Cold event at 8200 yr B.P. recorded in annually laminated lake sediments in eastern Europe

Siim Veski* Institute of Geology, Tallinn University of Technology, Estonia pst. 7, 10143 Tallinn, Estonia
Heikki Seppä† Department of Geology, University of Helsinki, P.O. Box 64, FIN-00014, Helsinki, Finland
Antti E.K. Ojala* Geological Survey of Finland, P.O. Box 96, FIN-02150, Espoo, Finland

ABSTRACT
A quantitative annual mean temperature reconstruction from an annually laminated lake-sediment sequence in Estonia, eastern Europe, shows a distinct cold period at 8400–8080 yr B.P. (= before A.D. 2000); the timing is consistent with that seen in the Greenland ice-core data and various high-resolution records from western Europe. During maximal cooling at 8250–8150 yr B.P., the annual mean temperature in Estonia was ~2.0 °C colder than prior to and ~3.0 °C colder than after the cooling. The pollen-stratigraphic and sedimentological data suggest especially cold and snowy winter conditions. The duration and amplitude of the cold event agree with the modeled impact of a sudden freshening of the North Atlantic surface water and subsequent perturbation of the thermohaline circulation. Provided that the cold event was caused by a pulse of freshwater—from the melting Laurentide Ice Sheet—to the North Atlantic, the results indicate a strong teleconnection between the North Atlantic oceanic forcing and the east European climate at least up to long 26°E, mediated probably by the changing intensity of the zonal atmospheric circulation.

Keywords: varve chronology, pollen, oxygen isotopes, 8200 yr B.P. cold event, thermohaline circulation, Estonia.

INTRODUCTION
The cold event at 8200 yr B.P. is the most extreme cold event after the Younger Dryas that has been unambiguously detected in various biological and physical proxies and in different sedimentary environments. Of the causes suggested for the cooling, the one that best explains its nature and geographic occurrence is a weakening of the North Atlantic thermohaline circulation (THC) (Barber et al., 1999; Renssen et al., 2001, 2002), which may have been triggered by a major pulse of freshwater from glacial Lakes Agassiz and Ojibway to the North Atlantic (Barber et al., 1999; Clark et al., 2001; Clarke et al., 2003). The potential role of the THC is particularly important because the variability in intensity of the THC and associated poleward heat flux is regarded as critical to the climate of northern Europe (Rahmstorf, 2000; Broecker, 2003), and studies of North Atlantic climatic variability in general are a focal point in modern climate research (Rodwell et al., 1999; Marotzke, 2000; Marshall et al., 2001; Sutton and Hodson, 2003). However, the role of the THC in abrupt climate changes in northern Europe has not been established in detail, and some contributions have questioned it as a cause of the relative mildness of the climate of northern Europe (Seager et al., 2002). Given that past changes in intensity of the THC can be estimated from paleoceanographic data (Bianchi and McCave, 1999; Keigwin and Boyle, 2000), high-resolution paleoclimatic reconstructions from the continents adjacent to the North Atlantic provide a tool for investigating possible continental-scale impacts of past perturbations of the THC. Consequently, understanding the connection between the cold event at 8200 yr B.P. and the THC poses a major scientific challenge and thus provides a powerful focus for paleoclimate research.

The cold event at 8200 yr B.P. has been detected in high-resolution records in western and central Europe (von Grafenstein et al., 1998; Nesje and Dahl, 2001; Tinner and Lotter, 2001; Hammarlund et al., 2003), but its occurrence farther east on the Eurasian continent is unknown. Here we provide evidence of a rapid cooling and major ecosystem change and recovery at 8400–8080 yr B.P. in Estonia, east of long 26°E, i.e., from a more continental part of Europe than has been documented previously. For reconstruction of the climatic and environmental change, we used biological and physical proxies preserved in an annually laminated lake-sediment sequence. Annually laminated (varved) sediments are one of the best repositories of boreal paleoclimatic records available, making it possible to develop an independent chronology that can be directly compared with ice-core records and with time scales of paleoclimatic modeling experiments. The physical and chemical properties of individual varves provide annual records of environmental and hydrological changes occurring within the lake and its catchment. Moreover, in Estonia, where many temperate, thermophilous tree species occur at their northern distribution limit so that their abundance, regeneration, and pollen production are constrained by climate, pollen deposited in the varves provides an opportunity for vegetation and climate reconstructions. Here we apply transfer functions of annual mean temperature (Tann) to the fossil pollen assemblages to generate a high-resolution quantitative reconstruction of temperature changes during the early to middle Holocene.

