Were abrupt Lateglacial and early-Holocene climatic changes in northwest Europe linked to freshwater outbursts to the North Atlantic and Arctic Oceans?

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Abstract: During the Lateglacial and early Holocene, abrupt, millennial-scale climatic variations are recorded in a wide range of high-resolution proxy records from marine and terrestrial archives in NW Europe. Our review of the evidence for these rapid climate events do not show an apparent link to possible forcing factors such as long-term, orbitally induced variations in solar radiation, short-term variations in solar activity as inferred from ^{14}C, atmospheric carbon dioxide concentration, or volcanic sulphate as recorded in the GISP2 ice-core record. There is, however, a remarkable degree of similarity with the number, duration and timing of episodes of increased flux of fresh water to the north Atlantic and Arctic Oceans from the Laurentide ice sheet and from the Baltic ice lake in SW Sweden. These freshwater outburst events occurred when continental runoff from the Laurentide ice sheet was rerouted from the Mississippi River to the Hudson River, St Lawrence River, Hudson Strait and along the Mackenzie River to the Atlantic and Arctic Oceans, and when the Baltic ice lake in SW Sweden drained to Skagerrak. Periods of increased freshwater flow to the North Atlantic and Arctic Oceans may thus provide a mechanism to explain the abrupt and significant Lateglacial and early-Holocene climate events in NW Europe. The idea that freshwater outbursts might drive abrupt climate events is not new, but previous work may have underestimated the extent of support from proxy data and overestimated the influence of the Laurentide ice sheet.

Key words: Lateglacial, early Holocene, NW Europe, abrupt climatic change, meltwater outbursts.

Introduction

Abrupt climate events have been recorded in a number of climate proxies and archives in the North Atlantic region during the last glacial period and the early Holocene (e.g., Dansgaard *et al.*, 1993; van Geel *et al.*, 1998; Bond *et al.*, 1997; Adams *et al.*, 1999). Several large climatic changes, involving regional changes in mean annual temperature of several degrees C, occurred on timescales of a few centuries, sometimes decades, and perhaps even a few years. Numerous palaeoclimate records obtained from recent years have revealed that climate has been highly variable even during periods of prevailing ice-age climate, switching abruptly between cold and warm modes (e.g., Dansgaard *et al.*, 1993). There has therefore been a growing realization that the climatic system has repeatedly switched, on a timescale of years to centuries, between significantly different climatic modes, but with fundamentally different amplitudes (e.g., Berger and Labeyrie, 1987; Lockwood, 2001).

The North Atlantic region underwent a series of abrupt climatic oscillations when the Northern Hemisphere ice sheets retreated during the last glacial termination. Evidence of these oscillations is recorded in European terrestrial sediments as the Oldest Dryas/Bølling/Older Dryas/Allerød/Younger Dryas vegetational sequence (e.g., Iversen, 1954; Mangerud *et al.*, 1974), in Greenland ice cores (e.g., Johnsen *et al.*, 1992; 1995; Dansgaard *et al.*, 1993; Stuiver *et al.*, 1995) and in marine sediments (e.g., Boyle and Keigwin, 1987; Koç Karpuz and Jansen, 1992; Lehman and Keigwin, 1992; Klitgaard-Kristensen *et al.*, 2001; Birks and Koç, 2002; Rahmstorf, 2002). In Antarctica, the Taylor Dome ice-core record shows an abrupt deglacial warming, near synchronous with

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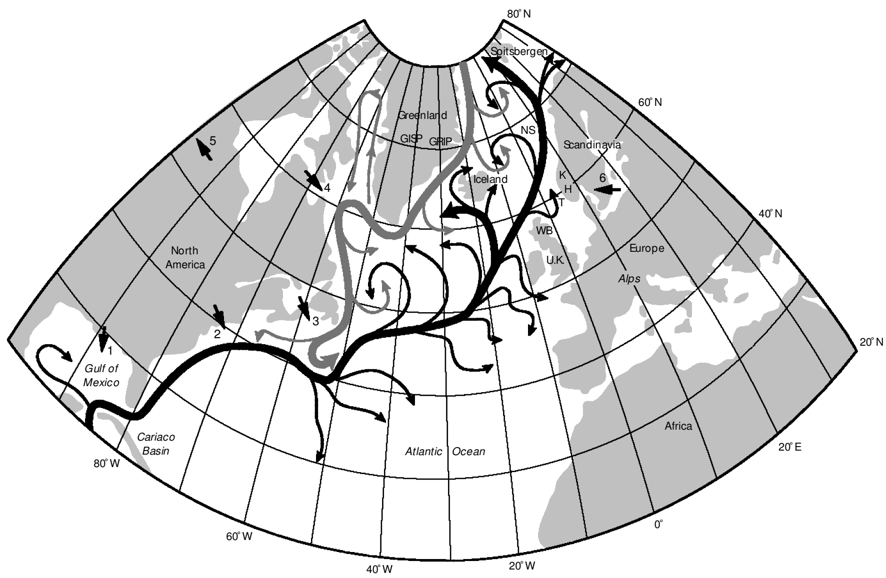

Figure 1 The North Atlantic region. Numbers refer to routes of continental freshwater runoff. (1) Mississippi River to the Gulf of Mexico. (2) Hudson River. (3) St Lawrence River. (4) Hudson Strait. (5) Mackenzie Valley to Arctic Ocean. (6) Baltic ice lake, SW Sweden. For detailed map showing general routing of Lake Agassiz (North America) overflow and outbursts to the oceans, see Teller *et al.,* (2002: 880). The Gulf Stream and its continuation as the North Atlantic Drift/Current and the Norwegian Current (black) and the East Greenland Current (grey) with branches are shown. WB = Whitrig Bog; NS = The Norwegian Sea; T = Troll; H = Haganesvatnet; K = Kråkenes.

the warming seen in the Greenland ice cores at ~14.6 ka (Figure 2), but lags the general warming trend in other Antarcic ice cores by at least 3000 years. Deglacial warming was followed by a warm interval and transient cooling between 14.6 and 11.7 ka, synchronous with the Bølling/Allerød warming and Younger Dryas cooling in Central Greenland and out of phase with the Antarctic Cold Reversal recorded in the Byrd ice core (Figure 2) in West Antarctica (Steig *et al.,* 2000).

