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# The 8k event: cause and consequences of a major Holocene abrupt climate change

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**Abstract**

A prominent, abrupt climate event about 8200 years ago brought generally cold and dry conditions to broad northern-hemisphere regions especially in wintertime, in response to a very large outburst flood that freshened the North Atlantic. Changes were much larger than typical climate variability before and after the event, with anomalies up to many degrees contributing to major displacement of vegetative patterns. This "8k" event provides a clear case of cause and effect in the paleoclimatic realm, and so offers an excellent opportunity for model testing. The response to North Atlantic freshening has the same general anomaly pattern as observed for older events associated with abrupt climate changes following North Atlantic freshening, and so greatly strengthens the case that those older events also reflect North Atlantic changes. The North Atlantic involvement in the 8k event helps in estimating limits on climate anomalies that might result in the future if warming-caused ice-melt and hydrologic-cycle intensification at high latitudes lead to major changes in North Atlantic circulation. Few model experiments have directly addressed the 8k event, and most studies of proxy records across this event lack the time resolution to fully characterize the anomalies, so much work remains to be done.


## 1. Introduction

Abrupt climate change is of great societal interest, with potentially large and far-reaching consequences (e.g., National Research Council, 2002; Alley et al., 2003). Abrupt climate change typically occurs when the climate system is forced across some threshold, causing evolution to a new, more-or-less persistent state at a rate determined by the system and faster than the cause.

Almost any part of the climate system might be involved. However, consideration of paleoclimatic records focuses attention first on regional land-surface moisture (e.g., Hodell et al., 1995; Laird et al., 1996; Gasse, 2000), and on those especially large and rapid, predominantly ice-age events characterized by a strong North Atlantic signature and hemispheric to global extent (e.g., Alley et al., 2003; Broecker, 2003). The remarkable ties between cold temperatures in the North Atlantic and drought in Asian and African monsoonal regions (e.g., Street-Perrott and Perrott, 1990; Overpeck et al., 1996; Wang et al., 2001) link concerns about drought and the North Atlantic in some cases.

The North Atlantic events, including the Younger Dryas cold interval and the Dansgaard-Oeschger and Heinrich-Bond events or oscillations (e.g., Broecker, 1997), have especially captured attention from the press and the public. In the case of the termination of the Younger Dryas cold event, for example, $\frac{1}{3}$ to $\frac{1}{2}$ of the entire 10,000-year deglacial warming in Greenland was achieved in order of 10 years (Cuffey et al., 1995; Severinghaus et al., 1998), with most of the accumulation-rate change apparently in a single year (Alley et al.,

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1993). The scaling of $\frac{1}{3}$ to $\frac{1}{2}$ the deglacial change in about a decade probably applies in many places (Alley, 2000). Any event for which rate of change is anomalous by two to three orders of magnitude merits attention. Older events were even larger, with a rapid shift of about 16 °C in Greenland in one case (Lang et al., 1999).

Debate surrounds the origin of the ice-age events associated with Heinrich-Bond and Dansgaard-Oeschger cycling, as reviewed by Broecker (2003). Some workers argue for tropical causes (e.g., Clement et al., 2001). A pacing role for solar variability has been suggested (e.g., Denton and Karlén, 1973; van Geel et al., 1999; Alley et al., 2001; Bond et al., 2001). It remains (e.g., Sarnthein et al., 1995; Alley and Clark, 1999; Stocker 2000) that the older events share characteristics with each other and with younger events including the 8k, including: (1) the climate anomalies seem to have been biggest around the north Atlantic; (2) many of the cold anomalies have followed outburst flooding (Younger Dryas, Preboreal, 8k; Clark et al., 2002; Teller et al., 2002; Teller and Leverington, 2004) or ice-sheet surging (Broecker, 1994a; Alley and MacAyeal, 1994; Broecker and Hemming, 2001; Hemming, 2004) that freshened the North Atlantic; and (3) important similarities exist between reconstructed anomaly patterns and patterns expected following a North Atlantic freshening (e.g., Stocker and Broecker, 1994; Fawcett et al., 1997; Manabe and Stouffer, 2000; Rind et al., 2001; Rahmstorf, 2002).

A potentially reassuring aspect of these remarkable past events is that they were most prominent during times colder and with more ice than recently. Owing to the large effect of ice cover, and especially of topographically high as well as reflective continental ice sheets (e.g., Shinn and Barron, 1989), the ice-age world can be viewed as existing in a fundamentally different mode of operation than more recently. Colder temperatures allow more ice, hence a stronger ice-albedo feedback, hence greater temperature changes. (In the warm limit of zero snow and ice, there can be no ice-albedo feedback.) Ice sheets displace jet streams, with downwind consequences.

The major problem with this "reassuring" view of the paleoclimatic record is provided by the abrupt event about 8200 years ago (all ages are estimated in calendar years before 1950 unless otherwise specified). This event is often referred to by its age (the "8k" or "8.2k" event). It has been known for some time (e.g., Denton and Karlén, 1973), and has been termed the "Finse event" by Dahl and Nesje (1994) based on data from southern Norway. We will refer to it as the "8k" event here, pending any official action to formalize a name such as "Finse". (As noted below, the 8k event is possibly correlative to the Miser cold oscillation in Alpine pollen diagrams (Wick and Tinner, 1997), and perhaps to the Mesoglacial of Beget (1983) and the "younger Younger Dryas" of Mason et al. (2001), and other terms also may apply.)

This 8k event involved smaller, shorter-lived, and less areally extensive climatic anomalies than those associated with older events such as the Younger Dryas cold interval. Causation, as discussed below, likely had much in common with the older events, and involved processes no longer operative. Nonetheless, this event punctuated conditions that were similar to or even warmer than recently, it involved processes that might possibly be partially mimicked by human forcing in the future, and it may provide useful estimates of limits on the magnitude of climate changes possible in the future.

The literature on this event is increasing very rapidly. For example, the ISI Web of Science listed 165 citations to the paper by Alley et al. (1997) on the 8k climate anomalies as of August, 2002, and the Barber et al. (1999) paper on causation of the event was cited by 61 indexed articles; by June of 2004, these had increased to 127 citations for Barber et al. and 272 for Alley et al. With the literature large and growing, this review can be no better than representative; a comprehensive treatment likely will require an international meeting followed by a coordinated project to collect, collate, and evaluate the data. Such recommendations are discussed below.

## 2. Anomaly hunting

All paleoclimatic records showing some climate-linked variable as a function of time exhibit "wiggles", or anomalies, from a mean state or trend. When bioturbation or other diffusive processes are sufficiently small and sampling is sufficiently intensive, an anomaly of any desired age can be found. Furthermore, because zero-error ages are very scarce even a few millennia back in time, one can often have a choice in correlating possible anomalies across many records. Paleoclimatologists are of course well-aware of these difficulties, but they really do complicate determination of anomaly maps for specific events (e.g., Fairbanks, 1990): are two potentially correlated anomalies observed in records from widely separate places really representative of two different events, of one synchronous event, or of one time-transgressive event?

Ice-core records are central in helping solve this difficulty. An event that is recorded near-simultaneously by major changes in ice- and gas-isotopic ratios (recording temperature at the core site), annual-layer thickness (accumulation rate at the core site), wind-blown materials especially if fingerprinted by source (e.g., sea-salt, dust, forest-fire smoke and other materials from beyond the ice sheet; Mayewski et al., 1994; Taylor et al., 1996; Biscaye et al., 1997) and biochemically important trace gases with widespread rather than localized sources, such as methane (Severinghaus et al., 1998) and nitrous oxide (Sowers et al., 2003), must have occurred near-synchronously across broad regions. Furthermore, the sign of the anomaly in other regions often is indicated by the ice-core data. For example, a methane drop recorded equally in Greenland and Antarctic ice cores likely indicates drying of tropical wetlands (Blunier et al., 1995; Brook et al., 2000).

Once supplied with this information, we can then proceed to correlate anomalies observed in sedimentary records from widespread regions. Because the ice cores cannot record processes in all regions, this sort of correlation is absolutely necessary, but mistaken correlations remain possible. For the 8k event, an additional difficulty arises because the sharp, decades-long anomaly of greatest interest here appears to be embedded in a weak millennial oscillation of the same sign in Greenland ice-core records. The broad oscillation is possibly tied to solar forcing (Bond et al., 2001) or to meltwater or other forcing, with the sharp anomaly likely in response to large and rapid meltwater forcing of the North Atlantic. Records from elsewhere showing an anomaly but lacking exceptional time resolution may be recording the sharp anomaly, the broad one, or both. For example, records of low lake levels in Africa at ≈8 ka appear to document dry conditions for longer times than the short-lived anomaly (see below). However, the record with perhaps the highest time resolution from the appropriate region and age is that of Thompson et al. (2002) from ice cores on Mt. Kilimanjaro; this record shows a spike in wind-blown fluoride from dry lake surfaces at the appropriate age for the main anomaly in Greenland, spanning two 50-year-long samples. In general, in this review we rely on high-time-resolution records wherever possible to avoid confusing short- and long-lived anomalies, but we will use African lake records because of the additional confidence provided by the nearby high-time-resolution ice-core record.

We note that we have not even attempted to list those studies that did not find strong evidence of the 8k event. Many sites lack sufficiently high time resolution, in sampling or in the recorder itself (e.g., owing to bioturbation), or lack sufficiently precise dating, to clearly demonstrate lack of the event. The bias inherent in reporting occurrence and failing to report absence should be clear. We will, however, note general regions where it is difficult or very difficult to find evidence of the event.

Again, the Greenland ice-core records show that conditions changed synchronously in Greenland (temperature, snow accumulation rate), and far from Greenland including in those regions controlling the concentration of methane in the atmosphere and those controlling delivery of dust probably from Asia, sea salt from the ocean, and forest-fire smoke. Thus, a widespread, synchronous climate event did occur. The pattern of the changes (generally cold, dry and windy together) is consistent with that of older, cold climate anomalies such as the Younger Dryas, which was long enough to reach a stable although anomalous condition, and which can be shown to have involved widespread and roughly synchronous changes based on dates from various climate records. That an event is recorded about 8200 year ago in widespread records and that it in many ways mimics the distribution and anomaly type of the Younger Dryas provides additional, strong evidence that the various anomalies we correlate here are in fact recording one event.

The Greenland ice-core records and many other records indicate that the climatic anomalies of the 8k event never reached plateaus of relatively steady conditions; rather, a decade or even less of cooling and drying gave way to a few decades to a century or two of return to pre-event conditions. The short duration of the event would not have allowed the climate system to come to equilibrium through growth of reflective land ice and cooling of ocean and land, so it is likely that anomalies would have been larger had the event been sustained longer.

## 3. The event: terrestrial and nearshore-marine climate anomalies

The following will be a tedious recitation of some of the relevant evidence from different locations, to be followed by a broad-brush summary of the especially convincing results. As noted above, this list is NOT exhaustive. A summary is given in Fig. 1.

### 3.1. Central Greenland ice cores

Some information on the event was summarized by Alley et al. (1997), and is reproduced in Fig. 2. Briefly, the event in Greenland involved: a notable cooling; drop in snow accumulation rate; rise in wind-blown dust, sea salt and forest-fire smoke; and drop in methane. A close-up of the event in some of the indicators is shown in Fig. 3. Through correlation to tree-ring records using cosmogenic isotopes in the GRIP core from the summit of Greenland, Muscheler et al. (2004) estimated that the most extreme values of $\delta^{18}O$ during the event were reached about 8150 year BP.

Probably the most important recent result is the use of ice-core gas-isotopic fractionation to demonstrate rapid, large temperature change in central Greenland at the time of the ice-isotopic and other ice-core anomalies (Leuenberger et al., 1999; Kobashi et al., 2003). Leuenberger et al. (1999) found a cooling of 5.4–11.7 °C, with a best estimate of 7.4 °C. Kobashi et al. (2003) (so far reported only as an abstract) added use of


Fig. 1. Cartoon summary of climate anomalies associated with the 8k event. Drawing by Jack Cook, courtesy of Woods Hole Oceanographic Institution.

argon-isotopic ratios to nitrogen-isotopic ratios in trapped gases to separate thermal fractionation from any changes in firn thickness, and found a cooling for the event of about 5 °C (and an instantaneous cooling possibly as large as 8 °C).

