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Relationship between Holocene climate variations over southern Greenland and eastern Baffin Island and synoptic circulation pattern

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Abstract

Lake pollen records from southwest Greenland and eastern Baffin Island show strong regionalism in climate trends of the last 7000 years. Air temperature reconstructions from pollen indicate larger amplitude cooling in southwest Greenland ($>3.0^{\circ}\text{C}$) than in eastern Baffin Island ($<1.0^{\circ}\text{C}$). Such west-east gradient in climate change is consistent with paleoceanographical data that indicate decreasing temperature and/or strength of the North Atlantic Current to the east during the Holocene while the eastern Canadian margins under the Labrador Current influence display slight warming. Complementary to air and sea temperature records, the lake pollen data led to reconstruct increased cloudiness in southern Greenland, which points to increasing cyclonic activity since 7000 years west of Greenland. Together, the terrestrial and marine records of the northwest North Atlantic therefore suggest a shift from a dominant NAO+ during the early-mid Holocene to dominant NAO- in the late Holocene.

1 Introduction

Present-day climate conditions across the subpolar North Atlantic are by no means uniform or zonal, and regional scale differences need to be taken into account in paleoclimate studies and for climate modelling (e.g., Wohlfahrt et al., 2004; Renssen et al., 2005). Over the past few years, paleoecological studies at high latitudes of the Northern Hemisphere have reported a strong regionalism in both terrestrial climate and sea-surface conditions of the oceans (Marchal et al., 2002; Kaufman et al., 2004; Moros et al., 2004; de Vernal and Hillaire-Marcel, 2006). In particular, the northern North Atlantic has been marked by much larger cooling in surface water to the east than to the west from the early to late Holocene (Marchal et al., 2002; Moros et al., 2004; Andersen et al., 2004). In addition, variations in sea-surface salinity and sea-ice cover along the continental margin off Canada and strengthening of deep water formation in the Labrador Sea since the early Holocene suggest important changes in ocean

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thermohaline conditions and circulation pattern (de Vernal and Hillaire-Marcel, 2006). However, our understanding of the climate dynamics at high latitudes remains fragmentary because most paleoclimate studies report on surface ocean or air temperatures with little indication on seasonality or other climate parameters such as precipitation, wind patterns, moisture and cloud cover. The present study addresses the question of linkages between terrestrial climate and ocean records in the subpolar North Atlantic during the Holocene, with special attention paid to the climate parameters such as cloudiness in addition to surface air and ocean temperature, allowing interpretations in terms of large-scale circulation pattern involving the North Atlantic Oscillation (NAO) (Hurrell, 1995).

We use palynological data from marine and lacustrine cores collected in the north-west North Atlantic and adjacent lands (east Baffin Island and southwest Greenland) to derive climate records spanning about 8000 years (Fig. 1). The coring sites are located in the trajectory of surface ocean currents that play a major role in northward heat fluxes, the North Atlantic Current (NAC) and its westward branch making the west Greenland Current (WGC) and southward Arctic water flow through the Baffin Land Current (BLC) and the Labrador Current (LC). The core sites are well located to document synoptic scale changes, notably with regard to the trajectory of North Atlantic storm tracks in the Labrador Sea, which ends in south Greenland (Chen et al., 1997; Tsukernik et al., 2007). They are also suitably located to document NAO. Positive NAO is characterized by reduced strength and frequency of cyclonic activity in the Labrador Sea (Serreze et al., 1997), which results in overall cloudiness decrease over much of the North Atlantic, west of Greenland, whereas negative NAO rather results in cloudiness increase (Previdi and Veron, 2007).

2 Study area

The studied lakes are located on eastern Baffin Island (Akvaqia Lake [AKV]; 66°47' N, 63°57' W; 17 m a.s.l.) and in southwest Greenland (Qipisarqo Lake [QIP]; 61°00' N,

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47°45' W; 7 m a.s.l.) (Fig. 1). The climate conditions at the two sites are contrasted, especially in winter. The present-day July and January air temperatures average respectively 4.9°C and -24.1°C on eastern Baffin Island and 8.4°C and -6.2°C in southwest Greenland (Cappelen et al., 2001; Environment Canada, 2004). The milder climate of southern Greenland is related to the influence of the WGC, whereas the outflow of Arctic waters through the BLC results in cold winter conditions on eastern Baffin Island. Sunshine (inversely proportional to cloud cover) during the growing season of the vegetation (June–September) averages 37% and 32% respectively on eastern Baffin Island and in southwest Greenland (New et al., 2002; Whitmore et al., 2005). Sunshine is lower in southwest Greenland than eastern Baffin Island notably because south Greenland is located along a primary North Atlantic cyclone track, which is enhanced by the proximity of relatively warm ocean surface current (WGC) to the Greenland ice sheet (Chen et al., 1997; Tsukernik et al., 2007). Despite contrasting climate, the local vegetation of these sites is comparable. Vegetation is moderately lush shrub tundra dominated by shrub birch (*Betula*) and heaths (Ericales). Shrub alder (*Alnus*) is absent from the Baffin Island vegetation but is regionally common in southwest Greenland (61°–66° N) (e.g., Fredskild, 1996). The modern pollen flux is of the order of 500 grains/cm²/yr at Qipisarqo and of the order of 90 grains/cm²/yr at Akvaqiaq. Pollen assemblages are dominated by *Betula* but *Alnus* and herb pollen grains record higher percentages at Qipisarqo.

The studied marine cores were collected on the continental slope of the Canadian margin, at the vicinity of the center of Labrador Sea Water (LSW) formation (Core HU-84-030-021TWC [HU021]; 58°22.06' N, 57°30.42' W; water depth=2853 m), and in the area of the Charlie Gibbs Fracture Zone in the central part of the North Atlantic (Core HU-91-045-085TWC [HU085]; 53°58.51' N, 38°38.25' W; water depth=3603 m) (Fig. 1). The core HU021 is located close to a front between the LC and the WGC. Modern mean sea-surface temperature (SST) and salinity (SSS) are 6.7°C and 34.3 in summer and 3.4°C and 34.8 in winter, respectively, and sea-ice cover develops for about 2 months per year (2.0±1.05) (NODC, 2001). The core HU085 is along the axis

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of the warm NAC, where SSTs are 10.3°C and 5.3°C in summer and winter respectively and where SSS ranges 34.5 to 34.8 (NODC, 2001).