Several hypotheses have been proposed to explain the origin of the significant millennial-scale abrupt Lateglacial and early-Holocene climatic variations in the high-latitude Atlantic Ocean and on adjacent land masses (Figures 1 and 3). External climate forcings may be either natural, e.g., changes in insolation from orbital variations, solar activity or volcanic aerosols, or anthropogenic (e.g., greenhouse gases). Climatic effects of variations in solar activity and volcanic eruptions are considered to explain a

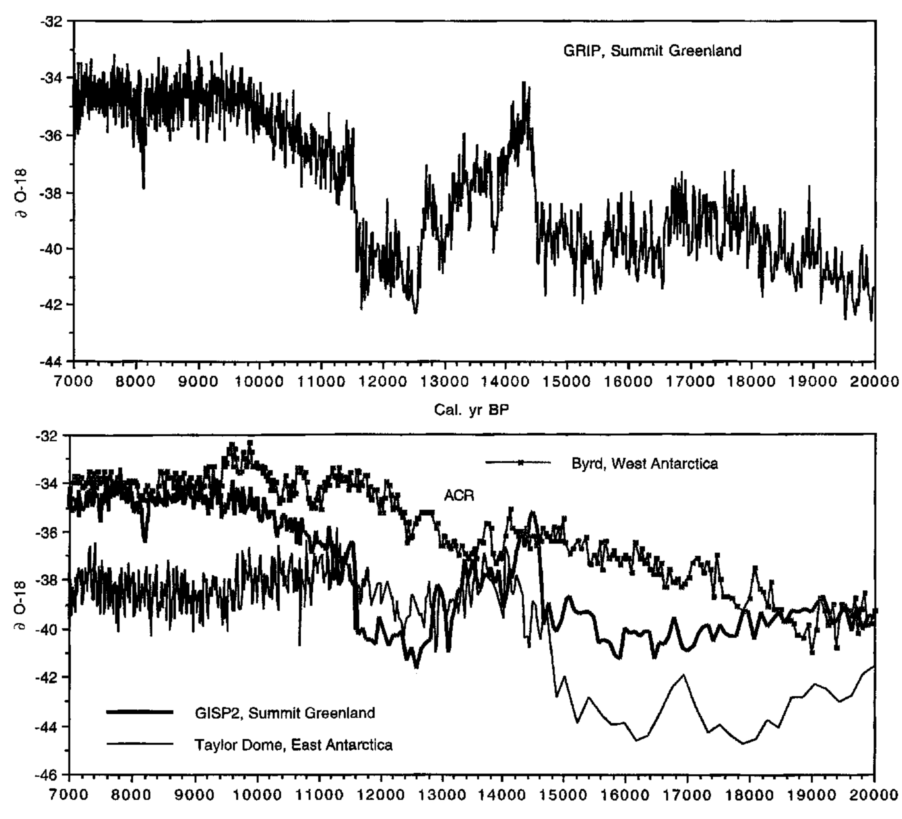

Figure 2 Top: the stable oxygen isotope ($\partial^{18}O$) record from the Greenland GRIP ice core (Johnsen *et al.*, 1992). Bottom: stable oxygen isotope ($\partial^{18}O$) records from GISP2 (Grootes *et al.*, 1993; Meese *et al.*, 1997), Taylor Dome, East Antarctica (Steig *et al.,* 2000; Grootes *et al.,* 2001) and Byrd, West Antarctica (Blunier and Brook, 2001). ACR = Antarctic cold reversal.

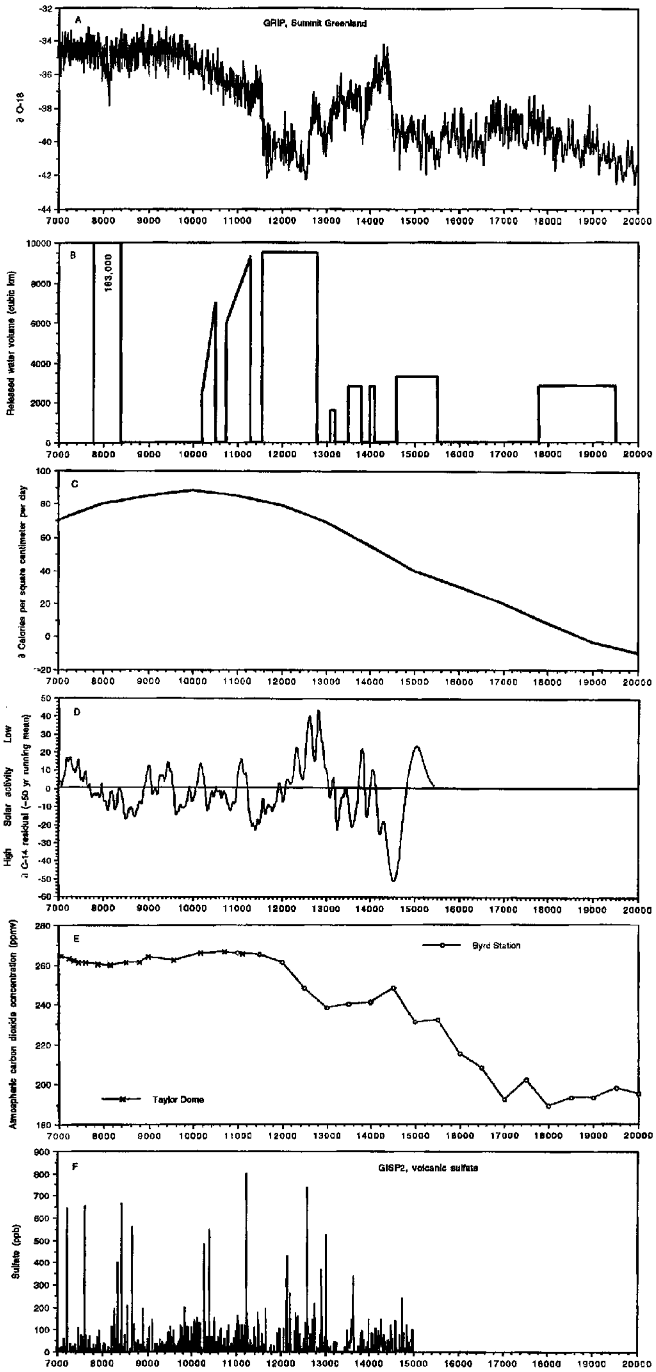

Figure 3 (A) The GRIP ice-core record 7000–20000 cal. yr BP (Johnsen *et al.*, 1992). The Pleistocene/Holocene boundary is ~11500 cal. yr BP. (B) Lateglacial and early-Holocene meltwater outflow and rerouting phases from ice-dammed lakes along the southern margin of the Laurentide ice sheet (adopted from Clark *et al.*, 2001; Fisher *et al.*, 2002; Teller *et al.*, 2002) and from the Baltic ice lake in SW Sweden (Björck *et al.*, 1996; Boden *et al.*, 1997) with estimated released water volumes during the drainage phases from the ice-dammed lakes along the Laurentide ice-sheet margin (Clark *et al.*, 2001; Teller *et al.*, 2002). See Table 1. (C) Long-term orbital deviation of July solar radiation from AD 1950 values at 60°N between 7000 and 20000 cal. yr BP (adapted from Berger, 1979). (D) Variations in $\partial^{14}C$, a proxy for solar activity, in tree rings 7000–~15400 cal. yr BP (Stuiver *et al.*, 1997). (E) Atmospheric CO_2 concentration integrated from the Byrd Station (Neftel *et al.*, 1988) and Taylor Dome (Indermühle *et al.*, 1999) in Antarctica 7000–20000 cal. yr BP. (F) GISP2 volcanic sulfate 7000–15000 cal. yr BP (Zielinski and Mershon, 1997).

