Holocene climatic instability: A prominent, widespread event 8200 yr ago

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ABSTRACT

The most prominent Holocene climatic event in Greenland ice-core proxies, with approximately half the amplitude of the Younger Dryas, occurred ~8000 to 8400 yr ago. This Holocene event affected regions well beyond the North Atlantic basin, as shown by synchronous increases in windblown chemical indicators together with a significant decrease in methane. Widespread proxy records from the tropics to the north polar regions show a short-lived cool, dry, or windy event of similar age. The spatial pattern of terrestrial and marine changes is similar to that of the Younger Dryas event, suggesting a role for North Atlantic thermohaline circulation. Possible forcings identified thus far for this Holocene event are small, consistent with recent model results indicating high sensitivity and strong linkages in the climatic system.

INTRODUCTION

Proxy records show that climatic variability was especially large during the most recent ice age (e.g., Johnsen et al., 1992), causing the warm Holocene in which we live to appear stable by comparison. However, Holocene sediments often record more variability than typically observed instrumentally during this century (e.g., Little Ice Age records; Grove, 1988).

Holocene climatic shifts larger than those of the Little Ice Age are recorded in many proxies, but typical dating uncertainties of a few centuries have limited our ability to correlate events that often lasted only a few centuries. Approximately correlative changes in proxy records from disparate regions may represent (1) a single, widespread, synchronous event; (2) a time-transgressive event; or (3) a number of local and uncorrelated events; with significantly different implications for our understanding of climatic change.

Ice cores help solve this difficulty because they record climatic conditions locally (e.g., temperature, snow accumulation), regionally (e.g., windblown sea salt and continental dust), and more broadly (via trapped-bubble records of concentrations of trace gases involved in global biogeochemical cycles). Local and regional indicators are delivered to the surface of the ice sheet synchronously by precipitation events. Gases are trapped in ice below the surface, but uncertainty in the age of trapped gas relative to the surrounding ice is less than 75 yr throughout the Holocene for central Greenland ice cores (Sowers et al., 1992). Because the troposphere is well mixed on decadal time scales, trapped-gas records provide a means of comparing local and regional climatic changes to various global biogeochemical cycles with minimal dating uncertainties.

