Abrupt Holocene climate change as an important factor for human migration in West Greenland

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West Greenland has had multiple episodes of human colonization and cultural transitions over the past 4,500 y. However, the explanations for these large-scale human migrations are varied, including climatic factors, resistance to adaptation, economic marginalization, mercantile exploration, and hostile neighborhood interactions. Evaluating the potential role of climate change is complicated by the lack of quantitative paleoclimate reconstructions near settlement areas and by the relative stability of Holocene temperature derived from ice cores atop the Greenland ice sheet. Here we present high-resolution records of temperature over the past 5,600 y based on alkenone unsaturation in sediments of two lakes in West Greenland. We find that major temperature changes in the past 4,500 y occurred abruptly (within decades), and were coeval in timing with the archaeological records of settlement and abandonment of the Saqqaq, Dorset, and Norse cultures, which suggests that abrupt temperature changes profoundly impacted human civilization in the region. Temperature variations in West Greenland display an antiphased relationship to temperature changes in Ireland over centennial to millennial timescales, resembling the interannual to multidecadal temperature seesaw associated with the North Atlantic Oscillation.

anthropology | Arctic | biomarker | paleoclimatology

The Baffin Bay region, comprising West Greenland and the eastern coast of Baffin Island, has a rich and dynamic history, with multiple episodes of human migration and cultural transitions during the mid to late Holocene (1–8) (*SI Appendix*, Fig. S1). Human occupation in Greenland began with the Saqqaq culture, which arrived *ca.* 4,500 y B.P. and soon colonized the island (3–5). Beginning *ca.* 2,800 y B.P., the Saqqaq were replaced by the Dorset culture, which persisted in West Greenland from *ca.* 2,800–2,200 y B.P., when records of their occupancy end abruptly (3). Archaeological evidence indicates the region remained unpopulated until the arrival of the Norse settlers *ca.* 1,000 y B.P. (3, 6). The Norse occupied the western settlement (Fig. 1 and *SI Appendix*, Fig. S1) until the middle of the 14th century (*ca.* 650 y B.P.) and the eastern settlement until *ca.* 550 y B.P. (6), whereas the Thule, ancestors of the modern Greenlandic Inuit who arrived two to three centuries after the Norse (7), remain in Greenland to the present day. Human migrations can result from numerous factors, including social change, conflict with neighbors, the search for better hunting grounds, response to shifting resources, economic stress, and climate change (2, 3, 6–8). Although it is difficult to determine how social factors may have influenced migrations, paleoclimate reconstructions offer the opportunity to examine the changing climatic conditions experienced by human populations in West Greenland. The existing lines of evidence for evaluating the impact of climate change on past human populations in West Greenland are generally qualitative and indirect. Greenland ice cores offer quantitative records of temperature from atop the ice sheet (9); however, climate did not change uniformly across Greenland during the late Holocene (10) and quantitative temperature estimates from locations adjacent to and representative of settlement sites are required

to assess the influence of climate on observed patterns of human migration.

An Alkenone-Based Paleotemperature Record for West Greenland

Here we present a record of temperature variability with decadal-scale resolution for approximately the past 5,600 y from two independently ^{14}C dated, finely laminated sediment cores from two meromictic lakes, Braya Sø and Lake E (approximately 10 km apart) in Kangerlussuaq, West Greenland (67° 0′ N, 50° 42′ W; Fig. 1 and *SI Appendix*, Section 1). Our paleoclimate time series are based on measurements of alkenone unsaturation (U^K_{37}), a well-established method for reconstructing sea-surface temperatures from marine sediment cores (11) (*SI Appendix*, Section 2) and whose utility has been demonstrated in lakes from Europe, China, and North America (12–14). The alkenone producers in Braya Sø and Lake E are a newly discovered member of the algal class Haptophyceae (15, 16) and bloom between mid-June and mid-July (Fig. 2A). Air temperature has been shown to exert primary control on lake water temperature in the Søndre Strømfjord region (17). Furthermore, instrumental temperature measurements indicate that Kangerlussuaq air temperature is well correlated with the air temperature of other sites on West Greenland (18) (Pearson correlation coefficients decrease gradually from 0.83 to 0.52 as distance from Kangerlussuaq increases from 130 to 1,200 km for the period 1961–1990 AD). Therefore, Kangerlussuaq lake water temperature primarily reflects air temperature in the Kangerlussuaq area, which is correlated to that of other West Greenland sites as a function of distance. We developed a U^K_{37}-temperature calibration for the lakes in Kangerlussuaq (Fig. 2B) by combining a calibration from Braya Sø, based on U^K_{37} of filtered alkenones and in situ water temperature, with a previously published lacustrine alkenone calibration from sites containing alkenones of similar molecular composition to those in the Greenland lakes (12, 15) (*SI Appendix*, Fig. S2). The in situ calibration approach has been successfully employed in North American lakes (14). Our calibration (Fig. 2B; $T = 40.8\ U^K_{37} + 31.8$, $r^2 = 0.96$, $n = 34$), which has a mean standard error of estimation of 1.3 °C (*SI Appendix*, Section 3), implies that mid-June to mid-July lake water temperature in the Kangerlussuaq region varied by as much as 5.5 °C over the past 5,600 y (Fig. 3A).

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Fig. 1. (*A*) Site map identifying Kangerlussuaq and other locations in West Greenland mentioned in the text. (*B*) Map of the Søndre Strømfjord region showing locations discussed in the text. (*C*) Map of the North Atlantic region noting the locations of Kangerlussuaq, Crag Cave (38), and the Bermuda Rise (39). Coloration indicates the modern temperature pattern observed during the positive mode of the North Atlantic Oscillation, where red is warm and blue is cool.