considerable part of the mid- to late Holocene climatic variability (e.g., Beer *et al.*, 2000; Zielinski, 2000), but considered too small to explain climatic variations of such magnitude as during the Lateglacial and early Holocene (e.g., Lockwood, 2001). The ^{10}Be concentration (proxy for solar variability) and the electrical conductivity (mainly a proxy for explosive volcanic activity) records from the GISP2 ice core (Finkel and Nishiizumi, 1997, and Taylor *et al.*, 1997, respectively) do not indicate that there is a direct link between these parameters and the abrupt Lateglacial and early-Holocene climatic changes. In addition, the evidence of these abrupt climate events do not show an apparent link to long-term orbital variations in solar radiation, solar activity as inferred from ^{14}C variations, atmospheric carbon dioxide concentration and volcanic sulphate as recorded in the GISP2 ice-core record (Figure 3). There is, however, a remarkable degree of similarity with the number, duration and timing of episodes of increased flux of fresh water to the north Atlantic and Arctic Oceans from the Laurentide ice sheet and from the Baltic ice lake in SW Sweden (Figure 3). Therefore, variations in the thermohaline circulation (THC) in the North Atlantic Ocean that perturb deep ocean convection there have for some years been proposed to play a role in explaining the observed abrupt climatic variations during glacial periods (e.g., Stocker and Wright, 1991; Rahmstorf, 1994; Broecker, 1997; Stocker, 2000; Clark *et al.*, 2002; Renssen *et al.*, 2002). The oceanic THC transports large amounts of heat northward in the Atlantic (e.g., Rahmstorf, 2002) and variations in the THC have been attributed to inputs of fresh water in the North Atlantic that perturb deep-ocean convection (e.g., Stocker and Wright, 1991; Rahmstorf, 1994; Stocker, 2000). Alternative mechanisms have been proposed. It has been suggested that interactions between the Southern Ocean and the North Atlantic could also lead to large variations of the global THC (e.g., Broecker *et al.,* 1999). In addition, natural modes of climatic variability have been proposed, invoking a slow warming of the deep ocean resulting in a destabilization of the water-column that leads to large oceanic flushes characterized by a huge release of oceanic heat (e.g., Weaver *et al.,* 1993). Oxygen isotope ratios of bentic foraminifera from sediment cores ODP 1078C and M35003-4 (Hüls, 2000) suggest that intermediate-depth temperatures in the tropical Atlantic were in antiphase (warm in south when cold in the north) with the Greenland ice-core records during two Lateglacial periods (~17000–15300 and 13000–11600 cal. yr BP; Rühlemann *et al.,* 1999; 2003).

A prominent feature during the last deglaciation was the meltwater pulse 1A (mwp-1A), which led to a sea-level rise of ~20 m in less than 500 years. Mwp-1A occurred *c.* 14600 cal. yr BP at the same time as the onset of the Bølling-Allerød interstadial complex. With the use of a climate model of intermediate complexity, Weaver *et al.* (2003) suggested that the North Atlantic Deep Water formation increased and thereby warmed the North Atlantic region if the mwp-1a originated from the Antarctic ice sheet and not from the Laurentide or Scandinavian ice sheets, thus providing an explanation for the prevailing mild climate in the North Atlantic region during the Bølling-Allerød interval.

In a coupled general circulation model, Hall and Stouffer (2001) obtained a large cooling close to southern Greenland using no interannually varying forcing. This event, which is an exceptional example of the stochastic variability of their coupled system, lasted less than one century. Ganopolski and Rahmstorf (2001), using a climate model with intermediate complexity, showed that stochastic fluctuations of the freshwater fluxes in the North Atlantic could induce a shift in the latitude of deep convection during glacial times which resulted in millennial-scale variability.

The Northern Hemisphere ice sheets decayed rapidly during deglacial phases of the ice ages, producing meltwater fluxes which may have been of sufficient magnitude to perturb oceanic circulation. High-amplitude, millennial-scale climatic fluctuations throughout the last ice age may have provoked significant fluctuations of ice-sheet margins and meltwater runoff variability, yielding a complex pattern of freshwater delivery to the oceans. The meltwater that was discharged from the ice sheets was either drained along continental drainage routes or stored temporarily in ice-dammed lakes at the ice-sheet margins. A combination of several factors (e.g., volume, flux, geographic location, diversion of continental drainage systems, and iceberg release) may influence whether freshwater outbursts cause variations in the thermohaline circulation (Fisher *et al.*, 2002; Teller *et al.*, 2002). It has been suggested that the Younger Dryas cold period was caused by rerouting of runoff from the Mississippi River to the St Lawrence River between 11000 and 10000 ^{14}C yr BP (Broecker *et al.*, 1989; 1990). Recent reconstructions of freshwater runoff from the North American Laurentide ice sheet (e.g., Marshall and Clarke, 1999; Clark *et al.*, 2001) show strong evidence for freshwater rerouting when the Laurentide ice sheet was located in the Great Lakes region. Clark *et al.* (2001) compared the rerouting meltwater history with changes in the amount of IRD containing detrital carbonate lithologies in North Atlantic cores (Bard *et al.,* 1999; Bond *et al.,* 1999), detrended record of $\partial^{14}C_{atm}$ from Lake Suigetsu, Japan (Kitigawa and van der Plicht, 2000), the $\partial^{18}O$ record from the Greenland GISP2 ice core (Grootes *et al.*, 1993; Meese *et al.*, 1997), records of sea surface temperatures (SSTs) derived from alkenones measured in cores from the North Atlantic, tropical North Atlantic and South Atlantic (Bard *et al.,* 1999, Rühlemann *et al.,* 1999, and Sachs *et al.,* 2001, respectively), and the Byrd ice-core oxygen isotope record (Blunier and Brook, 2001). Based on data and model simulations, Clark *et al.* (2001) suggested that abrupt climatic change during the last glaciation originated through changes in the Atlantic thermohaline circulation in response to changes in the hydrological cycle. In addition, records obtained from the Cariaco Basin in the tropical North Atlantic show strong similarities with records from the North Atlantic region (e.g., Hughen *et al.*, 1996; Haug *et al.,* 2001).

