Wally Was Right: Predictive Ability of the North Atlantic "Conveyor Belt" Hypothesis for Abrupt Climate Change

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paleoclimatology, ocean circulation, sea ice, Younger Dryas, meridional overturning circulation

Abstract

Linked, abrupt changes of North Atlantic deep water formation, North Atlantic sea ice extent, and widespread climate occurred repeatedly during the last ice age cycle and beyond in response to changing freshwater fluxes and perhaps other causes. This paradigm, developed and championed especially by W.S. Broecker, has repeatedly proven to be successfully predictive as well as explanatory with high confidence. Much work remains to fully understand what happened and to assess possible implications for the future, but the foundations for this work are remarkably solid.

INTRODUCTION

The idea of North Atlantic abrupt climate change—freshening of the surface waters leading to a reorganization in oceanic circulation and coupled atmospheric changes with widespread consequences and often abrupt shifts—is now at least 25 years old (Rooth 1982). This rich field of study has especially been led, championed, publicized, and developed into a major paradigm of climate change by Prof. Wallace S. Broecker (e.g., Broecker et al. 1985, 1988, 1989, 1990; Broecker & Denton 1989; Broecker 1994, 1997, 1998). The remarkable success of this research program has opened new subdisciplines, including the nascent field of abrupt climate change, provided important insights to climate processes, feedbacks, and sensitivity, and captured public as well as scientific attention. Scientific skeptics do still remain (most notably Wunsch 2003, 2005, 2006), providing important impetus for additional research, but Broecker's North Atlantic/conveyor paradigm has gained widespread acceptance. For example, the Broecker papers listed above have been cited more than 2000 times as indexed by ISI, and a brief perusal indicates that at least most of those citations are in general agreement.

Of particular note is the predictive power of Broecker's paradigm. Far from being merely a consistent explanation of previously collected data sets, this hypothesis has spawned a range of tests that have been borne out, with high confidence. I summarize some of these successful predictions after a quick review of terminology. (The predictive power also shows the intellectual bankruptcy of those groups, such as the proponents of a 6000-year-old Earth, who deride "historical science" as an oxymoron.)

BESTIARY

The relevant terminology is arcane at best. The summary here may prove useful, but does not provide formal definitions.

Greenland ice-core records are often used as a type section of millennial climate change over the last ice age cycle owing to their high time resolution, multiproxy nature, and confident paleoclimatic reconstruction. **Figure 1** shows the GISP2, central Greenland record over the past 100,000 years (Grootes & Stuiver 1997).

The broad sweep of the orbitally paced ice age cycle is evident. The warmth of the previous interglacial approximately 130,000 years ago is variously called marine isotope stage (MIS) 5e, the Eemian in Europe, or the Sangamonian in North America; Greenland ice of that age and older has been recovered (Suwa et al. 2006), but an intact, ordered record through the complete Eemian has not yet been found, although likely is available given the proper core. The cooling into the most recent ice age (the Weichselian, Wurm, Wisconsinan, Devensian, etc., depending on intellectual or regional heritage) then passed through the cold of MIS 4, the somewhat warmer conditions of stage 3, the last glacial maximum (LGM) in stage 2, and the glacial termination or deglaciation leading to the warmth of stage 1 or the Holocene.

The abrupt climate changes were especially prominent during times when the ice age cycling reached intermediate temperatures. The youngest generally recognized abrupt event was the short-lived (roughly one century) cold interval approximately

