Making Sense of Millennial-Scale Climate Change

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Recent results, and especially those presented at the AGU Chapman Conference on Mechanisms of Millennial-Scale Global Climate Change, allow formulation of a consistent hypothesis for millennial-scale climate change. The observed large, abrupt, widespread millennial-scale climate changes of the last glaciation are hypothesized to have been forced by North Atlantic atmosphere-ocean-ice interactions. Shifts in ocean circulation (oceanic jumps) between modern and glacial modes caused the Dansgaard/Oeschger oscillations, in which the cold, dry and windy signal of the glacial mode was transmitted through the atmosphere to hemispheric or broader regions. These jumps were triggered by changes in freshwater delivery to the North Atlantic, and possibly by other causes extending beyond the North Atlantic. The additional jumps to the Heinrich mode caused atmospheric anomalies similar to but somewhat stronger and more-widespread than during the cold phases of the Dansgaard/Oeschger oscillation. Heinrich-mode effects also were transmitted through the ocean, with antiphase behavior between much of the world and some southern regions centered on and downwind of the South Atlantic. Surging of the Laurentide Ice Sheet supplied extra freshwater to force jumps to the Heinrich mode; surging probably was triggered by Dansgaard/Oeschger cooling after Laurentide growth exceeded a MacAyeal threshold for thawing the ice-sheet bed.

INTRODUCTION

Decades of research have established the importance of millennial-scale change in the paleoclimatic record [e.g., *Denton and Karlen*, 1973; *Pisias et al.*, 1973; *Mangerud et al.*, 1974]. A global network of high-resolution records, anchored by the results from the Greenland ice-coring projects at Summit [*Hammer et al.*, 1997], has demonstrated that abrupt, widespread, (nearly-) synchronous changes have been important or dominant in paleoclimatic variability at many times and places. These data motivated the AGU Chapman Conference on Mechanisms of Millennial-Scale Global Climate Change (June, 1998).

During the conference, the Program Committee attempted to formulate a consistent hypothesis for millennial-scale climate change, which we expand upon here. This hypothesis is based on the assumption that ice sheet-ocean-atmosphere interactions in the North Atlantic basin drive climate change elsewhere. These North Atlantic changes are postulated to be transmitted through the atmosphere and the ocean with various feedbacks amplifying and further broadcasting the signal hemispherically to globally. We have not attempted to present a consensus document for the meeting, for the Program Committee, or even the four of us, although we certainly acknowledge insight and inspiration both from the Program Committee and from other meeting attendees. Other hypotheses for mechanisms of millennial-

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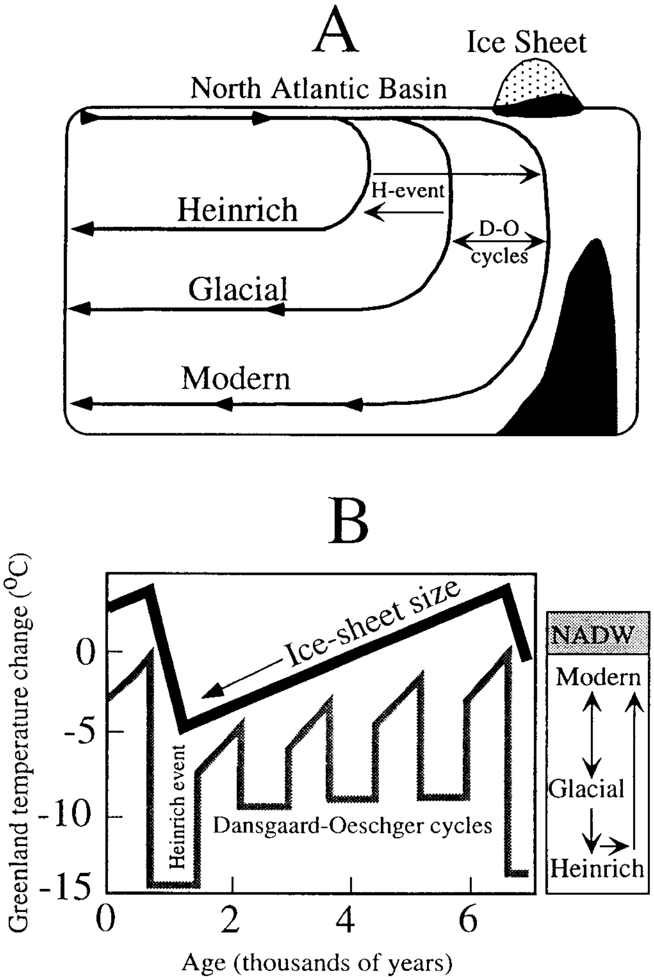