Alkenone production began approximately 500 y earlier in Braya Sø than in Lake E, and this interval (approximately 6,100–5,600 y B.P.) includes the warmest reconstructed lake water temperatures from either time series (Fig. 3*A*). Because this time interval is not represented in Lake E, we cannot determine whether this reflects a local period of extreme mid-Holocene warming, if the high U_{37}^K values reflect non-temperature-related factors (e.g., nutrients, growth rates) as the haptophyte algae colonized and exploited a new habitat, or if the temperature sensitivity of the alkenones becomes nonlinear at warm temperatures (a possibility that would be undetectable with our calibration approach). We therefore do not interpret this 500 y time period in the Braya Sø record. During the 5,600 y where they overlap, the Braya Sø and Lake E alkenone records show very similar trends on multidecadal to millennial timescales (Fig. 3*A*; $r = 0.53$, $p < 0.001$). After adjusting the two records within 2σ of their calibrated ^{14}C ages, they were resampled at 20-y intervals and averaged to generate a single record that best estimates past lake water temperature variability in the Kangerlussuaq region of West Greenland (Kanger Stack; Fig. 3*B*).

Kangerlussuaq lake water temperatures cooled by approximately 4 °C between 5,600 and 5,000 y B.P., followed by warming of approximately 5.5 °C that culminated between 3,200 and 3,000 y B.P. and then another sharp temperature drop of approximately 5 °C by 2,800 y B.P. (Fig. 3*B*). The temperature history from alkenone paleothermometry is consistent with previous qualitative temperature inferences for West Greenland from pollen (19, 20) and loss-on-ignition analyses (Fig. 3*C*) from lake sediments (21) that indicate peak warmth between 4,000 and 3,000 y B.P., followed by Neoglacial cooling *ca.* 3,000 y B.P. The Greenland Ice Sheet Project Two ice core from Summit (9, 22, 23) (Fig. 1*A*) also depicts similar trends for millennial-scale

Fig. 2. (*A*) C$_{37}$ alkenone flux to Braya Sø lake bottom determined using interval sediment traps. (*B*) Temperature calibration developed for this study using in situ U_{37}^K from Braya Sø water filters collected during summer 2007 (red diamonds) and 2009 (blue squares) and a previously published calibration (12) from Europe (black circles).

Fig. 3. (*A*) Alkenone-based lake water temperature reconstruction for Lake E (gray) and Braya Sø (red), Kangerlussuaq, West Greenland. The time series have been visually aligned within the 2σ error of the calibrated ^{14}C dates. Error bars show standard error of estimation (S.E.) from the calibration and the analytical uncertainty (2σ) (*B*) The Kanger Stack was developed by resampling and calculating the arithmetic mean of the individual temperature reconstructions from Braya Sø and Lake E at 20-y intervals. Blue shading represents uncertainty from averaging the two records. (*C*) The loss-on-ignition paleoproductivity record from lake SFL4-1 (21), near Kangerlussuaq. (*D*) Temperature reconstruction from the Greenland Ice Sheet Project Two ice core, Summit, Greenland (23).

temperature variability (Fig. 3D). The large cooling event centered at 2,000 y B.P. in the alkenone record (lake water temperatures dropped by 2–3 °C) corresponds to the greatest Neoglacial advance of inland ice near Kangerlussuaq (24). A cooling trend from 3,000–2,800 y B.P. and the cold interval from 2,200–1,800 y B.P. also coincide with proxy-inferred episodes of increased eolian activity in the region, indicating enhanced windiness and aridity (25). Diatom-inferred lake salinity and lacustrine carbonate $\delta^{18}O$ records (26, 27), plus ^{14}C-dated paleo-shorelines from Kangerlussuaq (28) document an arid phase from 6,500–4,500 y B.P. followed by an interval of increased moisture from 4,500–3,500 y B.P. These intervals correspond to cooling and warming trends, respectively, in the alkenone temperature data (Fig. 3 A and B). Over the modern instrumental period, correspondence between aridity (humidity) and cold (warm) temperatures in West Greenland is largely due to the effects of the North Atlantic Oscillation (NAO) (18, 29). Although it has been previously suggested that the NAO influenced the climate of West Greenland throughout the mid to late Holocene (30) and there is some evidence (31, 32) for multi-centennial-scale mode dominance of the NAO (periods during which the NAO spends more time in either the negative or positive mode), it remains uncertain whether or not the NAO truly exhibits mode dominance over multicentennial to millennial timescales and we are thus hesitant to ascribe the observed climatic shifts to the NAO.

The History of Human Occupation of West Greenland Related to Climate Change

A comprehensive explanation of the human migration history of West Greenland over the past 4,500 y requires integration of the combined effects of climatic change, environmental degradation, economic stress, social conflict, and a variety of cultural factors. Although such a detailed assessment of West Greenland's settlement history is beyond the scope of this paper, our study allows evaluation of human migration in West Greenland in the context of Holocene temperature variability. Arriving in Greenland *ca.* 4,500 y B.P. (3–5), the Saqqaq would have experienced an interval

of warmth identified in our temperature reconstruction (Fig. 4A). They survived transient episodes of warming and cooling, especially between 4,100–3,400 y B.P. A cooler interval in the later phase of their occupation at about 3,400 y B.P. coincides with a contraction in the Saqqaq population toward West Greenland (3–5) and a shift from subarctic to arctic conditions in the Disko Bugt region (33) (approximately 250 km north of Kangerlussuaq; Fig. 1A) that likely affected resource availability (34). There is evidence from the Nipisat site near Sisimiut (Fig. 1B) that the Saqqaq developed new adaptive strategies around this time (4, 5). It is possible that climate variability during this period encouraged the diversification of the Saqqaq resource base with, for example, walrus becoming a more important food source. It is uncertain whether local climate conditions, increased contact with other members of the Arctic Small Tool tradition, or other factors are responsible for the adaptations observed in the archaeological record, but with the new strategies, the Saqqaq remained active near Sisimiut (approximately 100 km west of Kangerlussuaq; Fig. 1 A and B) until *ca.* 2,800 y B.P. (3–5). Perhaps the persistence of warm temperatures in Kangerlussuaq and Sisimiut afforded the Saqqaq adequate access to marine and terrestrial resources (4). Furthermore, large caribou populations in the Sisimiut region would have provided a terrestrial food source as marine resources became more difficult to procure (3). The Saqqaq departure from Sisimiut *ca.* 2,800 y B.P. is coincident with the culmination of a pronounced cooling trend recognized in our temperature reconstruction (approximately 4 °C in 200 y; Fig. 4A). The cooling that took place during this climate transition was no more abrupt than the transient cooling episodes that took place during the previous approximately 1,500 y of Saqqaq occupation and suggests that the magnitude was more important than the rate of change to the Saqqaq abandonment of the region.