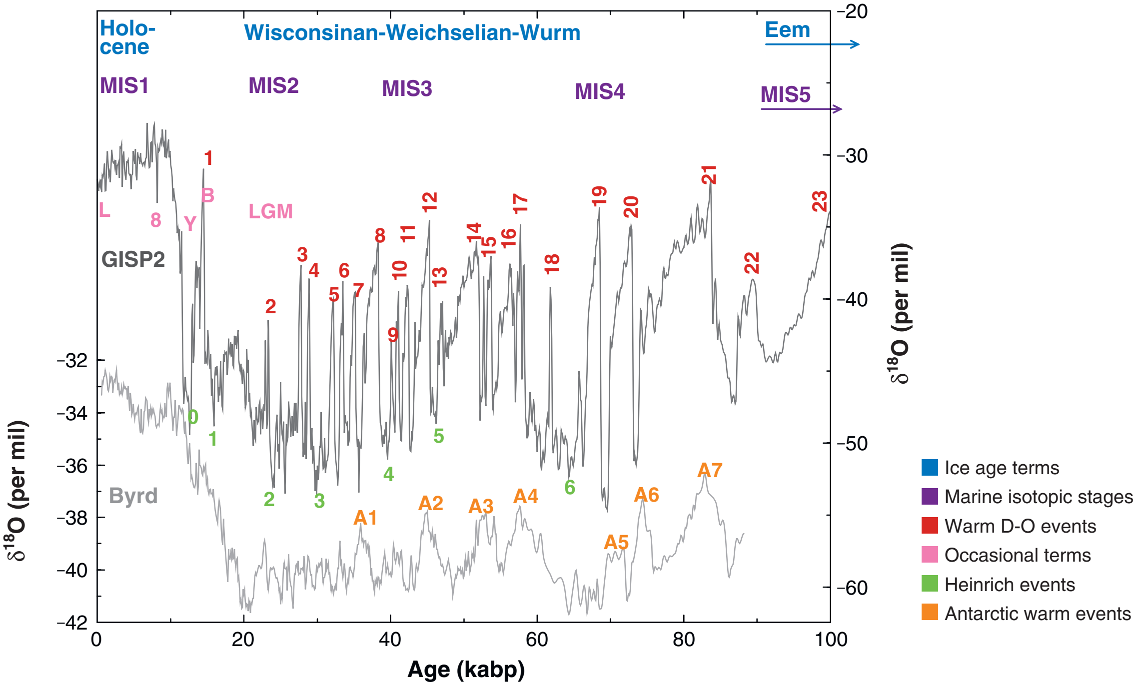

Figure 1

Ice-isotopic records (a proxy for temperature, with less-negative values indicating warmer conditions) from GISP2, Greenland (Grootes & Stuiver 1997) and Byrd Station, Antarctica, as synchronized by Blunier & Brook (2001), with various climate-event terminology indicated. Ice age terms are shown in blue (*top*); the classical Eemian/Sangamonian is slightly older than shown here, as is the peak of marine isotope stage (MIS, *shown in purple*) 5, known as 5e. Referring specifically to the GISP2 curve, the warm D-O events or stadial events, as numbered by Dansgaard et al. (1993), are indicated in red; D-O event 24 is older than shown here. Occasional terms (L = Little Ice Age, 8 = 8k event, Y = Younger Dryas, B = Bolling-Allerod, and LGM = Last Glacial Maximum) are shown in pink. Heinrich events are numbered in green just below the GISP2 isotopic curve, as placed by Bond et al. (1993). The Antarctic warm events A1–A7, as identified by Blunier & Brook (2001), are indicated for the Byrd record.

8200 years before present (8.2 kabp, where present is conventionally taken as the year 1950, and all ages are given in calendar years), often called the 8k event. The coldest time of the ice age was approximately 24 kabp (often called the LGM, although that term is also applied to the few millennia from 24 kabp to approximately 19 or 17 kabp, and often refers to the time of largest ice). The deglacial warming from the LGM to the Holocene was interrupted by the cooling into Heinrich event H1 (sometimes called the Oldest Dryas) approximately 16.8 kabp (Hemming 2004), and the abrupt jump to warmer conditions approximately 14.7 kabp at the start of the Bolling-Allerod warmth (which was interrupted by the Older Dryas and the Inter-Allerod Cold Periods). Cooling into the Younger Dryas (YD) followed, giving more than a millennium of cold, and then the abrupt warming at the end of the YD about 11.6 kabp, which may be taken as the start of the Holocene.

Older than the LGM, numerous large, abrupt climate jumps are evident. This millennial variability reached a notable fraction of the full glacial-interglacial amplitude (often roughly one half). Typically, a rapid warming (often completed in only 10–100 years) was followed by slow cooling, rapid cooling, and then little change or slow warming. Spacing between successive warmings was variable, but a value near 1500 years is most common (Alley et al. 2001). Broecker dubbed the warm intervals Dansgaard-Oeschger (D-O) events for the pioneering work of these paleoclimatologists (Dansgaard et al. 1984, Oeschger et al. 1984), with the implication that the events were anomalous warm times punctuating typical glacial conditions. Millennial warm intervals during the ice age are also referred to as interstadials, separating the glacial stadials. The warm interstadial/D-O events have been numbered from younger to older (Dansgaard et al. 1993), from 1 to 24 over the past 110,000 years, with the Bolling warmth given number 1; aficionados speak with fondness of "IS8" or "IS12" for interstadial or D-O warm interval number 8 or number 12. The idea that the millennial changes are not interruptions of glacial conditions, but instead that glacial-interglacial and stadial-interstadial changes represent separate, although somewhat related, oscillations, has led some workers to refer to D-O oscillations between warm and cold conditions in the Greenland records.

Bond et al. (1993) noted that a few successive D-O oscillations trended toward progressively colder conditions, and that the coldest point of such a cycle (a Bond cycle) was marked by an especially cold, long-lasting stadial. Furthermore, these coldest intervals included the Heinrich events in the ocean, short intervals of climatic and oceanographic anomalies, especially of anomalously rapid deposition, in a broad belt across the North Atlantic, of ice-rafted debris sourced largely from Hudson Bay (Broecker 1994, Hemming 2004). [Note that the putative 1500-year cycles in the Holocene, seen especially in records of ice-rafted hematite-stained grains off Greenland (Bond et al. 2001), are also sometimes referred to as Bond cycles, further confusing terminology.] The Heinrich events are numbered from younger to older (H1 to H6 over the past 100,000 years), with the YD sometimes added as H0. The coldest interval in Greenland correlates to H2. Major millennial warm intervals in Antarctic records, most of which peak near the times of Heinrich events, have been labeled Antarctic events A1, A2, . . . with increasing age (Blunier & Brook 2001).

BACKGROUND

Broecker et al. (1985) argued, "Until now, our thinking about past and future climate changes has been dominated by the assumption that the response to any gradual forcing will be smooth. But if . . . the system has more than one quasi-stable mode of operation, then the situation is more complex" (p. 25). The particular mode switch that Broecker et al. (1985) discussed was the "turning on and off of deep-water production in the northern Atlantic" (p. 24). Broecker and colleagues' argument can be summarized as (they did not order the argument in exactly this way, but these are the elements in their argument):

(a) Greenland ice-core data show many millennial climate events that began and ended abruptly (Oeschger et al. 1984, Dansgaard et al. 1984), each involving coupled shifts between near-glacial and near-interglacial values in many paleoclimate proxies, which argues against a purely local or minor explanation of the features.
(b) The most recent major oscillation in the ice-core records seems to match the well-known European pattern of warming into the Allerod (now typically termed the Bolling/Allerod), cooling into the Younger Dryas, and warming into the Holocene, confirming and extending the ice-core data.
(c) The climate anomaly pattern of the oscillation is consistent with expectations for response to changing sea-surface temperatures in the northern Atlantic.
(d) Knowledge of ocean circulation patterns shows the possibility of deep water on/off mode switches (Stommel 1961, Rooth 1982), in response to interaction between freshwater storage/release by ice sheets and salt export by deep water formation in the northern Atlantic, affecting northern Atlantic sea-surface temperatures.
(e) Available data show that changes in ocean circulation occurred.

Broecker et al. stated, “Despite the tenuous nature of the information presently available and of the difficulties inherent in thinking in terms of mode changes, we must begin to explore this alternate track” (p. 25).