MATERIAL AND METHODS
The lake-sediment core was sampled from Lake Röuge (local name Röuge Tõögjärv; 57°44′N, 26°54′E), a 4.2 ha lake located in southern Estonia (Fig. 1). A 730-cm-long core was recovered from the deepest point of the 17-m-deep lake in 2000. The sediment is visibly laminated (see Data Repository1). Chem-
ical and microscopic examination showed that the varves consist of clastic inorganic and calcitic spring-summer layers separated by darker organic humic layers. The continuous chronology for the core section downward of 419 cm is based on counting of varves of multiple cores with a typical 1%–2% cumulative error. This 4020-yr-long early Holocene part of the varve chronology is currently floating, but was anchored to the calendar-year time scale by correlation of the paleomagnetic secular variation curve with the well-dated magnetostratigraphic type section, Lake Nautajärvi in Finland (Ojala and Tiljander, 2003). The most reliable paleomagnetic anchor points are at levels 9380 ± 85, 8860 ± 82, 8520 ± 80, 8380 ± 80, and 6740 ± 71 yr B.P. (= before A.D. 2000). The chronology is further supported by five accelerator mass spectrometry

$^{14}$C dates from terrestrial macrofossils (see footnote 1). This correlation places the lower varve contact of the Lake Röuge core at 9400 ± 85 yr B.P. and the upper contact at 5380 ± 52 yr B.P., adopting the cumulative varve-counting error of Lake Nautajärvi.

Samples of constant volume (0.4 cm$^3$) and thickness (0.4 cm) for pollen and bulk carbonate oxygen isotope analysis comprise a known number of years (mean, 11 yr per sample; mean sedimentation rate, 0.038 cm-yr$^{-1}$; see footnote 1). The samples were taken at 12–25 yr intervals at 8450–8000 yr B.P. and 50 yr intervals in the other parts of the core (mean sampling interval of the total core, 39 yr). The relative lightness of the sediment was analyzed with digital imaging of the cores (Saarinen and Petterson, 2001). The grayscale diagram displays a two-dimensional graph that represents the intensities of pixels along a line within the sediment image. The increasing relative lightness is associated with an increase in calcite precipitation and higher content of clastic inorganic material in relationship to the organic content.

The $T_{\text{ann}}$ trends were reconstructed from the pollen-stratigraphic data. For this purpose we used a transfer-function approach based on a combined Finnish-Estonian pollen-climate calibration set (see footnote 1) of 137 lake-sediment surface samples from small- to medium-sized lakes in Finland (113 samples) and Estonia (24 samples). Modern pollen-climate transfer functions for $T_{\text{ann}}$ were constructed by using weighted averaging–partial least squares regression (ter Braak et al., 1993; ter Braak and Juggins, 1993). The performance of the resulting reconstruction model was tested by comparing the modern $T_{\text{ann}}$ values with those predicted by the model in leave-one-out cross-validation (ter Braak and Juggins, 1993). In our model, the coefficient of determination ($r^2$) between the observed and predicted $T_{\text{ann}}$ values is 0.88, root-mean-square error of prediction is 0.89, and maximum bias is 2.13 °C, all based on leave-one-out cross-validation. The modern pollen-climate transfer functions were applied to the fossil pollen assemblages of the Lake Röuge core.

