *Glaciology*, 53(60), 202-210.
27
28

29
30
31 Sutherland, D.A., Pickart, R. S., 2008. The East Greenland Coastal Current: structure, variability,
32 and forcing. *Progress in Oceanography*, doi:10.1016/j.pocean.2007.09.006.
33
34

35
36
37 Sutherland, D., F. Straneo, G.B. Stenson, F. J.M. Davidson, M. O. Hammill, A. Rosing-Asvid,
38 2013: Atlantic water variability on the SE Greenland continental shelf and its relationship to SST, *J.*
39 *Geophys. Res. Oceans*, 118-1-9, doi:10.1029/2012JC008354
40
41

42
43
44 Syvitski, J. P. M., Andrews, J. T., Dowdeswell, J. A. 1996. Sediment deposition in an iceberg-
45 dominated Glacimarine Environment, East Greenland: Basin Fill Implications. *Global and Planetary*
46 *Change* 12, 251-270.
47
48

49
50
51 Ternois Y., Sicre M. -A., Boireau A., Conte M. H., Eglinton, G. 1997. Evaluation of long-chain
52 alkenones as paleo-temperature indicators in the Mediterranean Sea. *Deep-Sea Res.* 44, 271–286.
53
54
55
56
57
58
59
60
61
62
63
64
65

1 Ternois Y., Sicre M.-A., Boireau A., L. Beaufort, J-C Miquel and C. Jeandel, Hydrocarbons, sterols
2 and alkenones in sinking particles in the Indian sector of the Southern Ocean. *Organic*
3 *Geochemistry* 28, 489-501, 1998.
4
5
6

7
8 Thordardóttir T., 1977. Primary production in North Icelandic waters in relation to recent climatic
9 change. In *Polar Oceans: Proceedings of the polar oceans conference held at McGill University,*
10 *Montreal, in May 1974, pp. 655–665. Ed. By M. J. Dunbar. SCOR/SCAR, Canada. 681 pp.*
11
12
13

14
15 Valeur, H.H.. Polar ice variations off the Greenland west coast 1900–72. *Int. Commission for the*
16 *Northwest Atlantic Fisheries, Special Publication 9, 27 pp. (1976).*
17
18
19

20
21 Van den Broeke, M.R., Bamber, J., Ettema, J., Rignot E., Schrama, E., van de Berg, W. J., van
22 Meijgaard, E., Velicogna, I., Wouters, B., 2009. Partitioning recent Greenland mass loss. *Science*
23 326, 984-986.
24
25
26

27
28 Vieli, A., and F. M. Nick (2011), Understanding and modeling rapid dynamic changes of tidewater
29 outlet glaciers: issues and implications. *Surv.*
30 *Geophys.*, 32, doi:10.1007/s10712-011-9132-4.
31
32
33

34
35 Volkman, J. K. 2000. Ecological and environmental factors affecting alkenone distributions in
36 seawater and sediments, *Geochem. Geophys. Geosyst.* 1, 2000GC000061.
37
38
39

40
41 Våge, K., Pickart, R. S., Sarafanov, A., Knutsen, Ø., Mercier, H., Lherminier, P., van Aken, H. M.,
42 Meincke, J., Quadfasel, D., Bacon, S., 2011. The Irminger Gyre: Circulation, convection, and
43 interannual variability. *Deep Sea Research Part I: Oceanographic Research Papers* 58(5), 590–614.
44
45
46

47
48 Wilks, D. S., 1997: Resampling hypothesis tests for autocorrelated fields. *J. Climate*, 10, 65–82.
49
50

51
52 Wood, K. R., Overland, J. E., 2010. Early 20th century Arctic warming in retrospect. *Int. J.*
53 *Climatol.* 30: 1269–1279. DOI: 10.1002/joc.1973.
54
55
56

57 **Figure captions**

58
59
60
61
62
63
64
65

1 Fig 1. A. Main currents in the North Atlantic Ocean (Straneo et al., 2012) and location of Helheim
2 Glacier (HG), Kangerdluqssuaq Glacier (KG), Disko Bay (DB), Jakobshavn Isbrae (JI),
3 Scoresbysund (SU), Fyllas Banke (FB) and region south of Iceland from where SSTs of the IC were
4 obtained. B. Helheim Glacier and Sermilik Fjord with position of core ER07 (bathymetry from
5 Schjøth et al., 2012) and the pathways of the EGC/EGCC system and the IC (Straneo et al., 2010).
6 Box 1 indicates the region in which the alkenone-derived SST reconstruction is interpreted to record
7 variability.
8
9