Twenty years later, the data and models available are much stronger, and the arguments have been extended and sharpened in many ways, but Broecker et al.’s basic picture remains accurate: Abrupt climate changes happened, their large geographical extent is confirmed by Greenland ice-core data and by geographically widespread records, the pattern closely matches that modeled for North Atlantic causes, and models and data agree on the involvement of the meridional overturning circulation [MOC; also, loosely, the conveyor-belt circulation or the thermohaline circulation (THC); see Wunsch 2002 on terminology linked to physical processes]. The hypothesis has led to successful predictions in these areas, which have been confirmed by new observations or models.

THE ICE-CORE DATA

Data from Greenland ice cores (e.g., Dansgaard et al. 1993, Cuffey & Clow 1997, Grootes & Stuiver 1997, Johnsen et al. 2001) clearly show the orbitally modulated ice age cycles and abrupt suborbital or millennial variability. Steps in gas-isotopic fractionation, and their locations relative to changes in other ice-core indicators, show with high confidence that large temperature changes accompanied large changes in the oxygen- and hydrogen-isotopic ratios of the ice (Severinghaus et al. 1998, 2004; also see Alley 2000).

Most indicators in the ice cores correlate closely with the ice-isotopic changes (Mayewski et al. 1997). In comparison to the millennial warm times (the D-O events), the ice from millennial cold times has more sea-salt (likely indicating wind-blown “frost flowers” from newly formed sea ice; Rankin et al. 2004) and dust (likely from Asia; Biscaye et al. 1997). Neither the sea salt nor the dust have important sources in Greenland, and the higher concentrations in the ice formed during colder times cannot be explained by reduced dilution owing to reduced snow accumulation rate (Alley et al. 1995). For the dust, attempts to explain the large (to order-of-magnitude) changes have required source changes; consistent explanations involving subtle shifts in wind-fields (Wunsch 2006) have not been found (Fuhrer et al. 1999). Deuterium excess of the ice is usually argued to reflect primarily evaporation rate at the moisture source, with Greenland data interpreted as indicating more southerly moisture sources in colder millennial intervals (Masson-Delmotte et al. 2005).

Of particular importance are the Greenland records of methane (CH_4) (**Supplemental Figure 1**, follow the Supplemental Material link from the Annual Reviews home page at **http://www.annualreviews.org**) and nitrous oxide (N_2O). The concentrations of these gases began rising when abrupt warming occurred in Greenland and fell with Greenland cooling (Chappellaz et al. 1993, Severinghaus et al. 1998, Brook et al. 2000, Sowers et al. 2003, Fluckiger et al. 2004). CH_4 changed with all of the major Greenland millennial climate shifts (although amplitudes of changes were modulated orbitally), and N_2O changes have been found with all of the Greenland millennial shifts for which detailed data are available (see Supplemental Material).

CH_4 and N_2O are globally mixed, with widely distributed sources and no dominant localized sources. Although atmospheric sinks may have changed, large concentration changes are interpreted to require notable source changes (e.g., Chappellaz et al. 1993, Sowers et al. 2003). Preanthropogenic CH_4 sources were dominantly terrestrial wetlands, with important terrestrial and oceanic sources for N_2O. Terrestrial N_2O production is typically from wet soils not as saturated as for optimal CH_4 production; thus, CH_4 and N_2O sources are not exactly colocated in space and time. The oxygen- and nitrogen-isotopic data from Sowers et al. (2003) are most parsimoniously interpreted as indicating parallel changes in both terrestrial and marine N_2O sources during N_2O shifts. Deuterium-isotopic CH_4 data across the deglacial abrupt oscillations exclude the hypothesis of important contributions to concentration increases from sea-bed CH_4 (Sowers 2006).

With atmospheric-concentration changes as large as 50% associated with the D-O oscillations, the distributed sources of CH_4 and N_2O require involvement of trace-gas sources across large regions of the globe. CH_4 and terrestrial N_2O sources require wetlands. During warm D-O events, expanded or more-productive wetlands are indicated, perhaps with reduced oceanic ventilation or enhanced organic-matter flux promoting N_2O from denitrification in low-oxygen regions (Sowers et al. 2003).

Balance calculations for CH_4 require tropical sources to supplement high-northern-latitude production, especially during cold times when ice cover reduced northern sources (Chappellaz et al. 1993, Smith et al. 2004). This inference is supported by reconstructions of interhemispheric gradients in CH_4. Because the tropospheric lifetime of CH_4 is not too much longer than the interhemispheric mixing time, an increase in northern CH_4 sources will raise concentrations in Greenland more than in Antarctica, whereas an increase in tropical CH_4 sources will have a more hemispherically symmetric impact. Brook et al. (2000) found that the rise in CH_4 at the onset of the Bolling-Allerod and the rise at the termination of the YD were driven by increases in tropical as well as boreal sources, with boreal sources less important during the YD than during the warm Holocene that followed.

There is still much work to do, but ice cores show that large, abrupt shifts occurred repeatedly, affecting Greenland temperature and snow accumulation (Alley et al. 1993b), and also likely seasonality, as described below, and moisture-source locations, etc. These were accompanied by sufficiently large climate changes beyond Greenland to cause factor-of-several changes in delivery of wind-blown materials, likely involving source changes, and to cause major changes in wetlands and probably marine conditions extending across broad areas of Earth's surface, including tropical regions. These changes occurred before as well as after the last glacial maximum. Thus, the first point in the Broecker et al. (1985) argument, that Greenland ice-core data show the existence of abrupt climate changes affecting broad regions, has been confirmed very strongly, with much of the confirmation involving measurements of paleoclimatic indicators that have been developed since 1985 on samples that have been collected since 1985.