If the reconstructed Lateglacial and early-Holocene freshwater rerouting events along the southern margin of the Laurentide ice sheet (e.g., Clark *et al.*, 2001) caused climatic variations along the North Atlantic Current/Drift and its continuation into the Nordic Seas, these should have been registered as more or less simultaneous climate events in high-resolution Lateglacial and early-Holocene climate records from the Nordic Seas, Scotland and Norway (Figure 1). In this paper, we have therefore compared the record of meltwater rerouting events from the North American Laurentide ice sheet (e.g., Teller, 1990; Clark *et al.*, 2001; Fisher *et al.*, 2002; Teller *et al.*, 2002) and drainage episodes from the Baltic ice lake in SW Sweden (e.g., Björck *et al.*, 1996; Boden *et al.*, 1997; Figures 3 and 4) with well-dated, high-resolution Lateglacial and early-Holocene climate reconstructions in NW Europe – Lateglacial climate coolings in western Norway inferred from biological proxies (Paus, 1988; 1989; Birks *et al.*, 1994; 2000), record of Younger Dryas and early-Holocene glacier variations in southern Norway (Larsen *et al.*, 1984; Nesje *et al.*, 1991; 2000; 2001; Dahl and Nesje, 1992; 1994; 1996; Dahl *et al.*, 2002), the oxygen isotope record from the GRIP ice core in Greenland (Johnsen *et al.*, 1992), percentage variations of a cold water planktonic foraminifera (*G. pachyderma* sin.) and a warm water living planktonic foraminifera (*G. pachyderma* dex.) in the Troll core, North Sea (Klitgaard-Kristensen *et al.*, 2001), variations in loss-on-ignition in the Kråkenes (Birks *et al.*, 2000) and Haganesvatnet (authors, unpublished data) lake-sediment records in western Norway, sea-surface winter and summer temperatures in the southeast Norwegian Sea during the last glacial-interglacial transition based on diatom data (Koç Karpuz and Jansen, 1992), and a chironomid-based summer temperature reconstruction from Whitrig Bog, SE Scotland (Brooks and Birks, 2000; 2001; Figures 4 and 5). A similar climatic development as recorded in the above-cited records has been inferred from European tree-ring chronologies (Friedrich *et al.*, 2001), northern and central European annually laminated lacustrine sediments (Litt *et al.,* 2001) and in a Late-glacial lake sequence from Hawes Water, NW England (Jones *et al.*, 2002). The climatic development is put into the context of the event stratigraphy for the Last Termination in the North Atlantic region proposed by the INTIMATE group (Björck *et al.*, 1998; Lowe *et al.*, 2001; Figure 4). The idea that freshwater outbursts might drive climatic change is not new (e.g., Johnson and McClure, 1976; Broecker *et al.*, 1988; Keigwin *et al.,* 1991; Licciardi *et al.,* 1999; Clark *et al.,* 2001; Fisher *et al.,* 2002; Teller *et al.,* 2002), but in this paper we have linked it to a range of different high-resolution, well-dated records of proxy evidence from the North Atlantic region. The emphasis has previously mainly been on the Laurentide ice, but there may also have been other important sources of meltwater input during the actual timespan.

The thermohaline circulation (THC)

The ocean circulation is mainly controlled by the density of the seawater (function of temperature and salinity) and wind curl stress, which together determines the strength of the thermohaline circulation (THC). In the North Atlantic this contributes to the northward flow of warm surface water followed by heat release and sinking of the cooler water in the Nordic Seas with southern flow of intermediate and deep water. If the input of fresh water to the Nordic Seas and the balance between the input and deep-water exit rises above a threshold value, the thermohaline circulation may jump from its equilibrium state (Paillard, 2001; Rahmstorf, 2002). This new state corresponds to reduced circulation causing colder temperatures in the Nordic Seas and adjacent land masses. When the freshwater perturbation ends, the ocean circulation may not return to the initial state but may stay inactive. Removal of fresh water may bring the circulation back to normal (Paillard, 2001). Recent data indicate that the rapid climatic fluctuations in the North Atlantic at the end of the last glacial were not caused by the THC being switched 'on' or 'off' (e.g., Weinelt *et al.,* 1995). Instead, evidence suggests that, even during cold periods, the THC continued at almost similar intensity as at present (see review by Lockwood, 2001). Bond *et al.* (2001) showed evidence of a close correlation between inferred changes in production rates of ^{14}C and ^{10}Be and centennial to millennial timescale changes during the Holocene in proxies of drift ice from sediment cores from the North Atlantic Ocean. Thus, the wind and ocean hydrography variations during the Holocene in the subpolar North Atlantic appear to have been influenced also by variations in solar output. Björk *et al.* (2001) presented evidence that a climatic cooling peaking around 9100 ^{14}C years (10 300 cal. yr BP) coincides with one of the largest ^{10}Be flux peaks, implying that the climatic system may be sensitive to solar-related changes and thus important for sub-Milankovitch climatic variability.

The abrupt Lateglacial and early-Holocene climatic changes recorded in the North Atlantic realm are more pronounced than climatic change recorded in the Southern Hemisphere, for example in Antarctic ice-core records (Steig *et al.*, 1998; 2000; Petit *et al.,* 1999; Grootes *et al.,* 2001; Blunier and Brook, 2001). In addition, these climate reversals occurred at a time of maximum solar insolation to the Northern Hemisphere (Kutzbach and Webb, 1993; Figure 3C). Reductions in NADW have been associated with freshwater inflow to the North Atlantic, either from melting of glaciers (e.g., Broecker *et al.*, 1985) or from ice-sheet instabilities leading to influx of fresh water from icebergs (reflected in IRD; Alley and MacAyeal, 1994) and drift ice. Several studies have documented large reductions in NADW production associated with the millennial-scale glacial cooling events (Charles *et al.*, 1996; Bond *et al.*, 1997; Zahn *et al.*, 1997). One

