Holocene century-scale temperature variability from West Greenland lake records

SPECIAL REPORT

Nico W. Willemse*
Torbjörn E. Törnqvist**
The Netherlands Centre for Geo-ecological Research (ICG), Faculty of Geographical Sciences, Utrecht University, P.O. Box 80115, NL-3508 TC Utrecht, Netherlands

ABSTRACT

Synchronous changes in high-resolution loss on ignition profiles from widely separated shallow Arctic lakes in West Greenland suggest that sedimentary records of lake productivity provide a sensitive century-scale time series of variability in surface-air temperatures throughout the Holocene. Ice cover greatly reduces biological activity in arctic lakes, and the common productivity response among lakes is attributed to air-temperature–controlled variations in the length of the ice-cover period. Comparison with the Greenland oxygen isotope records from Summit ice cores demonstrates that the inferred temperature fluctuations in the lakes closely follow the century-scale fluctuations in the Greenland Ice Core Project $\delta^{18}O$ record but correlate less well with the Greenland Ice Sheet Project 2 record. Low-altitude continental lake records thus not only confirm features of Holocene atmospheric temperature variability otherwise seen only in high-altitude ice cores from central Greenland, but also highlight discrepancies between the ice-core time series. The combined lake and ice-core data provide corroborative evidence for an intrinsically unstable Holocene climate in Greenland, including the 8200 yr B.P. event that is currently recognized as the most pronounced Holocene climatic cooling with possible global significance. Our finding of a link between paleoproductivity and surface-air temperature has important implications for reconstructing natural climate variability in areas where such information is still rare. The results illustrate the large potential of paleolimnological studies in the Arctic.

INTRODUCTION

Feedback mechanisms among high-latitude oceans, the cryosphere, and the atmosphere are the main control of Northern Hemisphere temperature and precipitation anomalies on decadal to century time scales (e.g., Anderson and Willebrand, 1996). This fact has focused attention on the polar regions, because global climate change is probably amplified in the Arctic (e.g., Kattenberg et al., 1996), and preferential warming in the high latitudes could cause changes in global climate (e.g., Webb and Overpeck, 1993; Blair Fitzharris, 1996). However, the sparse nature of long-term instrumental observations of polar climate limits our understanding of spatial patterns and underlying mechanisms of low-frequency natural climate variability (Rind and Overpeck, 1993).

The geographic distribution of detailed (annual to century scale) paleoenvironmental records of Arctic climate variability is still limited, reflecting the difficulty of obtaining appropriate proxies, among other problems. Detailed paleoclimatic information is largely based on a limited number of ice-core records from high-altitude sites, but there is ongoing debate about the exact interpretation of oxygen isotope thermometry (e.g., MacAyeal, 1995; Jouzel et al., 1997; White et al., 1997). Tree-ring–based climatic reconstructions are largely absent and are of limited use for resolving low-frequency climate variability (e.g., Cook et al., 1995). Continuous sedimentary records from the large number of lakes in high-latitude areas potentially provide an important source of information for deciphering past climate variability (e.g., Hughen et al., 1996; Bradley et al., 1996). High-latitude and high-altitude lake ecosystems have been shown to be extremely sensitive to climate change (Schindler et al., 1990; Sommaruga-Wögrath et al., 1997). The short active biological period in such lakes is largely controlled by the ice-cover period, availability of light, water temperature, and lake depth, exerting a strong influence on the biological and chemical cycle (Schindler et al., 1974; Welch et al., 1987; Smol, 1988).

APPROACH

We carried out a high-resolution analysis of Holocene lacustrine sediments from six lakes along a 120-km-long transect from the West Greenland inland ice-sheet margin to the Sukkertoppen ice sheet (Fig. 1). Bedrock consists of glacially scoured metamorphic rocks with relief up to 600 m. The present-day climate is continental subarctic with mean annual temperatures of –5.2 °C (1943–1992) and continuous permafrost. The average temperature is –26 °C for February, and +11 °C for July. Mean annual precipitation is low (1943–1992: 155 mm), maximum precipitation occurs in summer, and runoff is very low. We focused on the numerous small (0.5–2 ha), shallow (3–8 m), alkaline (pH 7–9.5), and moderately conductive (150–450 µS/cm) lakes with simple basin morphometries, small (4–20 ha) drainage areas, and no inlets or outlets. Faunal, floristic, and chemical composition (Böcher, 1949; Hansen, 1967; Beyens et al., 1992) indicate that lake waters are relatively nutrient rich (mesotrophic to eutrophic) and, according to macrofossil and pollen analysis (Eisner et al., 1995), they have remained so over time. In such small water bodies, the response of water temperature, ice-cover duration, nutrient loading, and