3 Methods

3.1 Lacustrine sediment cores chronology and pollen analysis

5 Akvaqiaq (98BIR-02, 98BIR-G01) and Qipisarqo (98QIP-02, 98QIP-G01) lake cores were collected in May 1998 from the frozen lake surface. Qipisarqo Lake sedimentology is thoroughly discussed in Kaplan et al. (2002). At the two lakes, piston and gravity (Glew) cores were used for the establishment of composite records, in which the Glew cores provide the upper part of the sedimentary sequences. The chronology
10 of the Akvaqiaq Lake record is based on seven accelerator mass spectrometry (AMS) ¹⁴C dates on bryophyte macrofossils and humic acid extracts (Table 1). The chronology of the Qipisarqo Lake record is based on six AMS-¹⁴C dates on bryophyte macrofossils and humic acid extracts (see Kaplan et al., 2002) (Table 1). Paired macrofossil and humic acid dates have been obtained at three levels in the Akvaqiaq Lake core and one
15 level in the Qipisarqo Lake core, producing humic acid ages that are older than adjacent macrofossils. This has led to age correction of 537 and 230 years for humic acid dates in Akvaqiaq and Qipisarqo lakes, respectively. All corrected (humic acid) and uncorrected (bryophyte) dates have been calibrated to calendar years using the CALIB program (version 5.0.2) (Stuiver and Reimer, 1993) updated with the Intcal04c14 dataset
20 (Reimer et al., 2004). Age models were then derived from smoothed linear interpolation between calibrated ages (Fig. 2). For the last 8000 years, sediment accumulation rates average 11.35±4.41 cm/ka at Akvaqiaq Lake and 26.77±16.84 cm/ka at Qipisarqo Lake.

Standard pollen preparation techniques, including dispersion with KOH, digestion
25 with HF and HCl, and acetolysis (Faegri and Iversen, 1975), were applied to 1.0 or 2.0 cm³ samples of fresh (wet) sediment. Pollen and spores were identified using the

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taxonomic keys of Richard (1970), McAndrews et al. (1973) and Moore et al. (1991), as well as reference to modern collection archived at the Laboratoire Jacques-Rousseau, Université de Montréal. Palynological analyses performed at 3 to 5 cm interval yield a centennial resolution, which permits to identify long term trend. For consistency, the pollen sum used for computing relative frequencies from the fossil assemblages includes only the 39 pollen types contained in the modern database (cf. Table 1 in Fréchette et al., 2008a). The pollen sums average 555 ± 48 grains for Akvaqiak lake, and 516 ± 44 grains for Qipisarqo lake.

3.2 Marine sediment cores chronology and dinocyst analysis

Cores HU021 and HU085 were collected during expeditions of the CSS-Hudson. The chronology was established on the basis of AMS ^{14}C dates on planktic foraminifera. For core HU021 three dates are available and for core HU085 two dates are available. The conventional ^{14}C ages have been calibrated into calendar years using the CALIB Rev 5.0.1 program (Stuiver and Reimer, 1993) and the marine calibration dataset (Marine04.14C) of Hughen et al. (2004). The marine calibration was made with a global ocean reservoir correction of 400 years, but no further correction of reservoir age (ΔR) was applied to account for local effects. The age models were established from linear interpolation between calibrated ages. For the last 8000 years, sediment accumulation rates average 17.6 cm/ka in core HU021 and 6.2 cm/ka in core HU085.

Palynological preparation for the analyses of dinocysts were made following standardized laboratory procedure that include sieving at $10\ \mu\text{m}$ to eliminate fine silt and clays, in addition to repeated HCl (10%) and HF (52%) treatments to dissolve carbonate and silica particles. No oxidation treatment was done. Palynological analyses performed at 1 to 2 cm interval yield a centennial resolution. For consistency, the dinocyst sum used for computing relative frequencies from the fossil assemblages includes only the 60 dinocyst taxa of the modern database (cf. Table 1 in de Vernal et al., 2005). The sums average 345 ± 70 cysts for core HU021, and 256 ± 87 cysts for core HU085.

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3.3 Principal component analysis

Detrended correspondence analysis (DCA) was first used to estimate the compositional gradient lengths along the first few DCA axes in the lacustrine and marine records (Gauch, 1982; ter Braak and Prentice, 1988; Birks, 1995). For DCA calculations we used the pollen types and the dinoflagellates cysts selected for the quantitative climate and hydrographic reconstructions. Among the 39 pollen types, 25 were present at Akvaqia Lake and 31 at Qipisarqo Lake. Among the 60 dinocyst taxa, 25 were recorded in core HU021 and 21 in core HU085. The length of gradient of DCA axis 1 is 0.87 and 1.01 SD (standard deviation) units for Akvaqia and Qipisarqo lakes, respectively, and 1.09 and 1.41 SD units for cores HU021 and HU085, respectively, which indicates linear responses of both pollen and dinocysts to the underlying environmental gradient. Therefore, linear ordination (Principal Component Analysis) was applied. Principal Component Analysis (PCA) was used to detect the major gradient among the fossil pollen and dinocyst spectra. Because the variables are dimensionally homogeneous, a dispersion (variance/covariance) matrix was used (Birks, 1995; Legendre and Legendre, 1998). The number of pollen and dinocysts was lowered. We selected taxa with a value greater-than or equal to 1% in at least one sample and created a collective category among the pollen types (*Picea+Pinus*). This selection resulted in 10 pollen types for Akvaqia Lake, 17 pollen types for Qipisarqo Lake, 15 dinocyst types for core HU021 and 17 dinocyst types for core HU085. For PCA, as for the quantitative climate and hydrographic reconstructions, the relative frequencies (in percent) of the pollen types was square-root transformed and the relative frequencies (in per mil) of dinocysts was logarithmic transformed. These transformations were done in order to optimize the signal-to-noise ratio and stabilize the variances. DCA was implemented with CANOCO version 4.0 (ter Braak and Šmilauer, 1998) with rare taxa not down-weighted. PCA calculations were performed using the computer program Prociel R (version 4) (Legendre and Legendre, 1998). Informations on PCA results (first three eigenvalues, % variance and loadings) are given on supplementary Tables 1 and 2

