Present-day temperatures in northern Scandinavia during the last glaciation

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ABSTRACT

Scandinavia is generally considered to have been covered extensively with ice throughout marine isotope stages (MIS) 4–2 between 75 and 10 ka. Here we present evidence for ice-free, warm conditions in the central area of the Scandinavian glaciations during MIS 3. Our multiproxy data obtained from a lacustrine sequence in northern Finland reveal not only significant response in the northeastern sector of the Scandinavian Ice Sheet to warming during the early part of MIS 3, but also indicate rapid climate warming to present-day temperatures in this ice-free period. New climate-model simulations for interstadial conditions in MIS 3 confirm the high mean July temperatures northeast of the Scandinavian Ice Sheet in response to the high insolation values and the presence of the ice sheet during MIS 3.

Keywords: climate variability, MIS 3, Scandinavia, multiproxy, climate modeling.

INTRODUCTION

High climate variability during the last glacial cycle, shown in oxygen isotope records in Greenland ice cores (Johnsen et al., 2001) and foraminifera assemblages in North Atlantic deep-sea sediments (Bond et al., 1993), was characterized by frequent rapid shifts from cold stadial to warm interstadial conditions referred to as Dansgaard-Oeschger (D-O) oscillations (Dansgaard et al., 1993). High-frequency climate variability on the adjacent European continent has been inferred from long pollen records in the Mediterranean region (Allen et al., 1999), high-resolution sediment studies of maar lake sequences in Germany (Sirocko et al., 2005), and speleothem records in the Austrian Alps (Holzkämper et al., 2004). The Mediterranean records mostly reflect changes in precipitation, whereas the absence of permafrost is indicated by stalagmite formation at a high-altitude site in Austria that suggests near present-day temperature conditions during the early part of marine isotope stage (MIS) 3. The generally discontinuous nature of sedimentation and repeated erosion combined with poor dating control and a scarcity of high-resolution records, however, hamper a detailed study of the last glacial climate in Europe. As such, the magnitude of climate change on the continent through the last glacial cycle remains mostly unknown.

An extensive database of geological sections and absolute age determinations along the mountainous Norwegian coast has recently indicated rapid phases of ice retreat, reaching to inland areas, along the western margin of the Scandinavian Ice Sheet during the late part of MIS 3 and MIS 2 (Olsen et al., 2001). In this paper we present evidence for significant ice-front retreat along the northeastern (continental) sector of the Scandinavian Ice Sheet during the early part of MIS 3. Quantification of the associated climate warming is made through a multiproxy study on lacustrine sediments formed in northern Finland during deglaciation. A climate model experiment with an MIS 3 interstadial setup is performed in order to test our proxy-based climate reconstructions.

MATERIALS AND METHODS

The sediments from the Sokli B-series borehole (Fig. 1), northern Finland (lat 67°48′N, long 29°18′E, elevation 220 m above sea level), form part of an unusually long and continuous sedimentary sequence of tills, glacio-fluvial beds, and fluvial beds, interlayered with fossil-rich lacustrine sediments that extend from the present into the late Saalian (MIS 1–6, i.e., representing the past ~130 k.y.; Helmens et al., 2007). The Sokli sediments have been protected from erosion by subsequent ice sheets due to their sheltered position in a steep depression. This depression occurs in relatively soft, highly fractured, and deeply weathered rocks of a carbonate-rich magma intrusion in the crystalline Precambrian shield.

An initial study of the Sokli sequence indicated that the nonglacial sediment intercalations each have a characteristic lithological and palynological content, and represent individual and successive developments both in terms of depositional and vegetational change (Helmens et al., 2000, 2007). The Sokli B-series borehole is dated by independent accelerator mass spectrometer ^{14}C and optically stimulated luminescence (OSL) dating and by stratigraphic dating based on correlations with the deep-sea record (Helmens et al., 2007; Fig. 1).