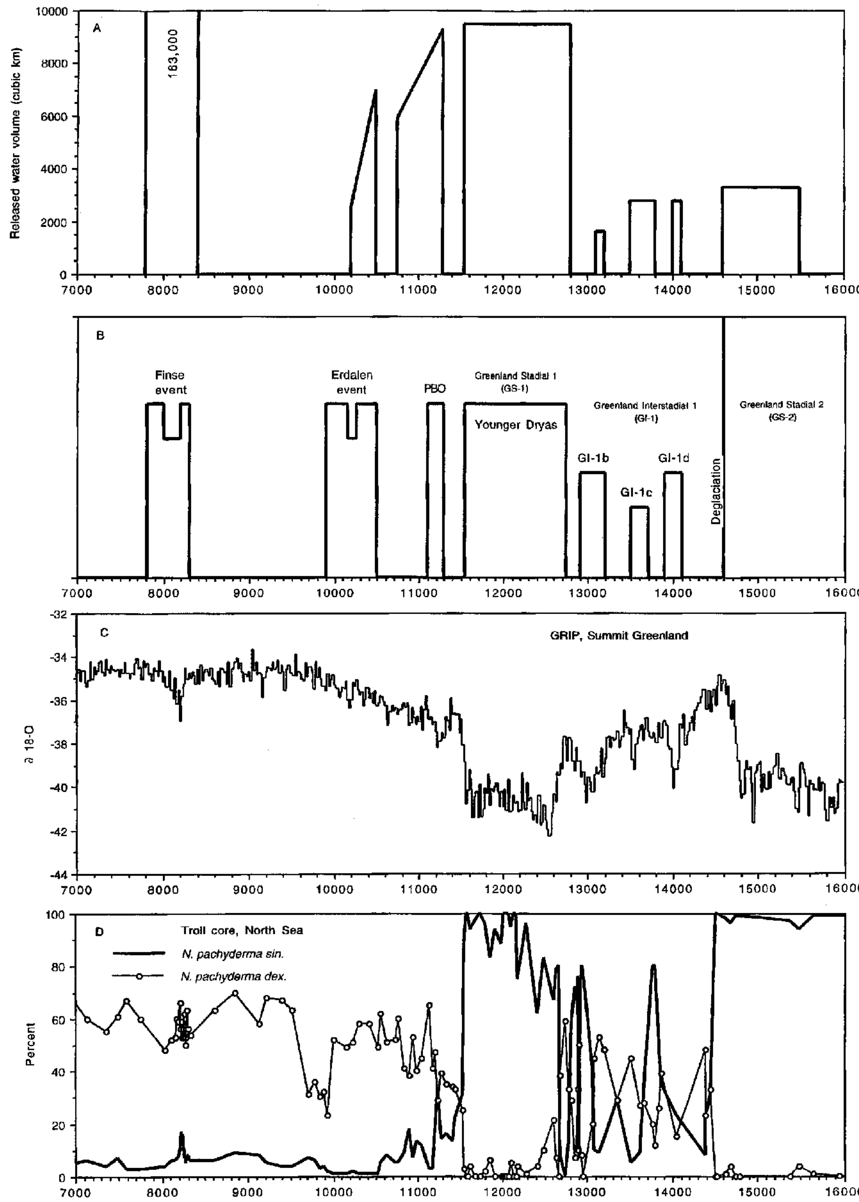

Figure 4 (A) Periods between 16000 and 7000 cal. yr BP of freshwater outflows from the eastern margin of the Laurentide ice sheet (adapted from Clark *et al.*, 2001) with estimated released water volumes during the drainage phases from the ice-dammed lakes along the Laurentide ice-sheet margin (Clark *et al.*, 2001; Teller *et al.*, 2002). The meltwater outflow centred ~11300 cal. yr BP was from the Baltic ice lake in southern Sweden (Björck *et al.*, 1996; Boden *et al.*, 1997). See Table 1. The Pleistocene/Holocene boundary is ~11500 cal. yr BP. (B) Approximate timing of the deglaciation of the Scandinavian ice sheet from the coast of western Norway, three climatic coolings recorded in lake records in western Norway (pollen/loss-on-ignition; Paus, 1988; 1989; Birks *et al.,* 1994; 2001), and Younger Dryas and early-Holocene climatically forced glacial readvances in southern Norway (Larsen *et al.*, 1984; Nesje *et al.*, 1991; 2000; 2001; Dahl and Nesje, 1992; 1994; 1996; Dahl *et al.*, 2002). The proposed Lateglacial event stratigraphy from the INTIMATE group (Björck *et al.*, 1998; Lowe *et al.*, 2001) is shown. The Finse event has been correlated to the 8.2 ka event (Nesje and Dahl, 2001). PBO = Preboreal Oscillation. (C) The stable oxygen isotope ($\partial^{18}O$) record from the Greenland GRIP ice core (Johnsen *et al.*, 1992). (D) Relative frequency (in percent) of the cold water planktonic foraminifera species *N. pachyderma* sinistral and the warm water planktonic foraminifera species *N. pachyderma* dextral in the marine Troll core, North Sea (Klitgaard-Kristensen *et al.*, 2001).

of the most favoured hypotheses to explain the observed Lateglacial and Holocene climatic variations in the North Atlantic region has therefore been changes in the rate of formation of North Atlantic Deep Water (NADW) and their effect on ocean heat transport (e.g., Broecker *et al.*, 1985). Numerical modelling experiments indicate that the THC in the North Atlantic is sensitive to changes in the freshwater budget where the deep water is formed (e.g., Manabe and Stouffer, 1995; 1997; Rahmstorf, 1995; Fanning and Weaver, 1997; Ganopolski and Rahmstorf, 2001; Renssen *et al.,* 2001; 2002; Goosse *et al.,* 2002). Model experiments indicate that formation of deep water is decreased by increased freshwater flux, thus reducing the oceanic and atmospheric heat transport to the high-latitude Atlantic Ocean and NW Europe (Rind *et al.*, 2001). Renssen *et al.* (2002), for example, studied the effect of freshwater pulses on the early-Holocene climate with a global coupled atmosphere-sea ice-ocean model. In the model, an early-Holocene equilibrium climate state was perturbed by releasing a fixed amount of fresh water into the Labrador Sea at three different constant rates. The freshwater pulses produced a weakening of the THC and the registered perturbation is in agreement with proxy evidence for the 8.2 ka event. One of the scenarios, with fresh water added to the Labrador Sea at a rate of 0.75 Sv during 20 years, resulted in weakening of the North Atlantic THC during 320 years and surface cooling of 1–5°C over adjacent continents.