Figure 1. (A) Conceptual cartoon of three modes of North Atlantic circulation (*modern, glacial*, and *Heinrich*). Oceanic jumps between modern and glacial modes caused the Dansgaard/Oeschger oscillations, in which the cold, dry and windy signal of the glacial mode were transmitted elsewhere largely through the atmosphere. D/O oscillations were amplified during times of intermediate sized circum-North Atlantic ice sheets. The additional jumps to the Heinrich mode occurred in response to surging of the Laurentide Ice Sheet, and caused atmospheric anomalies similar to the cold phases of the D/O oscillations, but also transmitted climate change through the ocean. (B) An idealized time series of changes in climate between Heinrich events, during which several D/O oscillations occur (after *Alley* [1998]). Changes in ocean circulation associated with D/O oscillations and Heinrich events are shown on the right. Note that not all Heinrich events are colder than D/O oscillations in the Greenland ice cores.

scale climate change were discussed at the conference and are presented elsewhere in this volume [e.g., *Bond et al., Clement and Cane, Cane and Clement, Ninnemann and Charles*]. Nevertheless, by presenting a unified hypothesis for millennial-scale climate change that strives to reconcile the data and paleoclimate modeling results, we hope to show strengths, weaknesses, and interrelationships that may help guide further research.

MODES OF NORTH ATLANTIC DEEP WATER FORMATION

Data and models suggest that the North Atlantic Ocean usually operates in one of three distinct modes or bands of circulation; small changes may occur within a mode, but jumps in conditions separate the modes (Figure 1, 2, 3) [cf. *Rahmstorf*, 1994, 1995; *Sarnthein et al.*, 1994; *Oppo and Lehman*, 1995; *Maslin et al.*, 1995; *Manabe and Stouffer*, 1997; *Vidal et al.*, 1997; *Ganopolski et al.*, 1998; *Seidov and Maslin*, 1999; *Weaver*, this volume]. The first mode is characterized by deep-water formation in both the Nordic Seas and farther south in the North Atlantic (Figure 1A, 2A) (the two-pump ocean of *Imbrie et al.* [1993]; Holocene or interglacial mode of *Sarnthein et al.* [1994]; mode 1G of *Stocker* [Chapman Conference Abstracts, 1998, hereafter designated C*]; modern mode of *Alley and Clark* [1999]). In the second mode, deep-water formation largely stopped in the Nordic Seas but with continued vigorous deep-intermediate water formation farther south in the North Atlantic (Figure 1B, 2B) (the one-pump ocean of *Imbrie et al.* [1993]; glacial mode of *Sarnthein et al.* [1994] and *Alley and Clark* [1999]; mode 1L of *Stocker* [C*]). In the third mode, deep-intermediate water formation are greatly reduced in both locations (Figure 1C, 2C) (a no-pump mode not discussed by *Imbrie et al.* [1993]; meltwater mode of *Sarnthein et al.* [1994]; mode 0 of *Stocker* [C*]; Heinrich (H) mode of *Alley and Clark* [1999]; Imbrie et al. [1993] did not discuss the possibility of a "no-pump mode"). Although debate remains within the community on whether there was complete shutdown of circulation in the North Atlantic at least for a part of the time during each Heinrich event, within our hypothesis we chose to treat the greatly reduced deep and intermediate water formation within Heinrich as an extreme amplification of the partial shutdown during glacial maximum. Throughout the rest of the paper, we refer to these three distinct modes of North Atlantic Ocean circulation as *modern, glacial*, and *H* modes, respectively (Figures 1, 2, 3).

The modern mode of circulation is associated with warm times in the North Atlantic. The glacial mode is reached at glacial maximum and during the cold or stadial times of the ~1500 year Dansgaard/Oeschger (D/O) oscillation. The H mode is achieved during especially large meltwater inputs, such as are associated with some Heinrich (H) events. Milankovitch-linked glacial-interglacial cycles cause the ocean to remain primarily in the glacial mode near glacial maximum and the modern mode during interglacials, but even at these times mode-jumps are possible with sufficient forcing.