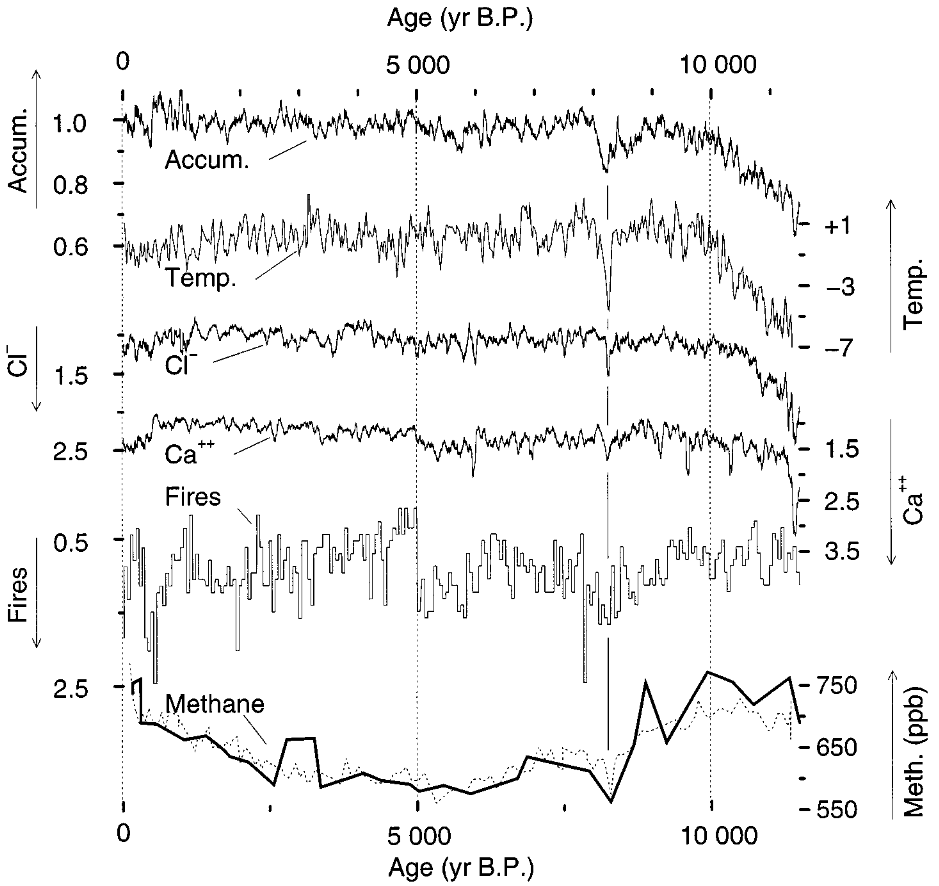

Figure 1. Climatic data from the GISP2 core, central Greenland. Approximately 50 yr running means of accumulation (Alley et al., 1993; Spinelli, 1996), chloride and calcium (O'Brien et al., 1995), and a 50 yr histogram of frequency of fallout from fires (Taylor et al., 1996), expressed as ratios to their average values during the approximately 2000 yr just prior to the Little Ice Age. Temperature (°C) is calculated as deviation from average over same 2000 yr, from $\delta^{18}O_{ice}$ (Stuiver et al., 1995), assuming calibration of 0.33‰/°C (Cuffey et al., 1995). Methane concentrations are shown in parts per billion by volume (ppb) for the GRIP core (thin, dashed line; Chappellaz et al., 1993; Blunier et al., 1995) and the GISP2 core (thick, solid line; 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). Note that some scales increase upward and others downward, as indicated, so that all curves vary together at major events.

ICE-CORE DATA

Holocene climatic records from the Greenland Ice Sheet Project II (GISP2) ice core (Fig. 1) were dated by counting visible layers, with typically 1% errors (Alley et al., 1993; Spinelli, 1996). Snow accumulation was calculated by correcting annual layer thicknesses for ice flow following Alley et al. (1993); accumulation is controlled primarily by local temperature and local-to-regional atmospheric circulation patterns. Oxygen isotopic ratios of ice, $\delta^{18}O_{ice}$, (Grootes et al., 1993; Stuiver et al., 1995) primarily reflect the site temperature (Cuffey et al., 1995), although atmospheric circulation and other factors play a secondary role (e.g., Steig et al., 1994; Fawcett et al., 1997); our calibration to temperature (0.33‰/°C) is from Cuffey et al. (1995).

Chemical concentrations in the ice (O'Brien et al., 1995) reflect atmospheric loading, but fluctuations of concentrations in the ice may be magnified because colder, dustier times typically have reduced snow accumulation and thus reduced dilution of the chemicals. We have corrected for this effect, reducing the magnitudes of fluctuations in the chemical time series, following Alley et al. (1995). Because snow-accumulation variations are typically smaller than chemical-concentration variations, this correction is quite small. Chloride, primarily from sea salt, represents vigor of atmospheric circulation or distance from oceanic source areas; calcium, primarily from continental dust, is a signal of dust availability, dryness, and transport vigor from continental regions beyond Greenland and probably beyond the North Atlantic basin (e.g., Mayewski et al., 1994; Biscaye et al., 1996).

The record of forest fires is derived from the frequency of occurrence along the core of anomalously low electrical-conductivity values caused by fire-produced ammonium; this record integrates changes within source regions as well as changes in the geographic location of sources (Taylor et al., 1996). Methane, shown for the GRIP (Chappellaz et al., 1993; Blunier et al., 1995) and GISP2 (Brook et al., 1996) ice cores, was produced within the terrestrial biosphere under anaerobic conditions generally associated with wetlands. Holocene methane concentrations prior to the large human effects of recent centuries reflect moisture availability in broad land areas extending beyond the North Atlantic basin, probably including both high-latitude and low-latitude (monsoonal) regions (e.g., Chappellaz et al., 1993).

RESULTS AND DISCUSSION

The records in Figure 1 reveal large and abrupt climatic changes, and possible cyclicities (e.g., O'Brien et al., 1995; Stuiver et al., 1995). After the end of the deglaciation (the Preboreal warming) between ca. 11.5 and ca. 9.5 ka (calendar years before 1950), the largest deviations for almost all indicators occur between ca. 8.4 and ca. 8.0 ka, typically peaking at ca. 8.25 ka or ca. 7500 ^{14}C yr B.P. The pattern of this 8.2 ka event (cold, dry, dusty, and low methane occurring together) is the same as observed during the Younger Dryas and in many older stadial events (e.g., Johnsen et al., 1992; Alley et al., 1993; Chappellaz et al., 1993; Mayewski et al., 1994).