Indirect evidence suggests the NADW production oscillated

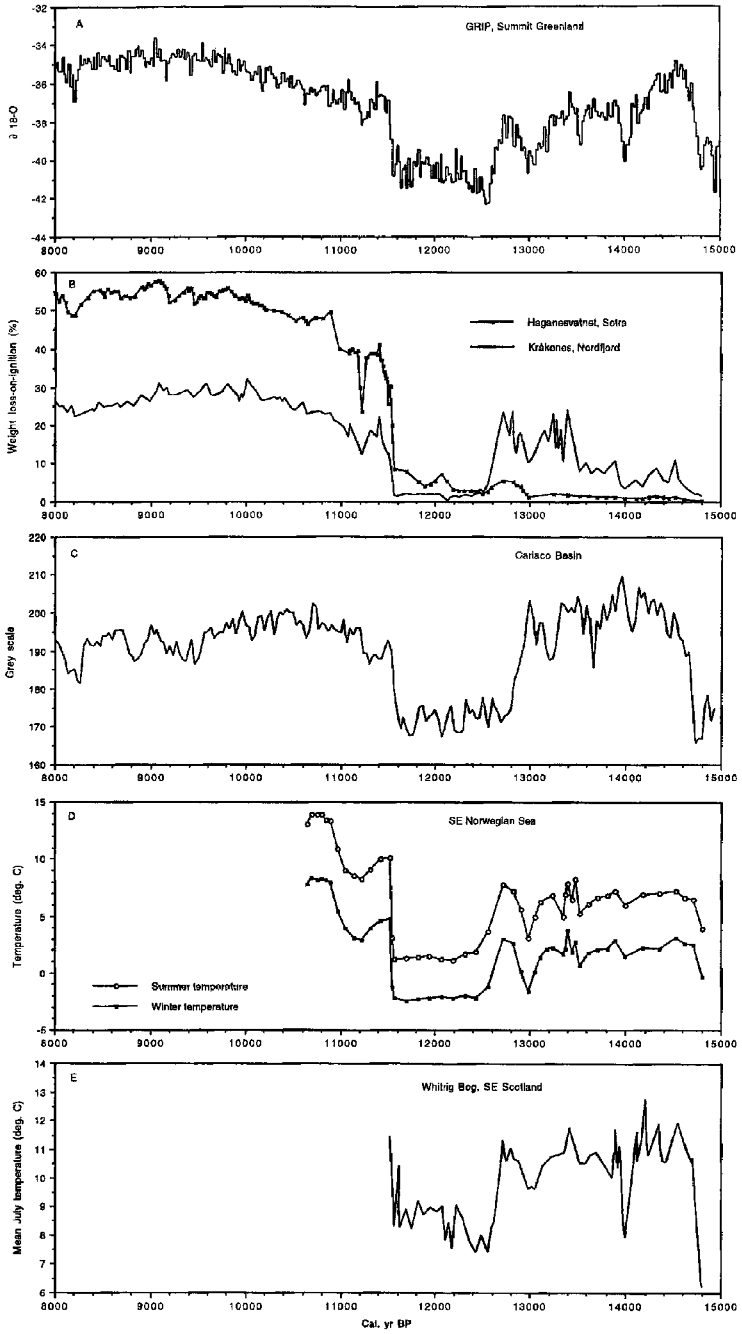

Figure 5 (A) The stable oxygen isotope ($\partial^{18}O$) record from the Greenland GRIP ice core (Johnsen *et al.*, 1992). The Pleistocene/Holocene boundary is ~11 500 cal. yr BP. (B) Loss-on-ignition records from two lakes in western Norway; Haganesvatnet, Sotra at Bergen (studied by the authors) and Kråkenes (Birks *et al.*, 2000). The records have been 'wiggle-matched' (e.g., Hoek and Bohncke, 2001) to the GRIP record (e.g., Björck *et al.*, 1998; Lowe *et al.*, 2001). (C) The grey-scale record from the Cariaco Basin off Venezuela (Hughen *et al.*, 1996). (D) Sea-surface winter and summer temperatures in the southeast Norwegian Sea during the last glacial-interglacial transition based on diatom data (modified from Koç Karpuz and Jansen, 1992). (E) Chironomid-inferred Lateglacial air temperatures at Whitrig Bog, southeast Scotland (Brooks and Birks, 2000), wiggle-matched to the GRIP ice-core timescale (e.g., Lowe *et al.*, 2001).

during the last glacial stage and during the Holocene (Bond *et al.*, 1997). Different proxies of surface ocean temperatures, including planktonic foraminifera and diatom assemblages (Bond *et al.*, 1993; Koç Karpuz and Jansen, 1992), alkenone (Sachs and Lehman, 1999) and oxygen isotope data (Cacho *et al.*, 1999) indicate lower temperatures along with these variations which match the Dansgaard-Oeschger oscillations in the Greenland ice cores (Johnsen *et al.*, 1995). The occurrence of ice-rafted debris (IRD) during Heinrich Events is interpreted to represent millennial-scale coolings followed by warming.

During the early part of the Weichselian/Valdaian glaciation an ice sheet formed over the shallow Barents and Kara Seas (Mangerud *et al.*, 2001b), blocking the north-flowing rivers that drain into the Arctic Ocean. This resulted in the formation of large ice-dammed lakes between the ice margin in the north and the continental water divides in the south. Mangerud *et al.* (2001a) postulate that a sudden outburst of freshwater from the ice-dammed lakes influenced sea-ice formation, climate and ocean circulation in the Arctic Ocean. Due to lack of well-dated marine cores from the Arctic Ocean, it is difficult to evaluate evidence of meltwater outbursts. Sediment parameters in cores from the central Arctic Ocean may, however, suggest variations in freshwater supply during glacial-interglacial cycles (Jakobsson *et al.*, 2000).

Comparison of freshwater rerouting to the North Atlantic and abrupt climatic change in NW Europe during the Lateglacial and early Holocene

The detrended record of atmospheric radiocarbon ($\partial^{14}C$) has been suggested to be a reflection of ocean circulation (e.g., Clark *et al.*, 2001, and references therein; Andrews and Giraudeau, 2003). The decrease in $\partial^{14}C$ after the last glacial maximum indicates that the thermohaline circulation increased to interglacial levels at *c.* 16000 ^{14}C yr BP (*c.* 19000 cal. yr BP; e.g., Clark *et al.*, 2001). The GRIP and GISP2 Greenland ice-core records and numerous marine records indicate, however, that the climate in the north Atlantic region remained relatively cold during this time interval. The reconstruction of rerouting events from the Laurentide ice sheet shows that this period was characterized by increased freshwater flow to the North Atlantic through the Hudson River (Figures 1 and 2; Table 1). The cold climate during the Oldest Dryas with reduced heat transport to the North Atlantic, despite variability in deep-water formation, was most probably caused by increased freshwater flux through the Hudson and St. Lawrence rivers (Clark *et al.*, 2001; Figure 3). The abrupt warming at 14600 cal. yr BP (12800 ^{14}C yr BP) seen in the different proxy records and deglaciation of the coastal region of western Norway (Figures 4 and 5) coincided with the termination of a second rerouting event through the Hudson River (Figures 3 and 4). Ocean circulation proxies suggest that the THC increased to interglacial levels during this period (Clark *et al.*, 2001). Changes in the freshwater fluxes, thermohaline circulation and climatic development were suggested to be the result of prolonged freshwater flux which delayed the transition from a glacial to interglacial climate in the North Atlantic region.