Both estimates are reassuringly close to the 6 °C estimated by Alley et al. (1997) from a slightly smoothed version of the ice-isotopic ratios of Grootes and Stuiver (1997) and an assumed calibration of this isotopic paleothermometer based on Cuffey et al. (1995). As shown in Figs. 2 and 3, the drop in ice-isotopic ratio was completed in about 5 years (three samples). Given the noise inherent in ice-isotopic ratios, the possibility of aliasing of the (largely but perhaps not totally diffused) annual cycle, and the roughly 2-year sampling interval, the drop might have been somewhat faster or slower than 5 years, but is rather clearly sub-decadal.

A similarly large, rapid-onset ice-isotopic signature is common to other deep ice cores in Greenland and has been known for some time (Johnsen et al., 2001).

Siggaard-Anderson et al. (2002) found an anomalously high peak in lithium concentration in the 8k event in the NorthGRIP ice core. The significance is not immediately obvious, but is intriguing; the lithium excess does not simply record an increase in dust, but a change in ratios of chemicals delivered to the site, hence a perturbation not yet fully understood.

In indicators especially of temperature, but also of snow accumulation rate and methane, no younger but preanthropogenic anomalies are similarly large. For some other indicators such as dust and sea salt, the event involves a notable anomaly but other, younger events are of similar magnitude.

### 3.2. Europe

Numerous paleoclimatic records from across Europe show an event probably correlative with the 8k. The European anomaly amplitudes are quite different in size in different records, and as will be discussed, this may at least in part have to do with the seasonal impact of the climate change versus that of the paleoclimatic recorder.

In the United Kingdom, a spectacular speleothem record from Ireland shows a prominent event peaking in a 37-year interval, with an 8 per mil shift in $\delta^{18}O$ of calcite and with other indications of dry and cold conditions. The record indicates greater seasonal differences during the event than at other times, hence likely greater wintertime than summertime anomalies associated with the event (Baldini et al., 2002a,b; also see Denton et al., in press).

Climate reconstruction based on subfossil snails in southeastern England indicates roughly 1 °C cooling for

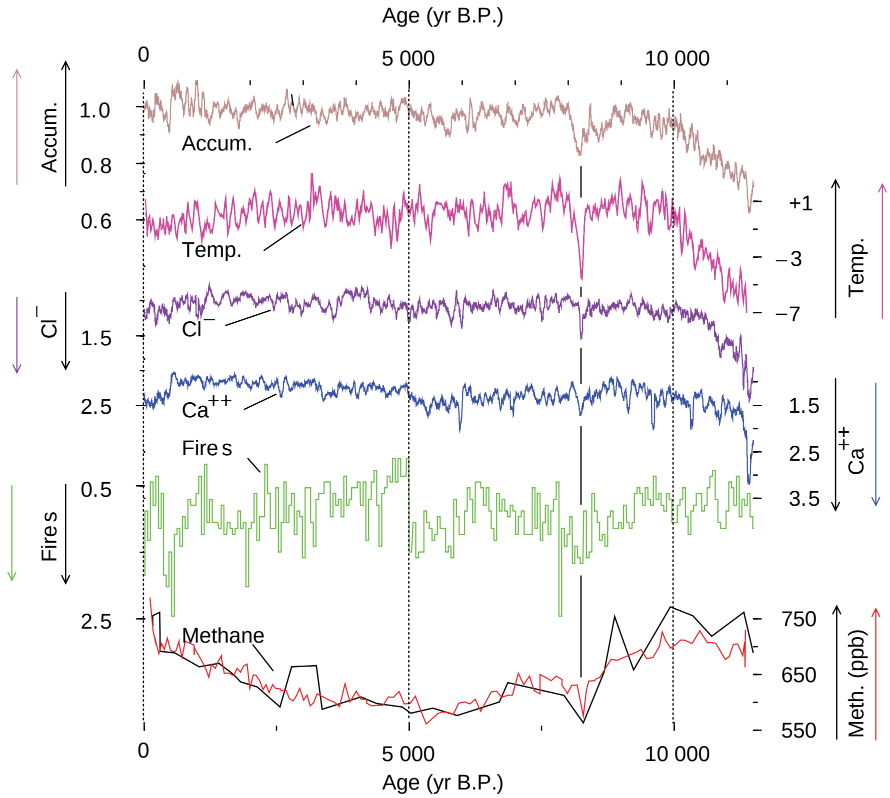


Fig. 2. Ice-core climate anomalies from the GISP2 core (as well as methane from the GRIP ice core), slightly modified from Alley et al. (1997). Approximately 50-yr running means of accumulation (Alley et al., 1993; Spinelli, 1996), chloride, and calcium (O'Brien et al., 1995), and a 50-year histogram of frequency of fallout from fires (Taylor et al., 1996), expressed as ratios to their average values during the approximately 2000 year just prior to the Little Ice Age. Temperature is calculated as deviation from average over same 2000-year interval, from oxygen-isotopic data of ice (Stuiver et al., 1995), assuming calibration of 0.33 per mil/°C (Cuffey et al., 1995). Methane concentrations are shown in parts per billion by volume (ppb) for the GRIP core (more densely sampled; Chappellaz et al., 1993; Blunier et al., 1995) and the GISP2 core (Brook et al., 1996), with the GRIP data adjusted slightly for interlaboratory differences and time-scale differences to match GISP2 values following Sowers et al. (1997). Notice that some curves increase downward (calcium, chloride, and frequency of occurrence of fallout of forest-fire smoke) and others decrease downward (snow accumulation rate, temperature, and methane concentrations from the GISP2 and GRIP cores). Most of the data are from the The Greenland Summit Ice Cores CD-ROM, 1997, National Snow and Ice Data Center, University of Colorado at Boulder, and the World Data Center-A for Paleoclimatology, National Geophysical Data Center, Boulder, Colorado.

the event, but without extremely high time resolution in the record (Rousseau et al., 1998). A suite of geochemical measurements on tufa deposits and ostracod shells from Wateringbury, southern England shows a short-lived cold, dry event probably correlative with the 8k event (Garnett et al., 2004).

Extensive records from Scandinavia provide strong evidence of the 8k, which was named the Finse event by Dahl and Nesje (1994) based on glacial advances in central and southern Norway. Seierstad et al. (2002) reported a glacial advance of Grovabreen in western Norway constrained to a few centuries centered roughly on the 8k event. Nesje et al. (2001) reported an advance of Flatebreen in western Norway between about 8.3 and 8.0 ka with roughly 200 m drop in equilibrium-line altitude, and with notably dry winters inferred between 8.3 and 8.2 ka (also see Nesje and Dahl, 2001). Pollen from a lake in northern Finland indicates a July cooling of roughly 1 °C (Seppä and Birks, 2001), with diatoms indicating roughly 0.75 °C cooling at that time based on a regional calibration (Korhola et al., 2000). In northern Sweden, Rosen et al. (2001) studied diatoms, chironomids and pollen in an Alpine lake, and found a sharp cooling in inferred July temperature of roughly 1 °C (0.5–1.7 °C). Denton and Karlén (1973) suggested a glacier advance in Swedish Lapland that is probably correlative. Other Scandinavian records seem to give a similar signal of a clear, probably short-lived (but with insufficient time resolution in some cases) event that was of order 1 °C in summertime, and with little indication of wintertime conditions. In summertime records, although the event is quite evident, it often is not especially large compared to other Holocene fluctuations.

Spurk et al. (2002) reported strong anomalies in the River Main, Germany tree-ring record. Reduced ring-width of oaks implies poor summertime growing conditions (Klitgaard-Kristensen et al., 1998). Spurk

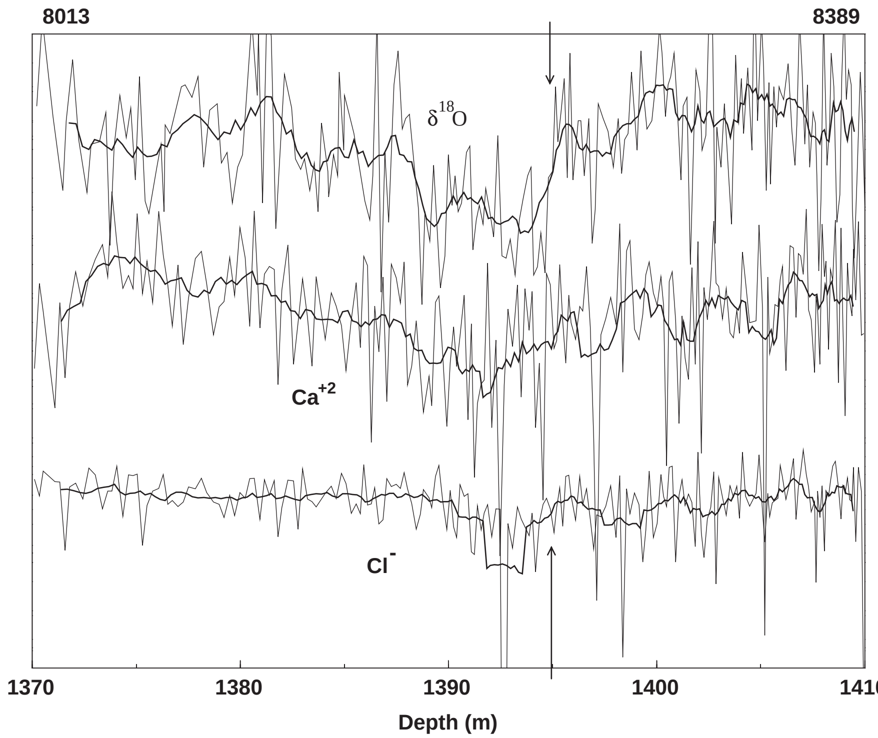


Fig. 3. Depth section spanning the anomaly, largely following Fig. 2. Data shown are $\delta^{18}O_{ice}$ (Stuiver et al., 1995; Grootes and Stuiver, 1997) with temperature increasing upward, $Ca^{+2}$ and $Cl^{-}$ (O'Brien et al., 1995) from the GISP2 core, with concentration increasing downward. Approximate ages are given at top. Samples are approximately biyearly, and a 10-sample (hence ≈20 year) running average is shown as well as the raw data. The onset of the event, as picked from the $\delta^{18}O_{ice}$ record, is shown by arrow. The event begins at identically the same place in the running averages of all these indicators, and in nearly the same place in the noisier raw data. Data for $\delta^{18}O_{ice}$ courtesy of Minze Stuiver and Pieter Grootes from http://depts.washington.edu/qil/.

et al. (2002) also found indications from pollen records of decreased oak and increased pine nearby during the 8k event, very low deposition rate of trees in the river valley, and reduced germination of oaks, consistent with cooler and drier climate there during the event.

Seppä and Poska (2004) used Estonian lake pollen to estimate a 1.5–2 °C cooling, stated to be mean-annual, at approximately the age of the event but possibly somewhat longer-lasting than reported for Greenland. Contrary to many other European records, this anomaly stands out as the dominant Holocene feature.

Based on pollen in annually laminated German and Swiss Alpine lake sediments, Tinner and Lotter (2001) reconstructed a major climatic change leading to a fundamental vegetation shift within a 0–20 year interval correlative with the 8k event (which may in turn be correlative with the previously identified Miser cold oscillation in pollen diagrams; Wick and Tinner, 1997). A summertime cooling of 1.5–2 °C leading to less drought stress may have been important in the vegetative changes. In Ammersee, Germany, von Grafenstein et al. (1998) found an ≈200-year anomaly in isotopic composition of ostracod-valve carbonate of about 1 per mil toward lighter values, versus 3 per mil for the Younger Dryas. Heiri et al. (2003) found a cool interval recorded by chironomids in a small lake in the northern Swiss Alps between about 8.2 and 7.7 ka, possibly correlative. From sediments in Lake Annecy, France, Magny et al. (2003) inferred a 2.5 °C cooling and 130 mm/year increase in precipitation-minus-evaporation as the event anomaly. Magny and Begeot (2004) provided a summary of lake-level and other 8k anomalies across Europe and beyond, indicating strong lake-level rise in central Alpine regions including France, Switzerland and northern Italy, but drying north of about 50°N and south of about 43°N including drying in Spain, Italy and northern Africa. Productivity was reduced at Lake Albano in central Italy during the event with cooling likely (Ariztegui et al., 2001), and with drying of this age at Laguna de Medina, Spain (Reed et al., 2001).