The assigned age for the 8.2 ka event is indistinguishable from that of the correlative $\delta^{18}O^{ice}$ minimum in other Greenland ice cores (8.21 ± 0.03 ka for GRIP, Johnsen et al., 1992; and 8.23 ± 0.05 ka for Dye 3 and Camp Century, Dansgaard, 1987). Some of the curves in Figure 1 could be interpreted to indicate that this event is part of a longer-lived anomaly from ca. 9.0 to 7.8 ka. Compared to later Holocene events, the 8.2 ka deviations are more anomalous in records of local conditions (temperature, accumulation) than for wind-blown indicators (dust, sea salt), suggesting that the Greenland climate stabilized relative to other regions in the latter Holocene.

To assess the magnitude of the 8.2 ka event, we calculate the deviation of each 8.2 ka "spike" from a baseline defined by values near 8.0 and 8.4 ka in 50-yr-average data (Fig. 1), and we similarly calculate Younger Dryas deviations from a baseline in the early part of the warm Preboreal that followed (Table 1). Forest-fire frequency increased 90% during the 8.2 ka event with a brief fivefold increase about a century later; however, insensitivity of the forest-fire proxy in the alkaline ice of the Younger Dryas (Taylor et al., 1996) precludes comparison between the events.

The $\delta^{18}O_{ice}$ change indicates a peak 8.2 ka cooling of 6 ± 2 °C when the Cuffey et al. (1994; 1995) deglacial, Holocene, and Little Ice Age calibrations are used, and is slightly more than half of the $\delta^{18}O_{ice}$ change of the Younger Dryas. Climatic deviations in the 8.2 ka event for several other indicators also are about half as large as those of the Younger Dryas, although the Younger Dryas conditions were sustained for more than a millennium whereas the maximum 8.2 ka deviations lasted for less than a century. The relatively larger Younger Dryas perturbations in wind-blown sea-salt and dust (roughly four times larger and ten times larger than at 8.2 ka, respectively) are at least in part explainable because entrainment of wind-blown materials is observed to increase much more rapidly than wind speed (reviewed by Petit et al., 1981).

CORRELATION WITH REGIONAL CHANGES

The 8.2 ka climatic perturbation has long been recognized as a significant event in Greenland (e.g., Dansgaard, 1987). Many climatic records from other regions show potentially correlative events (e.g., O'Brien et al., 1995), although problems with sample resolution and dating accuracy complicate deduction of the exact temporal relationships. Estimated calendar dates at these different sites for the midpoint of the "correlative" event range over a millennium, with estimated durations ranging from 100 to 1000 yr or more.

TABLE 1. CHANGES IN SEVERAL PALEOCLIMATIC PROXIES FOR THE 8.2 ka AND YOUNGER DRYAS EVENTS

	Event deviation from baseline	
Indicator	8.2 ka	Younger Dryas
accumulation	–20%	–50%
methane	–10 to –15%	–30%
Na^+	+60%	+260%
Cl^-	+60%	+200%
Ca^{++}	+60%	+600%
Mg^{++}	+40%	+370%
K^+	+110%	+230%
NO_3^-	+20%	+10%
$\delta^{18}O_{ice}$	–2‰	–3.5 to –4‰

Note: For the 8.2 ka event, the difference between the extreme value near 8.25 ka and a baseline defined by the values near 8.0 and 8.4 ka is expressed as a percentage of that baseline. The Younger Dryas is similarly compared to a baseline defined by the early Preboreal. (Percentage differences in $\delta^{18}O_{ice}$ are not especially meaningful, so they are left as per mil.) Most data are ~50 yr averages. Methane is sampled at discrete points. Younger Dryas chemical changes are from Alley et al. (1995) and average over several centuries, which improves statistical confidence without greatly changing the results.