DANSGAARD-OESCHGER OSCILLATIONS

The D/O oscillation is the dominant millennial-scale climate-change signal (Figure 4). Prominent events have had an approximate spacing of 1500 years [*Bond and Lotti*, 1995; *Bond et al.*, 1997; *Grootes and Stuiver*, 1997; *Mayewski et al.*, 1997]. D/O changes are centered on the North Atlantic (Figure 4A), and on regions with strong atmospheric response to changes in the North Atlantic, including tropical and subtropical monsoonal areas of Africa and to a lesser extent Asia [e.g., *Street-Perrott and Perrott*, 1990; *Gasse and van Campo*, 1994; *Hostetler et al.*, 1999]. Warm North Atlantic conditions associated with the modern mode of circulation produce enhanced monsoonal precipitation, contributing to the increased methane (Figure 4B) that apparently is an almost-instantaneous (<30 years) feedback on North Atlantic warming [*Severinghaus et al.*, 1998]. The synchroneity (within dating uncertainties) in changes in widespread regions, including (1) the Cariaco Basin off Venezuela (weaker trade-wind-driven upwelling with warm North Atlantic [*Hughen et al.*, 1998]), (2) the Arabian Sea (increased monsoon strength with warm North Atlantic [*Schulz et al.*, 1998]) (Figure 4C), and (3) the Santa Barbara Basin off California (decreased oxygenation with warm North Atlantic [*Behl and Kennett*, 1996]) (Figure 4D), argues for atmospheric transmission of the signal. At least some modeling studies [e.g., *Fawcett et al.*, 1997; *Hostetler et al.*, 1999; *Agustsdottir et al.*, in press] indicate