### TEMPERATURE RECONSTRUCTION

The $T_{\text{ann}}$ reconstruction (Fig. 2A) shows that the gradually rising trend since the lower varve contact at 9400 yr B.P. was punctuated by an abrupt decline at 8400 yr B.P. The cooling trend culminated at 8250–8150 yr B.P., when the level for $T_{\text{ann}}$ was 0.5–1.0 °C below the modern values for the region and ~2.0 °C colder than prior to the cooling. The cold period ended abruptly at 8080 yr B.P., with the temperature rising ~2.0 °C in 25 yr. The reconstructed coldest period at 8250–8150 yr B.P. agrees with the minimum $\delta^{18}$O values of the Greenland ice cores. The beginning of the event at 8400 yr B.P. is consistent with the approximate date of 8450 cal. yr B.P. for the freshwater pulse from Lake Agassiz (Barber et al., 1999), whereas most of the other precisely dated high-resolution records from the North Atlantic, including $\delta^{18}$O records from the Greenland ice cores, indicate a shorter cold event focusing ca. 8250–8100 yr B.P. (Alley et al., 1997). It is therefore possible that the records from the more oceanic parts of northern Europe record only the coldest period of the event. After 8080 yr B.P., the $T_{\text{ann}}$ values stabilized at a level ~2.0–3.0 °C above the modern $T_{\text{ann}}$ levels, reflecting the anomalous nature of the cold event at 8200 yr B.P. during the early to mid-Holocene. The relative lightness record (Fig. 2B) suggests that the lake underwent sedimentological changes concurrently with the climatic changes. The sudden increase in inorganic material content in the sediment at 8400 yr B.P. reflects increased erosion of the catchment topsoil. The high content of inorganic material in the varved boreal lakes correlates with the intensity of the spring flood during snowmelt and is hence an indicator of particularly severe and snow-rich winters. The warming at 8080 yr B.P. is reflected in the lower relative lightness values, probably due to the lower content of clastic inorganic material and higher organic content of the sediment, the latter resulting from higher biological productivity.

The bulk carbonate $\delta^{18}$O record fluctuated between ~$-11.20\%$ and ~$-1.60\%$ during the early Holocene (Fig. 2C). The values dropped below ~$-11.60\%$ at 8280 yr B.P. and rose to ~$-11.30\%$ after 8150 yr B.P. The climatic interpretation of the record is somewhat am-

![Figure 2. A: Pollen-based annual mean temperature ($T_{\text{ann}}$) reconstruction of Lake Röuge for 9400–7200 yr B.P. (=before A.D. 2000). Black curve is original data and gray curve is LOESS smoother with span of 0.15. Dotted line shows reconstructed modern $T_{\text{ann}}$ values for period A.D. 1950–1999. Sample-specific root-mean-square error of prediction for each reconstructed value (not shown) was generated with Monte Carlo simulation by using weighted averaging partial least squares regression program (ter Braak and Juggins, 1993). Errors range from 0.97 °C to 1.35 °C. B: Image analysis data of sediment sequence, expressed as grayscale intensities (inverted to match other records). C: $\delta^{18}$O record of Lake Röuge shown with LOESS smoother with span of 0.15 (black curve). Original measured values are indicated by black dots. NorthGRIP $\delta^{18}$O record from Greenland (Johnsen et al., 2001), presented as 20 yr means, is shown for comparison (gray bars).](image-url)
VEGETATION RESPONSE TO CLIMATE CHANGE