*E-mail: n.willemse@geog.uu.nl.
**Present address: Department of Earth and Environmental Sciences, University of Illinois, Chicago, Illinois 60607-7059.

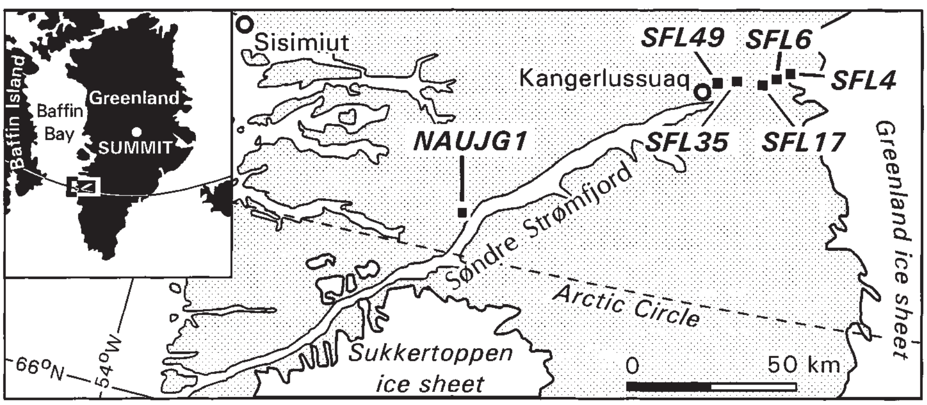

Figure 1. Location of sampling sites in Kangerlussuaq region of Greenland.

Data Repository item 9953 contains additional material related to this article.

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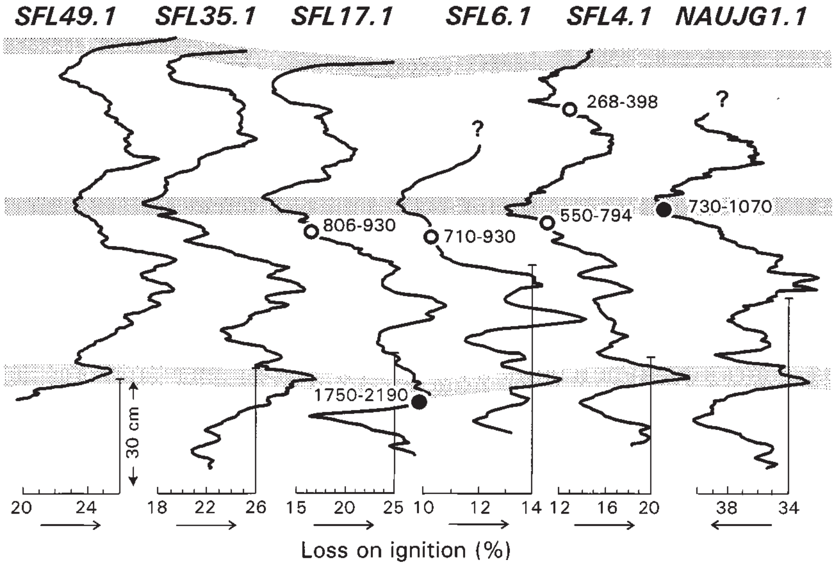

Figure 2. Lithostratigraphic correlation of smoothed LOI curves from uppermost (50–100 cm) sediments in six West Greenland lakes plotted vs. depth. LOI data shown as eight-point equal-weight averages. Vertical bars indicate 30 cm depth, for scale. Note inverted scale for NAUJG1.1. Contiguous oven-dried (105 °C) ~600 mg samples were ignited at 550 °C for 4 h. Analytical error of LOI estimates (0.8%) was determined by measurement of 39 replicate samples. Clay and iron contents are too low to significantly influence LOI signal. In situ aquatic mosses and a thin oxidized sediment layer were used to diagnose water-sediment interface. Water-sediment interface (upper gray band) and stratigraphically conspicuous LOI excursions constrained by ^{14}C ages (middle and lower gray bands) used for correlation. Calibrated ^{14}C ages indicated by 2σ confidence intervals. Open circles represent bulk-sediment samples; solid circles represent terrestrial macrofossils.

trophic interactions to short-term (interannual) air-temperature fluctuations is expected to be maximal (Fee et al., 1987; Smol, 1988).