10
11
12
13
14
15
16 Fig. 2. Profiles of temperature versus depth taken inside Sermilik Fjord during the summers of
17 2008, 2009, 2010 and 2011 (blue) via ship-based hydrography (the 2008 and 2009 are those
18 described in Straneo et al. 2010; 2011) and outside the fjord via tagged seals (red, see Box 1 in Fig.
19 1B). The seal-derived temperatures represent summer/fall conditions when Irminger Sea water was
20 present (29% of all profiles) over the time period 2004—2010 (Sutherland et al. 2013).
21
22
23
24
25

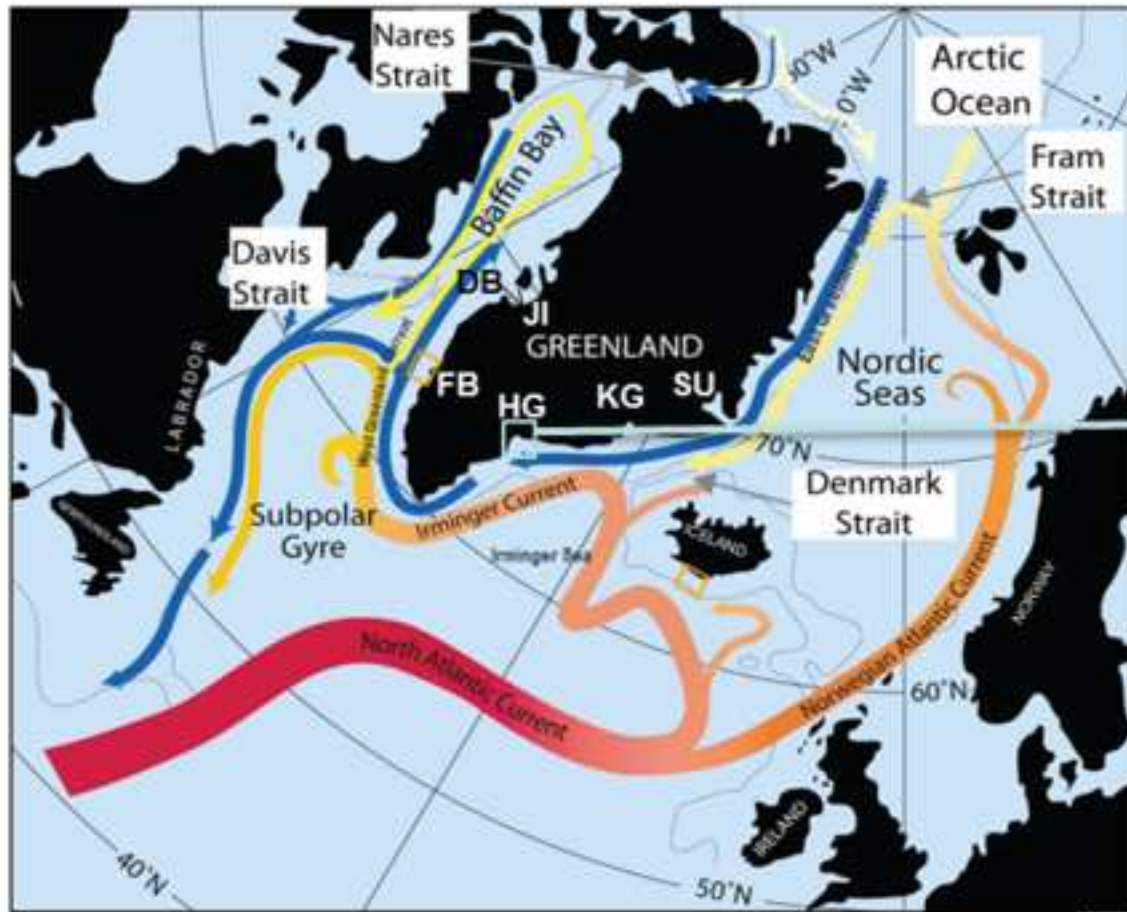
26
27 Fig. 3. Core ER07 sedimentology and chronology (Andresen et al., 2012). A. Grain size distribution
28 (wt%) of clay, silt and sand. B. Unsupported ^{210}Pb and ^{137}Cs . C. Age model based on ^{210}Pb and
29 ^{137}Cs dating (one sigma error bars).
30
31
32
33

34 Fig. 4. Core ER07 $\text{U37k}'$ values (left axis) and alkenone-derived SST data (right axis). Internal
35 precision is estimated to 0.5°C .
36
37
38