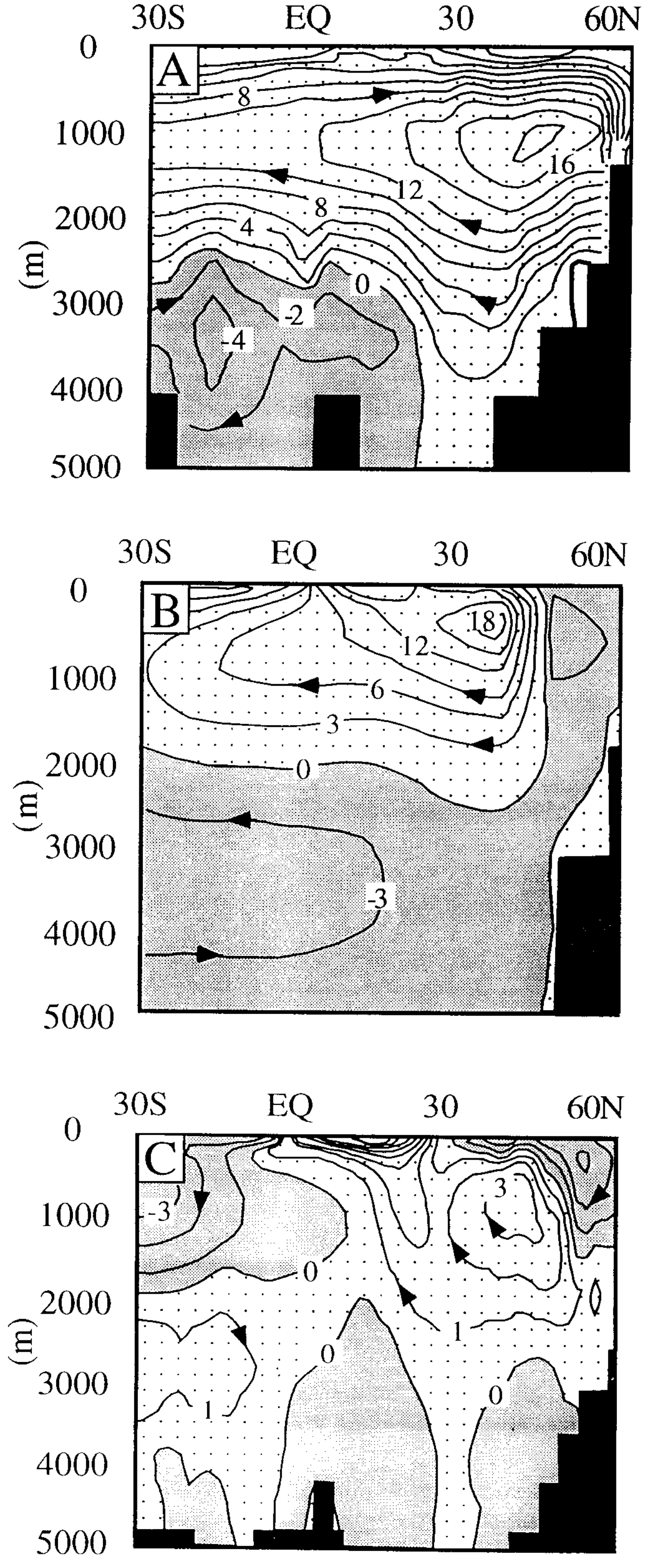

Figure 2. Model results suggesting three modes of North Atlantic deep-water circulation. (A) The modern mode is suggested by the meridional transport stream function of the thermohaline circulation (THC) [in units of sverdrups (Sv = $10^6 m^{-3}$)] from the control experiment of *Manabe and Stouffer* [1997]. The model is a coupled atmosphere-ocean general circulation model. Model results show sinking of North Atlantic Deep Water (NADW) to fill the northern North Atlantic basin (light stipple pattern). (B) The glacial mode is represented by the stream function of THC from the model of the last glacial maximum by *Ganopolski et al.* [1998]. The model couples a dynamical-statistical atmosphere model to a zonally averaged ocean model with three separate basins and is forced by insolation, CO_2, ice sheets, and sea level consistent with boundary conditions of the last glacial maximum. Model results show a shoaling of NADW and a southward shift in convection sites, but indicate that the overall rate of NADW formation was only slightly reduced from modern. (C) The Heinrich mode is represented by the stream function of THC from the model of a Heinrich event by *Weaver* [this volume]. The model is an energy-moisture balance model coupled to an ocean general circulation model. Model results show that the response to a 105-year freshwater forcing with an average flux of 0.013 Sv results in shoaling to ~2000 m as well as a significant reduction in rate of formation of NAIW (light stipple pattern) compared to NADW (e.g., A or B).

that warming in the Nordic Seas increases monsoon strength and precipitation-minus-evaporation in monsoonal regions of Africa and Asia, and reduces Ekman divergence over the Santa Barbara and Cariaco Basins. Feedbacks associated with changes in monsoon strength and oceanic upwelling probably contribute to the geographic extent of D/O impacts.

Intermediate to deep oceanic impacts of the modern-to-glacial D/O jumps are probably small beyond the high-latitude North Atlantic. These impacts are limited to northward cross-equatorial surface-water flow in the Atlantic that continues during cold and warm phases, as does ventilation to at least mid-depth in the Atlantic [*Rahmstorf*, 1995; *Yu et al.*, 1996; *Ganopolski et al.*, 1998; *Stocker*, C*] (Figure 2) and supply of North Atlantic-origin waters to the Antarctic thermocline. Some model results suggest that glacial-mode conditions are accompanied by increased formation of intermediate water in the North Pacific [*Ganopolski et al.*, 1998; *Keigwin*, 1998], causing Pacific and Atlantic glacial circulations to be similar.