We assume that time-parallel sediment variability from widely separated lakes indicates a dominating regional forcing mechanism (Snowball and Sandgren, 1996; Overpeck, 1996) rather than local changes within a single lake's physical and biological system (e.g., variable erosion rates in the catchment, differential nutrient loading, and changing sediment-filling patterns). Detection of a possible climate signature therefore occurs by comparison of individually dated lake-sediment stratigraphies from different basins.

Coring sites were selected following detailed mapping of the lacustrine deposits. Sediment cores were collected by using a modified 50 mm diameter Livingstone sampler, and we used scuba equipment to carefully collect 75 mm diameter sediment cores from the fragile uppermost ~60 cm. Loss on ignition (LOI) measurements (Dean, 1974) were performed on contiguous 2–3-mm-thick samples, followed by microscopic examination of the residual matter for fossil remains (calcified *Chara* "stems," abundance of diatom cells). Biogenic-silica analysis was used to estimate diatom productivity (Engstrom and Wright, 1984). Slow accumulation and mixing obscure the seasonal sediment layers in these basins, and we relied on accelerator mass spectrometry (AMS) ^{14}C ages for temporal control.[1] Macrofossil material was submitted for dating within five months after collection of the cores (cf. Wohlfarth et al., 1998). AMS ^{14}C measurements were carried out at the Robert J. Van de Graaff Laboratory, Utrecht University, and converted to calendar years (cal yr B.P., meaning before 1950) by using the Groningen CAL20 program (Van der Plicht, 1993) and smoothed calibration curves (Törnqvist and Bierkens, 1994). Because of the scarcity or total lack of identifiable terrestrial macrofossils, bulk-sediment samples had to be used in numerous cases. Reservoir effects are unlikely, owing to the absence of carbonates (or other rocks containing old carbon) in the catchments and the rapid mixing that occurs in these shallow lakes, and we found no indications to suspect the ^{14}C results used in this study. A full discussion of the reliability of the ^{14}C ages is provided elsewhere (see footnote 1).

RESULTS AND INTERPRETATION

Lake sediments close to the Greenland ice-sheet margin (SFL sites; Fig. 1) consist mainly of eolian silts mixed with homogeneous, undifferentiated organic matter (Eisner et al., 1995). The prominent loess cover found in the ice-marginal area (Dijkmans and Törnqvist, 1991) is absent around Sukkertoppen, and the extremely fine grained sediments in lake NAUJG1 lack the coarse eolian silt fraction typical at the SFL sites. The organic component (gyttja) in all lakes consists of structureless pelleted detritus and dominantly limnic macrofossil remains. Terrestrial macrofossils are generally lacking, and the organic compounds in the sediments are thought to be almost entirely derived from within-lake sources. Siliceous diatom frustules are present but not abundant in the five SFL cores, whereas they abound in the sediments of lake NAUJG1.

At all the sites we find strikingly similar fluctuations of organic-matter content (Fig. 2). ^{14}C ages of a stratigraphically pronounced LOI excursion demonstrate the synchroneity of this event, and chronostratigraphic alignment of the individual sequences supports a common external forcing. The time shifts necessary to synchronize the individual records are all within confidence limits of the ^{14}C age. The LOI fluctuations may be related to both within-lake processes (e.g., covarying lake-productivity changes) or regional atmospheric input of mineral grains. For instance, deposition of eolian silt is a considerable factor close to the ice-sheet margin, and variable influx rates might be an eligible explanation for the SFL sites (cf. Eisner et al., 1995). This possibility, however, is not supported by data from lake NAUJG1 (90 km southwest of the SFL sites), situated in an area outside the range of eolian sedimentation. Here we observe strikingly similar but inverse cycles in diatomaceous sediments (Fig. 2), and a large body of evidence suggests that the lithological variations in the six lakes are primarily caused by fluctuating lake productivity.