The Dorset occupation of West Greenland began *ca.* 2,800 y B.P. (3) and their tool inventory, which included sledge shoes, soapstone vessels for burning seal fat, and snow knives, suggests they were better adapted to sea-ice hunting than were the Saqqaq (3, 35). The Dorset lifestyle appears therefore well adapted to the colder conditions from 2,800 and 2,000 y B.P. observed in the Kangerlussuaq temperature reconstruction (Fig. 4A). Like the brief warming and cooling episodes experienced by the Saqqaq, the period of Dorset occupation was also characterized by high-amplitude centennial-scale temperature variability, but their continuous occupation in the region indicates that their livelihood strategies allowed them to cope with these temperature fluctuations. These observations prompt the question whether abrupt climate change played a role in the Dorset abandonment of West Greenland. Given the complexity of human behavior, archaeological approaches alone cannot answer this question, but paleoclimatological investigations can help address it. Moros et al. (33) inferred warm sea-surface temperatures and limited sea ice in the Disko Bugt region (Fig. 1A) from 2,000–1,800 y B.P. and suggested that these conditions would have been unfavorable to the Dorset, given that they were predominantly sea-ice hunters. The progressive warming of Kangerlussuaq lake waters to nearly pre-Neoglacial temperatures at this time (2,000–1,800 y B.P.; Fig. 4A) represents a strongly amplified feature of the centennial-scale variability. These temporal data reinforce Moros et al.'s (33) evidence for increased temperature and support the idea that dramatic regional climate change could have greatly impacted the Dorset culture at this time. However, it seems unlikely that there was an extant Dorset population in West Greenland to experience it because archaeological evidence places the latest population at *ca.* 2,200 y B.P. (3), two centuries prior to the observed warming (33) (Fig. 4A). Moreover, faunal remains from the Dorset Malmquist site, which is located between Kangerlussuaq and Sisimiut (Fig. 1B), are dominated by caribou, indicating that the resource base was diverse and not solely tied to sea-ice hunting (3). In addition, there is an

Fig. 4. (A) Alkenone-based Kangerlussuaq lake water temperature reconstruction (blue curve). Error bars depict the standard error of estimation (S.E.) from the calibration and the analytical uncertainty (2σ) (B) $\delta^{18}O$ record from speleothem CC3, southwestern Ireland (38) (red curve; lower $\delta^{18}O$ values reflect colder temperatures). (C) $\delta^{18}O$ record from Sargasso Sea (39) (black curve, lower $\delta^{18}O$ values reflect warmer temperatures). (D) Difference between normalized time series (Greenland-Ireland) after 21-point smoothing.

absence of archaeological evidence for a northward migration of the Dorset at this time, which would seem likely if warming temperatures forced them from West Greenland. Thus, the Dorset disappearance may not be directly related to the intense warming from *ca.* 2,000–1,800 y B.P. Perhaps their disappearance is related to the particularly cold interval observed in the Kangerlussuaq temperature reconstruction beginning *ca.* 2,200 y B.P. and centered at *ca.* 2,000 y B.P., except that it is difficult to explain why the impact on Dorset livelihood during this particular cool episode was sufficient to cause the abandonment of the region in contrast to two previous comparable cooling episodes (*ca.* 2,800 and 2,500 y B.P.; Fig. 4*A*).

The temperature reconstruction also reveals warming from *ca.* 1,100 to 850 y B.P., coincident with Norse migration to Greenland. The abrupt temperature decline beginning *ca.* 850 y B.P. (4 °C in approximately 80 y; Fig. 4*A*) coupled with the persistence of cooler temperatures until approximately 630 y B.P. yielded a progressively unfavorable climate over several decades with a cumulative adverse effect on the sedentary Norse farming population in West Greenland (36). Thus, a shift toward lower temperatures likely contributed to the abandonment of the western Norse settlement near Nuuk (Fig. 1*A*) at *ca.* 650 y B.P., which supports arguments that climatic deterioration played a critical role in the demise of Norse settlements in Greenland (6, 36, 37) (Fig. 1*A*).

Spatial Patterns of Temperature Change Across the North Atlantic

How did temperature variability in Kangerlussuaq compare with other regions around the North Atlantic? Remarkably, the Kangerlussuaq temperature record shows a strong antiphased relationship at centennial to millennial timescales with the $\delta^{18}O$ record from speleothem CC3 at Crag Cave, southwestern Ireland (38) (Figs. 1*C* and 4*A* and *B*). The Crag Cave record is not simply temperature (moisture source and precipitation amount may also play a role), but provides a qualitative record of climate variability with higher $\delta^{18}O$ corresponding to warmer conditions (38). Together the records indicate multicentennial to millennial length intervals of anticorrelation between temperature in West Greenland and southwestern Ireland over the past 5,600 y (Fig. 4 *A* and *B*). When the normalized records are differenced (Fig. 4*D*), the intervals 5,200–4,600; 3,000–1,900; and 1,200–0 y B.P. are shown to be characterized by cold Kangerlussuaq temperatures and warm temperatures in southwestern Ireland, whereas the intervals 4,600–3,000 and 1,900–1,600 y B.P. depict warm temperatures in Kangerlussuaq and cold temperatures in southwestern Ireland. Furthermore, cross-spectral analysis reveals that the records are highly coherent (above the 95% confidence level) at periods of 252–278, 211–231, and 122–124 y (*SI Appendix,* Fig. S7). If such coherence in temperature variability across the North Atlantic were observed at known periods of NAO variability (which are too short to resolve from this dataset), we would likely attribute forcing to the NAO (29). Although there is no clear evidence that the NAO operates at the periods identified from our coherency analysis, multicentennial persistence