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3.4 Continental climate reconstruction

Continental climate reconstruction were made from the Modern Analogue Technique (MAT) using a modern database of 828 sites from lakes of the Boreal, Subarctic and Arctic biomes of North America (north of 50° N) and Greenland. The surface air temperature (SAT), sunshine (S) and precipitation (P) (Whitmore et al., 2005; Fréchet-
5 et al., 2008a) were calculated from the Climatic Research Unit (CRU) gridded climatology using 1961–1990 climatological averages (New et al., 2002) and interpolated to each 828 pollen sites via lapse-rate collected bilinear interpolation. Whitmore et al. (2005)
10 describe in full the method used to estimate modern climate. The gridded sunshine data provided by New et al. (2002) are expressed as percent of possible bright sunshine and were derived from sunshine averages at given stations or from conversion of cloud cover to sunshine. Modern climate parameters at Akvaqiak and Qipisarqo lakes were estimated in the same way.

The pollen data include the 39 most common vascular taxa (18 woody plants and 21 herbs). The reconstructions based on MAT followed the procedure described in detail by Fréchet-
15 et al. (2008a). Similarity between fossil and modern pollen assemblages is based on the squared chord distance (SCD) dissimilarity metric (Birks, 1977; Prentice, 1980; Overpeck et al., 1985; Gavin et al., 2003), which is an euclidean distance calculated on the square-root transformed pollen types abundances expressed in percent. Values of SCD vary between zero and 200, with larger values indicating larger dissimilarity. The adopted SCD threshold for the present study is 26. The climate estimates are calculated from the 5 best modern analogues.

Reconstructions of the July (warmest month) SAT and growing season (June–September=JJAS) sunshine were performed with the 3Pbase software (Guiot and Goeury, 1996). The accuracy of the approach (RMSE) is estimated to $\pm 1.4^{\circ}\text{C}$ ($r=0.92$) for July SAT and $\pm 2.1\%$ ($r=0.87$) for JJAS sunshine. It is of note that the errors are close to the squared root generalized cross validation (RTGCV), which provides an es-
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5 timate of the mean predictive error (and hence power) of the fitted surface. At the scale of North America and Greenland (20°–85° N, 20°–180° W), the RTGVC of July SAT is of 0.7°C and the RTGVC of summer sunshine is 4.5% (New et al., 1999, 2002). The accuracy of the interpolated monthly sunshine at high northern latitudes is influenced by the effect of low sun angles on the amount of bright sunshine recorded (New et al., 1999). Therefore, it is important to look at the station networks and cross-validation statistics for assessing the accuracy of the interpolation in the study region (New et al., 2002). At Akvaqiaq and Qipisarqo lakes, July SAT is 6.2±1.0°C and 9.0±1.1°C respectively (Cappelen et al., 2001; Environment Canada, 2004), and JJAS sunshine is 39.6±5.8% and 33.2±1.9% respectively (New et al., 2002; Whitmore et al., 2005).

10 Redundancy Analysis (RDA) was used to estimate long term trend in winter SAT and annual precipitation. RDA ordination of the Arctic reference sites ($n=256$, 35 pollen types, 4 climate variables: July and January SAT, annual precipitation, JJAS sunshine) demonstrates that the first RDA axis ($\lambda_1=0.184$; 18.4% of the total variance in the pollen data alone, and 62.5% of variance in the weighted-averages of the pollen taxa constrained to climate variables) positively correlates with January SAT ($r=0.79$) and annual precipitation ($r=0.63$) (cf., Fig. 5a). In the Arctic, these two climate parameters are strongly correlated together ($r=0.86$). Fossil pollen assemblages of Akvaqiaq and Qipisarqo lakes were projected passively onto the ordination space, without influencing the RDA analysis in any other way. Therefore, the scores of Akavaqik and Qipisarqo spectra projected on RDA axis 1 of the Arctic-site modern assemblages allow semi-quantitative estimates of January SAT. For RDA ordination the frequencies of the 35 pollen types were square-root transformed and rare taxa were not down-weighted. RDA was performed with CANOCO version 4.0 (ter Braak and Šmilauer, 1998). Informations on RDA results (first three eigenvalues, % variance and loadings) and correlation matrix between the 4 climate variables are given in supplementary Tables 3 and 4 <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>.

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3.5 Hydrographic reconstruction

Quantitative reconstruction of past sea-surface conditions is based on MAT applied to dinocyst assemblages. The reference database includes 60 taxa and 1054 reference sites from mid- to high latitude North Atlantic, North Pacific and Arctic oceans, and adjacent sub-polar seas (de Vernal and Hillaire-Marcel, 2006). The dissimilarity metric used is the euclidean distance calculated on neperian logarithmic transformed dinocysts abundance, expressed in per mil (de Vernal et al., 2001; 2005). Unlike the SCD used with the pollen database, the dissimilarity metric used with the dinocyst database has no upper limit. The adopted dissimilarity threshold for the present study is 74. The hydrographic values were estimated from the 5 best modern analogues. Reconstruction of the August (warmest month) sea-surface temperature (SST) was performed with the 3Pbase software (Guiot and Goeury, 1996). The error of prediction (RMSE) for August SST is estimated to $\pm 1.7^{\circ}\text{C}$. It is of note that this error is close to the actual standard deviation around the mean for the summer temperature, which averages $\pm 1.6^{\circ}\text{C}$ in the modern hydrographical database (NODC, 2001). Relatively close analogues for dinocyst assemblages exist in the modern database, with distances lower than 44 and 78 for cores HU021 and HU085, respectively. At sites HU021 and HU085, August SST is $6.7 \pm 0.9^{\circ}\text{C}$ and $10.6 \pm 0.8^{\circ}\text{C}$ respectively (NODC, 2001).