Three centennial-scale climatic deteriorations recorded during the Lateglacial Greenland Interstadial 1 (GI-1) in lake, marine and ice-core records (Figures 4 and 5) were probably linked to three corresponding rerouting events which caused reduction in THC and cooling in the North Atlantic region. The first and third of these coolings seem to have been the most severe. These three cooling events have also been recorded in different proxy data from the eastern Atlantic seaboard (Nesje and Dahl, 1992; Birks *et al.*, 1994; Lowe and Walker, 1997: 344) and in pollen investigations along the coast of western Norway (Paus, 1988; 1989).

The abrupt and simultaneous initiation of the Younger Dryas seen in the proxy records (Figures 4 and 5), formation of local glaciers and the significant glacier readvance along the western margin of the Scandinavian ice sheet (e.g., Andersen *et al.*, 1995) and Scotland (e.g., Ballantyne, 1989) coincides with the diversion of drainage from the Mississippi River to the St Lawrence River when the southern margin of the Laurentide ice sheet retreated out of the Lake Superior Basin (Licciardi *et al.*, 1999). In addition, further increases in freshwater flow to the North Atlantic during the Younger Dryas was from icebergs through the Hudson Strait (Heinrich event 0; Andrews *et al.,* 1995; Figure 1) and from sudden drainage of the Baltic ice lake (BIL) in Scandinavia (Figures 1, 3 and 4; Björck *et al.*, 1996; Boden *et al.*, 1997). The initial BIL drainage at the Billingen threshold occurred approximately 10900 ^{14}C yr BP, whereas the final drainage of the BIL occurred in two steps during the younger part of the radiocarbon plateau at 10000 ^{14}C yr BP (Boden *et al.*, 1997). Several proxies indicate strongly reduced NADW formation during the Younger Dryas (Muscheler *et al.*, 2000). The readvance of the ice margin (Marquette readvance of the Lake Superior lobe) across the eastern outlet of Lake Agassiz at 10000 ^{14}C yr BP (11400 cal. yr BP; Licciardi *et al.*, 1999) caused an abrupt decrease in the freshwater flux through the St Lawrence River. This marked the abrupt termination of the Younger Dryas as seen in the records from NW Europe (Figures 4 and 5).

A short-lived (~150–200 year) climatic oscillation termed the Preboreal Oscillation (PBO; e.g., Björck *et al.*, 1997), occurred approximately 300 years after the termination of the Younger Dryas (Figures 4 and 5). Teller *et al.* (2002) suggest several factors to explain why the PBO cooling was not as significant as that of the Younger Dryas; Lake Agassiz outflow was to the Arctic Ocean and not into the North Atlantic Ocean; the THC may have entered a more stable interglacial mode, as modelled by Ganopolski and Rahmstorf (2001); and finally the Gulf of Mexico no longer received glacial meltwater which may be a prerequisite for THC changes in the North Atlantic. A review of the climate evidence from lacustrine, tree-ring and glacial records of the PBO around the Nordic Seas indicates humid and cool conditions in northwestern and central Europe (Björck *et al.*, 1997). Proxy records from lake sediments and moraines in Iceland (Geirsdottir *et al.,* 2000) indicate cooler conditions than during the initial Preboreal period, but not as cold as during the Younger Dryas. The PBO has been attributed to a sudden and short-lived release of meltwater, but the source(s) of the meltwater and a causative mechanism of the PBO has (have) been debated. It has been suggested that drainage of the BIL (Figures 3 and 4) caused the PBO by affecting the THC in the Nordic Seas (Björck *et al.*, 1996; 1997; Boden *et al.*, 1997; Hald and Hagen, 1998). Fisher *et al.*

Table 1 Record of freshwater fluxes to the North Atlantic between ~16500 ^{14}C yr BP (~19500 cal. yr BP) and ~7000 ^{14}C yr BP (~7800 cal. yr BP). R1–R8 are rerouting events along the southern and eastern margin of the Laurentide ice sheet. MDR = main drainage routes; HR = Hudson River; SLR = St Lawrence River; BIL = Baltic ice lake; HS = Hudson Strait; MR = Mackenzie River; YD = Younger Dryas. The calculated released water volumes and corresponding fluxes (if water released in one year) are adopted and calculated from Clark *et al.* (2001) and Teller *et al.* (2002); for further references, see text

	^{14}C yr BP		Cal. yr BP		MDR	Corresponding climate events	Released water volume (km^3)	Water flux (Sv)
	Start	End	Start	End				
R8	~16500	~15200	~19500	~17800	HR	Greenland Stadial 2c (GS-2c)	~2800	~0.1
R7	~13000	~12900	~15500	~14600	HR	Greenland Stadial 2a (GS-2a)	~3300	~0.12
R6	~12000	~12050	~14100	~14000	HR	Greenland Interstadial 1d (GI-1d)	~2800	~0.1
R5	~12000	~11700	~13800	~13500	HR	Greenland Interstadial 1c (GI-1c)	~2800	~0.1
R4	~11500	~11400	~13200	~13100	HR + SLR	Greenland Interstadial 1b (GI-1b)	~1600	~0.06
R3	~11000	~10000	~12800	~11500	SLR + BIL	Greenland Stadial 1 (GS-1) (YD)	9500	~0.3
R2	~9900	~9300	~11335	~10750	MR + BIL	Preboreal Oscillation (PBO)	9300 and 5900	0.29 and 0.19
R1	~9200	~9000	~10500	~10200	SLR	Erdalen event	2500–7000	0.09–0.22
	~7700	~7000	~ 8400	~7800	HS	‘8200 cal. yr BP event’/Finse event	163000	5.2