In this study, a high-resolution analysis of a large variety of fossil remains was carried out on a lacustrine interval of laminated silts and clays at 5–7 m depth dated to the early part of MIS 3 (Fig. 1). This ice-free interval at Sokli has been defined as the Tulppio Interstadial (Helmens et al., 2007). A detailed lithological column and a selection of proxy indicators reflecting local environmental and regional vegetational changes are summarized in Figure 2. Different proxies were analyzed from the same samples. The frequencies of microfossils were calculated as percentages of the sum of tree, shrub, dwarf shrub, and herb pollen (sum ~275–400). The sum of head capsules of chironomids ranges from 54 to 199. Counts were lower in the lowermost part of the profile (below 6.75 m core depth) and these samples were therefore lumped. Counts of macrofossils of plants and other aquatic animals were made for 10 cm^3 and 20 cm^3 samples.

Mean July air temperatures were reconstructed by applying transfer functions based on modern-day animal/plant climate calibration sets from northern Europe to the pollen (Seppä and Birks, 2001) and chironomid (Brooks and Birks, 2001; right side of Fig. 2) records. The sample-specific prediction errors for the chironomid-based temperature inferences, as

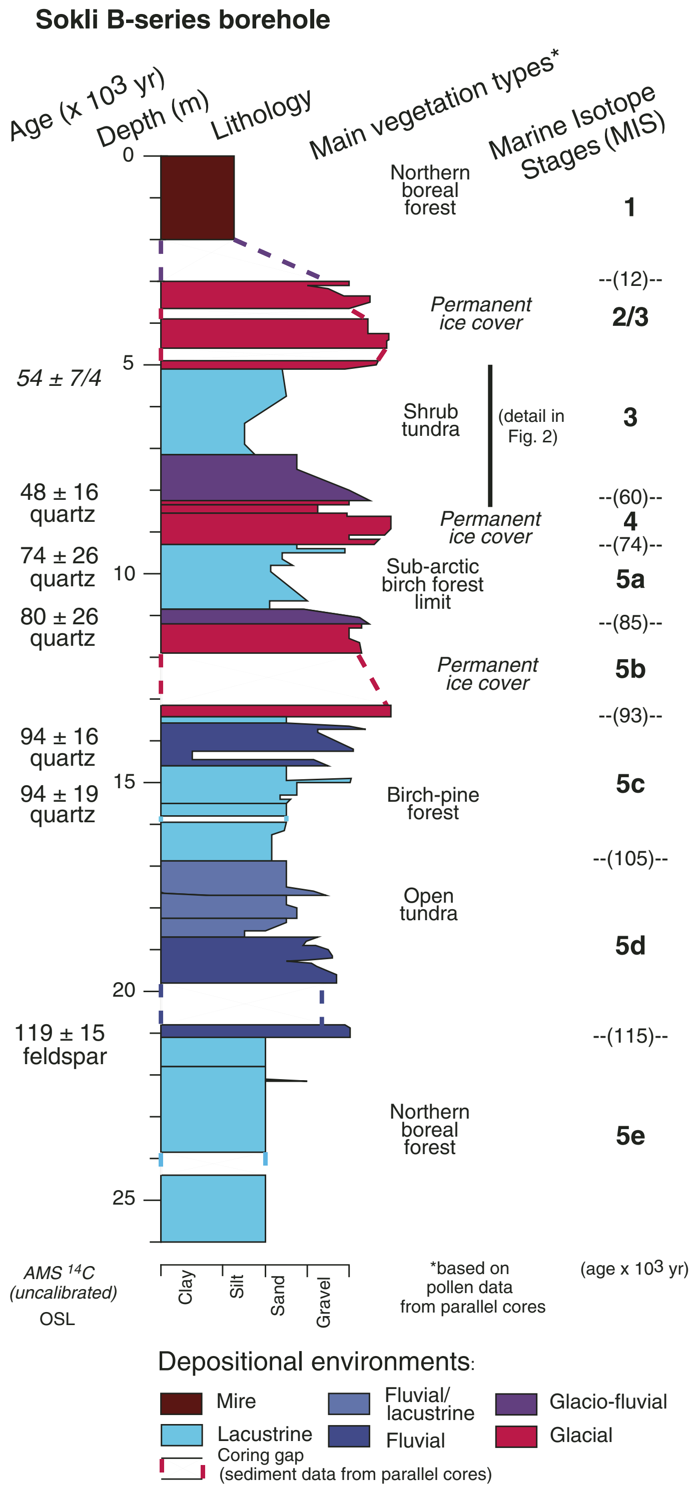

Figure 1. Simplified lithology of Sokli B-series borehole plotted against depth. Changes in depositional environments and main regional vegetation types are shown back to the last interglacial. The independent accelerator mass spectrometry (AMS) ^{14}C/optically stimulated luminescence (OSL) chronology for the Sokli B-series borehole is indicated on the left, and correlations with the deep-sea record (Martinson et al., 1987) are on the right.

estimated by bootstrapping, range between ±1.1 °C and 1.2 °C. The average prediction error for the pollen-based inferences is ±1 °C.