4 Results

4.1 Lacustrine sediment cores

The diagram of pollen assemblages of Akvaqiaq and Qipisarqo cores is given in supplementary Fig. 1 <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. The mid to late Holocene pollen influxes are of the order of $450 \text{ grains/cm}^2/\text{yr}$ at Qipisarqo and $150 \text{ grains/cm}^2/\text{yr}$ at Akvaqiaq.

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At both sites, the mid-late Holocene pollen assemblages are dominated by *Betula* and Ericales and are characterized by the increase of *Betula* onwards. However, discrepancies exist regarding *Alnus* and pollen grains of coniferous trees (*Picea* and *Pinus*). These taxa are best represented at Qipisarqo Lake and are related to long-distance transport (e.g., Rousseau et al., 2008). The present local vegetation of these sites is comparable and the similarity is well expressed in their respective modern pollen assemblages. The SCD between the uppermost pollen assemblage of Akvaqiaq and Qipisarqo lacustrine sequences is 14 (or 0.14), which indicates that they are indeed very similar to each other (cf. Overpeck et al., 1985; Anderson et al., 1989).

PCA performed on pollen assemblages show strong linear trends since 8000 years (Fig. 3a, c). The first eigenvalue (λ_1) of the eastern site (Qipisarqo) is two times higher than that of western site (Akvaqiaq), which indicates much higher amplitude changes in pollen assemblages in southwest Greenland than in eastern Baffin Island. At both sites, low PCA axis 1 sample scores are driven by *Betula* and Ericales, two erect dwarf shrubs, whereas high PCA axis 1 sample scores are driven by Cyperaceae at Akvaqiaq and *Alnus* at Qipisarqo (supplementary Tables 2a, 2b) <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. At Akvaqiaq and Qipisarqo, there is a pronounced change at about 5000 years BP. The change is gradual at Akvaqiaq, whereas it appears more abrupt at Qipisarqo.

Close analogues for the fossil pollen assemblages exist in the modern database, with SCD values lower than 11 and 18 for Akvaqiaq and Qipisarqo lakes, respectively. At both sites, July SAT was maximum before 5000 years BP. However, the subsequent cooling trend is more pronounced at the eastern site (Qipisarqo) than at the western site (Akvaqiaq). From 7000 years BP to present, July SAT decreased by 0.5°C/ka at Qipisarqo and by 0.1°C/ka at Akvaqiaq (Fig. 4a, b). Conversely, contrasting trends in the mid-late Holocene growing season sunshine are observed. From 7000 years BP to present, growing season sunshine increased at Akvaqiaq (+0.6%/ka), whereas it decreased at Qipisarqo (−0.8%/ka) (Fig. 4c, d).

RDA performed on pollen assemblages show increasing trend since 8000 years BP

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(Fig. 5b, c). First RDA axis is positively correlated with January SAT and annual precipitation (Fig. 5a). This increasing trend can thus be translated by a slight winter warming and higher precipitation. *Betula* has the highest species score on the first RDA axis on Arctic reference sites (supplementary Table 3) and in both lake sediment cores, there is an increase in *Betula* frequencies onward (supplementary Fig. 1) <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. Warm winter and high depth of snow cover are likely critical to the survival of *Betula* (cf. Fredskild, 1991).

4.2 Marine sediment cores

The diagram of dinocyst assemblages of cores HU021 and HU085 is given in supplementary Fig. 2 <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. In cores HU021 and HU085, the dinocyst fluxes are of the order of 50 000 and 2000 cysts/cm²/ka, respectively, which indicate a relatively high productivity at both sites. In core HU021, the assemblages are characterized by the increase of *Nematosphaeropsis labyrinthus* and temperate taxa from the early to late Holocene. In core HU085, the dinocyst assemblages are dominated by temperate taxa and characterized by maximum of thermophilic species (*Spiniferites mirabilis*, *Impagidinium* spp.) in the early Holocene. These dinocyst assemblages are consistent with the more temperate conditions in the axis of the NAC than off the Canadian margins (de Vernal and Hillaire-Marcel, 2006).

PCA performed on dinocyst assemblages show strong linear trends since 8000 years (Fig. 3b, d). The first eigenvalue (λ_1) of the eastern site (HU085) is two times higher than that of the western sites (HU021), which indicate much larger amplitude in the changes of dinocyst assemblages in central North Atlantic than along the Canadian margin. High PCA axis 1 sample scores are driven by the subpolar taxon *Spiniferites elongatus* in core HU021, whereas they are notably driven by the thermophilic species *Spiniferites mirabilis* in core HU085 (supplementary Tables 2c, 2d) <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. As

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is was observed from the continental records, there is a pronounced change at about 5000 years BP. Again, the change seems gradual at the western site (HU021), whereas it appears more abrupt at the eastern site (HU085).

5 Good modern analogues of dinocyst assemblages exist in the modern database, with dissimilarity values lower than 44 and 78 for assemblages of cores HU021 and HU085, respectively. However, the dissimilarity values of most samples are respectively lower than 23 and 47 in cores HU021 and HU085 which is much lower than the adopted threshold of 74. August SST was maximum before 5000 years BP at the eastern site (HU085), whereas no trend is observed at the western site (HU021). From 10 7000 years BP to present, August SST decreased by 0.7°C/ka at site HU085, whereas a slight warming of 0.3°C/ka is observed at site HU021 (Fig. 4e, f).

5 Discussion

5.1 Mid-Holocene alder occurrence in southwest Greenland

15 A feature deserving attention from the pollen record of Qipisarqo is the early occurrence of *Alnus crispa*, which raised the question of the timing of its migration in southwest Greenland during the Holocene. At present, *Alnus crispa* has its main area of distribution between 63° and 66° N in west Greenland, with isolated populations growing as far south as 61° N (Fredskild, 1973, 1996). Although it is regionally common at 61° N, shrub alder is not present today on the Qipisarqo foreland presumably due to 20 the glacier's proximity (less than 2 km) (Kaplan et al., 2002).