39 Fig. 5. Comparison with other records. A. SST from offshore South Iceland (black line 3 point
40 running mean). The AMO Index (from Enfield et al. 2001) is shown above (3 point running annual
41 mean). Red (blue) scrapings indicate positive (negative) Index. B. The Storis Index (black line 3
42 point running mean). C. The shelf Index (black line 3 point running mean). D. Fylla Banke SST
43 (black line 3 point running mean) (Ribergaard et al., 2011). E. ER07 alkenone-derived SST (black
44 line 3 point running mean). F. Reconstructed calving variability of Helheim Glacier. Data in A-C
45 and F from Andresen et al., 2012. G. % Warm water foraminifera in Egedesminde Dyb by Disko
46 Bay (Lloyd et al., 2012). Warm SST episodes in alkenone data highlighted with red boxes. Blue
47 stipled lines indicate Great Salinity Anomalies (GSAs).
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure
[Click here to download high resolution image](#)

A



B

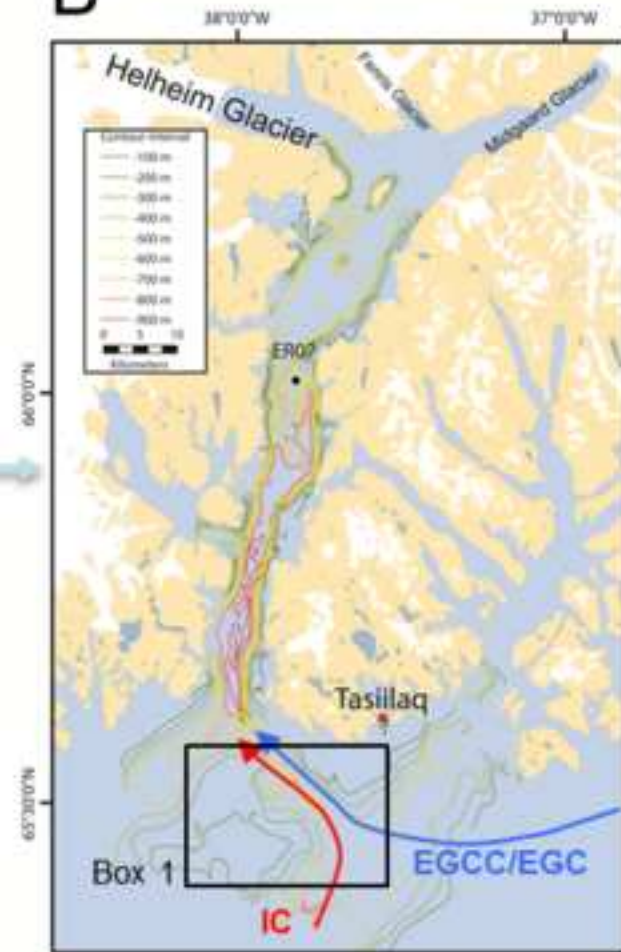


Figure
[Click here to download high resolution image](#)