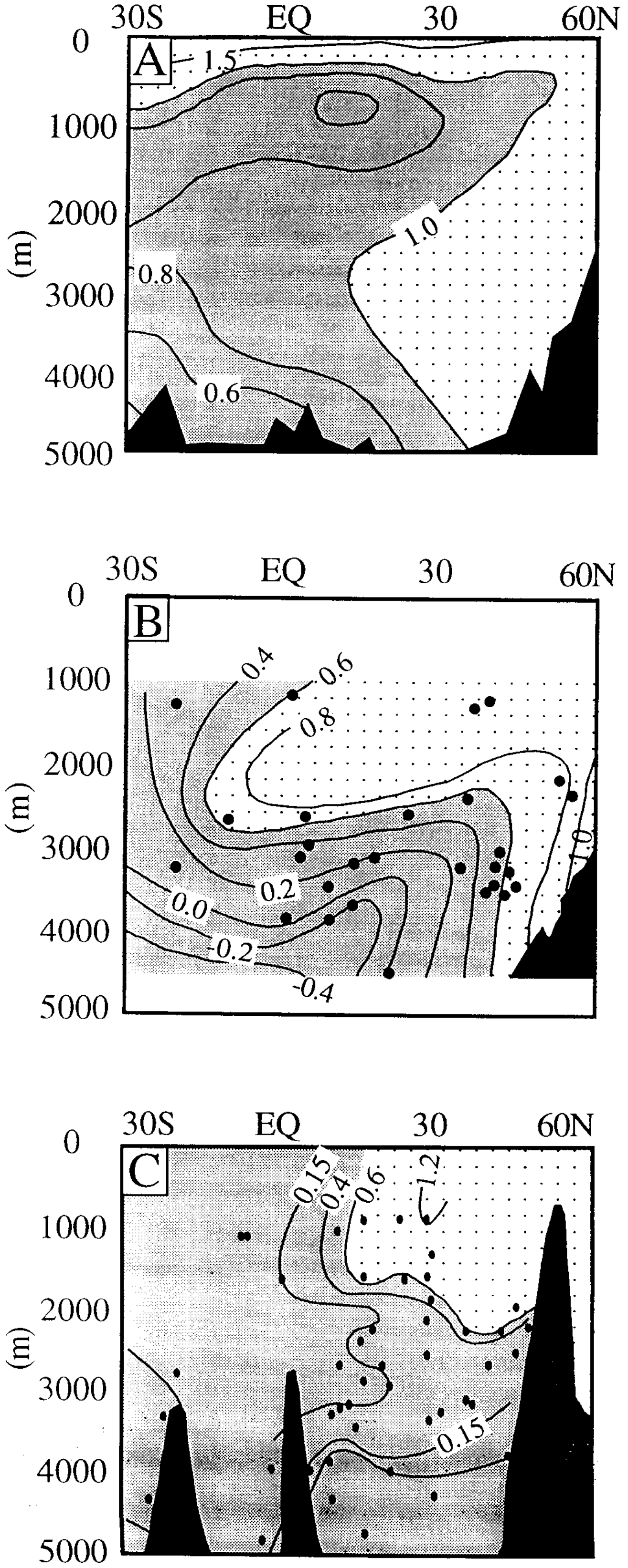

Figure 3. δ^{13}C data suggesting three modes of North Atlantic Ocean deep-water circulation. (A) The modern mode is represented by the modern distribution of δ^{13}C in the western North Atlantic basin [after *Kroopnick*, 1985]. Nutrient-depleted North Atlantic Deep Water (NADW) is characterized by high δ^{13}C values (light stipple pattern) and sinks to fill the deep western North Atlantic basin. (B) The glacial mode is represented by the distribution of δ^{13}C during the last glacial maximum in the eastern North Atlantic basin (after *Duplessy et al.* [1988], as recontoured by *Broecker* [1989]). δ^{13}C values indicate that NADW (identified by values >0.6 per mil to account for the glacial-interglacial δ^{13}C shift of ~0.4 per mil; *Curry et al.* [1988]) was shallower (to a depth of ~3000 m) than modern. (C) The Heinrich mode is represented by the distribution of δ^{13}C during H1 in the eastern North Atlantic [after *Sarnthein et al.*, 1994]. δ^{13}C values indicate that NADW shoaled to ~2000 m to form North Atlantic Intermediate Water (NAIW) (light stipple pattern) and that this water mass did not penetrate south of the equator. Long time series of surface and deep-water variations suggest that the most pronounced deep-water responses such as illustrated in (C) occurred during other Heinrich events [*Oppo and Lehman*, 1995; *Maslin et al.*, 1995; *Rasmussen et al.*, 1996; *Vidal et al.*, 1997; *Curry et al.*, this volume]. It is clear from comparing timeslices in (B) and (C), however, that in many cases a single record of deep-water variability will not be able to discriminate clearly between glacial and Heinrich modes. Furthermore, a response in the eastern North Atlantic does not necessarily reflect a strong effect in what was exported from the basin, which can only be measured from the western North Atlantic. Finally, model results by *Marchal et al.* [1998] indicate that the relation between changes in NADW formation rate and in δ^{13}C values is not linear. Model (Figure 2) and data (this figure) results are thus consistent in suggesting significant changes in formation of NADW, but one cannot extrapolate absolute changes in NADW formation rates from δ^{13}C records.

The D/O oscillation is an oceanic process, often triggered by meltwater changes but possibly oscillating freely in response to some as-yet-unidentified process(es). Although the oscillations appear periodic, close inspection indicates that there is much variability about the mean spacing [*Bond and Lotti*, 1995], and our impression is that during certain times (especially during the deglaciation) there is some uncertainty in identifying D/O-type events and in determining their temporal spacing. Persistence of an apparent D/O-type oscillation during the Holocene (at greatly reduced amplitude) [*Denton and Karlen*, 1973; *Keigwin and Jones*, 1989; *Bond et al.*, 1997; *Bianchi and McCave*, 1999] also involves much deviation in event spacing. One cannot exclude great variability in spacing of tones off Milankovitch or of solar or other forcing [*Mayewski et al.*, 1997], but a more-periodic behavior might be expected by analogy to known shorter solar cycles and longer Milankovitch cycles [e.g., *Imbrie et al.*, 1992]. A solar forcing is further questioned by the lack of a cosmogenic-nuclide signal of solar-wind changes in Holocene ice-core records [e.g., *Finkel and Nishiizumi*, 1997]; the ice cores record both solar forcing and climatic response at higher frequencies [*Finkel and Nishiizumi*, 1997; *Grootes and Stuiver*, 1997], but thus far we know of no credible evidence for significant solar forcing at the millennial scale.

Internal processes are strongly supported by the observation that all of the events during the most recent deglaciation are plausibly related to changes in meltwater delivery to the North Atlantic [e.g., *Broecker et al.*, 1988; *Teller*, 1990; *Keigwin et al.*, 1991; *Clark et al.*, 1996; *Barber et al.*, C*; *Liccardi et al.*, this volume], a process which has been shown in numerous models to force oceanic changes [e.g., *Rahmstorf*, 1995; *Fanning and Weaver*, 1997; *Stocker*, C*]. Modeled response to such forcing often has shown a similar timescale to observations [e.g., *Broecker et al.*, 1990; *Weaver and Hughes*, 1994].