In the literature, there is a debate regarding *Alnus* migration in Greenland. Based on pollen studies from southwest Greenland, around 62° N, Kelly and Funder (1974) proposed an early migration of alder at about 7500 ^{14}C years BP, i.e. ca. 8400 cal. years BP (Figs. 6, 7e). However, Fredskild (1973, 1983, 1985) suggested that *Alnus* rather 25 migrated in west Greenland (64° N) during the late Holocene (ca. 3500–4000 ^{14}C BP) (Fig. 7a, b) arguing that *Alnus* never occupied southern Greenland ($<60^{\circ}$ N)

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(Fig. 7g, h, i) and that all *Alnus* pollen grains accumulated in Holocene sediment were related to long distance transport and carried mainly from Newfoundland and Labrador. At lake Qipisaqo, *Alnus* pollen relative frequency and fluxes increase at about 8400 cal. years BP to reach maximum values between 6500 and 5000 ^{14}C BP, i.e. 7400 and 5600 cal. years BP (Fig. 7f).

As shown in Fig. 7, which summarize available records of pollen influxes over south-western Greenland during the Holocene, large variations in *Alnus* frequency from site to site are observed. This may be due to the mosaic character of the local vegetation. Nevertheless, the records strongly suggest time transgressive migration from about 7000 ^{14}C years BP in the south (site Isoëtes, 59.58° N) to about 3500 ^{14}C years BP in the north (site Johs. Iversen, 64.24° N).

5.2 West to east gradient

At all sites there is a pronounced palynological change around the mid-late Holocene transition, at about 5000 years BP (Fig. 3). The change seems abrupt in the dinocyst and pollen records of eastern sites (HU085 and Qipisarqo), whereas it appears more gradual westward (HU021 and Akvaqiaq). An abrupt mid to late Holocene transition has been also reported from coccolith and dinocyst data in marine cores from the central North Atlantic, south of Iceland (Giraudeau et al., 2000) and on the northern Iceland shelf (Solignac et al., 2006). It seems therefore to be a robust feature in the regional and global climate (e.g., Steig, 1999).

The records of Akvaqiaq and Qipisarqo lakes show a progressive decrease in July SAT since 7000 years BP. However, the cooling at Qipisarqo is about 3.5°C, which is much larger than at Akvaqiaq, where it does not exceed 1°C (Fig. 8a). Similarly, the marine records show a progressive decrease in August SST of about 5°C in the central North Atlantic site (HU085), whereas no significant trend is observed at the Canadian margin site (HU021; Fig. 8b). West to east gradient in the amplitude of the Holocene cooling trend seems to be a consistent feature across mid- to high latitude North Atlantic (e.g., Andersen et al., 2004; de Vernal and Hillaire-Marcel, 2006).

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The opposition between the eastern and western sites is also seen in the growing season sunshine reconstruction from pollen data. The record of Akvaqiaq Lake shows a slight increase since 7000 years, whereas a progressive decrease is reconstructed at Qipisarqo Lake (Fig. 8c). Independent evidence for changes in growing season sunshine comes from pollen fluxes (grains/cm²/yr), which relate to pollen production and positively correlate with meteorological factors such as daily thermal oscillation, maximum and minimum temperatures and sunshine hours (cf. Rodríguez-Rajo et al., 2005). Since 7000 years, pollen fluxes have decreased at Qipisarqo while they display an increase at Akvaqiaq (Fig. 8d), thus supporting the growing season sunshine reconstruction based on transfer functions. The trend in pollen fluxes provides an illustration of the response of Arctic plants to changes in climate parameters such as sunshine (Fréchette et al., 2008b).

6 Conclusions

Our reconstructions show summer cooling trend since 7000 years particularly pronounced in southern Greenland. They also indicate a slight winter warming from the mid to late Holocene (Fig. 8e), which suggests a decrease in the seasonal contrast of temperatures from winter to summer. Such an interpretation in terms of seasonality that applies to both terrestrial and marine environments is supported by paleoecological data from Scandinavia (e.g., Hammarlund et al., 2002) and paleoceanographic records from the northern North Atlantic (de Vernal and Hillaire-Marcel, 2006; Solignac et al., 2006). It appears consistent with mid-late Holocene summer vs. winter insolation changes (Fig. 8f) (Berger and Loutre, 1991).

The mid to late Holocene insolation change certainly accounts for a large part in the cooling recorded and the decreasing winter to summer contrast of temperature. However, the amplitude of the cooling is much smaller in the western North Atlantic than in the eastern North Atlantic and most probably reflect changes in the ocean circulation pattern. Particularly strong west to east thermal gradient during the mid Holocene

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may have been related to stronger and/or warmer NAC which resulted in enhanced poleward heat fluxes in eastern North Atlantic and Nordic Seas (e.g., Duplessy et al., 2001; Birks and Koç, 2002). Conversely, high freshwater and meltwater export from the Arctic through BLC and LC may have maintained cold conditions along the continental margins of the western North Atlantic during the early and middle Holocene despite higher insolation (e.g., de Vernal and Hillaire-Marcel, 2006). An accelerated hydrographical cycle with higher northward flux of warm Atlantic waters to the east and higher southward export of Arctic waters to the west in the northern North Atlantic thus seem to have characterized the mid Holocene. On these bases, relationships with positive NAO type of synoptic can be proposed (e.g., Hurrell and Dickson, 2004). Positive phases of the NAO are presently characterized by reduced strength and frequency of cyclonic activity in the Labrador Sea (Serreze et al., 1997), which result in overall decrease in cloudiness over much of the North Atlantic, west of Greenland (Previdi and Veron, 2007). The increasing trend of cloud cover in southern Greenland might thus be related to long-term changes in synoptic scale atmospheric circulation patterns, with a progressive shift from dominant NAO+ in the mid Holocene (e.g., Gladstone et al., 2005; Davis and Stevenson, 2007) to negative NAO in the late Holocene. Finally, the present study provides an illustration of the response of Arctic plants to the NAO (Mysterud et al., 2003).