(2002), however, attribute the PBO to a massive meltwater discharge (21000 km^3 over a period of 1.5–3 years) from an abrupt drainage of Lake Agassiz through the waterway of the present Mackenzie River and into the Arctic Ocean. The initial flood occurred ~11335 cal. yr BP and was followed by a flow until 10750 cal. yr BP, when the southern outlet of Lake Agassiz reopened and meltwater was diverted into the Mississippi River system. An increase in the flux of meltwater to the North Atlantic through the St Lawrence River started approximately 9200 ^{14}C yr BP (~ 10500 cal. yr BP) and lasted until 9000 ^{14}C yr BP (~10200 cal. yr BP; Figures 4 and 5). This event started with an abrupt, two-stepped release of a large water volume from the proglacial Lake Agassiz (Leverington *et al.*, 2000; Clark *et al.*, 2001). During the initial part of this event, the formation of North Atlantic Deep Water was reduced (Clark *et al.*, 2001) and a climatic cooling occurred (Björck *et al.*, 1996; 2001). The lack of a sustained climate response to this freshwater rerouting, compared to the Younger Dryas, may indicate a more interglacial-like THC and the lack of additional freshwater sources and iceberg discharges (Clark *et al.*, 2001). A sudden and not previously considered as a possible climate cooling trigger in SW Scandinavia was a meltwater release to the Skagerrak area from an ice-dammed lake (Nedre Glåmsjø) which existed north of the downwasting ice sheet in eastern Norway (e.g., Holmsen, 1915). The total water volume of the outburst, dated at approximately 9200 ^{14}C yr BP (~10300 cal. yr BP), has been calculated to 120 km^3 (1/3 of the present-day calving off Greenland) with an estimated water discharge of 350000 m^3/sec (Longva, 1994). A sudden 5–10 m drainage of the Baltic Ancylus Lake stage (Björck, 1995) with a maximum age of 8870 ± 85 ^{14}C yr BP (10160–9790 cal. yr BP) is a candidate for North Sea freshwater forcing (Björck *et al.*, 2001). These meltwater outbursts occurred contemporaneously with a significant, two-stage glacier readvance in western Norway, termed the Erdalen event, with formation of two sets of terminal moraines beyond the 'Little Ice Age' maximum position. Nesje *et al.* (1991) suggested an age of 9100 ± 200 ^{14}C yr BP [10235 (10500–9925) cal. yr BP] for this event. Recently, this double glacier readvance has been confirmed stratigraphically at Nigardsbreen, an eastern outlet glacier from Jostedalsbreen in western Norway, and dated at 10100 and 9700 cal. yr BP (Dahl *et al.*, 2002). The timing of the first of these readvances indicate that it may have been triggered by the freshwater outburst from the Laurentide ice sheet, whereas the second may have been related to the drainage of the Baltic Ancylus Lake. In the Troll core, North Sea, this event is registered as a decrease in abundance of the warm water living foraminifera *N. pachyderma* dextral (Klitgaard-Kristensen *et al.*, 2001; Figure 4). Despite substantial climatic variability in the North Atlantic region during this period (Hughen *et al.*, 1996; Bond *et al.*, 1997) and reduced THC (Tziperman, 1997), this event is not registered as a significant climatic cooling in the GRIP and GISP2 Greenland ice cores (Figure 2).

The final meltwater rerouting from the Laurentide ice sheet occurred when the ice centre over Hudson Bay collapsed approximately 7700 ^{14}C yr BP (~8400 cal. yr BP) when an ice-dammed lake released in the order of 2×10^{14} m^3 of water in less than 100 years through the Hudson Strait (Barber *et al.*, 1999; Clarke *et al.,* 2003; Figures 1, 3 and 4). This ice-sheet collapse also caused a capture of a substantial part of the drainage from the interior continent (e.g., Clark *et al.*, 2001) which sustained until the final melting of the ice sheet at ~7000 ^{14}C yr BP (~7800 cal. yr BP; Figures 3 and 4). This resulted in a two-stage sequence of freshwater flux similar to that of the Younger Dryas and the Erdalen events. This two-stage sequence is registered in proglacial as well as in non-glacial lakes in southern Norway as a two-peaked reduction of loss-on-ignition (LOI; Nesje and Dahl, 2001). In non-glacier-fed lakes, LOI reductions may reflect a decline in lake productivity and hence a decrease in summer temperature, whereas reductions in organic content in proglacial lakes mainly reflect increased glacier activity in the catchment. Evidence of a significant climatic deterioration around 8400–8000 cal. yr BP was first emphasized by Karlén (1976), who recognized an abrupt fall in the pine tree limit in northern Sweden associated with reduced LOI values in lake sediments. Investigations carried out in the Finse area showed that Hardangerjøkulen in central south Norway readvanced around 8200 cal. yr BP (Nesje and Dahl, 1991; Dahl and Nesje, 1994; 1996). This has also been shown by Matthews *et al.* (2000) and Nesje *et al.* (2000; 2001) in proglacial lake records from Jostedalsbreen and Jotunheimen in southern Norway and in pollen records from Scandinavian mountains (Barnekow and Sandgren, 2001; Barnett *et al.*, 2001). Ice-core data from Greenland (Figures 2 and 3), and evidence from European lake sequences demonstrate that this not only was a local event, but influenced the Northern Hemisphere (Dansgaard *et al.*, 1993; Meese *et al.*, 1994; O'Brien *et al.*, 1995; Alley *et al.*, 1997; Grafenstein *et al.*, 1998; Haas *et al.*, 1998; Nesje and Dahl, 2001; Snowball *et al.*, 2002). The large amount of meltwater released through the Hudson Strait at that time is assumed to have influenced the North Atlantic THC (Kerwin, 1996; Alley *et al.*, 1997; Klitgaard-Kristensen *et al.*, 1998; Barber *et al.*, 1999).

The remarkable degree of consistency between the different records based on different proxies in NW Europe and the greyscale record (proxy for surface ocean biological productivity) from the Cariaco Basin (Figure 1) in the tropical Atlantic ocean (Hughen *et al.*, 1996; Figures 4 and 5) indicates that abrupt changes in the tropical Atlantic Ocean during the Lateglacial and early Holocene may have a common forcing mechanism. The different geographical (regional and altitudinal) climate response to the meltwater outburst phases may, however, be due to different climate responses to the oceanic and atmospheric systems.

Summary and conclusions

During melting of the Laurentide ice sheet, outlets from Lake Agassiz were periodically open, resulting in abrupt release of thousands of cubic kilometres of water and rerouting of meltwater runoff to the North Atlantic and Arctic oceans (e.g., Clark *et al.*, 2001; Fisher *et al.*, 2002; Teller *et al.*, 2002). The abrupt climatic shifts in high-resolution Lateglacial and early-Holocene climate records in NW Europe indicate a remarkable degree of similarity in the number, duration and timing of continental meltwater rerouting and meltwater outbursts to the North Atlantic and Arctic Oceans. The close agreement with the timing and magnitude of increased freshwater flux from the Laurentide ice sheet to the North Atlantic and Arctic oceans, meltwater drainage from the Baltic ice lake in SW Sweden and the climatic development in NW Europe during the Lateglacial and early Holocene strongly supports that rapid, millennial-scale fluctuations of the southern margin of the Laurentide ice sheet in the Great Lakes region of North America may be an important triggering mechanism of these abrupt climatic changes, as previously suggested by Johnson and McClure (1976), Broecker *et al.* (1988), Keigwin *et al.* (1991), Licciardi *et al.* (1999), Clark *et al.* (2001), Fisher *et al.* (2002) and Teller *et al.* (2002). Some of these climatic oscillations may, however, also have been influenced by solar-related changes (e.g., Björck *et al.*, 2001; Bond *et al.*, 2001).

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