The synchronous occurrence of this event in local, regional, and global proxy climate records in central Greenland requires that the event also occurred in other places, thereby strengthening correlations suggested by other workers (e.g., Chappellaz et al., 1993; Gasse and van Campo, 1994). We consider it especially likely that this event correlates to (Fig. 2) cold conditions in northern Sweden (Karlén, 1976) and on the Agassiz Ice Cap, Ellesmere Island, Canada (Fisher et al., 1995); fresh, cool surface conditions in the North Atlantic (Duplessy et al., 1992; Keigwin and Jones, 1995; Bond, 1995), dry, windy conditions in the Laurentian Great Lakes and surrounding regions (Dean, 1993; Rea et al., 1994); dry conditions in broad monsoonal regions of Africa, the Arabian Peninsula, Tibet, and northwest India (Sirocko et al., 1993; Gasse and van Campo, 1994; Lamb et al., 1995; and references therein); and windy conditions in the Cariaco Basin, offshore Venezuela (Hughen et al., 1996). In general, the better-dated and more densely sampled records show greater similarity to the ice-core record in timing and duration.

The cause of this event is unknown. It may be related to periodicity in the climatic system (Bond, 1995; O'Brien et al., 1995) or other causes. The pattern in Greenland (cold, dry, windy, disturbed continental source regions, low methane) and elsewhere (cold North Atlantic basin, strong North Atlantic trade winds, dry monsoonal regions) closely

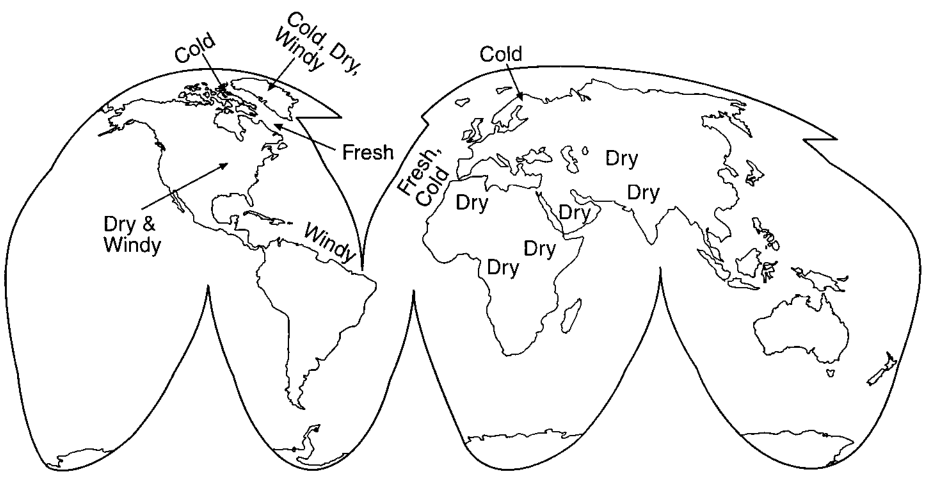

Figure 2. Regional changes probably correlative with prominent 8.4–8.0 ka event recorded in GISP2 ice core. References are given in text.

matches that of the Younger Dryas and stadial cold times of the ice age (e.g., Street-Perrott and Perrott, 1990; Peteet, 1995). Such a pattern is consistent with model simulations for a reduction of North Atlantic oceanic heat transport (e.g., Manabe and Stouffer, 1988; Mikolajewicz, 1996; Fawcett et al., 1997) and with climate-anomaly patterns observed this century in association with cold conditions in the North Atlantic (Parker et al., 1988).

Increased fresh-water supply to the North Atlantic triggering a slowdown of its thermohaline circulation is often suggested to explain this pattern (e.g., Broecker et al., 1990). However, no extraordinarily large increase in fresh-water flux to the North Atlantic has been identified at 8.2 ka. This may indicate for the 8.2 ka event that (1) increased fresh-water supply was not involved; (2) some large fresh-water source has been overlooked; or (3) the system was quite sensitive to small changes in fresh-water supply.

Based on the data and interpretations of Fairbanks (1990; also see Bard et al., 1996), 8.2 ka was a time of typically slow and slowing sea-level rise compared to the several preceding millennia (fresh-water delivery to the oceans of ~0.07 Sv = 0.07×10^6 $m^3 \cdot s^{-1}$ if this was the only cause of sea-level rise, with most of the supply probably from the Antarctic, Peltier, 1994). The abrupt sea-level rise proposed by Blanchon and Shaw (1995) (but see Bard et al., 1996) is dated by them as having started at 7.6 ± 0.1 ka, significantly more recently than the termination of the climatic event at 8.0 ± 0.1 ka in our records. The data of Larcombe et al. (1995) allow, but do not require, accelerated sea-level rise just before the event and a reduced rate of rise during the event. Deglaciation of Hudson Bay and retreat of the mid-latitude ice sheets from many marine margins significantly preceded the event, although calving margins in Foxe Basin and along Ungava Bay, Canada, probably persisted through the event (Andrews, 1989). The remnant of the Laurentide ice sheet during the event is reconstructed as having been smaller than the modern Greenland ice sheet in volume and area (Dyke and Prest, 1987; Peltier, 1994).