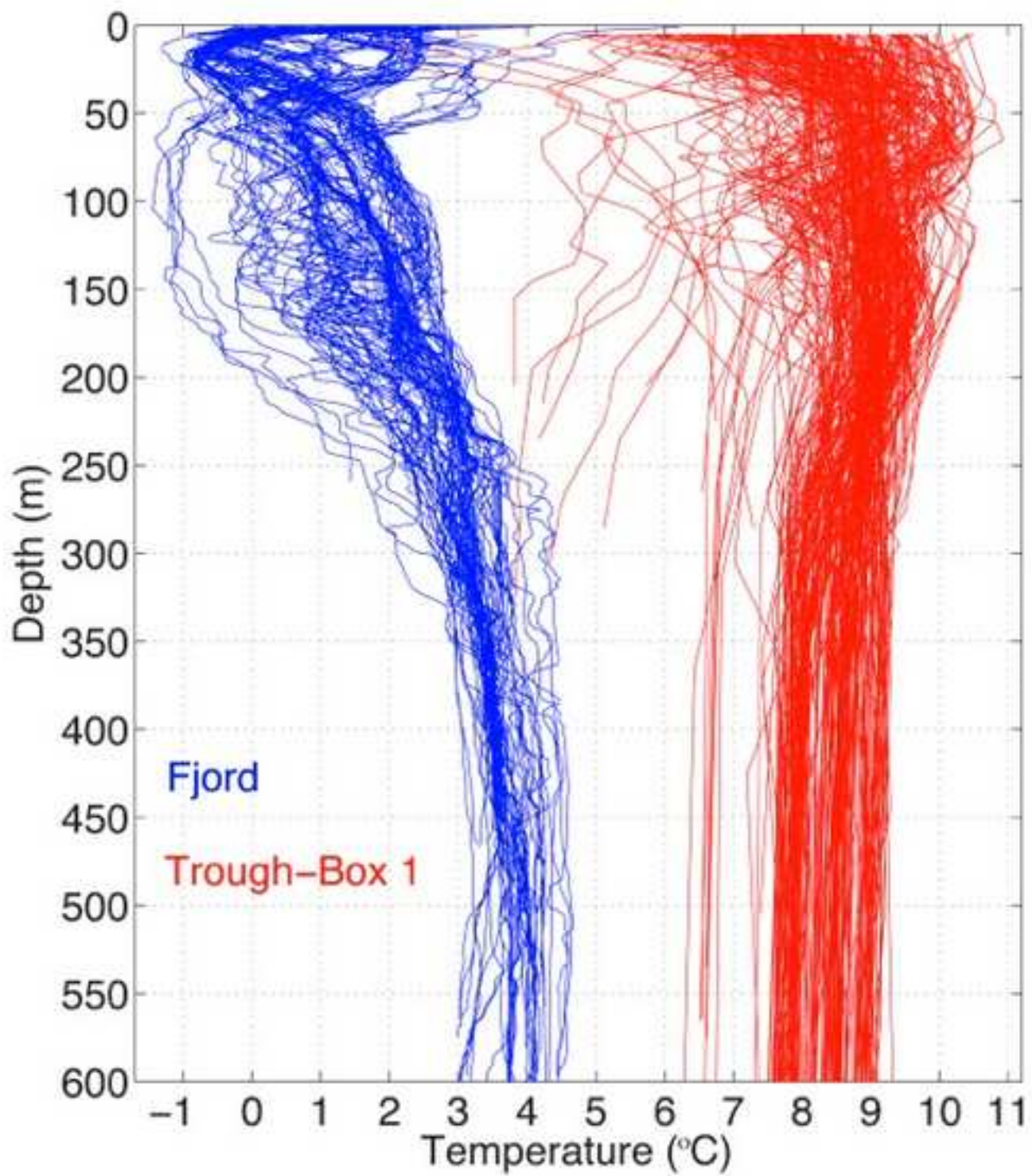


Figure
[Click here to download high resolution image](#)