Minimum mean July air temperatures were estimated based on aquatic plant fossils and information on the present distribution of these species in northern Europe (Kolstrup, 1980). Pollen of *Myriophyllum spicatum* and macroscopic remains of *Potamogeton mucronatus* were used to infer minimum mean July temperatures of 10 °C (Kolstrup, 1980) and 13 °C (Brinkkemper et al., 1987), respectively, in Figure 2.

We applied the LOVECLIM three-dimensional climate model (Driesschaert, 2005) to simulate the average MIS 3 interstadial climate. The extent and elevation of the continental ice sheets and other forcings (orbital parameters, atmospheric greenhouse gases, dust content) are modified from full glacial conditions (Roche et al., 2007).

The Sokli site is in the northern boreal forest (Helmens et al., 2000). Climate today is cool temperate, with a mean July temperature of ~13 °C and mean February temperature of ~–14 °C. Mean annual precipitation is ~500 mm.

RESULTS

Macrofossils are scarce in the lowermost part of the silt-clay sequence, but algal microfossils indicate local aquatic conditions (zone C1a in Fig. 2). A more distinct lake environment fringed by wetland vegetation is recorded in the finely laminated sediments of zone C1b. However, it is not until zone C2 that a large diversification of aquatic life is observed, reflected by, among others, the abundance of chironomids and the bryozoan *Fredericella indica*. Chironomid-based temperature inferences indicate a warming to present-day mean July temperatures (~13–14 °C ±1 °C) in C2. Elevated minimum mean July temperatures of 13 °C are also indicated by finds of the aquatic plant *Potamogeton mucronatus* (Brinkkemper et al., 1987) in C2. *Fredericella indica* is currently reported to prefer mean summer water temperatures from 11 °C to 15 °C (Økland and Økland, 2001).

The chironomid record subsequently indicates decreasing mean July temperatures to ~11 °C ± 1 °C, which coincides with a fall in the abundance and diversity of aquatic biota during zone C3. Although temperatures stabilized during C4, it is only at this latter stage that the proxies record a distinct response to cooling in the lake catchment. Presence of the soil fungi *Glomus* and *Cenococcum geophilum* indicate an increase in soil erosion (Van Geel et al., 1989; Walker et al., 2003), whereas an increased influence of the nearby ice sheet through proglacial streams is suggested by the presence of various stream-inhabiting chironomids (e.g., *Eukiefferiella*-type, *Prodiamesa*, and *Rheotanytarsus*). As a result, sandy silts accumulated in the lake. Eventually, a re-advancing ice margin overriding the vegetated land is suggested by the findings of a dropstone and pieces of wood in the uppermost part of zone C4, and the final deposition of basal till (lithofacies unit D in Fig. 2).

The pollen assemblage in this lacustrine interval and the relatively warm pollen-inferred mean July temperature(s) of ~11 °C ± 1 °C (Fig. 2) are similar to those currently recorded in the shrub-tundra region close to the subarctic birch forest limit in coastal northern Norway. However, the distinct warming to present-day mean July temperatures, shown in our chironomid record for zone C2 only, did not result in the local immigration of pine or spruce, i.e., trees that today are important components of the boreal forest at Sokli. This indicates that the latter warming may have been rapid, only allowing time for rapidly migrating aquatic fauna and flora to respond.

In agreement with the proxy-based reconstructions, the climate model simulation suggests high mean July temperatures for the sector northeast of the Scandinavian Ice Sheet (Fig. 3). In the model, warm summer conditions are the combined result of enhanced July insolation compared to present (+19 W/m^2; Berger and Loutre, 1991) and northwesterly winds advecting cool, but very dry air from the ice sheet. The winds are produced by a thermal high-pressure cell over the ice sheet that is an extension of the anticyclonal cell situated over the cool northeastern Atlantic Ocean. The combination of high insolation and dry air leads to a strong sensible heat flux and relatively warm conditions near the surface.