of NAO mode dominance has previously been suggested from paleoclimate records spanning the Holocene (31) and the past millennium (32). It is possible that the intervals identified in Fig. 4*D* correspond to periods during which the NAO spent more time in one mode, and we note that a $\delta^{18}O$-based qualitative sea-surface temperature (SST) record from the Bermuda rise (39) (Fig. 4*C*) supports this interpretation, depicting millennial-scale warming of western Atlantic SSTs corresponding to cold intervals in West Greenland and warm intervals in southwestern Ireland, and fitting the expected NAO spatial pattern (Figs. 1*C* and 4 *A–C*). However, although the spatial temperature patterns are suggestive of the NAO, the available data are insufficient to constrain the observed temperature patterns to NAO forcing. Consideration of volcanic and solar forcing is necessary to explain temporal patterns of climate variability over the past 1,000 y (40) and the influence of these climate drivers likely predate the past millennium. Our results indicate that the ice-free region of West Greenland experienced much greater temperature variability during the Holocene than the top of the Greenland ice sheet, probably as a result of interactions among oceanic, atmospheric, solar, and volcanic forcing, and that climatic changes were important in influencing cultural transitions and human settlement patterns in West Greenland.

Materials and Methods

Sediment cores were sampled at 0.5-cm intervals. Samples were freeze-dried and homogenized by mortar and pestle and extracted with dichloromethane using an ASE200 (Dionex). Total lipid extracts were dried under N_2 gas and quantified by gas chromatography-flame ionization detection (HP6890 Series). U_{37}^{K} was measured with a precision of ±0.01, using an alkenone standard run once every 10 sample injections, and yielding analytical precision of ±0.4 °C. Alkenones from representative samples were identified by comparison of mass-spectral data with previously reported standards and GC retention times (15). To evaluate the timing of alkenone production, sediment trap material in Braya Sø was collected in 10-d intervals at approximately 20 m water depth during the summer of 2006 using a Technicap PPS 3/3 automated cylindroconical sediment trap (collecting area = 0.125 m²). Material collected in sediment trap bottles was filtered through precombusted (550 °C) Whatman© glass microfiber filters, freeze-dried, and processed as sediment samples (described above), without homogenization. To establish an in situ U_{37}^{K}-temperature calibration, lake water samples from Braya Sø (approximately 1 L each) were collected from various water depths in late-June 2007 and 2009 and filtered through precombusted (550 °C) Whatman© glass microfiber filters, which were freeze-dried and processed as sediment samples (described above), without homogenization. Water temperatures at each depth were determined by direct measurement using a YSI, Inc., sonde.

Total organic carbon for core BS01-01 (E-01) was measured at Brown University (University of Nebraska-Lincoln) on a Carlo-Erba elemental analyzer after acidification of samples with HCl to remove carbonates.

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Appendix: Supporting Information

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SI Text

1) Radiocarbon dating and chronology
The sedimentation rates of the lakes average 28 and 21 cm kyr^{-1} during the past 5,600 yr. The age model for Braya Sø is based on 8 AMS (accelerator mass spectrometry) ^{14}C dates of bulk sediment, 3 of wood fragments and 1 of a gastropod shell, and the age model for Lake E is based on 6 AMS ^{14}C dates of bulk sediment. Dating errors are all less than ±75 yr for bulk sediment and ±160 yr for macrofossils within the 1σ interval of the AMS ^{14}C method. Braya Sø and Lake E lie 10 km apart, ~170 m above sea level, have water depths of 24 and 22 m, respectively and are meromictic, resulting in bottom water anoxia and finely laminated sediments. Ten ^{14}C dates were used to establish chronological control for core BS01-01 from Braya Sø (Fig. S3A). Radiocarbon dates were calibrated to years before present (BP; years before 1950 AD) using the Fairbanks0107 calibration curve (*41*). Core BS01-01 was taken with a single drive piston corer, maintaining the sediment water interface and allowing the core top to be assigned a modern age of 2005 AD, the year prior to core recovery. Five of the radiocarbon dates were from core BS01-01 (AMS ^{14}C analysis performed at Woods Hole Oceanographic Institution) and five were from an overlapping core (AMS ^{14}C analysis performed at the University of Aarhus, DK) that was stratigraphically aligned to BS01-01 using loss-on-ignition and total organic carbon measurements (Fig. S4). Three paired macrofossil and bulk sediment dates yielded a reservoir correction of 360 years, which was applied to the ^{14}C dates prior to calibration. The "reservoir effect" in these meromictic lakes is likely caused by 1) deposition of old carbon from the water column due to lack of complete lake overturn resulting in incomplete exchange of CO_2 with the atmosphere (*42*), and 2) deposition of ^{14}C-depleted organic matter from the lake catchments, due to the low rates of decomposition typical of Arctic environments (*26*). Age reversals in the meromictic lakes of this region after ~1000 yrs BP have been previously noted (*26, 27*) and two ^{14}C dates from this time period were excluded from the age model. Another erroneously old ^{14}C date at 2982 ± 61 yrs BP was excluded from the age model. A 4th order polynomial was fit to the ten remaining calibrated dates and the core top date to establish an age model.

Chronological control for the Lake E core (E-01; Fig. S3B) was established using six AMS ^{14}C dates of bulk sediment (analysis was performed at the Arizona Accelerator Mass Spectrometry Lab). A seventh date that was erroneously old was excluded from the age model. Core E-01 was taken with a Russian Corer, which does not preserve the sediment water interface. To identify the depth of the core top, the % organic carbon record from core E-01 was compared to the % organic carbon record from an overlapping freeze-core (Fig. S5). This allowed identification of the E-01 core top to a depth of 9 cm

in the freeze-core. The top of the freeze-core represents the sediment water interface and was assigned an age of 2000 AD, the year the freeze-core was recovered. This approach allowed us to assign an age of 2000 AD to a theoretical -9 cm in the E-01 core, providing chronologic control for the top of the core. No macrofossils were isolated from the E-01 core, prohibiting the establishment of a carbon reservoir age for Lake E. Therefore, the reservoir age of 360 years determined in Braya Sø was applied to Lake E. A 4th order polynomial was fit to the six radiocarbon dates and the core top to establish the age model.