CORRELATED CLIMATE-ANOMALY PATTERNS

Dating uncertainties of paleoclimatic records typically preclude confident construction of absolutely dated climate-anomaly maps for the 8k and older millennial events, except for the sequence of events from H1 through the end of the YD. However, absolutely dated climate anomalies for this sequence (and especially for the YD) from many sites agree with the ice-core records, including cool, dry anomalies in source regions of CH_4 and Asian dust when Greenland ice showed cool, dusty, low-CH_4 anomalies. Other millennial climate anomalies in the Greenland ice cores have the same signature, and, within the dating uncertainties, widespread sites show correlative events akin to the YD.

Looking first at the YD, Broecker et al. (1985) noted the similarity in age, duration, and sign of climate anomalies in Greenland ice-core records and in widespread pollen records primarily from Europe. Much subsequent work, especially by D. Peteet [Peteet 1995a,b; Alley et al. 1993a (organized by Peteet but authored alphabetically)] summarized this effort through the mid-1990s. Recent studies, including Hughen et al. (1998), Wang et al. (2001), Shuman et al. (2002), and Vacco et al. (2005), have clarified the picture further. The YD is seen to have been a cold event across much of the Northern Hemisphere, but especially centered on the northeastern Atlantic, with anomalously dry conditions in broad monsoonal regions of Africa and Asia, tropical atmospheric circulation shifted southward especially in the Americas, and southern warmth.

The anomaly pattern of the YD is quite similar to that of the 8k event (**Figure 2**) (Alley et al. 1997a, Alley & Agustsdottir 2005, Wiersma & Renssen 2006) (although the YD anomalies were larger, persisted longer, and exhibited a Southern Hemisphere warm signature that has not yet been reported for the 8k event). Because typical dating errors for the 8k event are as large as the event duration, correlations necessarily involve some shifting of ages. The anomalously low CH_4 (and likely N_2O;

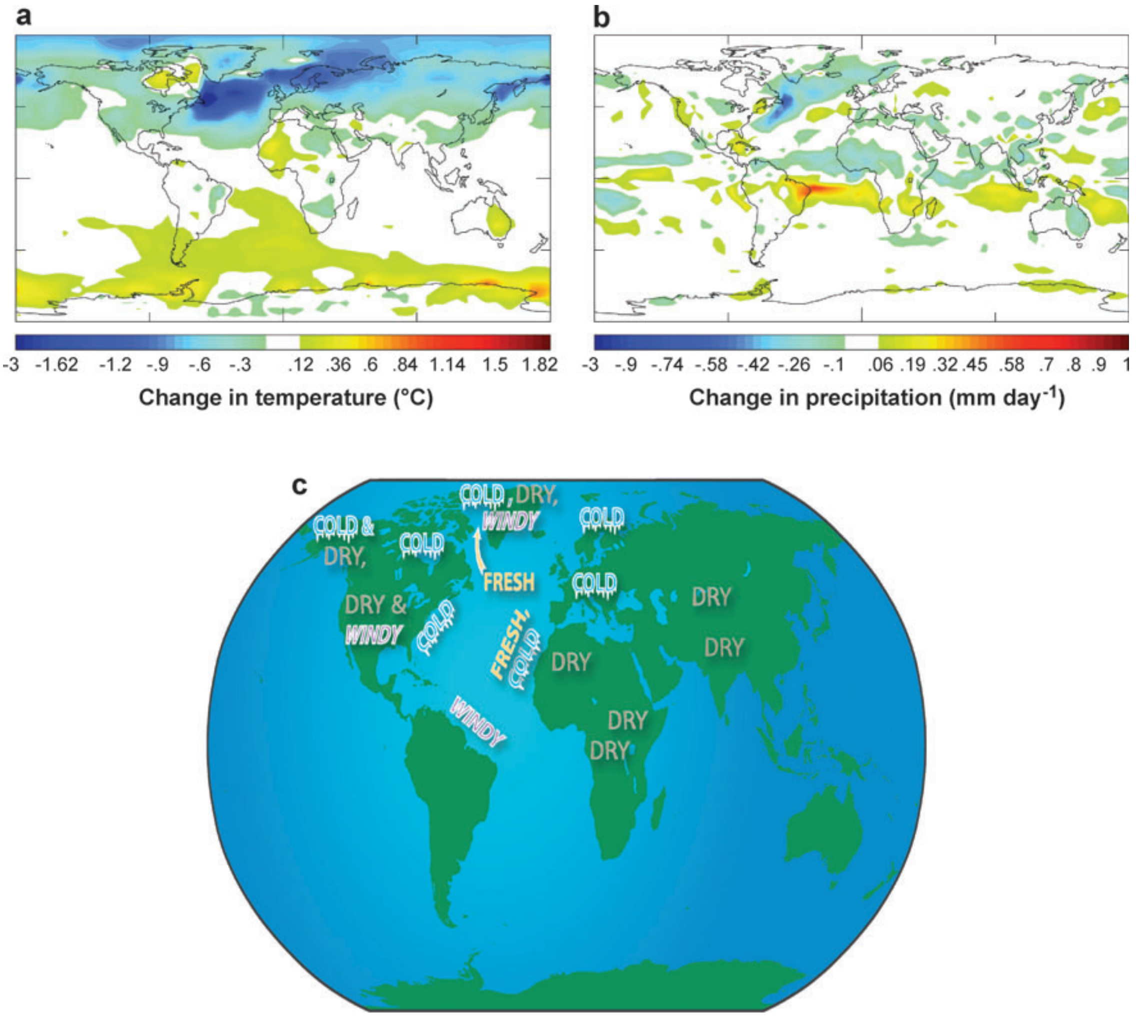

Figure 2

Simulated response to large freshwater forcing simulating the 8k event, modified from LeGrande et al. (2006). The NASA Goddard Institute for Space Studies (GISS) ModelE was used, with preindustrial boundary conditions and with freshwater addition simulated to Hudson Bay. Averages are given for five simulations using realistic forcings similar to those reconstructed for the event (2.5 and 5 Sv year of melt water over 0.5 or 1 year). Decadal-mean surface-air-temperature anomalies (°C) (*panel a*) and precipitation changes (mm/day) (*panel b*) are shown. See LeGrande et al. (2006) for the methodology of extracting the short-lived anomalies. The ensemble showed a 40% reduction in MOC from the freshwater input. Also shown is a summary map of climate anomalies, from Alley & Agustsdottir (2005). Panels *a* and *b* copyright 1993–2005 by The National Academy of Sciences of the United States of America.