Compilation of pollen data from across Europe (Davis et al., 2003) shows an anomaly at about the correct time for Europe as a whole and for most subregions, of roughly 1 °C. There remains the obvious difficulty that stacking of records with dating uncertainties will "smear" such a short-lived event, reducing the apparent anomaly size while increasing its duration.

Overall, most European records with high time resolution seem to record the occurrence of the 8k event clearly. It is marked in general by cooling, with summertime values of order 1 °C, by change in hydrology including northern and southern drying and central increase in water availability, and by strong shifts in vegetation. The available indicators seem to be weighted heavily toward summer climate; the Irish speleothem of Baldini et al. (2002a,b) may be the exception, and shows a much more prominent anomaly than in most other records (see Denton et al., in press). For summertime indicators, most show a prominent anomaly but one that is not especially large compared to other Holocene anomalies.

### 3.3. The Americas

Some records in the Americas rather clearly show the event, with the evidence probably strongest in eastern North America and offshore Venezuela. The most intriguing signals are perhaps those from the US Great Plains.

Starting in northeastern North America, Yu and Eicher (1998) found an oxygen-isotopic shift in carbonate toward "colder" values of about 0.8 per mil, roughly 1/3 of the Younger Dryas anomaly (depending on how the anomalies are chosen), in a lake in southern Ontario, Canada. The lake record of Spooner et al. (2002) from central Nova Scotia, Canada shows a short-lived shift to more minerogenic conditions at the age of the event with ecologic change in the lake but no clear pollen signal. The authors noted that many other lake records from the region and beyond lack evidence of this clear feature, and suggested insufficient sampling resolution in previous studies as one contributing factor. Kurek et al. (2004) found a sharp drop in loss-on-ignition, hence a shift from organic to minerogenic sediments, in two lakes of the White Mountains, New Hampshire, USA, coincident with the event, similar to signals from Nova Scotia. However, consistent indications of temperature change were not obtained from chironimid faunas, perhaps in part because of no-analog conditions and high variability. Shuman et al. (2002) reported clear indications of a century-scale cool period in pollen diagrams along with high lake levels in Massachusetts, USA; furthermore, the authors suggested that sites in Quebec, Canada (increased spruce and fir), Maine, USA (increased pine at one site and birch at another) and Pennsylvania, USA (increased birch) also record the 8k event as shifts in pollen.

Further south, Kneller and Peteet (1999) found a short-lived spike in montane conifers indicating cool conditions at the approximate time of the 8k event in cores from Browns Pond in the central Appalachians of Virginia, USA. Complicating interpretations, however, this site does not show a classic Younger Dryas cooling.

To the west, prominent changes in conditions occurred at about the age of the 8k event near the prairie/forest ecotone in the northern Great Plains of the US. A major and persistent change occurred in Elk Lake, Minnesota, USA 8200 varve years before present (Dean and Schwalb, 2000), and Dean and Schwalb (2000) tentatively correlated this to a light isotopic anomaly of about 2 per mil and other anomalies (Fig. 4) in Deep Lake, Clearwater County, Minnesota, just north of Elk Lake (Hu et al., 1997, 1999; note that Hu et al. argued that the event in Deep Lake was older than the 8k event) and to a pulse in detrital clastic material in Pickerel Lake, South Dakota, USA, although with questions about the dating of the Deep Lake and Pickerel Lake records. Some records from Elk Lake, such as percent silica in sediments, show a peak at 8.2 ka rather than a switch between states (Dean et al., 2002). (Note that Dean et al. (2002) argued that the drainage of proglacial lakes was older than the event about 8200 years ago despite the correlation drawn by Barber et al. (1999), and that neither the Elk Lake nor the Greenland ice-core anomalies are linked to the lake drainage, but that both anomaly sets are linked somehow through the atmosphere.)

To the north, Fisher et al. (1995) found reduced melting and anomalously light oxygen-isotopic ratios of ice at about 8 ka (Fisher et al., 1995) in the Agassiz Ice Cap on Ellesmere Island, Canada. Consistent with this, Dyke et al. (1996) reported a scarcity of whale bones of the age of the 8k event along the coasts of Canadian Arctic islands, consistent with cold 8k conditions bringing heavy sea ice.

Data-mining efforts by Campbell et al. (2000; looking at basal dates of western interior Canada peatlands) and Viau et al. (2002; looking at clustering of dating in pollen diagrams across all of North America) suggested major changes at about the age of the 8k event. However, the techniques necessarily have low time resolution and difficulty characterizing just what was happening.

Mason et al. (2001) and Andreev and Peteet (1997) noted low water levels and a decline in spruce in the Fairbanks, Alaska, USA region possibly showing cooling at the age of the event. Mason et al. further suggested extensive erosion and deflation in the general region at that time. Denton and Karlén (1973) showed indication of a glacial advance in the St. Elias Mountains, Alaska, USA culminating at about the same age as the 8k event. Pollen results from TK-2 Lake at about 66°N, 105°W in Nunavut, Canada, indicate a tundra expansion into tree-covered regions for about 200 years at the age of the 8k event (Seppä et al., 2003). Menounos et al. (2004) collected data on timing of a small advance of glaciers in the southern Coast

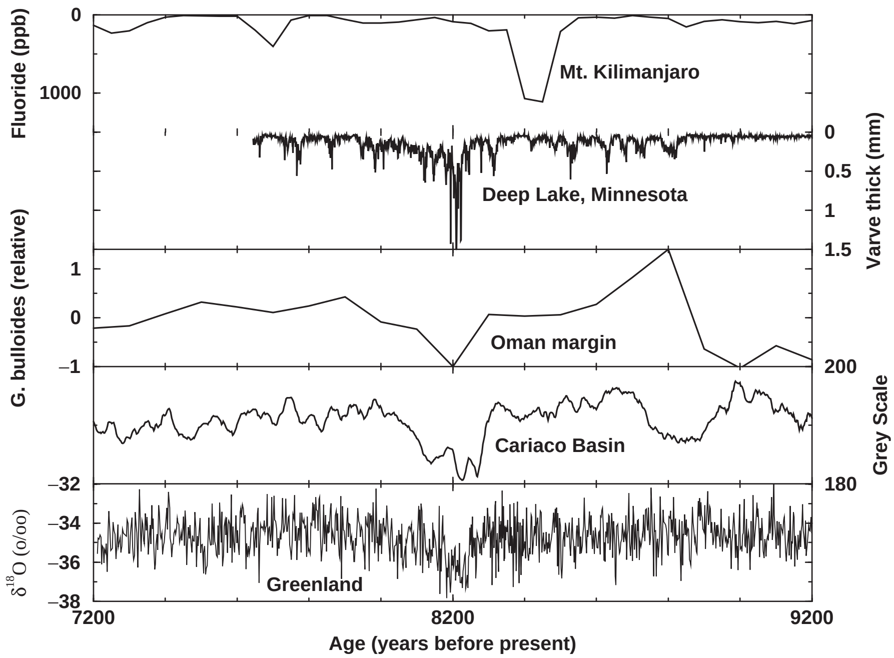


Fig. 4. Various anomalies probably correlative with the event, on published age scales. From the top: the 50-year average record of fluoride (ppb) from the KNIF2 core on Mt. Kilimanjaro, increasing downward (Thompson et al., 2002); the record of varve thickness from Deep Lake, Minnesota (Hu et al., 1997, 1999), increasing downward; the detrended and normalized record of abundance of *G. bulloides*, increasing upwards, an indicator of wind-driven upwelling in the Arabian Sea, with a decrease corresponding to a weakening of the monsoonal circulation (Gupta et al., 2003); gray scale of core pc56 from the Cariaco Basin, offshore Venezuela, with darker sediments upward (Hughen et al., 1996, 1998a,b); and, the high-resolution $\delta^{18}O_{ice}$ record from the GISP2 core (Stuiver et al., 1995), with warmer temperatures increasing upward. The slight offsets in event age, especially for the fluoride record relative to the others, illustrate the difficulties of "anomaly hunting", as discussed in the text. Data from the IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series, NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA, include Gupta, A.K., et al., 2003, #2003-041; Hu, F.S., et al., 2000, #2000-013; Hughen, K., 1999, #97-027; and Thompson, L.G., et al., 2002, #2002-071.

Mountains of British Columbia, Canada, and on intervals of minerogenic sedimentation in nearby lakes, and found indications of a cold anomaly at the same age as the 8k event.

Perhaps the most important records are those from offshore Venezuela (Hughen et al., 1996, 1998a,b; Haug et al., 2001). The gray-scale (Figs. 4 and 5) and titanium records from the Cariaco Basin indicate a very-fast-onset dry and windy event, probably the largest in the Holocene, consistent with a southward shift of the intertropical convergence zone (ITCZ). The duration is perhaps slightly longer than for most of the Greenland records, and the dating uncertainties combined are possibly slightly larger than one would like, but the Cariaco Basin records rather clearly show the 8k event strongly expressed in the northern tropics.

The involvement of the ITCZ in controlling the character of the Cariaco Basin records (Hughen et al., 1996, 1998a,b; Ágústsdóttir et al., 1999; Peterson et al., 2000; Haug et al., 2001), the very important role of the ITCZ in widespread climatic processes, and the good evidence for 8k anomalies in the Cariaco Basin hence the ITCZ provide strong evidence in addition to that from Greenland ice cores that the event must have occurred in widespread regions. This leads one to at least entertain the possibility of drawing correlations to the probably dry event based on pollen from Colombia at about 3°N (Berrio et al., 2002), and based on diatoms from Mexico at about 20°N (Metcalfe, 1995).

The new results of Lachniet et al. (2004) from Costa Rica strengthen this. Speleothem $\delta^{18}O$ data from Venado Cave, 11°N, 85°W, show a prominent shift to heavier values approximately coincident with the 8k event, consistent with a dry event there. In common with many anomalies, picking the onset and end of the event in this record is not easy; the event could be 300 years long in the record, but also could be argued to be much shorter.

Overall, it is rather clear that the 8k event affected the Cariaco Basin offshore Venezuela, Costa Rica, the northeastern seaboard of North America, and probably into the Arctic Islands of Canada and into the US Great Plains. Potentially correlative events can be found from other regions, including Alaska, British Columbia, and perhaps Mexico and Colombia, but even better records with higher time resolution would improve confidence in interpretations. The strong indications from the Cariaco Basin almost require that signals will be found elsewhere if appropriate records are discovered. Climate anomalies associated with the event include a southward-shifted

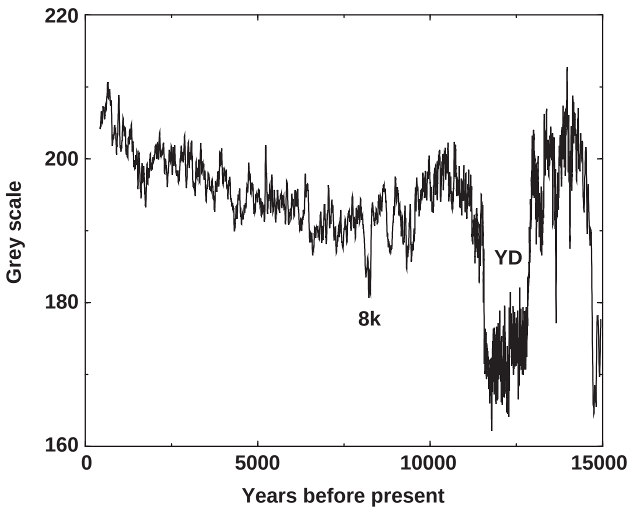


Fig. 5. Gray-scale record from the Cariaco Basin, offshore Venezuela. Lighter-colored sediments, plotting down, arise from some combination of enhanced wind-driven upwelling to produce light-colored foraminiferal shells, and decreased rain-driven runoff carrying dark-colored sediment from the adjacent continent (Hughen et al., 1996; 1998a,b). Younger Dryas (YD) and 8k events (8k) are indicated. Data source as in Fig. 4.