Braya Sø and Lake E are both oligosaline (3-4 psu), meromictic lakes with fully developed chemoclines. The lack of hydrologic outflow along with locally negative precipitation minus evaporation has led to evaporative concentration of salts in the lakes. Braya Sø is ~ 170 m above sea level (a.s.l.) and Lake E ~150 m a.s.l., well above the regional marine limit (~60 m), precluding seawater entrapment during isostatic uplift as a source of elevated salinity in the lakes. Braya Sø has an area of 73 ha and a maximum depth of 23 m. Lake E has an area of 22 ha and a maximum depth of 22 m.

2) Unsaturation index
The unsaturation index (U_{37}^{K}) as defined by Brassell *et al*., 1986 (*43*):

$$U_{37}^{K} = \frac{[C_{37:2}] - [C_{37:4}]}{[C_{37:2}] + [C_{37:3}] + [C_{37:4}]}$$

where, $[C_{37:x}]$ is the concentration of the alkenone with 37 carbon atoms and *x* carbon-carbon double bonds.

3) Standard error calculation
The standard error of estimation for the U_{37}^{K}-temperature calibration was calculated with the following formula:

$$SE = \sqrt{\frac{1}{(n-2)}[\sum(y - \bar{y})^2 - \frac{[\sum(x - \bar{x})(y - \bar{y})]^2}{\sum(x - \bar{x})^2}]}$$

where, *n* = sample size; $\bar{x}$ and $\bar{y}$ are sample means.

4) Correlation of paleoclimate time series data
Correlation between Braya Sø and Lake E U_{37}^{K} time series data was determined by visually aligning the resampled time series' within 2σ of their chronological uncertainty, resampling each data set at 20-yr intervals using the linear integration interpolation function in the Analyseries 2.0 program, and performing linear regression analysis (Fig. S6). The calculated correlation coefficient of 0.53 (p < 0.001) indicates a strong agreement between the records and implies a common forcing mechanism for U_{37}^{K} at both lakes.

5) Supporting References

41.   Fairbanks RG*, et al.* (2005) Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. *Quaternary Science Reviews* 24(16-17):1781-1796.

42.   Olsson IU (1986) Radiometric Dating. *Handbook of Holocene palaeoecology and palaeohydrology*, ed Berglund BE (Wiley, Chichester), pp 273-312.

43.   Brassell SC, Eglinton, G., Marlowe, I.T., Pflaumann, U. and Sarnthein, M. (1986) Molecular stratigraphy: A new tool for climatic assessment. *Nature* 320:129-133.

44.   Grønnow B & Sørensen M (2006) Palaeo-Eskimo Migrations into Greenland: The Canadian Connection. *Dynamics of Northern Societies,* Studies in Archaeology and History, eds Arneborg J & Grønnow B (PNM Publications, Copenhagen), Vol 10, pp 59-74.

45.   Theroux S, D'Andrea WJ, Toney J, Amaral-Zettler L, & Huang Y (2010) Phylogenetic diversity and evolutionary relatedness of alkenone-producing haptophyte algae in lakes: Implications for continental paleotemperature reconstructions. *Earth and Planetary Science Letters* 300:311-320.

6) Supporting Figures
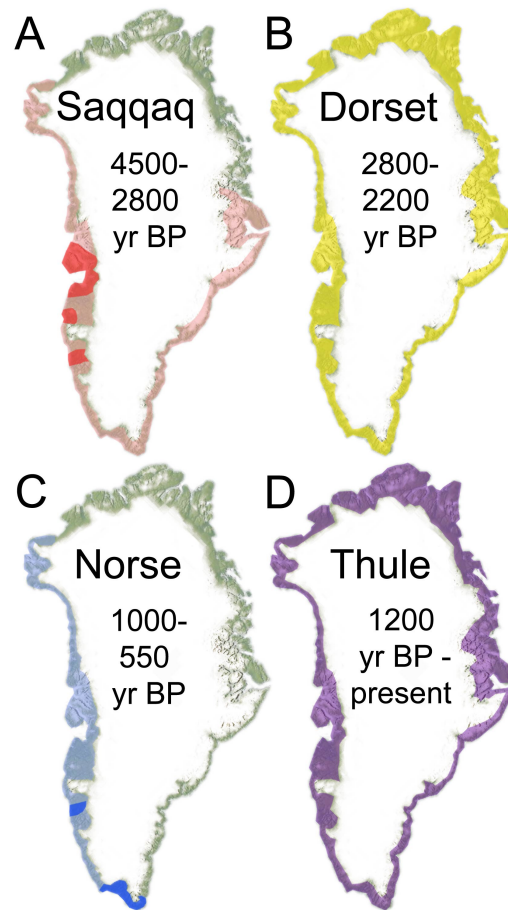
Figure S1. **Occupation history of Greenland.** Maps depicting the timing and extent of the occupation by different cultures in Greenland (after *SILA: The Greenland Research Centre at the National Museum of Denmark*; www.natmus.dk). White coloring represents the inland ice sheet. Green represents areas for which there is no archaeological evidence for presence of the specified culture. **(A)** Dark red depicts the regions with the largest number of Saqqaq sites, while light red indicates regions with archaeological evidence for Saqqaq presence. **(B)** Yellow shading represents the extent of Dorset occupation in Greenland. Following the convention of Grønnow and Sørensen, 2006 (*44*), Dorset here