We analyzed the LOI data in conjunction with volume-based concentration data (grams per unit volume of dry bulk sediment) and quantitatively determined the influence of variable contributions of organic and minerogenic sediments on the LOI signal (Table 1). For the ice-marginal SFL sites, concentration changes of organic matter alone explain 47%–57% of the variance in the LOI curves, whereas variations in minerogenic matter explain only 1%–18%, pointing to a predominant organic-productivity signature. This interpretation is supported by dramatic changes in the relative

TABLE 1. CORRELATION COEFFICIENTS BETWEEN LOI AND VOLUME-BASED CONCENTRATIONS OF ORGANIC MATTER AND MINEROGENIC MATTER IN FOUR WEST GREENLAND LAKES

Core no.		Organic matter (g/cm^3)	Minerogenic matter (g/cm^3)	Paired samples (*n*)
SFL4.1	LOI (%)	0.68	-0.07	424
SFL17.1	LOI (%)	0.74	0.26	447
SFL6.1	LOI (%)	0.58	-0.43	362
NAUJG1.1	LOI (%)	-0.13	-0.66	587

Note: R-values (correlation coefficients) calculated by linear regression analysis (α = 0.05, $P < 0.05$). LOI = loss on ignition.

[1]GSA Data Repository item 9953, AMS ^{14}C analytical data and curve-matching procedures, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm. Lake data sets are available at the World Data Center-A for Paleoclimatology (www.ngdc.noaa.gov).

abundance of calcified *Chara* "stems" that closely match LOI fluctuations in lake SFL6 (Fig. 3A), suggesting that charophyte population density follows changes in lake organic-matter production.

For NAUJG1 we have an inverse result. Here, we found minerogenic matter (including diatoms) to explain 44% of total variance in the LOI signature, whereas concentration changes of organic matter are not significant (Table 1). The sediments of NAUJG1 contain abundant diatom cells throughout the core, contributing up to 20% of dry bulk-sediment weight. Geochemical analysis of a representative data set (upper 45 cm of core NAUJG1.1) demonstrates the variations in the minerogenic fraction to be primarily driven by variations in biogenic silica, which is reflected in the LOI signal (Fig. 3B). The dominance of changes in diatom productivity over organic matter in the LOI signature of core NAUJG1.1 can be explained by the higher specific weight of diatoms compared to the nonsiliceous biogenic fraction. Major differences in the dominant zooplanktonic and algal communities are not uncommon for Greenland lakes (Hansen, 1967), and our results show that LOI fluctuations are primarily driven either by biogenic silica (lake NAUJG1) or organic matter (SFL lakes).

We relate the synchronous changes in paleoproductivity to air-temperature–controlled variations in the length of the ice-cover period and the open-water growing season (e.g., Smol, 1988; Williams, 1994). Ice-cover duration is primarily a function of surface-air temperature (Vavrus et al., 1996; Doran et al., 1996), particularly during the transition seasons (May and September-October). Standard deviations for annual break-up and freeze-up dates are typically on the order of 5–15 days (Palecki and Barry, 1986). Prolonged cold summers at northern latitudes can reduce the active biological period by 30% or more (Smol, 1988; Schindler et al., 1990; Doran et al., 1996), and warming in these settings is accompanied by a shorter period of snow and lake-ice cover, resulting in enhanced plant growth due to lengthening of the growing season, improved exchange of gases and nutrients, wind-driven circulation, and light conditions (Schindler et al., 1974, 1990; Sommaruga-Wögrath et al., 1997). Especially for mesotrophic and eutrophic lakes, nutrient depletion during the short growing season is unlikely to be a limiting factor for lake primary productivity, and we therefore infer that the lake records reflect primarily regional temperature fluctuations.