Ice-marginal lakes that formed and drained around the Laurentide ice sheet in Labrador at about the time of the 8.2 ka event (Clark and Fitzhugh, 1990) might have been involved (Keigwin and Jones, 1995). However, those described by Clark and Fitzhugh (1990) could have produced a fresh-water flux only on the order of 0.05 Sv if they drained in a single year, possibly associated with additional fluxes from ice-flow changes linked to lake drainage (the actual drainage time and rate are not constrained precisely). Some models project that enhanced fresh-water fluxes of this magnitude to the North Atlantic will slow or stop deep-water formation if maintained long enough (e.g., Manabe and Stouffer, 1994); 0.015 Sv delivered to the Labrador Sea is sufficient to stop convection there in one model (Rahmstorf, 1995). If these lakes were significant in causing the event, then our data support those models showing large North Atlantic climatic sensitivity to small forcings.

It is important to verify this result, because an increase in fresh-water flux of similar magnitude may occur in the future. For example, a global warming of 3 °C with a twofold polar amplification in response to the coming doubling of atmospheric CO_2 is projected to increase the total fresh-water flux from the Greenland ice sheet by about 0.02 Sv and to maintain this level over centuries (Warrick et al., 1995). In addition, enhanced high-latitude precipitation and sea-ice melting in response to projected warming might cause an increase of similar magnitude in fresh-water flux to the North Atlantic (Manabe and Stouffer, 1994; Rahmstorf, 1995). Such an occurrence, although perhaps providing a negative feedback on greenhouse warming in the North Atlantic region, could cause major climatic perturbations on the societally important time scales of decades to centuries.

Available data thus show that a cold, dry, windy event in and around the North Atlantic basin occurred at ca. 8.2 ka, well within the Holocene during climatic conditions similar to those of today. The cause of this event is not known. We cannot exclude the hypothesis that it records a decrease in North Atlantic thermohaline circulation caused by an increase in fresh-water flux to the North Atlantic of the same magnitude as is expected from anthropogenic forcing.

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REFERENCES CITED

Alley, R. B., and 10 others, 1993, Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event: Nature, v. 362, p. 527–528.

Alley, R. B., Finkel, R. C., Nishiizumi, K., Anandakrishnan, S., Shuman, C. A., Mershon, G. R., Zielinski, G. A., and Mayewski, P. A., 1995, Changes in continental and sea-salt atmospheric loadings in central Greenland during the most recent deglaciation: Journal of Glaciology, v. 41, p. 503–514.

Andrews, J. T., 1989, Quaternary geology of the northeastern Canadian shield, *in* Fulton, R. J., ed., Quaternary geology of Canada and Greenland: Geological Survey of Canada, Geology of Canada, no. 1, p. 276–302.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., and Rougerie, F., 1996, Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge: Nature, v. 382, p. 241–244.

Biscaye, P. E., Grousset, F. E., Revel, M., Van der Gaast, S., Vaars, A., and Zielinski, G. A., 1996, Asian source of dust to Summit, Greenland, during the last glacial maximum [abs.]: Eos (Transactions, American Geophysical Union), v. 77, p. S157.

Blanchon, P., and Shaw, J., 1995, Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse: Geology, v. 23, p. 4–8.

Blunier, T., Chappellaz, J., Schwander, J., Stauffer, B., and Raynaud, D., 1995, Variations in atmospheric methane concentration during the Holocene Epoch: Nature, v. 374, p. 46–49.

Bond, G., 1995, Millennial pacing of Holocene ice-rafting events between Iceland and Greenland [abs.]: Eos (Transactions, American Geophysical Union), v. 76, p. 282.

Broecker, W. S., Bond, G., Klas, M., Bonani, G., and Wolfli, W., 1990, A salt oscillator in the glacial Atlantic? 1. The concept: Paleoceanography, v. 5, p. 469–477.