comprises the cultures previously recognized as Dorset I (early Dorset) and Independence II. **(C)** Dark blue indicates the locations of the Norse western and eastern settlements. Light blue indicates areas of Norse influence, as determined by Norse archaeological remains. **(D)** Purple indicates the geographic extent of the Thule culture, the ancestors of the modern day Greenlandic Inuit.
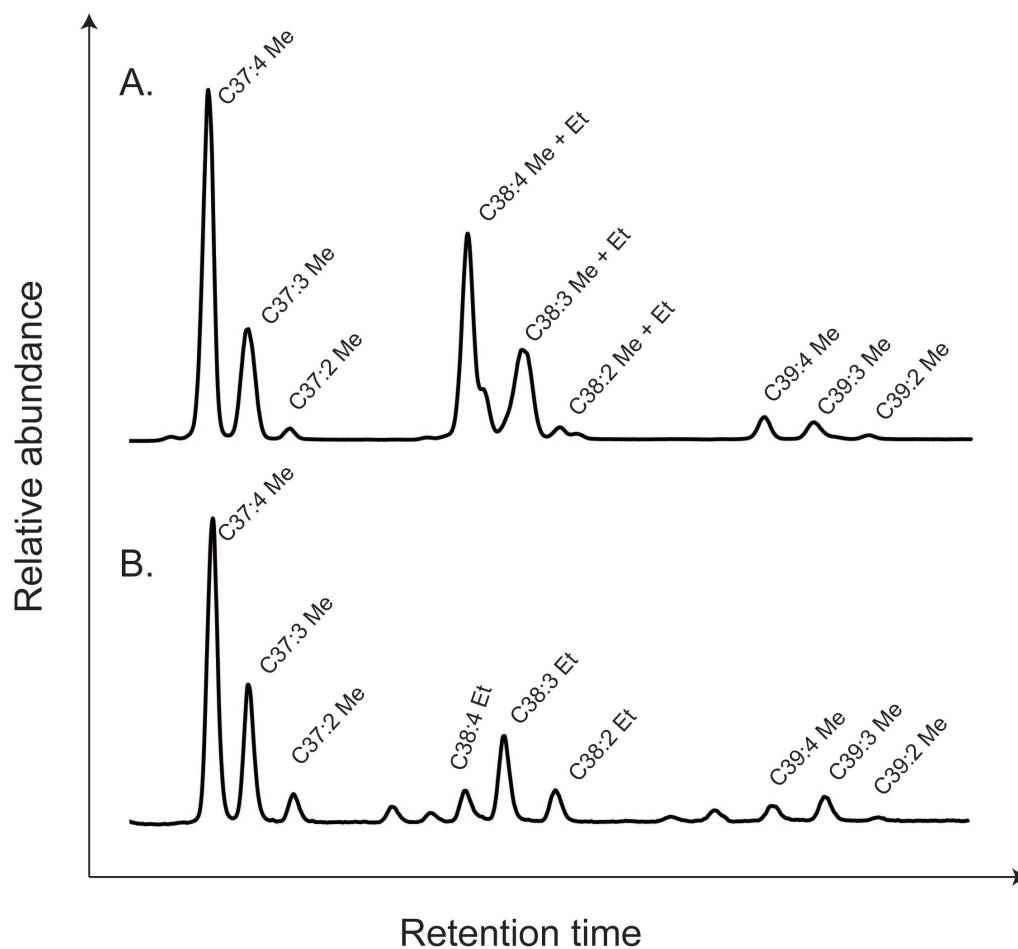
Figure S2. **Molecular composition of lacustrine alkenones. (A)** The molecular composition of alkenones from the Braya Sø and Lake E show dominance of the tetra-unsaturated alkenones and contain both methyl and ethyl C38 ketones (*15*). This molecular composition matches that of the lakes studied by Zink *et al*., 2001 (*12*). **(B)** For comparison, alkenones from Medicine Lake, South Dakota (*14*) do not contain C38 methyl ketones and are apparently produced by a haptophyte belonging to a separate phylotype (*45*).
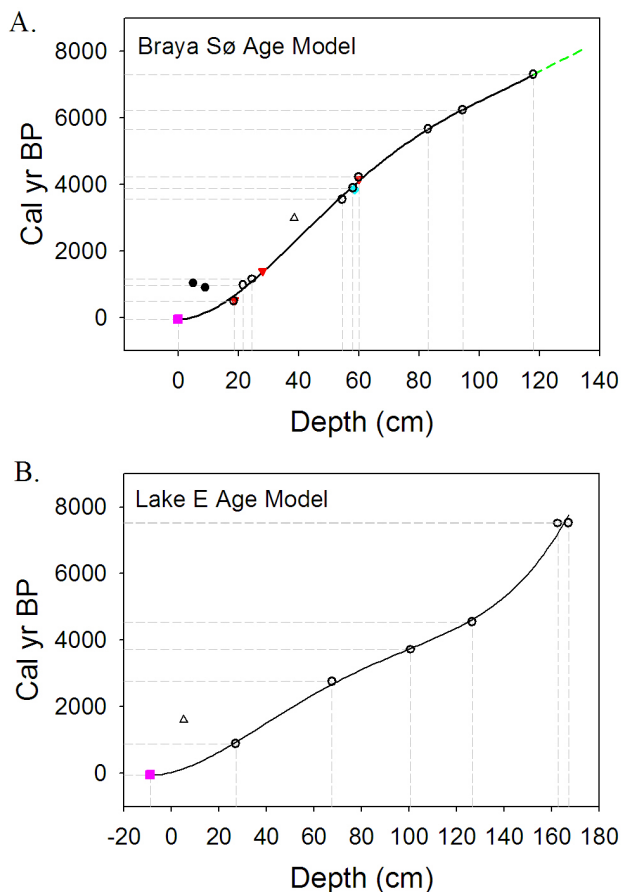
Figure S3. **Sediment core age models. (A)** Core BS01-01 from Braya Sø, and **(B)** core E-01 from Lake E. Open circles are calibrated ¹⁴C dates used in the age model. Pink squares are core tops, assigned a modern age and used in the age model. Open up-triangles are erroneously old ages that were excluded from the age model. Closed