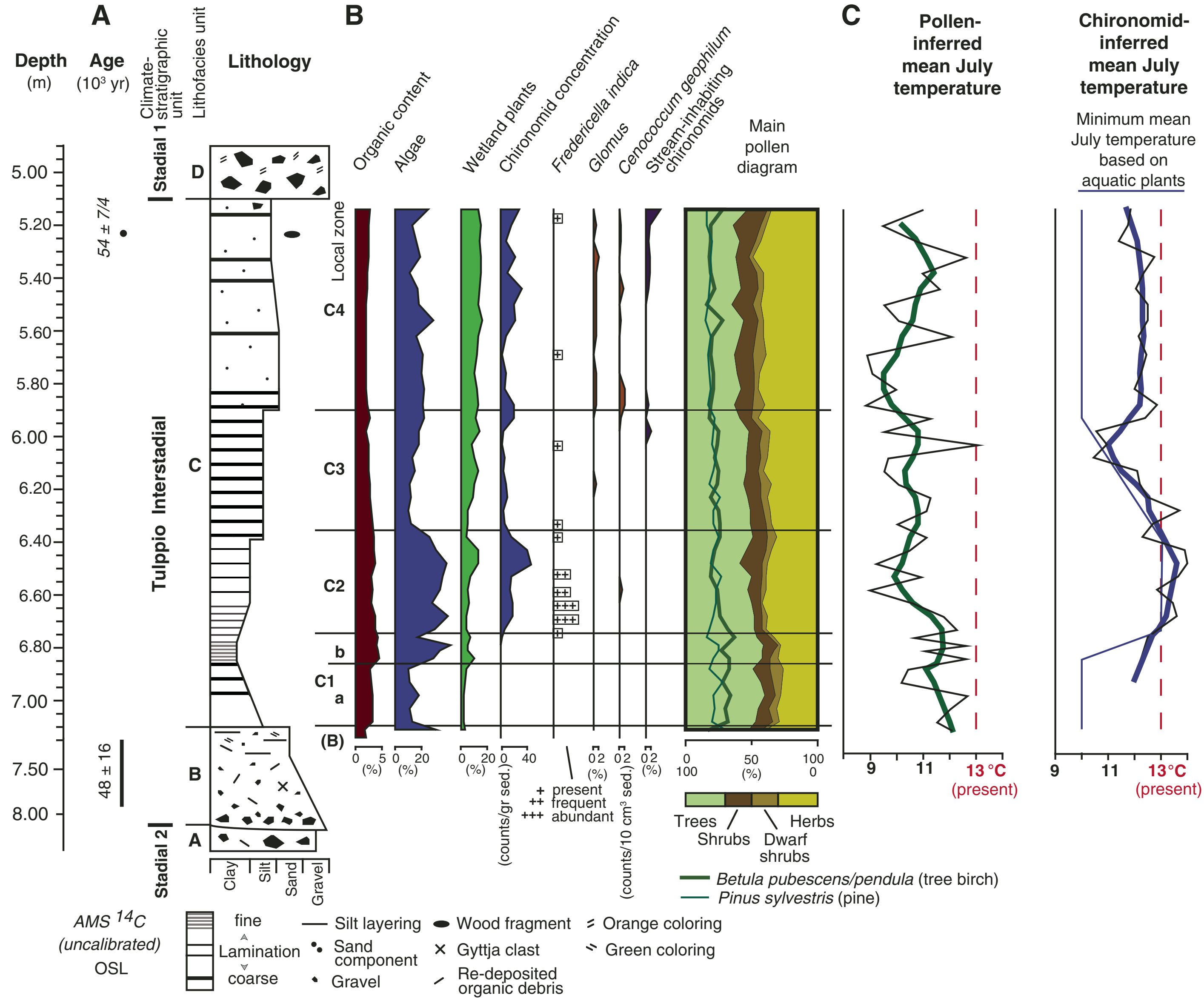

Figure 2. Multiproxy records from Sokli lacustrine sediments of the early part of marine isotope stage (MIS) 3 ca. 50 ka. A: Lithological column for depth interval 4.90–8.40 m in borehole Sokli B-series and absolute age determinations. Lithofacies units A and D represent glacial till, unit B comprises proglacial gravels and sands fining upward into sands interlayered with silts, and C is laminated lacustrine silts and clays. The accelerator mass spectrometer (AMS) ^{14}C dating (UtC 14712) was carried out on terrestrial plant macrofossils. OSL—optically stimulated luminescence. B: Selected proxy indicators from multiproxy analysis that reflect local environmental changes and changes in regional vegetation during local zones C1–C4. C: Curves of pollen- and chironomid- (aquatic insect) inferred mean July air temperatures, with Loess (locally weighted regression) smoother (span = 0.2) superimposed on inferred values to highlight major trends. Chironomid-based temperature curve additionally shows minimum mean July temperature values inferred from specific aquatic plant taxa (thin blue line). Present ~13 °C mean July temperature at Sokli is indicated for reference.

DISCUSSION

Although absolute and stratigraphic age determinations indicate that this lacustrine sequence has an early MIS 3 age (Fig. 1), the large error limits on both the OSL and ^{14}C dates preclude direct correlation of this warm interval with the interstadial sequence (IS) in the Greenland record. However, it is arguable that thinning and gradual retreat of the northeastern margin of the Scandinavian Ice Sheet from its MIS 4 limit in Russia (Svendsen et al., 2004) started during IS 16 in the earliest part of MIS 3, but that only the prominent IS 14 ca. 53 ka lasted long enough, and was warm enough, for the Sokli area to become deglaciated and the dramatic D-O warming event to be registered in the fossil record.