Fluckiger et al. 2002) concentrations at this time support correlations to features of appropriate duration.

Older, short-lived events also can have absolute dating errors as large as event durations, and caution in correlation is warranted (Wunsch 2003). When possible, workers (e.g., Wang et al. 2001, 2004; Sinha et al. 2005) test correlations in the younger part of the record for which absolute dating is sufficiently reliable, followed by matching of older events using magnitude, pattern, and duration. Again, the knowledge from the ice-core records that each event did have a geographically widespread impact increases confidence in the correlations.

Voelker (2002) developed a database of 183 paleoclimatic records from MIS 3 (taken by them as 59–29 kabp). Sites included marine, terrestrial, and ice archives, spread across the globe, but were especially concentrated in the north and in the ocean. An assessment of whether D-O-like oscillations were present was provided for over half of those sites, yielding "yes" in 78 cases, "no" in 12, and a range of other interpretations for an additional 24 (including 15 "possibly," some that showed H events but not other D-O oscillations, etc.). The anomaly patterns obtained closely match those for the YD and 8k events.

Of particular interest here is the see-saw pattern between the northern and high southern latitudes. Broecker et al. (1985) concentrated on the northern hemisphere. However, Crowley (1992) and Stocker et al. (1992a, with coauthor Broecker 1992b) suggested that, because cross-equatorial flow feeds MOC deep-water sinking in the northern Atlantic, a reduction in that sinking would warm the south while cooling the north in a bipolar see-saw (Broecker 1998, Stocker 1998).

Tests of this hypothesis have been provided by correlation of the millennial bands of northern and southern climate records to assess coherency and phasing. Remarkably, amid the numerous climate signals, the predicted see-saw is observed with high confidence. The isotopic ratios of ice from Greenland (GISP2, GRIP, NGRIP) and Antarctic (Vostok, Byrd) ice cores have especially been used as climate indicators (Alley & Cuffey 2001), with relative age established using well-mixed atmospheric tracers [isotopic composition of oxygen (Bender et al. 1994), CH_4 concentration (Stocker 2000, Blunier & Brook 2001)].

Significant conherency was found by Steig & Alley (2002), Hinnov et al. (2002), Schmittner et al. (2003; see discussion by Huybers 2004 and Schmittner et al. 2004), Knutti et al. (2004), and Roe & Steig (2004), among others, focusing especially on the 10–90 kabp interval in Greenland and Byrd records (**Figure 1**; **Supplemental Figure 2**). Significance levels for the correlations include >99% for stage 3 by Knutti et al. (2004), and 95% for Hinnov et al. (2002) arising primarily from the 10–50 kabp time interval. (Note that Roe & Steig found most coherency in the 50–80 kabp interval with little coherency in the 20–50 kabp interval. Note also that slight differences in the analyses, such as the inclusion or exclusion of the strong deglacial signal from 10–20 kabp in a particular window, can explain much of the divergence between the results.)

Although Wunsch (2003) failed to find significant coherency at millennial frequencies, his exploratory data analysis was not optimized to do so because it split the millennial band, lumping any see-saw oscillations slower than 2500 years with the globally in-phase response to ice age variations of greenhouse gases, and combining the rest of the millennial band with noise (both climatic and proxy, e.g., Benoist et al. 1982, White et al. 1997), and with high-frequency processes (solar variations, volcanic eruptions) that may be in-phase between the poles (**Supplemental Figure 2**) and that would not be reliably synchronized by the relative-dating procedure. Even so, Wunsch (2003) noted that in his analysis, up to 15% of the variance may be in common between northern and southern records. Roe & Steig (2004) found that the significant coherence between northern (GISP2) and southern (Byrd) records left most of the variance of both records unexplained. In view of the many influences on climate and ice-core records, significant coherence and not the fraction of variance explained is the more appropriate test of Broecker and colleagues' hypothesis.

Within this coherent millennial variability, Steig & Alley (2002) found correlation peaks for a northern lead of a few centuries, antiphased, or a southern lead of more than a millennium in-phase. Hinnov et al. (2002) found a southern lead of just under 400 years, but noted that this likely arose from the application of spectral tools to records with very different shapes (abrupt warmings in the north versus gradual warmings in the south), and argued for a synchronous antiphased signal between the hemispheres. Schmittner et al. (2003, 2004) found a northern lead of 400–500 years, antiphased, arguing that a secondary in-phase southern lead arose from the somewhat periodic nature of the signals. Although Huybers (2004) favored a southern lead for the antiphased behavior, he could not reject synchronous or northern-lead results as found in the other studies.

Perhaps of greatest importance in the discussion here, modeling efforts, including those by Stocker (2000), Ganopolski & Rahmstorf (2001), Stocker & Johnsen (2003), Schmittner et al. (2003), and Knutti et al. (2004), showed that the bipolar ice-core signals are reproduced with considerable accuracy by models forced with northern freshening activating a (modified) bipolar see-saw. The delay in full achievement of southern warming associated with oceanic timescales, and especially the heat capacity of the southern ocean, is increasingly viewed as important in explaining the different shapes of the northern and southern records (Stocker & Johnsen 2003), as well as the failure of the very short-lived 8k event to be observed clearly in records of southern climate.