ITCZ, a cool Atlantic Coast of North America, and probably cool and dry conditions across widespread regions.

### 3.4. Africa

A dry event in Africa in the general age interval of 8.5–7.8 ka (Gasse and Van Campo, 1994; Gasse, 2000), as indicated by low lake levels and other indicators in lake sediments, is likely correlative to the 8k event (Gasse, 2000). The ages assigned, and the duration, are somewhat different for different lakes, and more-accurate dating and higher-time-resolution sampling are not easy to obtain. Those lakes showing a strong signal include Lake Victoria (Stager and Mayewski, 1997), where the event marked a shift to drying, Lake Abhe (11°N, 42°E; Gasse, 1977), Lake Ziway-Shala (7°N, 39°E; Gillespie et al., 1983), the Bahr-El-Ghazal (18°N, 17°E; Servant and Servant-Vildary, 1980), and Lake Bosumtwi (6.5°N, 1°E; Talbot et al., 1984). As shown by Gasse (2000), correlative low stands also likely occur in Lakes Turkana (3°N, 36°E), Tanganyika (30°N, 7°E) and Malawi (35°N, 12°E). Lamb and van der Kaars (1995) reported a correlative dry interval at Lake Tigalmamine in Morocco (33°N, 5°W). Gasse et al. (1990) also found drought at this age in Sebkha Mellala (32°N, 5°E).

Many of these records are suggestive of a dry interval longer than the duration of the 8k event in Greenland ice cores, but the time resolution of many of the records is low, and because of a possible role for groundwater in controlling lake levels in some cases, the lake lowstands need not match the atmospheric conditions exactly in time. As noted above, the high-time-resolution record of Thompson et al. (2002) from Mt. Kilimanjaro (37°E, 3°S) indicates a dry event (Fig. 4) tightly coupled to that in Greenland. In addition, an ocean-sediment core from 80 km offshore in the Somalia Basin in 1567 m water depth shows a short-lived near-surface cooling (≈2 °C) based on $\delta^{18}$O of *G. bulloides* at the age of the event within dating uncertainties, with a larger anomaly than for any younger events in this record (Jung et al., 2004). Based on the widespread occurrence of the dry event in monsoonal regions around the modern Sahara, and the high-time-resolution results of Thompson et al. (2002) and Jung et al. (2004), it appears that monsoonal regions of Africa did experience a prominent event synchronous with the North Atlantic cooling, although this does not exclude the possibility of a short-lived, large anomaly embedded in a longer-lived, smaller anomaly of the same sign. African drying with North Atlantic cooling is also consistent with behavior during older cold events in the North Atlantic, and with younger and smaller Holocene events (reviewed by Gasse, 2000).

Evidence of coupling between Africa and Europe is provided by Magri and Parra (2002), who found that a deforestation event in central Italy correlative with the 8k event was marked by an anomalous influx of African *Cedrus* pollen.

An intriguing report from South Africa and Lesotho (Smith et al., 2002), based on isotopic analyses and radiocarbon dating of teeth from ungulate grazers found in archaeological sites, shows appearance of C-3 plants perhaps indicating a climate shift to cool conditions at about the same age as the 8k event, but with low time resolution in the records. If confirmed with higher time resolution, this would expand the well-documented anomalies well southward.

### 3.5. Asia

A dry interval at Shumxi Co (34°N, 81°E) in Tibet probably correlative with the 8k event is indicated by pollen and diatom records (van Campo and Gasse, 1993). Liu et al. (2003) suggested that a peak in eolian silt in northwestern China (Lop Nur (playa), Xinjiang, northwestern China; 40.5°N, 90°E) records the 8k event, and Liu et al. (2002) correlated a cold interval in pollen diagrams from Qinghai Lake (Koko-nur) at 37°N, 100°E with the 8k event. Yu et al. found an episode of reduced extreme flooding in the Ning-Zhen Mountains, lower Yangtze River area of China, between about 8.2 and 7.6 ka, possibly indicating a dry event correlative with the 8k event, but the time resolution is necessarily not very high. Jung et al. (2004) suggested correlation between the 8k event and a low in $\delta^{18}$O of ice, possibly indicating cooling, from the Dunde

(China) ice core at about 38°N, 96°E, 5325 m elevation (Thompson, 2000).

In a high-time-resolution marine-sediment core from the Oman continental margin, Gupta et al. (2003) used percentage concentration of the foraminiferal shells of *G. bulloides*, which is linked to upwelling in response to the Asian summer monsoon, to infer a short-lived weakening of the summer monsoon correlative with the 8k event (Fig. 4) (also see Jung et al., 2004 from the Somalia Basin, discussed with Africa, above). Similarly, Staubwasser et al. (2002) used results from a sediment core in the Arabian Sea to infer strength of discharge of the Indus River, and found a shift to lower discharge at 8.4 ka, consistent with drying at the start of the 8k event, and consistent with earlier results of Wang et al. (1999) and of Sirocko et al. (1993).

Fleitmann et al. (2003) found an oxygen-isotopic shift in a speleothem from Oman, consistent with anomalously dry conditions hence a weakened Asian summer monsoon, at almost identically the time of the event in Greenland ice-core records, and with similar duration. However, other Holocene anomalies show similar amplitudes, and the shape of the 8k Oman-speleothem anomaly includes a more-gradual onset and faster end than in Greenland records.

It is important to note that Morrill et al. (2003), in a review of 36 previously published studies relevant to the Asian monsoon, and using statistical tests for significance, "find no conclusive evidence for a change in the Asian monsoon at ≈8.2 cal ka, as suggested by several previous studies. More high-resolution data may be needed to observe this short-lived event."

Overall, it appears that there is little evidence for a signal of the 8k event in the east-Asian part of the monsoon; the signal in the western part in available records is muted, not much stronger than other Holocene anomalies in individual records, but rather clearly present. We would echo Morrill et al. (2003) in the need for additional records.

### 3.6. Rest of the world

An intriguing result reported by Gagan et al. (2002) shows an ≈3°C short-lived cooling nearly synchronous with the 8k event from Sr/Ca and $\delta^{18}$O records of coral from Alor, Indonesia, but so far appears to be available only in an abstract.

Overall, we have looked at numerous high-time-resolution, high-quality paleoclimatic records from many places. High confidence that an event is absent from a region is almost impossible, especially considering limitations placed by the finite size of samples, dating uncertainties, bioturbation, etc. But, thus far, we find no especially strong published evidence for the event beyond the northern-hemisphere regions discussed in previous sections.

## 4. The event: North Atlantic Ocean

### 4.1. North Atlantic Ocean—surface water

In continental-margin sediments off Nova Scotia, Keigwin and Jones (1995) found a minimum in oxygen-isotopic composition along with a maximum in abundance of shells of the cold-adapted foraminifer *N. pachyderma*, together likely indicating cooler conditions with freshening related to input of meteoric waters, but without an ice-rafting spike, at about 7.1 $^{14}$C ka possibly correlative with 8k calendar. Interestingly, while these sediments seem to show the 8k event, they do not have a signal of a meltwater spike at the Younger Dryas.

Note also that Andrews et al. (1999) questioned whether the 7.1 $^{14}$C ka event on the Scotian Shelf was correlative with the 8k event. Andrews et al. (1999) did, however, find several other indicators of an 8k outburst flood from Hudson Strait, including a peak in the "cold, fresh" benthic indicator foraminifer *Elphidium excavatum* forma *clavata* on the Labrador Shelf (Cartwright Saddle, 55°N, 56°W), a single-point light peak in $\delta^{18}$O of planktic foraminiferal shells, and a peak in carbonate. Overall, however, the anomalies do not appear especially large or prominent. Andrews et al. (1999) correlated these anomalies to a prominent red bed probably derived from the Keewatin Dubawnt Formation by the flood from drainage of Lake Agassiz (see below) (Kerwin, 1996).

Bond et al. (1997) presented several data sets from two cores across the North Atlantic at about 65°N, 30°W and 54°N, 17°W. Both showed clear evidence for a long string of cooling and warming events, with one of this sequence coincident with the 8k event. In some of the indicators, notably percentage of the cold-indicating foraminifera *N. pachyderma* (sin), the event shows an abrupt onset and relatively short (although poorly constrained) duration quite similar to the ice-isotopic record of Greenland temperature. As this is probably the most direct indicator of temperature studied by Bond et al. (1997), the short duration of the anomaly in this indicator in comparison to longer-lived anomalies in other indicators (such as ice-rafted grains and hematite-stained grains, with somewhat more-complicated interpretation linked to cooling) is consistent with a short-lived, abrupt anomaly embedded in a longer-lived, smaller anomaly. Numerous other records have been published (429 indexed citations to the Bond et al., 1997 paper in the ISI database in July, 2004), many showing the same coolings highlighted by Bond et al. (1997) including that correlative with the 8k event.

Strong, short-lived 8k anomalies are observed offshore Norway. Klitgaard-Kristensen et al. (2001), in core samples from the Norwegian Channel at about 61°N, 4°E, found short-lived, large shifts in foraminiferal populations indicating cooling during the 8k event. The amplitudes are much smaller than for the Younger Dryas and older events, but much larger than for younger Holocene events. This confirms and extends earlier work by Klitgaard-Kristensen et al. (1998) showing a short-lived, abrupt-onset cold event from the same region.

Nearby, Risebrobakken et al. (2003) provided high-resolution records from the Voring Plateau, eastern Norwegian Sea, 67°N, 8°E in 1048 m water depth. Prominent anomalies, generally larger than any other in the Holocene and approaching the Younger Dryas in magnitude in some cases, are present at about 8k, with extreme values having persisted for only about 70 year. The $\delta^{18}$O of planktic foraminifera *N. pachyderma* (sin) indicates event cooling of about 3 °C, occurring with increased abundance of this type. Peaks in total forams, in *N. pachyderma* (dex) as well as (sin), and in coarse fraction lithics also mark the event, along with slightly isotopically lighter benthic foraminifera. Comparison of the isotopic composition of the *N. pachyderma* (dex) and (sin) together with knowledge of their ecological behavior suggests that summers may have been shorter during the event than before or after, but that event summers remained warm. The isotopic change in the benthic foraminifera associated with the event may represent increased influence of brine waters from sea-ice formation in freshened surface waters. The increased coarse fraction during the event is consistent with greater ice rafting of debris.

Andrews and Giraudeau (2003) found evidence of a cooling off northern Iceland at about 66°N, 21°W at about the age of the 8k event. Similarly, nearby at about 67°N 18°W, Knudsen et al. (2004) found evidence in foraminiferal and diatom populations for an $\approx$3 °C cooling, although the age model adopted gives it a 600-year duration from about 8.6–8.0 ka. Castaneda et al. (2004) inferred minor cooling of bottom waters in water depths of 100–200 m off the northwest Iceland shelf based on a small isotopic anomaly.

Off Portugal (38°N, 10°W), Duplessy et al. (1992) found a strong freshening and slight cooling of surface waters, at approximately the same age as the event.

A high-resolution Arctic Ocean core was analyzed by Andrews and Dunhill (2004), from 70°N, 142°W on the Beaufort Sea slope west of the MacKenzie River delta. A cooling at about 7.8 $^{14}$C ka before present may be correlative with the 8k event.

It remains disturbing that stronger signals are not evident near the meltwater source from Hudson Bay (see below). The degree to which this reflects lack of a signal to record perhaps because of localization of meltwater influences, effects of bioturbation or inadequate sampling, offsetting effects of meltwater and of temperature changes on $\delta^{18}$O of planktonic foraminifera, or other factors probably differs for different records, and remains to be fully explored. Still, sufficient surface-water evidence exists to document occurrence of the event.