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Table 1. AMS ^{14}C dates from **(a)** Akvaqiaq and **(b)** Qipisarqo lake cores used for developing the age-depth model.

Raw depth (cm)	Composite depth (cm) ^a	Laboratory No.	Material	AMS ^{14}C date (yr BP)	Corrected date (yr BP) ^b	Calibrated date (yr BP) ^c	Range of solution 95.4% (1 σ)
(a) Akvaqiaq Lake (piston core: 98BIR-02)							
8.5	11.5	NSRL-11345	Macroflora	1000 $\pm$ 50	–	933	902–963
8.5	11.5	NSRL-11346	Humic acids	1700 $\pm$ 45	–	–	–
20.5	23.5	NSRL-10621	Humic acids	2510 $\pm$ 45	1973	1915	1879–1951
28.5	31.5	NSRL-11347	Macroflora	2270 $\pm$ 60	–	2211	2177–2245
28.5	31.5	NSRL-11348	Humic acids	2840 $\pm$ 55	–	–	–
40.5	43.5	NSRL-10622	Humic acids	4290 $\pm$ 50	3753	4117	4076–4158
60.5	63.5	NSRL-10623	Humic acids	6810 $\pm$ 55	6273	7214	7158–7270
80.0	83.0	NSRL-10624	Humic acids	7670 $\pm$ 60	–	–	–
80.0	83.0	NSRL-10176	Macroflora	7330 $\pm$ 95	7330	8113	8020–8205
139.5	142.5	NSRL-10139	Macroflora	8560 $\pm$ 100	8560	9550	9466–9634
(b) Qipisarqo Lake (piston core: 98QIP-02)							
20.0	22.5	CURL-4475	Humic acids	1240 $\pm$ 35	1010	937	910–964
23.0	25.5	CURL-3036	Humic acids	530 $\pm$ 40	300	394	357–431
40.0	42.5	CURL-4486	Humic acids	1330 $\pm$ 40	1100	989	963–1014
60.0	62.5	CURL-4476	Humic acids	2570 $\pm$ 35	2340	2346	2327–2365
86.5	89.0	CURL-3037	Humic acids	3970 $\pm$ 40	3740	4114	4076–4151
136.0	138.5	CURL-4487	Humic acids	5840 $\pm$ 60	5610	6377	6317–6437
136.0	138.5	CURL-4488	Macroflora	5610 $\pm$ 60	5610	6377	6317–6437
187.5	190.0	CURL-3038	Humic acids	8400 $\pm$ 40	8170	9079	9023–9135
264.0	266.5	CURL-4914	Macroflora	8560 $\pm$ 50	8560	9524	9498–9549

^a Depth added to correct for offset between piston and gravity (Glew) core depths.

^b Years subtracted from humic acid ages to correct for offset measured between paired macrofossil and humic acid dates.

^c Calibration using the CALIB program (version 5.0.2) (Stuiver and Reimer, 1993) updated with the Intcal04c14 (Remier et al., 2004).

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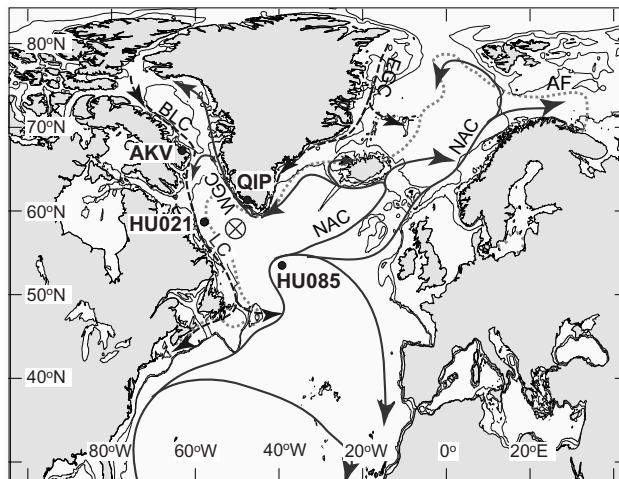


Fig. 1. Map of the northern North Atlantic showing the location of the study sites. The isolines correspond to the 200 m and 1000 m isobaths. The arrows illustrate schematically the surface circulation of the North Atlantic. The dark grey arrows correspond to the poleward flow of the North Atlantic Current (NAC), and its western branch, associated with the west Greenland Current (WGC). The dashed black arrows correspond to southward flow of Arctic waters through the East Greenland Current (EGC), the Baffin Current (BLC) and the Labrador Current (LC). Circle cross corresponds to the center of deep Labrador Sea Water (LSW) formation. The dashed grey line corresponds to the maximum extent of sea-ice cover in winter. Study sites: Akvaqiaq Lake (AKV), Qipisarqo Lake (QIP), Core HU021 (HU021), Core HU085 (HU085).

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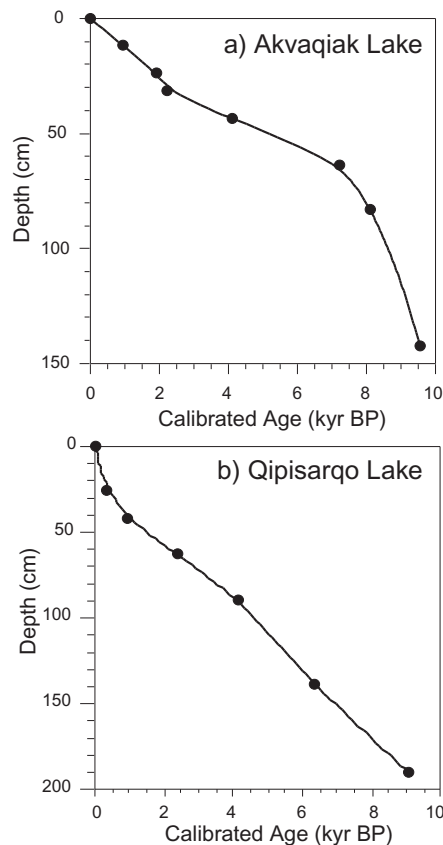


Fig. 2. Age-depth curves for the Akvaqiaq **(a)** and Qipisarqo **(b)** lake composite sediment cores. Age-depth models used for Akvaqiaq and Qipisarqo lake sediments are a smoothed linear interpolation between the available calibrated radiocarbon ages.