Our warm early MIS 3 eastern Scandinavian summer conditions are in strong contrast with cool summer temperatures shown in proxies at Oerel (northern Germany) directly south of the ice sheet. An ~12 °C mean July temperature was reconstructed at this more southern location (Behre et al., 2005). In the model simulation, the latter region is relatively cold in agreement with the palaeotemperature inferences from Oerel. In the model, these low temperatures are due to the prescribed land-ice configuration at this location, in combination with cold northerly winds descending from the center of the Scandinavian Ice Sheet. However, in early MIS 3, Oerel was ice free, implying that the model exaggerates the cool conditions here. It is interesting that near present-day conditions are recorded for MIS 3 by proxy data from the United Kingdom (Coope, 1987). As at Sokli, we ascribe this to higher insolation in combination with altered atmospheric circulation.

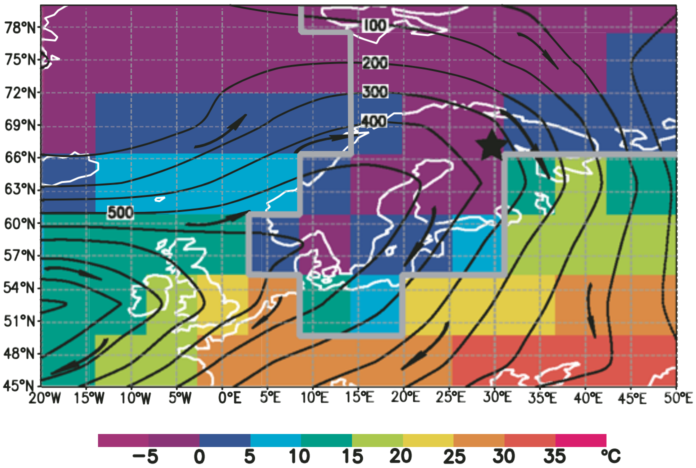

Figure 3. Simulated mean July surface air temperature over northern and middle parts of Europe. Contour lines represent geopotential height at 800 hPa, while arrows give schematic view of wind direction in lower atmosphere. Extent of the prescribed marine isotope stage 3 Scandinavian Ice Sheet is indicated in gray; star shows location of Sokli. Note that the model is not suitable for analyzing results at the grid-cell scale because of its low spatial resolution: the model is designed for continental and subcontinental scales.

CONCLUSION

Ice-free conditions in northern Finland facilitated the deposition of laminated lacustrine sediments during early MIS 3. A multiproxy-based reconstruction of climate and environmental parameters shows warming to present-day temperatures. Our climate model simulation for MIS 3 interstadial conditions confirms warm summer conditions and suggests that they result from high insolation in combination with dry winds blowing from the Scandinavian Ice Sheet. Our study not only reveals a highly dynamic Scandinavian Ice Sheet during the last glacial, but also demonstrates a clear response by biotic proxies to rapid climate warming.

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