circles (upper plot only) are erroneously old ages from a sedimentary interval previously shown to have age reversals (*26, 27*) and were excluded from the age model. Red down-triangles and the blue diamond (upper plot only) are calibrated dates from terrestrial wood fragments and a gastropod shell, respectively.
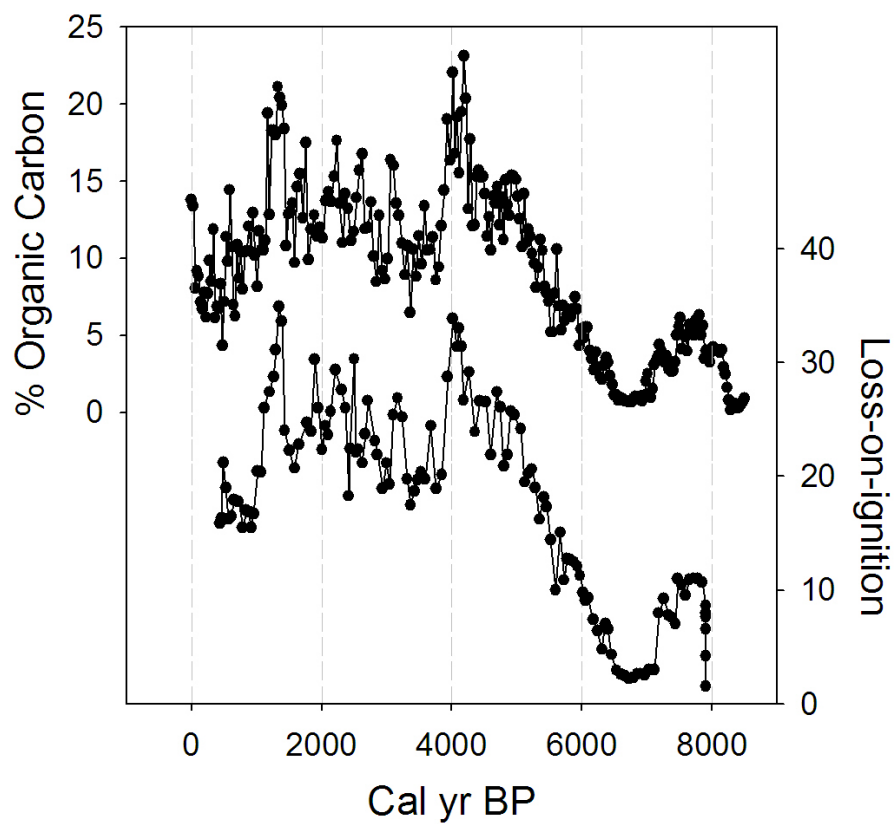
Figure S4. **Organic carbon content in overlapping cores from Braya Sø.** Percent organic carbon from core BS01-01 (top curve) and loss-on-ignition for an overlapping core (bottom curve) were used to stratigraphically align the overlapping cores, allowing five radiocarbon dates from the overlapping core to be transferred to core BS01-01.
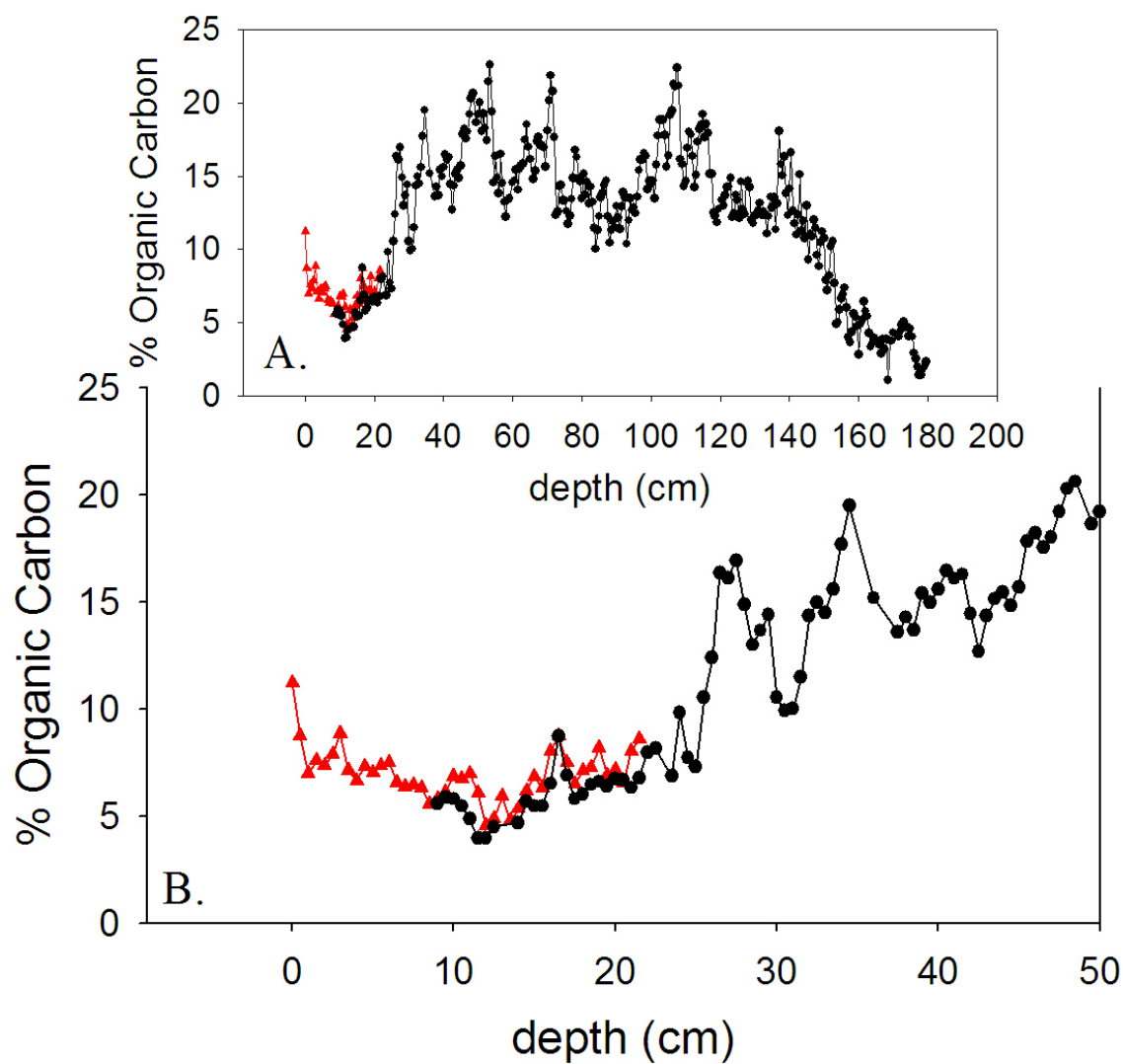
Figure S5. **Organic content in overlapping Lake E cores.** Black circles are percent organic carbon measurements from core E-01 (Russian core from Lake E). Red triangles are % organic carbon from an overlapping freeze-core. **(A)** The entire % organic carbon record from E-01 aligned with the % organic carbon records from the freeze core. **(B)** The top 50 cm, highlighting the excellent match between the overlapping records used to assign a core top age to core E-01.
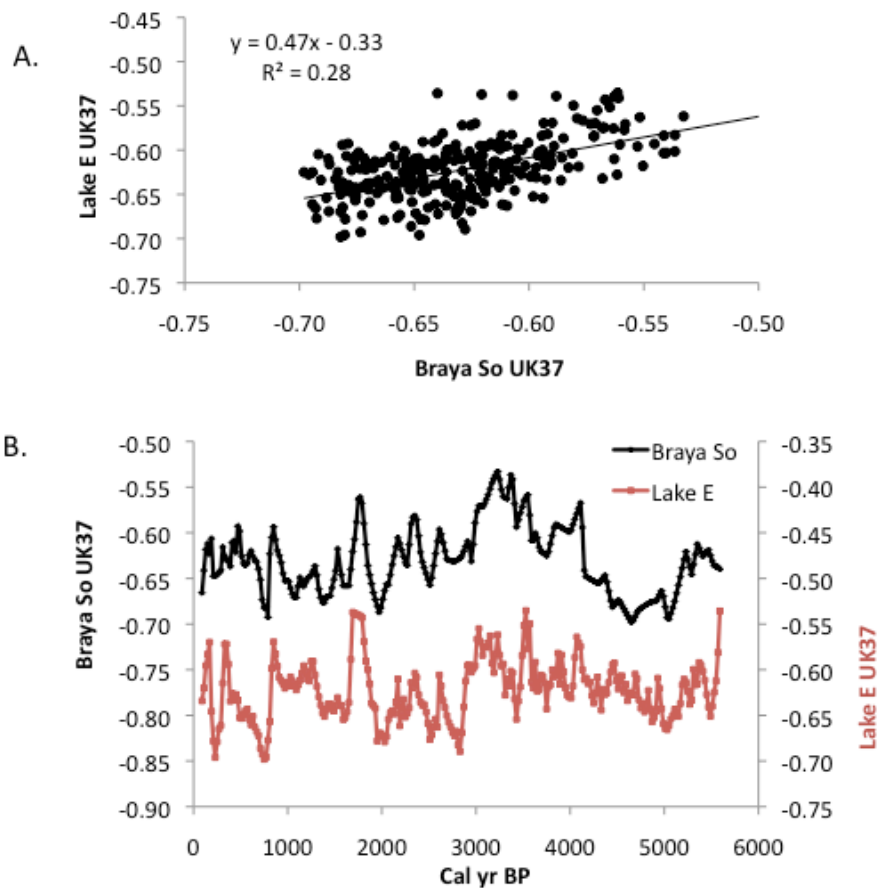
Figure S6. **Correlation between** U^K_{37} **records.** Correlation between Braya Sø and