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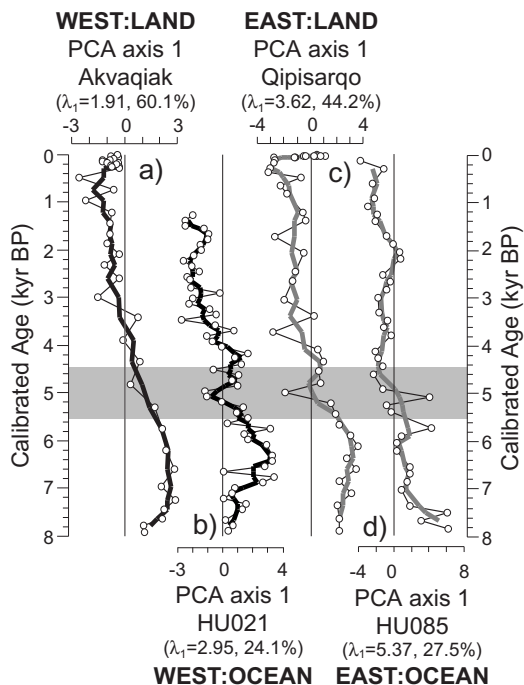


Fig. 3. Result of Principal Component Analysis (PCA). Stratigraphic plot of PCA axis 1 sample scores of **(a)** Akvaqia Lake, **(b)** core HU021, **(c)** Qipisarqo Lake, **(d)** core HU085. The thick grey and black lines correspond to 3-point moving averages. The first eigenvalue (λ_1) and percentage of variance are given for each sequence. WEST: western sector of north-west North Atlantic. EAST: eastern sector of northwest North Atlantic. The shaded horizontal zone marks the mid-late Holocene transition, which occurred at ca. 5000 year BP. Information on PCA summary and loadings are given on supplementary Tables 1 and 2. <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>

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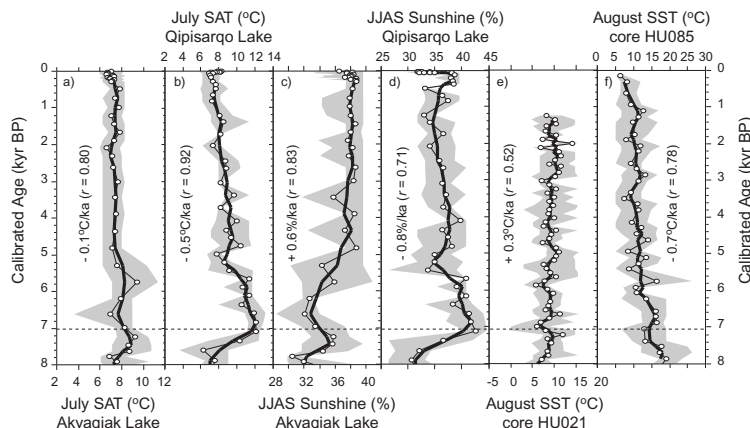


Fig. 4. Time series of climatic and sea-surface conditions. **(a)** July surface air temperature (SAT) at Akvaqiaq Lake. Modern value: $6.2 \pm 1.0^\circ\text{C}$ (Environment Canada, 2004). **(b)** July SAT at Qipisarqo Lake. Modern value: $9.0 \pm 1.1^\circ\text{C}$ (Cappelen et al., 2001). **(c)** Gowing season (JJAS) sunshine at Akvaqiaq Lake. Modern value: $39.6 \pm 5.8\%$ (New et al., 2002; Whitmore et al., 2005). **(d)** JJAS sunshine at Qipisarqo Lake. Modern value: $33.2 \pm 1.9\%$ (New et al., 2002; Whitmore et al., 2005). **(e)** August sea-surface temperature (SST) at core HU021 (de Vernal and Hillaire-Marcel, 2006). Modern value: $6.7 \pm 0.9^\circ\text{C}$ (NODC, 2001). **(f)** August SST at core HU085 (de Vernal and Hillaire-Marcel, 2006). Modern value: $10.6 \pm 0.8^\circ\text{C}$ (NODC, 2001). On each curve, the black lines correspond to 3-point moving averages. Climate trends by millennium since 7000 cal. years BP have been calculated from the 3-point moving average curves.

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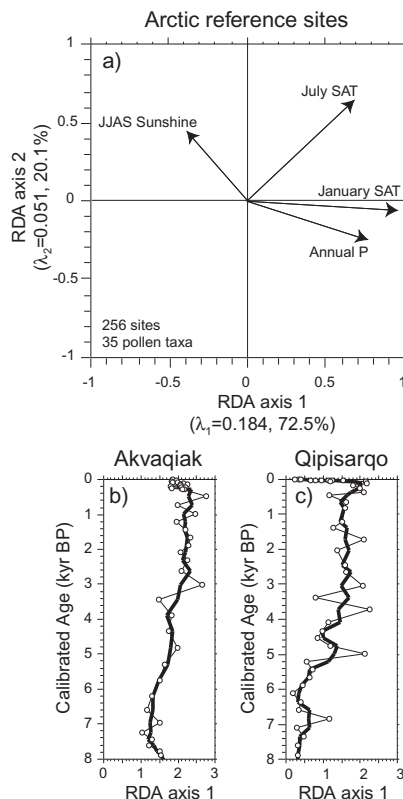


Fig. 5. Results of Redundancy Analysis (RDA). **(a)** RDA plot of environmental gradients associated with the 256 Arctic reference sites. The eigenvalue (λ) and percentage of variance are given for RDA axes 1 and 2. Stratigraphic plot of RDA axis 1 sample scores of **(b)** Akvaqiaq Lake and **(c)** Qipisarqo Lake. The black lines correspond to 3-point moving averages. Informations on RDA summary and loadings are given in supplementary Table 3. <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>