Brook, E. J., Sowers, T., and Orchardo, J., 1996, Rapid variations in atmospheric methane concentration during the past 110,000 years: Science, v. 273, p. 1087–1091.

Chappellaz, J., Blunier, T., Raynaud, D., Barnola, J. M., Schwander, J., and Stauffer, B., 1993, Synchronous changes in atmospheric CH^4 and Greenland climate between 40 and 8 kyr BP: Nature, v. 366, p. 443–445.

Clark, P. U., and Fitzhugh, W. W., 1990, Late deglaciation of the central Labrador coast and its implications for the age of glacial lakes Naskaupi and McLean and for prehistory: Quaternary Research, v. 34, p. 296–305.

Cuffey, K. M., Alley, R. B., Grootes, P. M., and Anandakrishnan, S., 1994, Calibration of the $\delta^{18}O$ paleothermometer for central Greenland, using borehole temperatures: Journal of Glaciology, v. 40, p. 341–349.

Cuffey, K. M., Clow, G. D., Alley, R. B., Stuiver, M., Waddington, E. D., and Saltus, R. W., 1995, Large Arctic temperature change at the Wisconsin-Holocene glacial transition: Science, v. 270, p. 455–458.

Dansgaard, W., 1987, Ice core evidence of abrupt climatic changes, *in* Berger, W. J., and Labeyrie, L. D., eds., Abrupt climatic change: Evidence and implications, Dordrecht, The Netherlands, Reidel, p. 223–233.

Dean, W. E., 1993, Physical properties, mineralogy, and geochemistry of Holocene varved sediments from Elk Lake, Minnesota, *in* Bradbury, J. P., and Dean, W. E., ed., Elk Lake, Minnesota: Evidence for rapid climate change in the north-central United States: Geological Society of America Special Paper 276, p. 135–157.

Duplessy, J. C., Labeyrie, L., Arnold, M., Paterne, M., Duprat, J., and van Weering, T. C. E., 1992, Changes in surface salinity of the North Atlantic Ocean during the last deglaciation: Nature, v. 358, p. 485–488.

Dyke, A. S., and Prest, V. K., 1987, Late Wisconsinan and Holocene history of the Laurentide ice sheet: Géographie Physique et Quaternaire, v. 41, p. 237–263.

Fairbanks, R. G., 1990, The age and origin of the "Younger Dryas climate event" in Greenland ice cores: Paleoceanography, v. 5, p. 937–948.

Fawcett, P. J., Ágústsdóttir, A. M., Alley, R. B., and Shuman, C. A., 1997, The Younger Dryas termination and North Atlantic deepwater formation: Insights from climate model simulations and Greenland ice core data: Paleoceanography, v. 12, p. 23–38.

Fisher, D. A., Koerner, R. M., and Reeh, N., 1995, Holocene climatic records from Agassiz ice cap, Ellesmere Island, NWT, Canada: Holocene, v. 5, p. 19–24.

Gasse, F., and van Campo, E., 1994, Abrupt post-glacial climate events in west Asia and north Africa monsoon domains: Earth and Planetary Science Letters, v. 126, p. 435–456.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, J., and Jouzel, J., 1993, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores: Nature, v. 366, p. 552–554.

Grove, J. M., 1988, The Little Ice Age: London, Methuen, 498 p.

Hughen, K., Overpeck, J. T., Peterson, L. C., and Trumbore, S., 1996, Rapid climate changes in the tropical Atlantic region during the last deglaciation: Nature, v. 380, p. 51–54.

Johnsen, S. J., and nine others, 1992, Irregular glacial interstadials recorded in a new Greenland ice core: Nature, v. 359, p. 311–313.

Karlén, W., 1976, Lacustrine sediments and tree-limit variations as indicators of Holocene climatic fluctuations in Lappland, northern Sweden: Geografiska Annaler, v. 58A, p. 1–34.

Keigwin, L. D., and Jones, G. A., 1995, The marine record of deglaciation from the continental margin off Nova Scotia: Paleoceanography, v. 10, p. 973–985.

Lamb, H. F., Gasse, F., Benkaddour, A., El Hamouti, N., Van de Kaars, S., Perkins, W. T., Pearce, N. J., and Roberts, C. N., 1995, Relation between century-scale Holocene arid intervals in tropical and temperate zones: Nature, v. 373, p. 134–137.