### 4.2. Atlantic Ocean-deep water

Keigwin and Boyle (2000) noted that "there are presently no paleochemical data that suggest the production of NADW was actually curtailed 8,200 year ago" (p. 1343). They went on to note, however, that this lack for Bermuda Rise "most likely" is linked to low sedimentation rate, and thus that the recorder may be unable to have preserved a clear indication of such a short-lived event.

Since then, however, Oppo et al. (2003) generated a $\delta^{13}$C record of benthic foraminiferal calcite from Ocean Drilling Project site 980 (55°N, 15°W, 2179 m water depth) on the Feni Drift, showing a shift to lighter values consistent with reduced North Atlantic deep-water formation at the time of the 8k event. Notice, however, that the anomaly is a little smaller than some younger anomalies.

Hall et al. (2004) found from a core in the Bjorn Drift, northern Iceland Basin (61°N, 24°W, 1627 m depth) monitoring the deep Iceland–Scotland Overflow Water of the meriodional overturning circulation, that benthic $\delta^{13}$C foraminiferal data indicate an $\approx$400 year negative excursion (weakened North Atlantic overturning). This indication is partially supported by data suggesting a brief decrease in the strength of the overflow water inferred from sediment grain size. However, the anomalies are not very large compared to typical Holocene "variability" seen in the records.

The 8k event was too short-lived to be detectable in Th-Pa techniques such as that of McManus et al. (2004).

As noted above, the Cariaco Basin shows a clear signal of the 8k event. Relatively cool and fresh conditions existed at that time in the North Atlantic from the Labrador Sea across to Portugal. Some records, especially from offshore Norway and in some of the Bond et al. (1997) indicators, are consistent with a short-lived cold event similar to that recorded in well-resolved terrestrial records, although this short-lived event likely is embedded in a longer-lasting climate anomaly of the same sign. Some evidence exists for a slight or short-lived interruption in the North Atlantic overturning circulation, but strong conclusions cannot be drawn, in part because of shortcomings in recorders.

## 5. Cause of the event: outburst flood

During deglaciation, pre-existing topography plus isostatic depression (e.g., Clarke et al., 2004) caused the southern margin of the Laurentide ice sheet to retreat into a lowland, and to develop ice-dammed lakes around the ice margin (Teller et al., 2002; Teller and Leverington, 2004). As summarized by Clarke et al. (2004), proglacial Lake Agassiz was formed around 11.7 $^{14}$C ka during retreat of the southern margin of the Laurentide ice sheet, and the lake persisted until about 7.6 $^{14}$C ka (8.3–8.4 ka; see Dyke et al., 2003) when final drainage occurred. Two major lakes, Agassiz and Ojibway, are recognized just before final drainage, but we will follow Clarke et al. (2004) in assuming confluence and calling the combined body Lake Agassiz.

The existence of the lake, and its subsequent drainage, are established with very high confidence. Drainage of ice-contact lakes is expected to be catastrophic (Clarke et al. (2004) and references therein); heat from turbulence in water flowing in ice-walled channels opens the channels and increases flow in a strong positive feedback loop. Hence, an outburst flood is almost unavoidable.

Geomorphic evidence of that outburst flood is not abundant, possibly because much of the flood path was below sea level and has been covered subsequently by marine sediments (Clarke et al., 2004). Nonetheless, as reviewed by Clarke et al. (2004), channels eroded to bedrock, a megaripple sand-wave bed, and an iceberg scour field in Hudson Bay are interpreted as evidence of the outburst flood, as is the prominent red bed in Hudson Strait, the sharp transition from lacustrine to marine deposition in the Hudson and James Bay lowlands (Barber et al., 1999), and the evidence for contemporaneous freshening off the mouth of Hudson Strait at Cartwright Saddle on the Labrador Shelf (Andrews et al., 1999) and at Orphan Knoll (50°N, 46°W; Bilodeau et al., 1998; Barber et al., 1999).

Some uncertainty is attached to the exact ice and lake configurations at drainage, the drainage path, etc. The extensive work of Clarke et al. (2004) tests sensitivity of calculated discharges, from an ice- and water-flow model, to the numerous uncertainties. Robust conclusions are a water volume release of order $10^{14}\,m^3$, and a flow duration of $\approx 0.5$ year at $\approx 5$ Sv. The possibility exists of moderately complex hydrographs and multiple floods. Sea-level impacts are not large; allowing for failure to achieve complete drainage, lake regions initially below sea level, etc., changes of $<0.2$ m are indicated (Clarke et al., 2004).

Put very simply, a really big flood happened (rather clearly, the largest of those from Laurentide-dammed lakes during the most recent deglaciation, by more than an order of magnitude; Teller et al., 2002; Teller and Leverington, 2004). Directly dating the age of the flood from lake sediments is complicated by the large hard-water effect for Hudson Bay immediately after drainage (Barber et al., 1999), and uncertainties of more than a century to many centuries seem likely, but an age of about 8.47 ka is indicated within those uncertainties.

## 6. Modeling of the event

### 6.1. General North Atlantic modeling

Rather little effort has been devoted specifically to the 8k event, but an immense amount of effort has addressed the influence of freshwater additions on the North Atlantic. A full review is far beyond the scope of this paper. The interested reader might see, to start, Stocker and Broecker (1994), Fawcett et al. (1997), Isarin and Renssen (1999), Manabe and Stouffer (1997, 2000), Marotzke (2000), Renssen et al. (2001a,b), Rind et al. (2001), Ganopolski and Rahmstorf (2001), Clark et al. (2002), Rahmstorf (2002), Seager et al. (2002), Vellinga and Wood (2002), Schmittner et al. (2003), Stocker and Johnsen (2003), and Wood et al. (2003), among many others. The field especially draws on work of Broecker (Broecker, 1994a,b, 1997, 1998; Broecker et al., 1988, 1990; Broecker and Denton, 1989, 1990).

The models applied range from simple box models to fully coupled three-dimensional Earth-system models. Many different forcings of different background climate states have been tested, with study of climate anomalies and tracer anomalies.

The general results of this great range of models, and associated data, include:

(1) Today, northward surface-water flow in the Atlantic feeds high-latitude wintertime sinking and a southward deep-water flow, so that in high-latitude regions including the Labrador Sea and the Greenland, Iceland and Norwegian Seas (the GIN or Nordic Seas), the wintertime surface waters sink before they freeze (this is the great "conveyor" circulation as described by Broecker, and forms an important link in what is variously called, loosely interchangeably, the thermohaline circulation (THC), the meridional overturning circulation (MOC), and some other terms).

(2) If the surface waters in the North Atlantic are made sufficiently fresh, then sinking is reduced or shifted southward, and North Atlantic surface waters freeze before they sink in the winter.

(3) This switch often but not always is modeled as abrupt, especially for the switch from fresh to salty, hence from "freezing" ("conveyor-off") to "sinking" ("conveyor-on"). In some models, under some boundary conditions, both the off and on modes are stable with a bifurcation between; under other conditions or in other models, one mode may be stable with the other unstable. Ice-age-type boundary conditions tend to favor the freezing/off mode, with modern boundary

conditions favoring the sinking/on mode. In some cases, three modes may occur, one with the North Atlantic off, a second with some sinking south of Iceland, and a third with much sinking including north of Iceland.

(4) The difference between "off" and "on" produces atmospheric climate anomalies. These anomalies are especially large over the North Atlantic, where they usually are many degrees to some tens of degrees. Changes generally are larger in wintertime, with cooling bringing expanded sea ice and a positive feedback. Cooling caused by switching off of north Atlantic sinking usually is simulated to extend across much or all of the northern hemisphere, although of order 1 °C far from the North Atlantic. Switching off often shifts North Atlantic winds to a more zonal (west to east) rather than meridional (southwest to northeast) trend. Other changes commonly modeled from freshwater addition to the North Atlantic include a general trend for northern-hemisphere drying, including a weakening of monsoonal rainfall in Africa and Asia, perhaps drying in the US Great Plains, and at least sometimes a southward shift of the ITCZ especially in the vicinity of South America. Probably the only universal result is the cooling over the north Atlantic, but the other signals occur frequently enough to be noticed.

(5) Southern hemisphere responses to North Atlantic freshening in models are less consistent than are northern signals. The most robust result is probably a slight warming especially around the south Atlantic, linked both to the conveyor shutdown leaving warm surface waters in the south rather than moving them across the equator to the north, and to an increase in southern deepwater formation to balance the loss in the north.

(6) Northern climate anomalies typically develop quite rapidly with atmospheric transmission of signals, but southern anomalies often are delayed, by decades or even longer, with oceanic transmission of signals.

### 6.2. *Modeling of the 8k event*

Here, we highlight a few efforts of which we are aware (Ágústsdóttir, 1998; Renssen et al., 2001a, 2002; Bauer et al., 2004) targeting the 8k event, and we also note the freshwater-addition experiments configured for recent times by Vellinga and Wood (2002) and Wood et al. (2003) as especially relevant. Overall, these models indicate close agreement between reconstructed climate anomalies and those expected from the known freshwater forcing.

We addressed the 8k event using the GENESIS Climate model (version 1.02) developed by Thompson and Pollard (1995), which is a modified version of the NCAR Community Climate Model CCM1. The model consists of an atmospheric general circulation model (AGCM), that is coupled to a land-surface-transfer model for the effects of vegetation (here set to a global intermediate type, so we did not study feedbacks of changes in vegetative cover), and to multilayer models of soil, snow and dynamic sea ice, and a mixed-layer slab ocean. The GENESIS model uses a spectral transform technique in the horizontal for mass, heat and momentum fluxes. A sigma-coordinate system is used in the vertical with 12 levels. A $2^\circ \times 2^\circ$ surface resolution with an atmospheric horizontal resolution of R15 (4.5° latitude × 7.5° longitude) was used.

The mixed-layer slab ocean is 50 m thick, with poleward ocean heat transport included as a zonally symmetric function of latitude based on present-day observations and held fixed in runs. A region of enhanced heat convergence during winter in the Norwegian Sea was added to prevent unrealistic buildup of sea ice. This flux warms the mixed layer whenever it cools below 1.04 °C in a region between 66–78°N and 10°W–56°E, and increases linearly to 500 $W/m^2$ if the ocean cools to its freezing point (−1.96 °C). This simulates the buffering effect of the deepening mixed layer in winter, and advection of heat by warm ocean currents. In the model, the Norwegian Sea adjustment is balanced at each time step by an additive global adjustment to keep the global integral of ocean heat convergence at zero, with the heat released in the Norwegian Sea taken uniformly from all oceanic grid boxes between 55°N and 55°S.

Our simulations of "shutdown" of North Atlantic overturning circulation involved setting the climate state (sea level and ice-sheet coverage, atmospheric $CO_2$ and $CH_4$ concentrations, orbital parameters) for a time of interest, running the model with the Norwegian Sea adjustment "off" and "on", and calculating differences between the two. This clearly is not the same as a shutdown experiment with an Earth-system model including deep-ocean processes. Our experiments have several limitations. In particular, the assumption to taking heat out of all open-ocean grid boxes in the low and mid latitudes to supply the Norwegian Sea adjustment largely controls the far-field effects of a North Atlantic "shutdown" in the model, and one can learn nothing about "see-saw behavior" between north and south, or similar issues. However, the GENESIS experiments are in some sense rather "clean"—we know what was done to the model, and we can analyze the response rather easily.

We conducted paired experiments (Ágústsdóttir, 1998) for the Younger Dryas (Fawcett et al., 1997; Ágústsdóttir et al., 1999) and for 8k, and also paired experiments using version 2 of the model for Younger Dryas and modern. Full results are given especially in Ágústsdóttir (1998).