Lake E U$^K_{37}$ measurements was evaluated by visually aligning the two series' within 2σ of

their chronological uncertainty and resampling each data series at 20-yr intervals using

the linear integration interpolation function in Analyseries 2.0. **(A)** Linear regression of

the resampled data sets. $R^2 = 0.28$. **(B)** The 20-yr resampled U$^K_{37}$ data from Braya Sø and

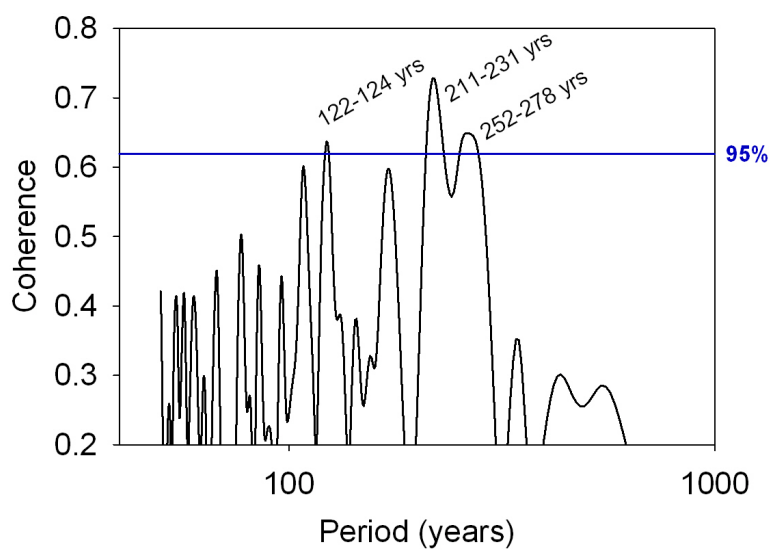Lake E after visual alignment within 2σ of the chronological uncertainty.

Figure S7. **Cross-spectral analysis of Kanger Stack and Crag Cave δ^{18}O.**

Blackman-Tukey cross-spectral analysis, performed with a Bartlett window and 30% lag.

Periods with coherence greater than the 95% confidence level (blue line) are labeled.