The pollen-stratigraphic data reflect the impact of the cold event on the forest ecosystem in the study region. The rapid cooling at 8400 yr B.P. induced rapid declines of temperate, thermophilous broad-leaved trees such as Alnus, Corylus, Ulmus, and Tilia, and a corresponding rise in Betula (Fig. 3). The decline in Alnus from >20% to <10% is particularly noteworthy because, unlike other species, it does not occur near its northern distribution limit in Estonia. Alnus begins to grow and flower early in the season and is particularly sensitive to frost damage in the early spring. In line with the formation of the paler varves, the Alnus decline suggests that winters and early springs were particularly cold in the study region during the cold event at 8200 yr B.P. This interpretation is further supported by the establishment of Picea during the event (Fig. 3F). In contrast to the temperate tree species, the successful sexual regeneration of Picea in the Hemiboreal Zone is favored by adequately cold and snowy winters (Dahl, 1998). The temperate deciduous tree species recovered at 8080 yr B.P. (Fig. 3). These abrupt pollen-stratigraphic changes during the decline and recovery do not necessarily indicate major changes in population sizes or in the species composition of the forest, but probably partly reflect the high interannual variability in pollen production of tree species at their range limits (van der Knaap and van Leeuwen, 2003). Pollen production of the thermophilous species was constrained by the low temperature and short growing season at 8400–8080 yr B.P., whereas climatic conditions became more favorable for flowering and pollen production of these species at 8080 yr B.P.

NATURE OF THE 8200 B.P. EVENT

The most probable scenario for the climatology of the cold event at 8200 yr B.P. in the study region is that the cooling was caused by a sudden weakening of the zonal flow pattern and associated transport of mild, moist air from the Atlantic with subsequent enhancement of the anticyclonic circulation and flow of cold air from the Eurasian continent. Shifts such as this and their impact on weather patterns in Estonia and elsewhere in eastern and northern Europe are well documented (Jaagus, 1997; Jacobiet et al., 2001), and the critical role of the shifting dominance of these two large-scale atmospheric circulation patterns on decadal-scale climatic variability has been shown in time-series analyses (Slonosky et al., 2000; Marshall et al., 2001; Jacobiet et al., 2001). Winter temperature variations in the study region, in particular, are directly dependent on the atmospheric flow pattern. The
westerly component is associated with positive temperature anomalies, high precipitation, and reduced snow cover. When the zonal flow and the influence of the Atlantic air masses are replaced by the Eurasian anticyclonic circulation, temperature falls and the snow cover becomes permanent (Jaagus, 1997; Chen and Hellström, 1999; Junge and Stephenson, 2003). In addition, model experiments simulating the climatic impact of a sudden weakening of the THC are consistent with the Lake Röuge data, which support the freshwater flux from the Laurentide glacial lakes as the ultimate cause of the reconstructed cooling in Estonia. It is particularly important that the models suggest that a shutdown of the THC would increase the sea-ice cover in the Nordic Seas and reduce the penetration of moist and mild Atlantic air into the European continent, resulting in colder winters with snow cover lasting 1–2 months longer (Renssen et al., 2002; Vellinga and Wood, 2002). Moreover, the inferred climatic and environmental processes in the study area during the cold event at 8200 yr B.P. are consistent with experiments carried out specifically for modeling the impact of freshwater pulses in the North Atlantic using the boundary conditions corresponding to the situation at 8500 yr B.P., prior to the drainage of Lake Agassiz. In an experiment in which the freshwater was released at a rate of 0.75 Sv (1 Sv = 10^6 m^3 s^-1) during a 20 yr period (Renssen et al., 2001, 2002), the simulated climatic response in northern Europe was a 300 yr cooling of 1.0–2.0 °C, with more pronounced cooling in winter. This experimental response is distinctly similar to the reconstructed response in Estonia.

ACKNOWLEDGMENTS

We thank K.D. Bennett, H.J.B. Birks, D. Hammarlund, H. Renssen, and an anonymous reviewer for comments and A. Heinsalu, T. Martma, and L. Saare for valuable discussion and assistance. Supported by the Swedish Research Council, Estonian Target Financing HM0331758s01, and Estonian Science Foundation grants 4963 and 5923.

REFERENCES CITED


Broecker, W.S., 2003, Does the trigger for abrupt climate change reside in the ocean or in the atmosphere?: Science, v. 300, p. 1519–1522.


Manuscript received 6 April 2004

Revised manuscript received 20 April 2004

Manuscript accepted 21 April 2004

Printed in USA