COMPARISON WITH SUMMIT ICE-CORE $\delta^{18}O$ RECORDS

We compared the raw data of our two longest lake records (cores NAUJG1.1 and SFL4.1) with the Summit Greenland Ice Core Project (GRIP) and Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$ ice-core records for the Holocene (Dansgaard et al., 1993; Grootes et al., 1993; Meese et al., 1994; Stuiver et al., 1995; Johnsen et al., 1998) (Fig. 4A). Values of $\delta^{18}O$ in ice are believed to reflect surface-air temperature at the precipitation site (Jouzel et al., 1997), and stacked annual Summit $\delta^{18}O$ records correlate well with West Greenland coastal temperatures, demonstrating its long-distance significance for the past century (White et al., 1997). Accumulation rates in our lakes have been rather constant (Fig. 4B), and the approximate time resolution per sample is 10–15 yr. In both lakes, a 2–3-cm-thick surficial layer of oxygenated sediments limits the mixing depth for benthic species. This thickness in which mixing occurs suggests bioturbation-caused time averaging of 60–100 yr, for which we corrected the ice-core time series by applying a low-pass filter to the original 20-yr averaged isotope chronology. We tuned our ^{14}C chronologies by cross-matching successive key features in the lake records to both ice-core time series (see footnote 1). Synchronization is justified because in all cases the difference between the ice-core and lake-sediment chronologies is within the 2σ confidence interval of the calibrated ^{14}C age probability distributions. In addition, we carried out a 500-yr period smoothing to compare millennium-scale temperature trends in the records.

The millennium-scale temperature history agrees well between the records, with minor trend deviations that we attribute to slowly changing spatial accumulation patterns during lake-basin in-fill (Blais and Kalff, 1995). All records show a climatic optimum shortly after 4000 cal yr B.P., consistent with what has previously been inferred from West Greenland pollen records (Fredskild, 1985; Eisner et al., 1995). Similar to the GRIP and GISP2 records, core NAUJG1.1 exhibits a major excursion around 8200 cal yr B.P., currently recognized as the most pronounced Holocene climatic cooling with possible global significance (Alley et al., 1997).

We calculated the century-scale correspondence between individual lake and ice-core records (Table 2). The good correlation between the lacustrine and GRIP records supports our proposition of a signature that is driven essentially by surface-air temperature. However, a less consistent correspondence is found between the lake and GISP2 records (notably for the time interval 150–1500 yr B.P.). Inconsistencies between the two Summit $\delta^{18}O$ records have been noted previously for the Holocene (Grootes et al., 1993; Stuiver et al., 1995), despite the fact that at higher (annual) frequencies, GRIP and GISP2 $\delta^{18}O$ records correlate fairly well (Stuiver et al., 1995; White et al., 1997). These inconsistencies are generally attributed to the complexity of the hydrological process delivering snow to the ice sheet and to (post)depositional noise (Fisher et al., 1985, 1996; Stuiver et al., 1995; Jouzel et al., 1997), limiting an unequivocal interpretation of individual ice-core records in terms of temperature variability on a decade to century scale (Cuffey et al., 1995).

When the smoothed $\delta^{18}O$ profiles are converted to temperature (Cuffey et al., 1995; Johnsen et al., 1995; White et al., 1997), the combined