D/O-type oscillations may have been a persistent feature of the climate system prior to as well as during the most recent glacial cycle [*Oppo et al.*, 1998; *Raymo et al.*, 1998; *McManus et al.*, 1999]. Such long-term persistence suggests that some D/O oscillations were not forced. If so, then a free oscillation of unknown cause is active, possibly related to ENSO [*Clement and Cane*, this volume; *Cane and Clement*, this volume], tidal [*Keeling*, C*], or other processes including stochastic variability [*Weaver and Hughes*, 1994; *Weaver*, this volume]. The millennial frequency points to a major role for the ocean; some ice sheets have longer response times, and the atmosphere has a much shorter response time. The increased ice-rafted debris from multiple sources in North Atlantic sediments from the cold phases of the D/O oscillations likely reflects the normal response of ice sheets to the cooling associated with the events rather than any ice-dynamical forcing of the coolings [*Bond and Lotti*, 1995; *McCabe and Clark*, 1998; *van Kreveld et al.*, C*].

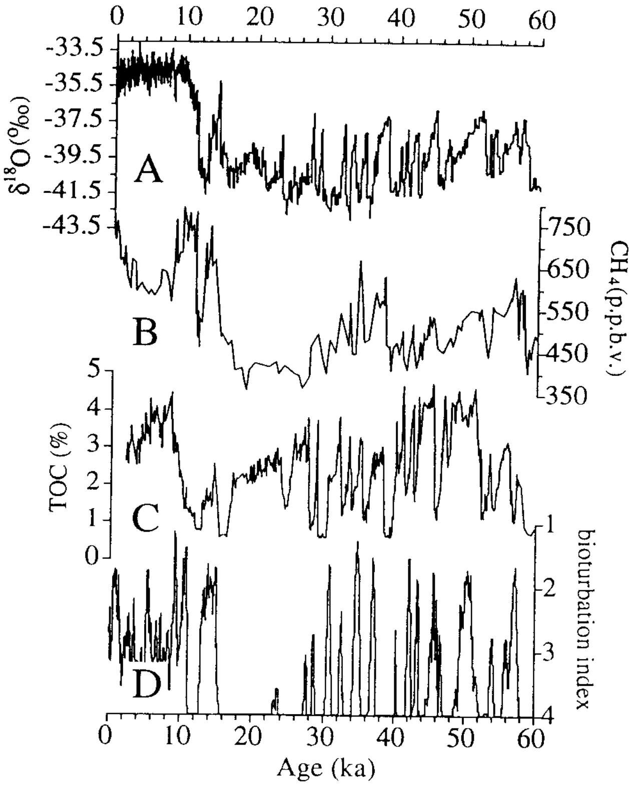

Figure 4. Records showing Dansgaard/Oeschger oscillations over the last 60 ka from: (A) the GISP2 $\delta^{18}O$ record (in per mil) [*Grootes et al.*, 1993]; (B) the GISP2 methane record [*Brook et al.*, 1996]; (C) total organic carbon (TOC) (in %) from Arabian Sea sediments [*Schulz et al., 1998*], and (D) changes in the bioturbation index from ODP Site 893 (Santa Barbara basin) (1 = laminated sediments, 4 = massive sediments) [*Behl and Kennett*, 1996].

D/O oscillations have been largest at times of intermediate temperatures and ice extent, often when orbital forcing and CO_2 were changing rapidly, rather than during the coldest or warmest times near insolation and CO_2 maxima or minima [*Alley and Clark*, 1999; *McManus et al.*, 1999]. This may indicate that the system can remain in one mode of operation with appropriate forcing, but that oscillations result when forcing would place the climate system in the gap between two modes. Alternatively, the stability of the system may be sensitive to the rate of change of forcing variables, such that climate response is analogous to that of a drunken human: when left alone, it sits; when forced to move, it staggers with abrupt changes in direction.

HEINRICH EVENTS

The H events (or at least most of them) involved surging of the Laurentide Ice Sheet through Hudson Strait apparently triggered by D/O cooling [*Bond et al.*, 1993]. The tremendous sediment volume [e.g., *Bond et al.*, 1993], dominant Hudson-Bay source [e.g., *Gwiazda et al.*, 1996], and rapid rate of sediment supply [e.g., *McManus et al.*, 1998] of H events set them apart from other stadials (millennial-scale cold events), and seem to require an ice-dynamics instability [*Alley and MacAyeal*, 1994]. In most marine sediment records, cooling preceded the sharp-based, carbonate-rich, rapidly deposited debris of H layers [e.g., *Bond et al.*, 1993; *Bond and Lotti*, 1995]. A spectrum of mechanisms has been proposed to explain the triggering of H events [*Alley et al.*, 1996; *Parizek et al.*, 1997; *Clarke et al.*, this volume; *MacAyeal*, C*], but triggering by cooling is at least plausible provided the key region is ice-marginal and so can respond rapidly to changing climate. The long (and variable) spacing of H events compared to D/O timing (Figure 5A) probably reflects the growth of the Laurentide ice sheet--surges are only possible once a growth threshold is reached, which may require several D/O cycles but which is easier/faster during colder times near glacial maximum [*McManus et al.*, 1999]. The overall cooling trend associated with the H events [*Bond et al.*, 1993] is plausibly the effect on the atmosphere of changing ice-sheet as well as oceanic conditions [*MacAyeal*, 1993; *Jackson*, this volume; *Hostetler et al.*, 1999].