The observational evidence for a (modified) see-saw is not limited to ice-core data by any means (e.g., Charles et al. 1996, Lamy et al. 2004, Lynch-Stieglitz 2004, Pahnke & Zahn 2001). As reviewed by Alley & Clark (1999) and Clark et al. (2002), among others, a global multiproxy data set covering the deglaciation can be described as a globally (near) synchronous ice age cycle plus a north-south millennial see-saw.

For example, the advance of the Franz Josef Glacier, New Zealand, to its prominent late-glacial moraine (the Waiho Loop) falls just before the onset of the YD (Denton & Hendy 1994), and likely is close to the time of warming-induced retreat from the moraine (Anderson & Mackintosh 2006). Hajdas et al. (2006) similarly indicated an Antarctic-like (anti-Greenland) record for New Zealand climate across the YD interval, based on a redated bog record (also see Turney et al. 2003). The evidence from the southern mid-latitudes includes some disagreements (e.g., Ivy-Ochs et al. 1999). However, available evidence increasingly indicates a millennial seesaw pivoting about a parallel fairly close to the equator, and with the position and conditions at the pivot point also responding to the orbitally modulated ice ages.

It would be too simplistic to argue that Broecker et al. predicted a see-saw, which was then discovered. But the Broecker et al. hypothesis, that northern Atlantic "shutdowns" led to the millennial cold events of Greenland, did lead ocean modelers to the corollary hypothesis of a bipolar see-saw, and development of new data sets showing this see-saw provides strong support for the hypothesis.

MODELS AND MODEL-DATA AGREEMENT

Translation and retranslation of Broecker and colleagues hypothesis into some corners of popular culture produced the coupled absurdities of a shutdown of the Gulf Stream causing a new ice age. Similarly, clarifications have led some in popular culture to mistakenly dismiss the clear importance of the MOC in the climate system.

As discussed by Seager et al. (2002) (also see Supplemental Material), the wintertime warmth of northwestern Europe relative to other regions at similar latitudes arises not just from heat transport in the MOC but also from the moderating effects of Europe's nearby oceans with the release of summertime heat stored in the ocean, and the component of winds from the south owing to planetary waves guided by the Rockies, as well as from heat transport in wind-driven ocean currents. And yet, in numerical experiments, Seager et al. (2002) found that turning off oceanic heat flux (wind-driven and in the MOC) while holding sea ice constant caused January cooling of at least 3°C across almost all of Europe, with changes exceeding 6°C in some regions. More striking, allowing sea-ice feedbacks produced, for January, maximum cooling over the far northeastern Atlantic of more than 24°C, maximum cooling in extreme northwestern Scandinavia of more than 21°C, with cooling of 3°C to 6°C extending across southern Europe. Such large changes are not easily dismissed as trivial.

A large literature has developed on the MOC in the North Atlantic, its coupling to the rest of the world ocean and to the atmosphere, multiple modes of operation, and causes of changes, etc. The reviews by Rahmstorf (1999, 2002), Stocker (2000), and Marotzke (2000) are good starting points; also see Stommel (1961), Bryan (1986), and Wunsch (2003).

Coupled processes involving the atmosphere lead to spatial (and temporal) variations in density of oceanic surface waters owing to temperature differences (cooling increases density, with the effect larger for warmer waters) and salinity differences (increasing salinity increases density). Net evaporation from warmer parts of the ocean increases salinity, whereas net precipitation in colder regions decreases salinity, causing partially offsetting effects on surface-water density and setting the stage for the feedbacks described below. Wind-driven and tidal processes (including northward wind-driven Ekman transport in the southern ocean) mix less-dense waters into the deeper ocean in widespread regions, increasing buoyancy there and allowing localized sinking (now primarily in the North Atlantic and around Antarctica) of the densest surface waters. The higher salinity of the North Atlantic than of the North Pacific largely restricts northern sinking to the Atlantic. Net northward near-surface flow in the narrow Atlantic basin is one result, with deep return flow perhaps the defining feature of the MOC. At present, northern and southern sinking fluxes are of similar magnitude.

The possibility of two or more modes of oceanic circulation has been known for more than a century (Stocker 2000). With appropriate boundary conditions and parameter choices, models can yield circulations including from pole to equator or dominated by sinking in the southern ocean or in the North Pacific. Its small size makes the North Atlantic more easily modified than other key regions that might participate in mode-switches of the ocean. Furthermore, the largest ice-age changes in topography and fresh-water fluxes were in the North Atlantic basin, which thus has been forced more strongly than other key areas. One must entertain the possibility that changes elsewhere propagated into and affected the North Atlantic (e.g., Weaver et al. 2003), but the primary role of North Atlantic forcing as well as response seems likely.

In models that are not too highly diffusive, the circulation pattern can exhibit hysteresis (**Supplemental Figure 3**), which often is discussed relative to freshwater supply to the surface of the North Atlantic. For sufficiently small supply, the total water flux in the MOC is large. Increasing freshwater supply typically reduces the MOC flux slightly and reversibly, with balance achieved by slower export of fresher waters. However, if a threshold freshwater supply is crossed, the MOC flux drops greatly. Subsequently decreasing the surface freshwater supply slightly below that threshold gives only a slight MOC increase, and a second, lower threshold must be crossed to restore the initial MOC flux.

Two interrelated feedbacks are especially implicated in the North Atlantic changes: advective and convective (Bryan 1986, Rahmstorf & Willebrand 1995). In the large-region advective feedback, a stronger MOC flow transports more high-salinity tropical waters to the high northern latitudes, giving higher densities there during wintertime cooling and therefore favoring stronger MOC flow. Some of the Atlantic-Pacific salinity difference is related to such processes; if there were strong North Pacific sinking and deep export, the surface of the North Pacific would be saltier. If a small anomalous freshwater flux is added to the northward flowing waters of a vigorous MOC, the overturning flux will be reduced slightly. Because precipitation exceeds evaporation in the high-latitude ocean, reduction in the MOC flux will allow further freshening in a positive feedback. The MOC (together with wind-driven circulation, when included in models) typically can remove the freshwater supply and remain active up to some threshold but not beyond. If such a threshold freshwater supply exists in a model and is exceeded, continuing accumulation of freshwater in the northern Atlantic as the MOC slows will eventually reduce the MOC to near zero. The timescale for "collapse" of the MOC under possible freshwater perturbations (such as might be associated with global warming) is often found to be on the order of a century, the time for the ongoing supply to freshen the northern Atlantic in competition with the slowing but still-active export of freshwater in the MOC. This advective feedback is viewed as affecting the whole MOC, hence involving freshening or salinification of the entire northward-flowing surface branch of the MOC.