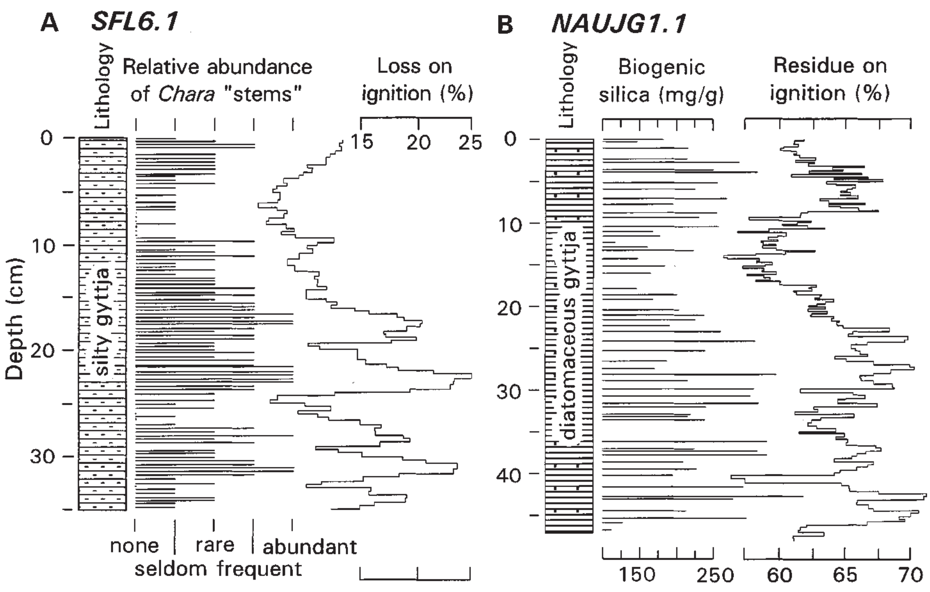

Figure 3. A: Comparison of relative abundance of calcified *Chara* "stems" and LOI in core SFL6.1; "abundant" denotes >1000 specimens per sample, "seldom" denotes 1–10 specimens per sample. B: Comparison of biogenic-silica content (BioSi) and residue on ignition (ROI) in core NAUJG1.1. BioSi expressed as mg/g total minerogenic matter. We oxidized 400–500 mg dry bulk samples to remove organic matter and then separated authigenic (formed within lake proper) from allogenic (detrital) mineral matter following extraction procedures of Engstrom and Wright (1984). BioSi in authigenic mineral fraction (selective dissolution with 0.2*M* NaOH) was measured by using ICP-AES (inductively coupled plasma–atomic emission spectrometry). Relative analytical error for BioSi is ~15%. Significant correlation of $r = 0.66$ ($\alpha = 0.05$, $p < 0.05$, 54 paired samples) between variations in BioSi in minerogenic fraction and ROI was found. No significant correlation was found between variations in remainder of authigenic and allogenic elemental composition and ROI.