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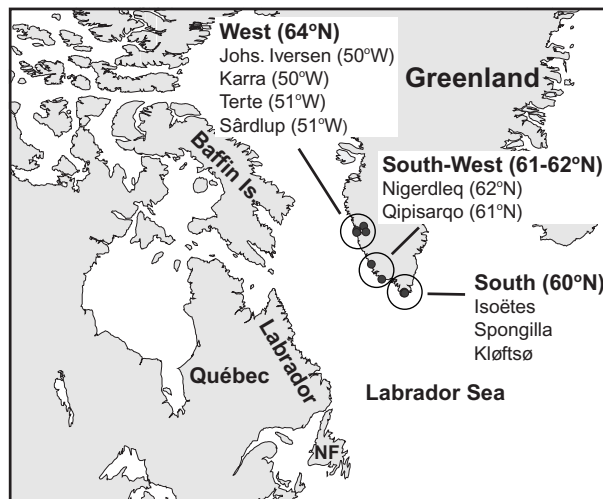


Fig. 6. Location map of southwestern Greenland pollen sites.

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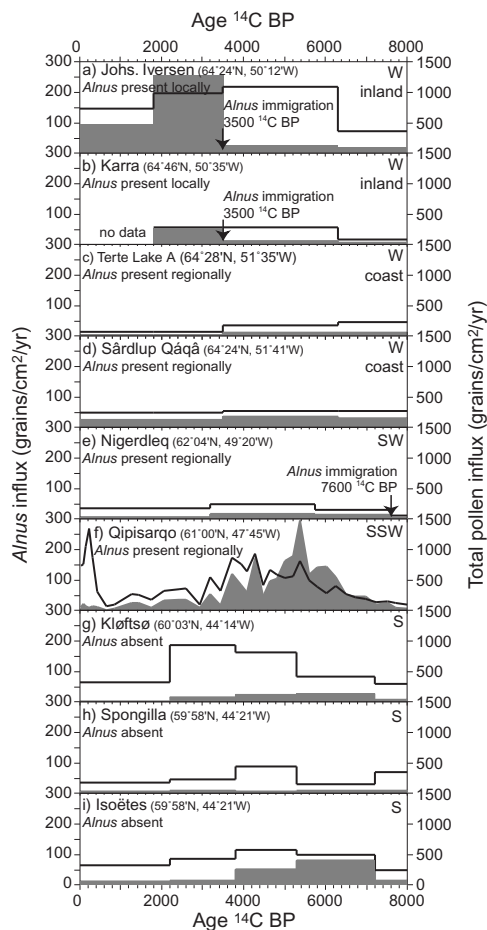


Fig. 7.

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Fig. 7. Mid-late Holocene *Alnus* and total pollen influxes of southwestern Greenland sites (cf. Fig. 6). **(a–d)** Data from west Greenland sites (Fredskild, 1983). **(e)** Data from south-west Greenland site (Kelly and Funder, 1974). **(g–i)** Data from south Greenland sites (Fredskild, 1973). The influxes were calculated by Fredskild (1973, 1983) and Kelly and Funder (1974) and presented as average for each pollen assemblage zones. **(f)** Data from Qipisarqo Lake (this study). At present, *Alnus crispa* grows only around (a) Johs. Iversen and (b) Karra sites. On each graph, the shaded curve corresponds to *Alnus* pollen influx and the tick black line corresponds to total pollen influx. The total pollen influx includes *Alnus* pollen grains but excludes long-distance pollen grains from trees, *Ambrosia* and Chenopodiaceae. High *Alnus* percentages (>20%) are recorded only at (a) Johs. Iversen and (f) Qipisarqo sites. At these sites, the *Alnus* pollen influx overlaps the total pollen influx at some levels.

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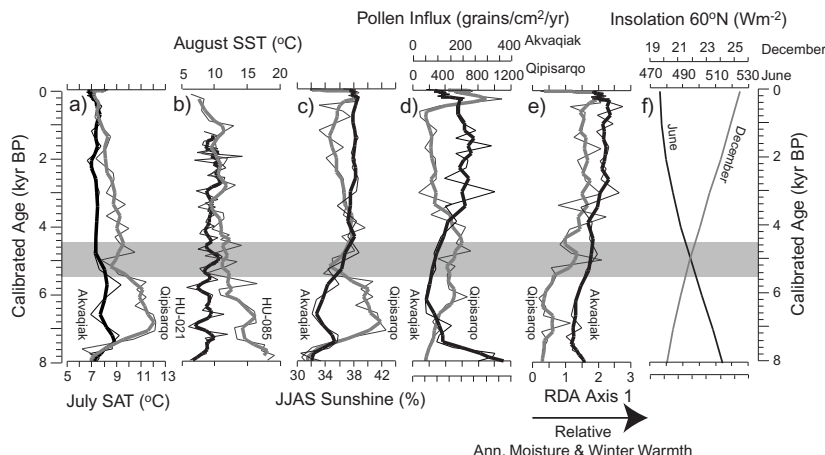


Fig. 8. Contrasting trend in climatic and sea-surface conditions. **(a)** July SAT reconstruction at Akvaqiaq (black) and Qipisarqo (grey) lakes. **(b)** August SST reconstruction from cores HU021 (black) and HU085 (grey) (de Vernal and Hillaire-Marcel, 2006). **(c)** JJAS sunshine reconstruction at Akvaqiaq (black) and Qipisarqo (grey) lakes. **(d)** Total pollen influx at Akvaqiaq (black) and Qipisarqo (grey) lakes. **(e)** Stratigraphic plot of RDA axis 1 scores at Akvaqiaq (black) and Qipisarqo (grey) lakes. This curve represents an estimation of the January air temperature and annual precipitation trends, which are co-variant parameters (supplementary Tables 3 and 4) <http://www.clim-past-discuss.net/5/879/2009/cpd-5-879-2009-supplement.pdf>. **(f)** Northern Hemisphere high-latitude (60° N) June and December insolation curves (Berger and Loutre, 1991). On figures a, b, c, d and e the thick lines correspond to 3-point moving averages. The shaded horizontal zone marks the mid-late Holocene transition, which occurred at ca. 5000 cal. years BP.

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