The convective feedback is more local. Wintertime sinking in high-latitude seas involves a host of local processes (e.g., Marshall & Schott 1999). A fairly shallow layer of sufficiently fresh water can interfere with the sinking of surface waters, locally stopping convection. Convection might still persist elsewhere, in response to more-favorable local conditions there and depending on the broader conditions of the MOC. However, were sufficient fresh water supplied rapidly to "cap" the entire North Atlantic by freshening the near-surface layer, a "halocline catastrophe" might occur and suppress sinking in widespread regions (Rahmstorf & Willebrand 1995). (As an imperfect analogy, a conveyor belt at a grocery store might be stopped by the widespread process of loading on too many weighty items, or by the local process of wedging a screwdriver where the belt goes down.)

The reader should also recall that, despite the relatively greater influence of salinity on water density at lower temperatures, density does still depend on temperature, and coupled temperature feedbacks or direct temperature forcing can be important. (Also note that Nilsson & Walin (2001) and subsequent papers include the possibility that northern freshening could increase overturning circulation, as well as decrease it, if the vertical mixing coefficient is a function of vertical density stratification. However, this is from a steady-state one-basin equator-to-pole rather than pole-to-pole model, and it does not seem to offset the great volume of literature, typically considering more-realistic or more-relevant settings, indicating that North Atlantic freshening would tend to decrease sinking there.)

There have been dozens, and probably hundreds, of studies of modes of ocean circulation, response of ocean circulation to freshwater or temperature forcing, hysteresis in the MOC strength, and related topics. Models have ranged from the simplest box models to fully coupled general circulation models. Background climates have included full-glacial conditions and preanthropogenic, modern, and future greenhouse. Simulated forcings have included sustained and impulse freshwater additions of various sizes in various places. A full review is far beyond the scope of this paper; the reviews noted above are good starting points. The intercomparison by Rahmstorf et al. (2005) is helpful, as well as Stouffer et al. (2006), Zhang & Delworth (2005), Vellinga & Wood (2002), and Wood et al. (2003).

My synopsis of this extensive literature is that typically (and considering only the models that calculate a quantity; clearly, a model that does not simulate sea ice does not tell us anything about sea-ice changes):

(*a*) Unless diffusion is set quite high (e.g., Manabe & Stouffer 1999; Schmittner & Weaver 2001), models exhibit bi- or multimodality and hysteresis in response to varying North Atlantic freshwater fluxes, with increased freshwater flux favoring reduced MOC.

(*b*) Mode switches include changes in locations of North Atlantic sinking, as well as in strength of sinking. A useful cartoon may be: a modern ocean with vigorous, high-latitude sinking to great depth; a glacial ocean with somewhat reduced sinking to intermediate depths at lower-latitude sites; and a Heinrich-event or MOC-off ocean with greatly reduced sinking (Sarnthein et al. 1995, Alley & Clark 1999, Alley et al. 1999, Stocker 2000, Rahmstorf 2002). However, the situation is unlikely to be this simple.

(*c*) Freshwater perturbations of given size are more effective in changing the oceanic circulation if applied more rapidly and if applied closer to the sites of deep water formation in the North Atlantic, although slow additions and additions elsewhere can affect the MOC (e.g., Rahmstorf & Willebrand 1995, Manabe & Stouffer 1997, Ganopolski & Rahmstorf 2001, cf. Weaver et al. 2003).

(*d*) Reduction of the MOC reduces the associated heat flux, leading to atmospheric anomalies and increases sea-ice extent, greatly amplifying atmospheric anomalies, especially in northern winter (e.g., Seager et al. 2002, Denton et al. 2005).

(*e*) Strong deep-water formation in the far northeastern Atlantic (the Greenland, Iceland, and Norwegian, or GIN, seas) is easier to maintain under modern than under glacial conditions; in turn, fresh water is less able to stop such high-latitude sinking in the modern than in the glacial climate (e.g., Ganopolski & Rahmstorf 2001).

(*f*) The atmospheric anomalies associated with southward shift or reduction of North Atlantic MOC sinking generally include: very strong cooling in the far northeastern Atlantic, especially in wintertime (many degrees to more than 20°C mean-annual); weaker cooling around much of the northern hemisphere, but typically of a few degrees or less remote from the North Atlantic; reduced precipitation in monsoonal areas of Africa and Asia; southward shift of the ITCZ at least over the Americas; and a somewhat delayed (decades or slightly longer) and muted warming in the middle and high southern latitudes, especially in the South Atlantic, but with more variability between models than in northern responses.

Numerous papers have assessed (dis)agreements between anomaly patterns associated with the 8k event, the YD, and various older events including the Heinrich events, and those (as described above) modeled in response to freshening or specified heat-convergence reduction in the North Atlantic (e.g., Fawcett et al. 1997, Fanning & Weaver 1997, Renssen 1997, Renssen et al. 2001, Renssen & Vandenberghe 2003, Stocker & Marchal 2000, Alley & Agustsdottir 2005, Zhang & Delworth 2005, Wiersma & Renssen 2006, LeGrande et al. 2006). Although there may be a tendency for the reconstructed climate anomalies to be slightly larger, or more easily caused, than the modeled anomalies (reviewed by Alley 2003), and specific mismatches are noted in almost every comparison, especially in quantitative aspects, the overall observed and modeled climate anomalies agree closely.