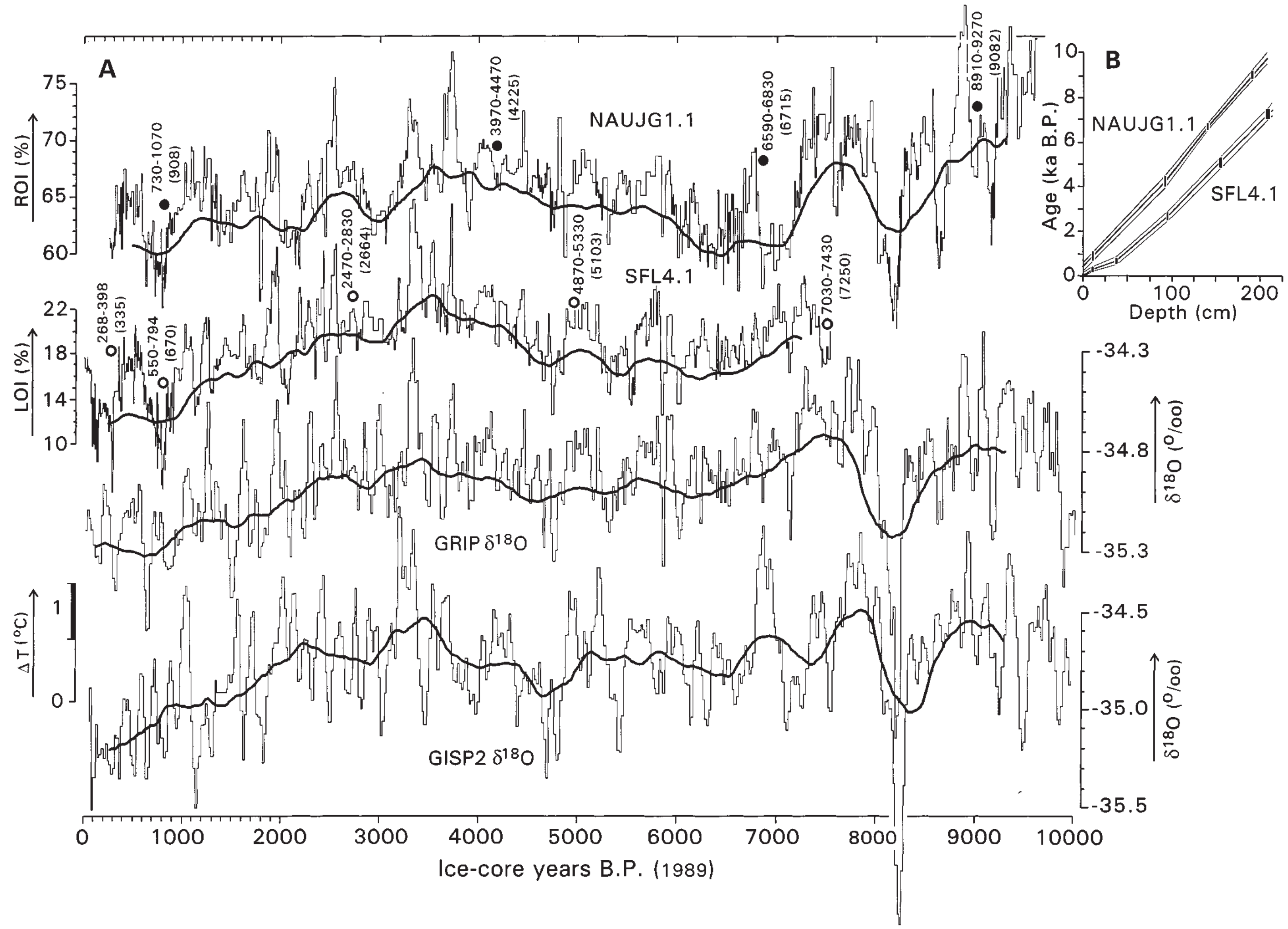

Figure 4. A: Correlation between lake sediment ROI and LOI records and smoothed Summit ice-core $\delta^{18}O$ records for past 10 000 yr (thin lines). We applied Gaussian low-pass filter with 100 yr bandwidth (weights 0.05, 0.22, 0.46, 0.22, 0.05) to original 20-yr-mean $\delta^{18}O$ Greenland Ice Core Project (GRIP) and Greenland Ice Sheet Project 2 (GISP2) chronologies to simulate 60–100 yr bioturbation-caused time averaging of lake sediments. Both lake records have been tuned to GRIP record (see footnote 1). Long-term trends (heavy lines) were calculated by using 500-yr-period equal-weight filter. Values of $\delta^{18}O$ are relative to SMOW (standard mean ocean water), and temperature conversion follows 0.33‰–0.6‰ per 1 °C calibration for Summit sites (Cuffey et al., 1995; Johnsen et al., 1995; White et al., 1997). Calibrated AMS ^{14}C ages are given as 2σ confidence intervals (cal yr B.P., meaning before 1950) and medians (in parentheses). Open circles represent bulk-sediment samples; solid circles represent terrestrial macrofossils. Note that time axis is in ice-core years (calendar years before 1989). B: Age vs. depth models for cores NAUJG1.1 and SFL4.1. Chronology for both cores is based on linear interpolation between median values of cumulative calibration probability distributions (2σ confidence limits are shown).

TABLE 2. BEST-FIT CORRELATION COEFFICIENTS BETWEEN LAKE SEDIMENT RECORDS AND GRIP AND GISP2 $\delta^{18}O$ RECORDS

	GRIP $\delta^{18}O$	GISP2 $\delta^{18}O$	Paired samples (*n*)
SFL4.1 (LOI)	0.72	0.53	377*
NAUJG1.1 (ROI)	0.62	0.31	456†

Note: Data comparison based on ~20 yr averages for LOI (loss on ignition) and ROI (residue on ignition). R-values (correlation coefficients) calculated by linear regression analysis (α = 0.01, P < 0.01).
*Compared time interval 0–7540 yr before 1989.
† Compared time interval 290–9230 yr before 1989.

lake and ice-core data present corroborative evidence for a pattern of rapid, century-scale 1–2 °C temperature variations, demonstrating an intrinsically unstable Holocene climate over Greenland. Our low-altitude subarctic lake records thus not only confirm features of Holocene climate otherwise seen solely in the high-altitude ice-core records from central Greenland, but also highlight discrepancies between the ice-core time series. These results illustrate the large potential of paleolimnological studies in the Arctic, and we believe that our finding of a link between paleoproductivity and surface-air temperature link will considerably help to expand high-resolution paleoclimate reconstructions to areas that play an important role in the global climate system, but where such time series are currently rare.

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