Larcombe, P., Carter, R. M., Dye, J., Gagan, M. K., and Johnson, D. P., 1995, New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia: Marine Geology, v. 127, p. 1–44.

Manabe, S., and Stouffer, R. J., 1988, Two stable equilibria of a coupled ocean-atmosphere model: Journal of Climate, v. 1, p. 841–866.

Manabe, S., and Stouffer, R. J., 1994, Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide: Journal of Climate, v. 7, p. 5–23.

Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Morrison, M. C., Alley, R. B., Bloomfield, P., and Taylor, K., 1994, The atmosphere during the Younger Dryas: Science, v. 263, p. 1747–1751.

Mikolajewicz, U., 1996, A meltwater induced collapse of the "conveyor belt" thermohaline circulation and its influence on the distribution of $\Delta^{14}C$ and $\delta^{18}O$ in the oceans: Hamburg, Max-Planck-Institut für Meteorologie, Report 189, 25 p.

O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S., and Whitlow, S. I., 1995, Complexity of Holocene climate as reconstructed from a Greenland ice core: Science, v. 270, p. 1962–1964.

Parker, D. E., Folland, C. K., and Ward, M. N., 1988, Sea-surface temperature anomaly patterns and prediction of seasonal rainfall in the Sahel region of Africa, *in* Gregory, S., ed., Recent climatic change: London, United Kingdom, Belhaven Press, p. 166–178.

Peltier, W. R., 1994, Ice age paleotopography: Science, v. 265, p. 195–201.

Peteet, D., 1995, Global Younger Dryas?: Quaternary International, v. 28, p. 93–104.

Petit, J.-R., Briat, M., and Royer, A., 1981, Ice age aerosol content from East Antarctic ice core samples and past wind strength: Nature, v. 293, p. 391–394.

Rahmstorf, S., 1995, Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle: Nature, v. 378, p. 145–149.

Rea, D. K., Moore, T. C., Jr., Anderson, T. W., Michael Lewis, C. F., Dobson, D. M., Dettman, D. L., Smith, A. J., and Mayer, L. J., 1994, Great Lakes paleohydrology: Complex interplay of glacial meltwater, lake levels, and sill depths: Geology, v. 22, p. 1059–1062.

Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., and Duplessy, J. C., 1993, Century-scale events in monsoonal climate over the past 24,000 years: Nature, v. 364, p. 322–324.

Sowers, T., Bender, M., Raynaud, D., and Korotkevich, Y. S., 1992, $\delta^{15}N$ of N_2 in air trapped in polar ice: A tracer of gas transport in the firn and a possible constraint on the ice age–gas age differences: Journal of Geophysical Research, v. 97, p. 15683–15697.

Sowers, T., and 10 others, 1997, An inter-laboratory comparison of techniques for extracting and analyzing trapped gases in ice cores: Journal of Geophysical Research (in press).

Spinelli, G., 1996, A statistical analysis of ice-accumulation level and variability in the GISP2 ice core and a reexamination of the age of the termination of the Younger Dryas cooling episode: University Park, Pennsylvania State University, Earth System Science Center Technical Report No. 96-001, 36 p.

Steig, E. J., Grootes, P. M., and Stuiver, M., 1994, Seasonal precipitation timing and ice core records: Science, v. 266, p. 1885–1886.

Street-Perrott, F. A., and Perrott, R. A., 1990, Abrupt climate fluctuations in the tropics: The influence of Atlantic Ocean circulation: Nature, v. 358, p. 607–612.

Stuiver, M., Grootes, P. M., and Brazunias, T. F., 1995, The GISP2 $\delta^{18}O$ record of the past 16,500 years and the role of the Sun, ocean and volcanoes: Quaternary Research, v. 44, p. 341–354.

Taylor, K. C., Mayewski, P. A., Twickler, M. S., and Whitlow, S. I., 1996, Biomass burning recorded in the GISP2 ice core: A record from eastern Canada?: Holocene, v. 6, p. 1–6.

Warrick, R. A., Le Provost, C., Meier, M. F., Oerlemans, J., and Woodworth, P. L., 1995, Changes in sea level, *in* Houghton, J. T., et al., eds., Climate change 1995: The science of climate change: Cambridge, United Kingdom, Cambridge University Press, p. 359–405.

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