In general, our results in the northern hemisphere are consistent with those of the range of

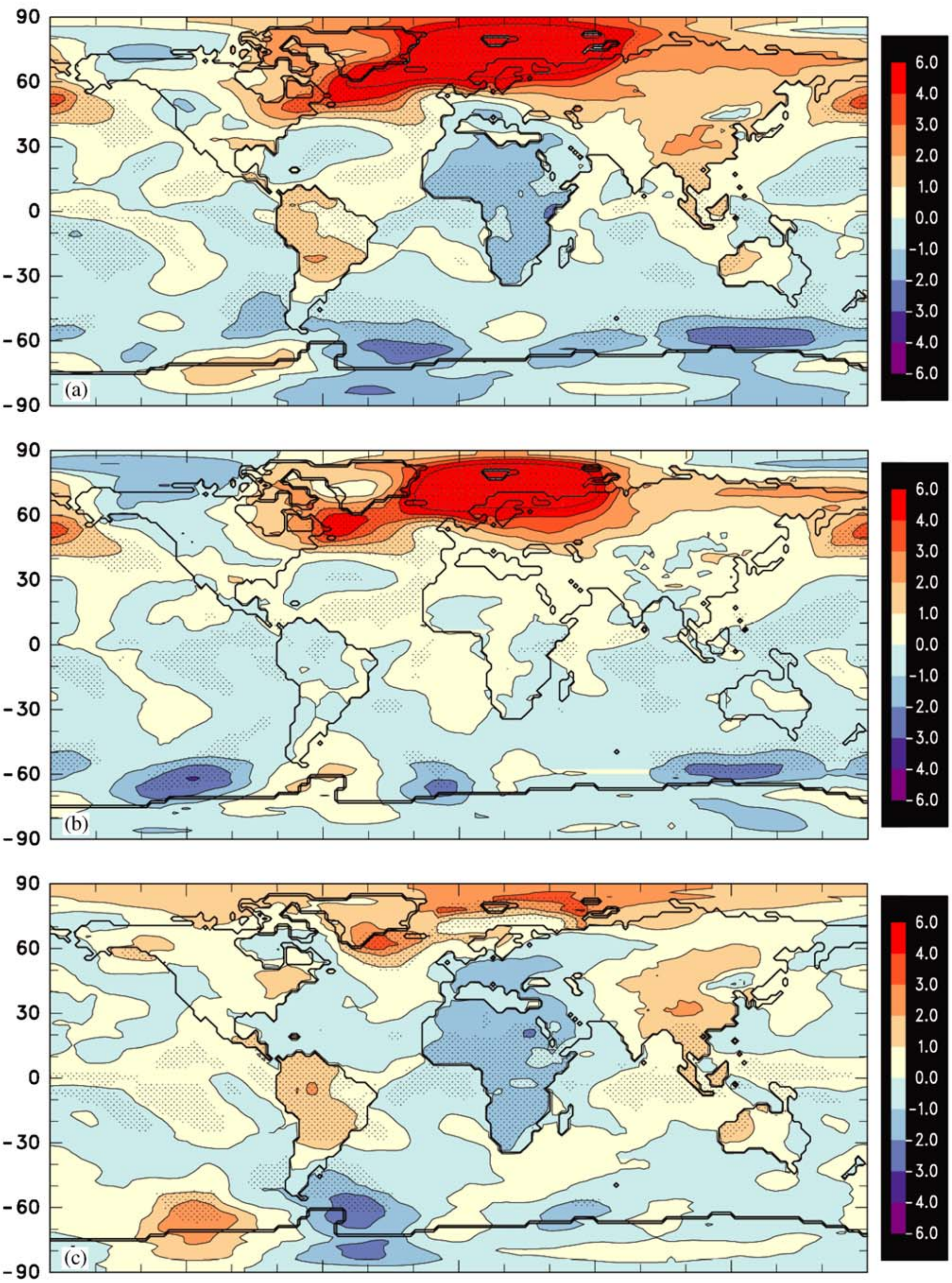


Fig. 6. Model anomaly map from Ágústsdóttir (1998), for GENESIS climate-model simulation of mean-annual temperature changes for the 8k event. Three simulations were conducted: WARM (a control simulation for the times before and after the event); HOT (an alternate control simulation assuming more-vigorous thermohaline circulation in the mid-Holocene than in preindustrial late-Holocene time), and COLD (simulation of the event, assuming it reached steady state). Anomaly maps are shown for (a) WARM–COLD, (b) HOT–COLD, and (c) HOT–WARM. Color bar shows temperature change. Contour interval 1 °C. In all cases, red indicates warming when ocean heat convergence is turned on in the North Atlantic. Regions in which the change is statistically significant with more than 90% confidence are shown stippled.

North-Atlantic-cooling/meltwater-hosing experiments as discussed above: compared to the ''on'' state, the North-Atlantic-''off'' state is generally cooler around the North Atlantic and through much of the northern hemisphere (Fig. 6), somewhat drier with a southward shift of the intertropical convergence zone especially in the Atlantic and South/Central American regions, with a stronger but more zonal storm track (Fig. 7) and expanded sea ice in the North Atlantic region (Fig. 8) contributing greatly to stronger cooling in wintertime than in summertime.

We furthermore find that the Younger Dryas time was more sensitive to the imposed change in the Norwegian Sea than the 8k or modern times, although

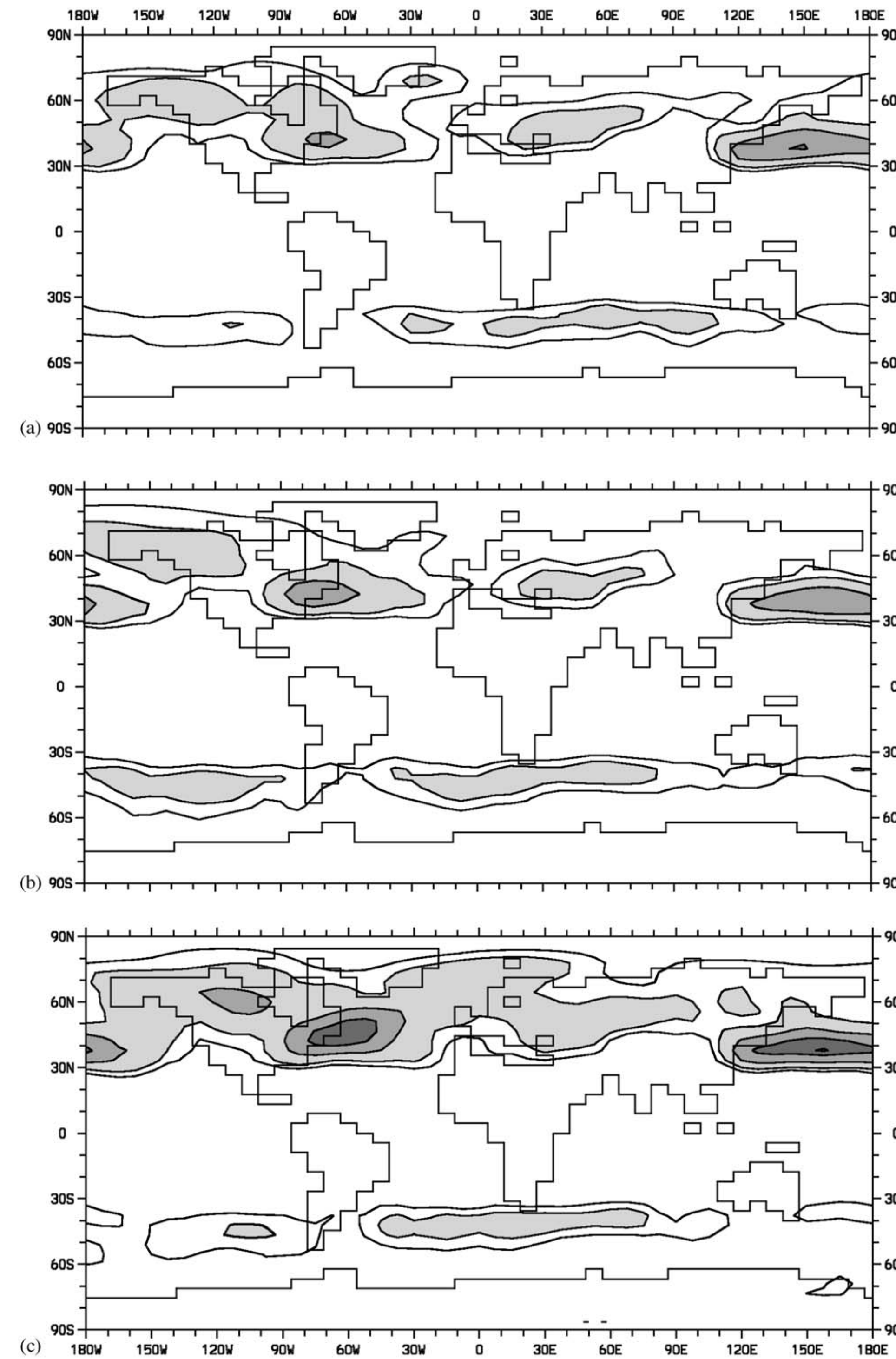


Fig. 7. As in Fig. 6, but showing calculated storm tracks (not anomalies) for the (a) HOT (upper), (b) WARM (middle), and (c) COLD (lower) simulations. The greater strength of the COLD storm track is evident, with tendency for slightly greater zonality especially in comparison to HOT.

simulated Younger Dryas anomalies were still somewhat smaller than reconstructed from paleoclimatic archives in many places and especially in central Greenland (Fawcett et al., 1997). The modern experiments, with $CO_2$ set to 340 ppmv, showed less sensitivity to the Norwegian Sea changes than did the Younger Dryas simulations. The 8k experiments with 260 ppmv $CO_2$ showed similar sensitivity to the modern ones, presumably because changes in orbital configuration and $CO_2$ have somewhat offsetting effects, although the use of a different model version makes exact comparison difficult. In light of the possibility of stronger North

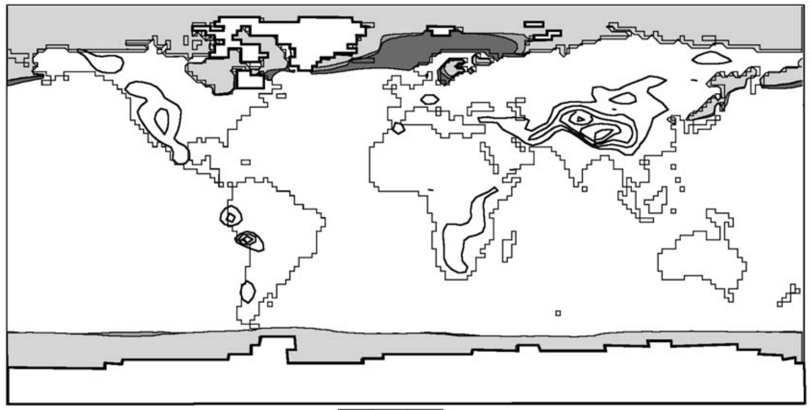


Fig. 8. As in Fig. 6, but showing sea-ice edge (25 cm thickness) for the HOT (lightest), WARM, and COLD (darkest) simulations. Heavy lines show the extent of land ice for simulations of Figs. 6–8; thin lines show model topography with 1000-m contour interval.

Atlantic circulation in the mid-Holocene than today (Alley et al., 1999a), we conducted an additional 8k experiment, setting the maximum heat-flux convergence in the Norwegian Sea to 800 W/m$^2$ rather than 500 W/m$^2$. (The choice of 800 W/m$^2$ was somewhat arbitrary.) Shutting off this "Hot" situation to obtain "Cold" conditions produced a better (and quite good) match to the observed paleoclimatic anomalies than did the switch either from "Hot" to "Warm" (500 W/m$^2$) or "Warm" to "Cold" (Ágústsdóttir, 1998).

Renssen et al. (2001a,b, 2002) addressed the 8k event using ECBilt-CLIO, an EMIC or Earth-System Model of Intermediate Complexity. This allowed multiple long integrations with coupled deep-ocean circulation. The atmospheric model used a spectral T21, three-level, quasi-geostrophic treatment, with 3° horizontal resolution in the ocean and 20 vertical layers. Experiments were conducted with boundary conditions appropriate to the 8k event. Freshwater perturbation experiments were run with $4.67 \times 10^{14}$ m$^3$, on the high end of estimates for the volume of water released (Clarke et al., 2004). Water release was modeled into the Labrador Sea at constant rates of either 1.5 Sv for 10 years, 0.75 Sv for 20 years, 0.3 Sv for 50 years, or 0.03 Sv for 500 years (versus the improved Clarke et al. estimates of 5 Sv for 0.5 years). Five experiments were run for each of the three faster rates, starting from slightly different times in the control run.