In addition to an atmospheric transmission as seen for D/O oscillations, H events are also transmitted elsewhere through the ocean. Meltwater associated with H events forces (or reinforces) the H mode or band of ocean circulation [*Keigwin and Lehman*, 1994; *Curry and Oppo*, 1997; *Vidal et al.*, 1997; *Curry et al.*, this volume]. Loss of the second site of deep-water formation has only a small additional direct effect on the atmosphere (oceanic heat being more important to the total energy budget in wintertime high latitudes than at lower latitudes), but affects the oceanic circulation more prominently than does loss of higher-latitude deep-water formation. The main effect of switching to the H mode is to reduce the cross-equatorial flow of Atlantic surface waters (Figure 2), which leaves heat in the South Atlantic, warming high southern latitudes [*Manabe and Stouffer*, 1988, 1997; *Stocker et al.*, 1992; *Crowley*, 1992; *Rahmstorf*, 1994; *Schiller et al.*, 1997; *Weaver*, this volume]. Loss of North Atlantic Deep Water formation probably also stimulates additional deep-water formation in specific places in the south [*Schiller et al.*, 1997; *Broecker*, 1998; *Stocker*, C*] and enhanced intermediate water formation in the North Pacific [*Rahmstorf*, 1995; *Keigwin*, 1998; *Lund and Mix*, 1998], resulting in an oceanic "see-saw" [*Broecker*, 1998; *Lund and Mix*, 1998]. The warming associated with vigorous deep-water formation is much smaller in the south than in the north, however, because the Coriolis effect prevents warm surface waters from crossing the Antarctic Circumpolar Current at the latitude of Drake Passage [*Toggweiler and Samuel*, C*] so that southern deep waters must be formed from upwelling of already-cool intermediate waters.

Antiphase behavior of northern and southern records is prominent for some H events at some sites probably centered on the South Atlantic and Indian Oceans (Figure 5) [*Charles et al.*, 1996; *Little et al.*, 1997; *Blunier et al.*, 1998; *Stocker*, C*; *Alley and Clark*, 1999; *Bender et al.*, this volume; *Niennemann and Charles*, this volume], but with other southern-hemisphere sites showing a northern-type record probably reflecting atmospheric transmission of signals [*Pichon et al.*, 1992; *Lowell et al.*, 1995; *Bard et al.*, 1997; *Steig et al.*, 1998]. Southern Hemisphere signals are muted compared to changes in the Northern Hemisphere (Figure 5).

COMPARISON TO ORBITAL TIMESCALES

The North Atlantic operates in the glacial band for both glacial-maximum and stadial conditions of the D/O oscillation, which appear similar in many North Atlantic records. Far from the North Atlantic, climate anomalies associated with glacial maximum are much more prominent than those during stadial conditions, because CO_2, ice sheets, and associated ice-albedo, vegetation and other feedbacks, change greatly from glacial to interglacial but not from stadial to interstadial [*Alley and Clark*, 1999; *Hostetler et al.*, 1999]. Controls on CO_2 are poorly understood. Enhanced polar cooling associated with ice-albedo and other feedbacks in response to CO_2 reduction and orbitally induced ice-sheet growth steepens the equator-to-pole temperature gradient. This steepened gradient increases wind strength, cooling the tropics through upwelling of colder waters or entrainment of colder extratropical waters [e.g., *Bush and Philander*, 1998; *Ganopolski et al.* 1998] and further cooling the tropics and extratropics through water-vapor feedbacks [*Pierrehumbert*, this volume]. Glacial and stadial modes thus differ primarily in ways that do not directly involve the deep ocean. In contrast with the glacial climate changes, the stadials do not persist long enough for major CO_2 and ice-sheet feedbacks, and may lack forcing in appropriate regions to trigger those feedbacks.