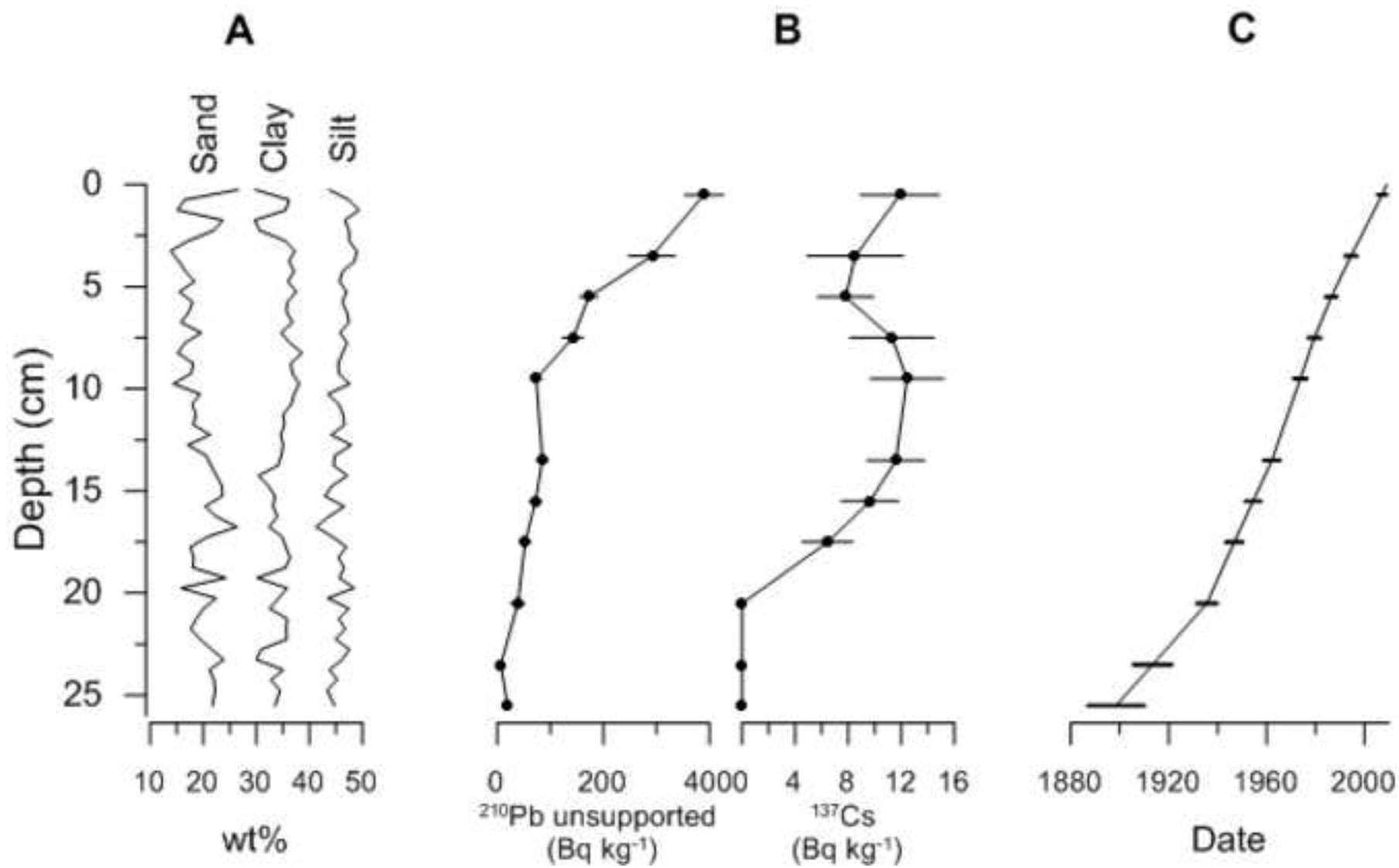


Figure
[Click here to download high resolution image](#)

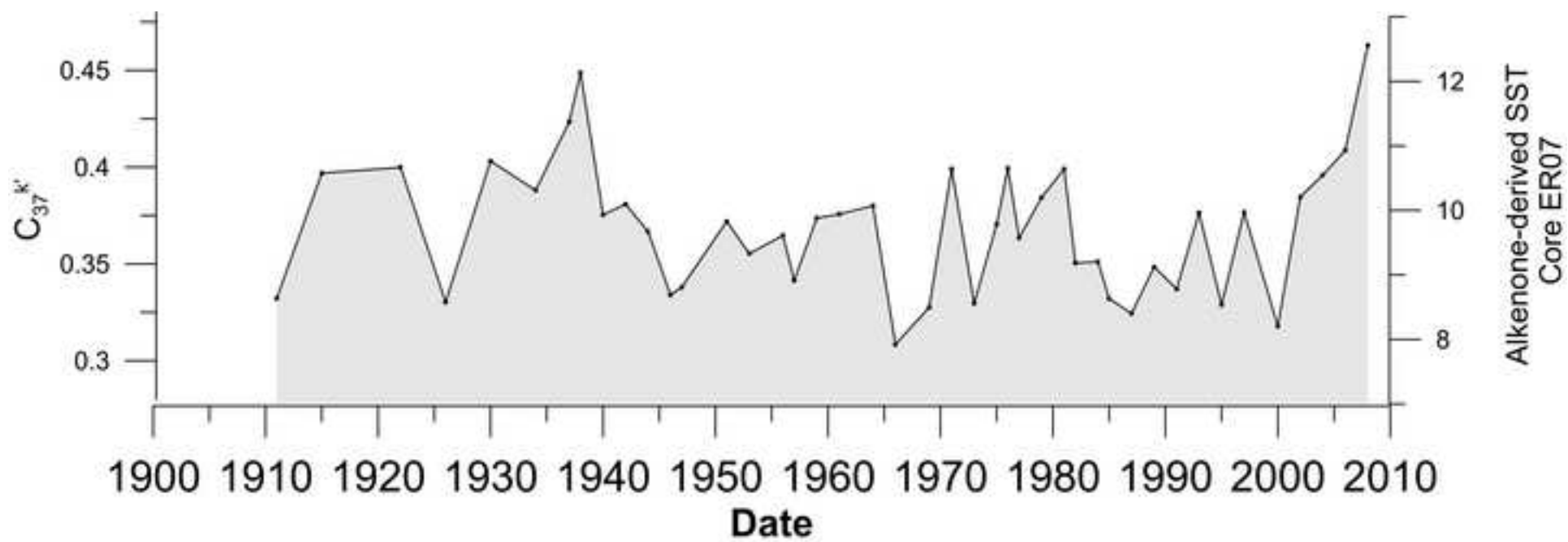


Figure
[Click here to download high resolution image](#)