The 500-year experiment had little effect on the oceanic or atmospheric climate of the model. The 50-year pulses produced gradual weakening in the North Atlantic overturning circulation, followed by recovery over 120–200 years. In the 10- and 20-year pulse experiments, some behaved similarly to the 50-year experiments, but others became "stuck" in a highly variable weak-overturning mode for centuries to more than one millennium.

The perturbed state with reduced thermohaline circulation produced cooler northern conditions, by more than 10 °C in the Nordic seas in winter, associated with increased sea-ice cover. Temperature anomalies were largely restricted to the northern hemisphere, and were generally largest near the Nordic seas and in winter. Increased wind strength in many regions, and drying in North Africa, the Middle East and southern Europe were also observed associated with the thermohaline reduction in the North Atlantic. Overall, comparison with proxy data showed "general agreement...we conclude that the simulated climatic changes associated with the freshwater pulses are realistic" (Renssen et al., 2002, pp. 10–13).

Thus, both the Ágústsdóttir and Renssen experiments directed at modeling the 8k response to North Atlantic freshening found model anomalies in good agreement with those reconstructed from paleoclimatic archives.

Bauer et al. (2004) addressed the 8k event using the CLIMBER2 EMIC, by discharging into the model North Atlantic over 2 years a volume of water similar to or slightly larger than that released in the 8k flood. They also found anomalies with similarities to those observed, although the model cooling in the North Atlantic of 3–4 °C is perhaps less than what happened. The duration of the modeled event is also somewhat shorter than observed. The authors show increased duration in some cases if noise is added to the model, but the time-evolution of the anomaly is then different from observed.

We focus on one additional set of experiments from the great range of North Atlantic freshening work (Vellinga and Wood, 2002; Wood et al., 2003). These experiments were not targeted at the 8k event, but used modern boundary conditions and preindustrial $CO_2$. The experiments are notable because they were run with a state-of-the-art, fully coupled atmosphere-ocean general circulation model without flux corrections, and because the perturbation imposed bears greater resemblance to the 8k forcing than for many such experiments. The model was the HadCM3 Hadley Center (UK) model, with sea-ice and land-surface schemes, run with atmospheric resolution of $2.5° \times 3.75°$ and 19 vertical levels, and oceanic resolution of $1.25° \times 1.25°$ and 20 vertical levels. The top 800 m of the North Atlantic (between 80°W and 20°E, and 50°N and 90°N) were made instantaneously fresher through addition of about $6 \times 10^{14}\,m^3$ of freshwater, with conservation maintained by redistributing the salt rejected from this region across the rest of the global ocean. The perturbation was not subsequently reinforced, but allowed to dissipate. Following the perturbation, the model was integrated for 150 years, although the climate anomalies were largely gone after about 120 years.

The model response has much in common with the reconstructed 8k anomalies. Modeled northern cooling is largest in the first decade after the perturbation, reaching $>12\,°C$ in the Nordic seas, 3–5 °C over the United Kingdom, and almost 2°C averaged across the northern hemisphere. These anomalies quickly became smaller, dropping to 8 °C in the Nordic seas, 2–3 °C over the United Kingdom and roughly 1 °C hemispherically averaged by the third decade (Fig. 9) (versus a Little Ice Age cooling in central England of $\approx 0.5\,°C$). Cooling extended across the northern hemisphere, preserving the temperature difference between eastern North America and western Europe as argued by Seager et al. (2002). Northern cooling was strongest in wintertime in most places and especially around the North Atlantic, the Labrador Sea (with cooling of up to 16 °C) and the Sea of Okhotsk, caused by major expansion of sea ice. Notably, the anomalous sea-ice cover melted in summertime. Slight warming developed in the southern hemisphere, especially in the South Atlantic, probably because of loss of northward heat transport in the overturning circulation. The southern anomalies were small, about 1°C in the South Atlantic and less elsewhere. The southern anomalies also were delayed, with the maximum hemispheric anomaly about 40–50 years after the perturbation, and of only a few tenths of a degree.

Strong perturbations developed in the hydrological cycle. Some of the largest changes were tropical, with anomalies of almost 1 m/year, and resulted from a southward shift in the Intertropical Convergence Zone (ITCZ) producing general drying in regions left by the ITCZ rains and wetting in regions to which those rains moved. Overall, reduced northern precipitation was modeled in response to the reduced temperature. Drying was simulated in the Indian monsoon and in sub-Saharan Africa, contributing to a global decrease in net primary productivity on land of about 5%.

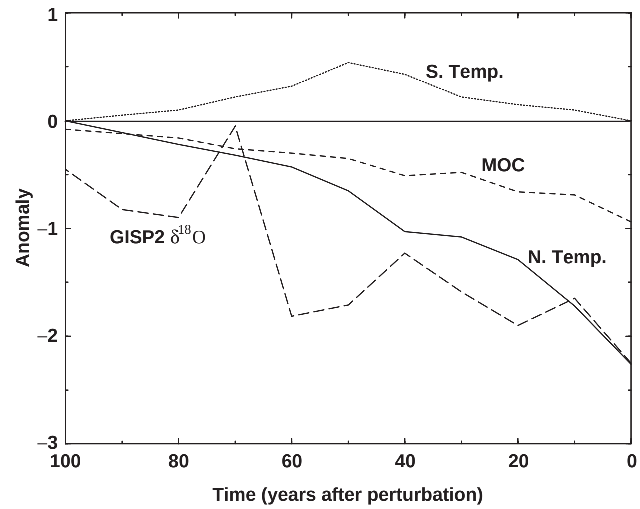


Fig. 9. Comparison of model simulations of Vellinga and Wood (2002) and Wood et al. (2003) for the northern- and southern-hemisphere temperature anomalies (°C), and for the strength of the meridional overturning circulation (MOC) (given as fractional reduction from control run, so that −1 would be a complete shutdown and 0 is the same strength as the control run), compared to the isotopic anomaly (per mil) of the GISP2 $\delta^{18}O_{ice}$. GISP2 data from the ten years before the event were used as a baseline, the first five years after the drop were averaged to obtain the zero-time value, and then ten-year intervals were averaged and plotted as shown. Note that time runs the way paleoclimatologists usually assume, so that the experiments started on the right-hand side and ended on the left-hand side.

The authors also noted that there are many similarities between the simulated anomaly patterns and those obtained by other groups using freshwater-forcing in the North Atlantic, but with different models and different forcing. Similar responses were obtained in experiments by Manabe and Stouffer (1988); Schiller et al. (1997), and Ganopolski et al. (2001), among others. Again, the strong similarity should be evident between anomalies modeled in response to North Atlantic freshening and anomalies reconstructed from paleoclimatic archives for immediately after North Atlantic freshening.

## 7. Significance of the 8k event

The 8k event is a highly important event for many reasons. Additional careful, targeted study thus seems warranted.

### *7.1. Model testing*

First, the 8k event may be the clearest example of a well-defined, well-characterized, large, preanthropogenic perturbation of the Earth system for which abundant, high-time-resolution records of climate response are available. Thus, the 8k event provides an outstanding opportunity for testing Earth-system models. The forcing is obviously very different from ongoing anthropogenic effects, and there also are some differences between the 8k world and today (notably, the anthropogenic effects on the atmosphere, land cover, etc., and the differences in orbital parameters and their effects on such factors as Saharan vegetation), but the 8k event involved perturbations from a warm climate recognizably similar to today, with similar ocean currents and nearly identical continental configurations. Were even better reconstructions of the 8k event anomalies available to join the robust estimate of the forcing from Clarke et al. (2004), the event really should serve as a test for all the major Earth-system models.

### 7.2. Possible future impacts of North Atlantic shutdown

The 8k event also provides some guidance in assessing possible effects of any future shutdown in the North Atlantic overturning circulation. Many simple models (e.g., Stocker and Schmittner, 1997) include the possibility of a thermohaline shutdown in the future, although more-complex models tend to restrict perturbations to slowdown without shutdown (IPCC, 2001). The future ocean-circulation changes are modeled to arise from high-latitude surface-ocean freshening in response to increased precipitation-minus-evaporation and increased ice melt at high latitudes during warming. There can be no doubt that the 8k forcing was very different from anything expected in the near future, and it is not our intention to choose between the simple and complex models as to whether complete shutdown is likely. We simply note that, if a shutdown were to occur, conditions before and after the 8k event were more like those of today than were environmental conditions associated with any of the older events likely caused by North Atlantic shutdowns. Thus, the 8k anomalies probably are more relevant to our possible future than are anomalies associated with older events.

As noted above, sea-ice feedbacks and perhaps snow-cover feedbacks were probably very important in amplifying and propagating the 8k anomalies around the hemisphere (Denton et al., in press). If a North Atlantic shutdown were to occur well into the future, warmth from $CO_2$ likely would partially or even completely moderate the effects by reducing snow and ice coverage, and the effects would be correspondingly muted. Thus, with a slow onset and only partial shutdown in the future projected by complex models, one might look at the 8k as an upper limit on the size of likely anomalies. Indeed, Wood et al. (2003) ran a global-warming scenario (IS92a) until the year 2049 and then used the same freshwater forcing as in the experiments discussed above to induce a complete shutdown of the overturning circulation in the North Atlantic. (Note that the model did not produce a complete shutdown in the year 2049 from global warming alone; additional freshwater forcing was introduced specifically to cause the shutdown.) The model did not simulate a new ice age, nor globally come close to reversing the effects of greenhouse-gas warming. However, temperatures in the North Atlantic were reduced below preanthropogenic values, by about 2 °C in central England and about 10 °C in the center of the anomaly in the Nordic Seas.

On the other hand, modeling suggests that the 8k orbital configuration, with much summertime sunshine at high northern latitudes tending to warm the surface ocean and prevent sea-ice growth during early winter, may produce a baseline climate less sensitive to the effects of North Atlantic shutdown than does the modern orbital configuration (e.g., Kutzbach et al., 1991; Mitchell et al., 1988 and the Vettoretti et al., 1998 simulations with realistic Laurentide ice sheet specified; also see Alley et al., 1999a). Supporting this, as noted above, our simulations with the GENESIS general circulation model indicate that the 8k world was less sensitive to North Atlantic changes than the Younger Dryas world (with no strong distinction from the modern world but without exactly comparable experiments for assessment). When one further notes that the 8k event never reached an equilibrium cold plateau, and thus that it is highly likely that larger anomalies would have resulted had the forcing persisted to maintain a North Atlantic shutdown, one is left with the possibility that the 8k event actually places a lower limit on the anomaly size and extent that might result were a North Atlantic shutdown to happen soon.

It may not be unreasonable to treat the 8k event as providing a lower limit on possible anomaly size in the (unlikely) event of a near-future, total North Atlantic shutdown, and an upper limit on anomaly size if a partial or total shutdown occurs well in the future. Much work is required to quantify how far in the future this switch-over occurs. (For a somewhat different view of the significance of the 8k event, see Weaver and Hillaire-Marcel, 2004.)

### 7.3. Understanding past abrupt changes with large high-latitude signals

The 8k event is also important as an analog for the older ice-age events. Because something that actually happened must be possible, the 8k strengthens the case that those earlier events had similar causes to the 8k. We briefly review the relevant evidence next; a little of this material partially repeats material above, but we group it here for clarity.