DISCUSSION

Based on current data and model results, we hypothesize that millennial-scale climate change during the last glaciation: (1) consists of quasi-periodic D/O oscillations and aperiodic H events; (2) is amplified during times of intermediate ice cover and rapidly changing forcing; (3) originates by jumps between three modes of NADW formation (modern, glacial, and H modes); (4) is transmitted from the North Atlantic elsewhere through the atmosphere (modern to glacial mode switch) and oceans (glacial to H mode

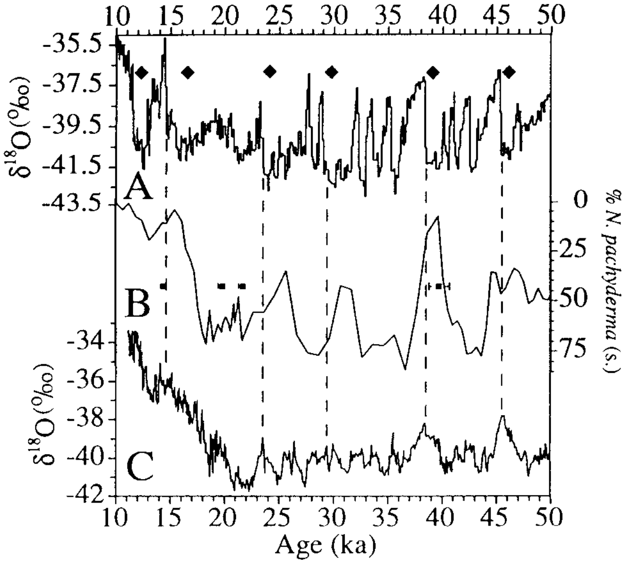

Figure 5. Records showing "bipolar seesaw" relationship between the North Atlantic (A: GISP2 $\delta^{18}O$ record (in per mil) [*Grootes et al.*, 1993]), the South Atlantic (B: percentage of *N. pachyderma* (s.) from core GeoB 1711 [*Little et al.*, 1997]; dating control indicated by squares), and Antarctica (C: Byrd $\delta^{18}O$ record (in per mil) [*Johnsen et al.*, 1972]). Heinrich Events are indicated by diamonds along the top of the figure (with increasing age, the Younger Dryas or H0, and then H1-H5). Ed Brook (personal communication, October, 1998) correlated the Byrd $\delta^{18}O$ chronology to the GISP2 $\delta^{18}O$ chronology using methane data from the GISP2 ice core [*Brook et al.*, 1996] and methane data from the Byrd ice core [*Blunier et al.*, 1998]. Specifically, GISP2 gas (methane) ages were assigned to depths in the Byrd record where there are corresponding rapid changes in methane, allowing interpolation of a gas-age timescale for the Byrd record. An ice-age timescale for the Byrd $\delta^{18}O$ record was then calculated using estimated delta age (ice-age/gas-age offset). Note that there are no control points for the interval 17-30 ka.

switch); and (5) is further propagated through various feedbacks (water vapor, upwelling). Switches to at least some glacial modes and all H modes are forced by changes in meltwater delivery.

Although our hypothesis focuses on ice sheet-ocean-atmosphere interactions in the North Atlantic region as the primary mechanism driving millennial-scale climate variability during the last glaciation, atmospheric and oceanic transmission of North Atlantic changes to other regions played key roles in constructing the overall climate-system circuitry that resulted in a complex global response. Global transmission of a signal originating (or amplified) in a small region of the Earth (ENSO variability in the western Pacific) is a well known characteristic of the climate system at decadal timescales [*Clement and Cane*, this volume]. We believe that the data of millennial-scale variability (e.g., Figure 4, 5) have similarly identified important pathways (monsoon, Southern Ocean) by which climate change in the North Atlantic is transmitted outside of the region. Nevertheless, additional well-dated high-resolution records from terrestrial and marine sites in the southern hemisphere are clearly needed to determine the extent and timing of H and non-H D/O oscillations. Also needed are well-dated, high-resolution records from all latitudes of the Pacific--the largest ocean looms as a large uncertainty in our hypothesis. Our understanding of teleconnections at decadal [e.g., *White et al.*, 1996; *Huang et al.*, 1998; *Mysak and Venegas*, 1998; *Barnett et al.*, 1999] and orbital [*Imbrie et al.*, 1992, 1993] timescales allows us to speculate that a number of a pathways in addition to those suggested by existing data served to further transmit millennial-scale climate change originating in the North Atlantic. Only further high-resolution records will be able to decipher these additional pathways. Significant ambiguities remain in the North Atlantic as well. Further understanding of the controls on CO_2 and ice sheets would be valuable, as would an understanding of millennial processes in ocean circulation.

We are impressed with the recent paleoclimate research and modeling results that have contributed to a rapid progress in our knowledge of millennial climate change. Nevertheless, complete understanding of the complex interactions of mechanisms and teleconnections of millennial-scale changes in the climate system remains elusive. Our current lack of complete understanding of the millennial climate processes, their relative timing, and whether these are internally or externally forced, limits our ability to unequivocally attribute these abrupt climate shifts to known forcings. The all-encompassing hypothesis we have presented to explain millennial climate change represents an attempt to summarize a series of complex interactions within the climate system, and should be recognized as only a cartoon providing a useful but certainly not yet complete description.

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