Studies of the last glacial cycle have shown variability with one- to few- millennial spacing, associated with sharp onsets of cold intervals and especially sharp onsets of warm intervals (reviewed by Alley et al., 1999b). The slower of these "millennial" oscillations were called Bond cycles by Broecker (1994a), with cooling culminating in Heinrich events (Heinrich, 1988; Hemming, 2004) marked by rapid sedimentation of ice-rafted debris under very cold and fresh surface-water conditions across the open North Atlantic, and large-amplitude, widespread climate anomalies probably covering the whole world. The faster of these millennial oscillations can be called Dansgaard-Oeschger oscillations, or the original usage of the warm intervals as Dansgaard-Oeschger events can be adopted (Broecker and Denton, 1989). (We have heard the term "Bond cycle" used for the small, ≈1500-year oscillations in the Holocene and earlier; that usage is distinct from the Heinrich-event-linked Bond cycles introduced by Broecker (1994a).)

The anomaly patterns are similar for the Dansgaard-Oeschger and Heinrich-Bond oscillations, but with larger, longer-lasting, more-extensive anomalies associated with the Heinrich-Bond oscillations. The anomaly patterns include generally cold, dry and windy conditions across much of the northern hemisphere but warming in the far south (Bender et al., 1994; Blunier and Brook, 2001).

Causes of these events have been widely debated. The leading hypothesis has been that of Broecker (1998), that North Atlantic freshening led to transient shutdown of the North Atlantic overturning circulation, and northern cooling with a "see-saw" behavior warming the far south. Data analyses (Sarnthein et al., 1994, 1995) and modeling (Ganopolski and Rahmstorf, 2001) indicate that the North Atlantic may have operated in one of three preferred modes or bands with jumps between: a modern mode with sinking in the GIN Seas as well as in the Labrador Sea, a glacial mode with the high-latitude sinking in the GIN seas largely or completely stopped but sinking persisting perhaps south and west of Iceland, and a Heinrich or off mode with even that sinking reduced or eliminated (Alley and Clark, 1999; Stocker, 2000).

In this view, reduction of North Atlantic sinking interrupts some of the cross-equatorial surface-ocean flow in the Atlantic. This current represents a net transfer of heat from south to north, because surface waters warmed south of the equator release their heat to the atmosphere off Norway in the wintertime. Leaving some of this water in the south causes some southern warming. The more northern shutdown occurs, the more the south warms. In addition, because tidal and wind-driven mixing processes continue to transfer buoyancy into the deep ocean regardless of the North Atlantic state, a reduction of deepwater formation in the north is likely to lead to a (possibly delayed) increase in southern deepwater formation as deep waters become less dense than some southern surface waters. Because deepwater formation in the modern ocean involves cooling, an increase in southern deepwater formation will cause southern warming. However, because southern deepwater formation involves few-degree surface-water cooling whereas northern deepwater formation involves much larger cooling, southern atmospheric changes are muted compared to those in the north. The time scale for such oceanic readjustments is likely longer than for atmospheric changes, and probably requires decades or longer (e.g., Stocker and Johnsen, 2003).

Not all models of the ocean–atmosphere system simulate the same response to North Atlantic forcing, but it is clear that many models are capable of simulating most or even all of the scenario sketched above (e.g., Stocker, 2000; Stocker and Johnsen, 2003; Ganopolski and Rahmstorf, 2001, 2002; Clark et al., 2002; Mogensen et al., 2002; Rahmstorf, 2002; Stocker and Marchal, 2000).

Thus, the 8k event is the best-documented case of a North Atlantic freshening. A very big flood happened very quickly. Immediately thereafter, changes occurred in the surface ocean indicating cooling and freshening expected from a freshwater addition, and limited data indicate a temporary reduction or elimination of deepwater formation in the North Atlantic. Widespread climate anomalies developed across much of the northern hemisphere, which closely match those expected based on climate-model simulations in response to North Atlantic freshening. The evidence of cause-and-effect is very good; with high confidence, the 8k event was caused by outburst-flood freshening of the North Atlantic.

Looking further back in time, the less-studied Preboreal Oscillation (van der Plicht et al., 2004) appears to have been a similar event following a smaller outburst flood (Björck et al., 1996; Teller et al., 2002; Nesje et al., 2004), and the Younger Dryas event is a prominent cold period with similar anomalies that also followed an outburst flood (Broecker et al., 1988). The close association of outburst floods and similar anomalies at 8k, Preboreal and Younger Dryas argues for similarity of behavior. True, one might argue that: the 8k event was caused by an outburst flood; outburst floods occurred just before similar older anomalies but were ineffectual; while, coincidentally, some other more important cause in far-distant regions happened to actually trigger the events. However, such an argument does not seem parsimonious.

The Younger Dryas cold event in the north began more-or-less at the same time as the end of the Antarctic Cold Reversal (Blunier et al., 1997; Blunier and Brook, 2001). The relative timing of northern and southern changes is such that one cannot unequivocally demonstrate a cause-and-effect, see-saw relation (e.g., Steig and

Alley, 2003; Wunsch, 2003), but the data are fully consistent with a northern flood causing northern cooling, leading to southern warming (Stocker and Johnsen, 2003). Based on the results of many models including Vellinga and Wood (2002) and Stocker and Johnsen (2003), the North Atlantic perturbations associated with the 8k event did not persist long enough to generate much southern response. In turn, this likely arises because the orbital and carbon-dioxide changes between glacial and interglacial times changed the preferred state of the North Atlantic circulation. Although mode changes were possible during glacial and interglacial times, the ocean likely tended to remain in a state with GIN Seas sinking shut down during the glacial, and a state with the high-latitude sinking active during the interglacial (e.g., Rahmstorf, 2002).

Even further back, the Heinrich events are times of greatly enhanced delivery of coarse clastic debris to open-ocean North Atlantic sites, very cold and probably fresh surface-water conditions in the North Atlantic, and especially strong and widespread climate anomalies having roughly the same pattern as for the Younger Dryas, 8k, and modeled response to North Atlantic freshening, and with evidence of greatly restricted North Atlantic overturning circulation (Broecker, 1994a; Sarnthein et al., 1994, 1995; Hemming, 2004; McManus et al., 2004). Iceberg-melt freshening of the North Atlantic forcing it into its most reduced overturning state is fully consistent with the observations. No plausible model exists for far-field effects to have triggered the climate changes and the ice-sheet surges simultaneously, because the slow response times of the ice sheets are so different from the faster response times of surface ocean and atmosphere. Fast ice-sheet changes are possible from warming, but the data do not show warming before the Heinrich events.

One cannot prove, of course, that all of the large, rapid changes in climate recorded over the last ice-age cycle in the Greenland ice cores resulted from changes in North Atlantic overturning circulation forced from the North Atlantic. It remains possible that some far-field forcing has "loaded" on the preferred mode of change in the North Atlantic (Weaver et al., 2003), or even that some of the North Atlantic anomalies are the far-field response to other climate change without involvement of the overturning circulation in the North Atlantic (Clement et al., 2001). It remains, however, that we now have very high confidence that North Atlantic freshening at 8k produced the observed climate anomalies then, that previous freshening events were followed by similar climate anomalies, that there has been no demonstration of the whole suite of observed anomalies arising from any far-field cause not involving the overturning circulation in the North Atlantic, and that it is easier to affect the North Atlantic overturning circulation from proximal causes than from distal ones. We argue that one can almost entirely rule out mechanisms for explaining the North Atlantic events that do not involve the overturning circulation there (McManus et al., 2004), and that North Atlantic causes are the most direct explanation of the events that happened.

## 8. Summary

During deglaciation of North America, large ice-marginal lakes formed. Geologic evidence and physical insights show that the largest of these lakes drained catastrophically within about two-three centuries of 8400 years ago (Clarke et al., 2004). Immediately thereafter, a remarkable climate-anomaly pattern developed across much of the Northern Hemisphere.

In general, conditions were cooler, drier, and perhaps windier during the event. Strong signals from central Greenland ice cores indicate decreased temperature and snow accumulation rate, increased wind-blown transport of sea-salt and of continental dust likely from Asia, and decreased methane. Anomalies were large within a few years, and faded over decades to a century or two. A difficulty is that the large, abrupt cold anomaly is embedded within a longer, smoother, smaller anomaly of the same sign. Hence, comparisons with low-time-resolution records from elsewhere are complicated by the difficulty of separating the slow and fast anomalies.

A review of climate anomalies from many areas shows little evidence for the event in the southern hemisphere, or in broad regions of the Pacific and East Asia. However, the event probably is recorded in the rest of the northern hemisphere. The event seems to have involved strong cooling and hydrologic changes in Europe, especially in wintertime, drying around the Sahara and in the western Asian monsoon, a southward shift of the ITCZ from the Cariaco Basin offshore Venezuela, cooling in northeastern North America, and probably drying in the US Great Plains and cooling across much of North America. The North Atlantic was cooled and freshened during the event, and deepwater formation there probably was suppressed.

General modeling of the atmospheric and oceanic response to prescribed North Atlantic freshening, and in particular model response to prescribed freshening for boundary conditions appropriate for the 8k event, simulates anomaly patterns that are quite similar to those reconstructed from sedimentary archives. The freshening is modeled to have produced great slowdown or shutdown of the North Atlantic overturning circulation, although in many models the event was too short-lived to have especially large southern-hemisphere effects transmitted through the ocean. Effects include northern cooling especially in winter and drying including the African and Asian monsoons, expanded sea ice, switch in storm tracks to a more zonal configuration in the North Atlantic, and southward shift of the ITCZ in places. (There is perhaps a suggestion that the models are less sensitive than the real world (Alley, 2003). For example, Renssen et al. (2002), Ágústsdóttir (1998), and Vellinga and Wood (2002) all used forcings that likely are larger than what happened to produce results that match data rather well, and Bauer et al. (2004) may have more closely matched the forcing but seem to have underestimated the response.)

Given the close correspondence in time of the large freshwater forcing and the large climate anomalies, and the close match between the climate anomalies and those expected from model runs forced with freshwater addition to the North Atlantic, there can be little doubt that the 8k event was caused by the large flood. In turn, the numerous similarities between climate and ocean-circulation anomalies of the 8k event and of older climate events that immediately followed North Atlantic freshening argue for a common origin for at least many, if not all, of the ice-age events (those often referred to as Dansgaard-Oeschger and Heinrich-Bond, or simply millennial events). The older forcings were smaller than for the 8k event, yet produced larger and longer-lasting climate anomalies with correlative see-saw events in the southern hemisphere. The southern response is explainable based on the longer persistence, and the longer persistence from smaller forcing is explainable from the effects of tens-of-millennial orbital changes on the background state of the North Atlantic Ocean.

Future freshening of the North Atlantic is projected by almost all global-warming models (IPCC, 2001; Wood et al., 2003). Some simple models produce shutdowns of overturning circulation and coolings around the North Atlantic, although complex models generally slow the overturning circulation without shutdown or net cooling. Because of shortcomings in understanding of North Atlantic processes, one cannot exclude the possibility of a shutdown in the future, although most modelers seem to consider this to be a low-probability event. Were a complete shutdown to occur rather soon, the 8k climate reconstructions might provide a useful guide to possible anomalies. Because the 8k climate anomalies never reached a plateau, and because the forcing was not maintained whereas future greenhouse forcing presumably will be maintained for centuries or longer, the 8k anomalies might serve as lower limits on the size of possible changes should a complete shutdown happen soon. However, with continued warming, the sea-ice amplifier will become less potent, and possible anomalies will shrink.

Despite the strong evidence for the 8k climate anomalies, it remains frustratingly difficult to draw anomaly maps. The event appears to have been especially large for only a few decades. Really characterizing the event would seem to require (near-)annually resolved and sampled records with minimal diffusion, bioturbation, or other smoothing processes. In addition, because the event appears to have had largest anomalies in wintertime but most paleoclimatic recorders may be more sensitive to summertime conditions, one wishes for more attention to winter changes. (The combined effect of diffusion or bioturbation, undersampling, low time resolution, and summertime-biased paleoclimatic indicators is to cause reconstructed anomalies to underestimate what happened.)

The 8k offers perhaps the best chance we have for a well-characterized, rigorous test of Earth-system-model response to a large perturbation, to assess the sensitivity and accuracy of the models. For such a test to be worthwhile, better evidence on paleoclimatic changes would be useful. In turn, this requires more and higher-resolution work. International coordination and cooperation likely would make such a large task much easier.

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