One of the main results of this data-model comparison is identification of the role of sea ice and seasonality in the events. Sea ice greatly affects regional temperature; the difference between wintertime near-surface air temperature over a sea ice–covered ocean and an open ocean may be tens of degrees. Models that simulate sea ice typically show that MOC shutdown and North Atlantic freshening favor seasonal sea ice formation in some regions (the GIN seas and perhaps the Labrador Sea are often involved) that had remained open during the winter when the MOC was vigorous, and the new sea ice growth gives strong and strongly seasonal cooling (e.g., Seager et al. 2002). Numerous proxy data sets (Denton et al. 2005; also see Lie & Paasche 2006) confirm much stronger wintertime than summertime cooling (**Supplemental Figure 4**). Shifts in seasonality of temperature and snowfall in Greenland (most cooling in wintertime, but also reduced precipitation in wintertime, so that the isotopic ratios do not record the full cooling) caused small changes in isotopic ratio of accumulated ice to represent large changes in temperature, as inferred from calibration of the ice-isotopic paleothermometer (Alley & Cuffey 2001, Li et al. 2005, LeGrande et al. 2006). A strong sea ice anomaly on one side of the equator is modeled to shift the ITCZ toward the other hemisphere (Chiang & Bitz 2005, Li et al. 2005), in part owing to cooling and drying in the hemisphere with the extra sea ice.

Broecker et al. (1985) did not predict all of this directly, but their hypothesis has led to this understanding. They focused on data-model agreement in the North Atlantic. Subsequent refinement of models increasingly demonstrated that the hypothesized northern Atlantic freshening would not only have cooled that region and immediately surrounding land, but also would have caused the other anomalies noted. Subsequent data collection, running more-or-less in parallel with the modeling, found those additional anomalies in close agreement with modeled expectations.

EVIDENCE OF MOC CHANGES CORRELATED WITH ABRUPT CLIMATE CHANGES

The evidence available to Broecker et al. (1985) on MOC changes was quite sketchy. Those authors cited isotopic data, and especially Cd:Ca ratios of benthic foraminifera in the North Atlantic (Boyle & Keigwin 1982), as indicating reduced deep water formation in the North Atlantic during glacial times, and also cited a personal communication from N. Shackleton suggesting deep water formation in the Pacific during glacial times. Broecker et al. then noted that the data linking different ocean-circulation patterns to different climate states were consistent with the idea that the short-lived (stadial-interstadial) temperature changes involved the same ocean-circulation changes as did the long-lived (glacial-interglacial) temperature changes.

Water-mass distributions for glacial-interglacial and stadial-interstadial changes are often reconstructed using tracers. Water that has been near the ocean's surface sufficiently long (decades or longer) is largely stripped of nutrients and chemicals, including cadmium (Cd), that follow nutrients in the ocean, and is depleted of carbon-12 (^{12}C; hence enriched in carbon-13, ^{13}C) because those materials are used preferentially in plant growth and eventually exported to the deep ocean in sinking fecal pellets and other materials. Near-surface water also approaches carbon-14 (^{14}C or radiocarbon) equilibrium with the atmosphere. In contrast, water that has been in the deep ocean for a long time (centuries to millennia) accumulates Cd and ^{12}C by dissolution of the sinking pellets and loses ^{14}C to decay.

Waters that sink around Antarctica first flow southward deeper than the floor of Drake Passage, and upwell before sinking again, failing to spend long enough on the surface to reach ^{14}C equilibrium and to be greatly depleted of ^{12}C and Cd. Waters that sink in the North Atlantic first flow northward near the surface from the South Atlantic, gaining the full surface signal. Thus, southern-sourced and northern-sourced deep waters can be differentiated based on tracer characteristics. Glacial-interglacial mapping has been achieved, and some stadial-interstadial mapping, of water-mass characteristics that exhibit these signals (e.g., Sarnthein et al. 1995). High time-resolution records from especially favorable sites with high deposition rates are also available.

Some of the difficulties in use of tracers to infer oceanic circulation are discussed by LeGrand & Wunsch (1995) in relation to the LGM ocean, an easier problem than during the shorter-lived stadial/interstadial oscillations. A chain of scientific reasoning is required to link an instrumental indication of Cd:Ca ratio in the shell of a bottom-dwelling foraminifer to the ocean circulation at the time that foraminifer lived. Accepting the measurement, dating, and linkage between shell and water compositions, and that southern-sourced and northern-sourced waters maintained their distinctive differences in ^{12}C, ^{14}C, Cd, and other tracers, a map of these characteristics still does not provide a three-dimensional representation of the locations, directions, and velocities of the flows supplying those water masses.

Nonetheless, the Broecker et al. (1985) hypothesis has led to specific predictions about correlations between climate shifts and changes in these and other tracers, which have been confirmed with high confidence, and I am aware of no other competing hypothesis that has done so. The modeled oceanic response to North Atlantic freshening generally includes a reduced flux or a shallowing of northern-sourced waters in the Atlantic, allowing northward and upward expansion of southern-sourced waters. This predicts the higher Cd and lower ^{13}C and ^{14}C observed in the northern deep Atlantic during colder times in the north. (Remembering, again, that the collection of data and development of modeling have proceeded together, and that not every record is equally clear or in equally strong agreement.)

Sarnthein et al. (1995) (also see Elliot et al. 2002), for example, mapped $\delta^{13}C$ in the eastern North Atlantic, and found evidence consistent with three modes of flow: a modern mode with vigorous high-latitude sinking, a glacial mode with sinking shifted farther south and not reaching as deeply in the ocean, and a Heinrich mode with little northern sinking. Keigwin & Boyle (1999) found, for stage 3 at Bermuda Rise, that each of the stadial-interstadial changes in Greenland ice cores between 32 and 58 kabp has a correlative in surface-temperature records (within the dating uncertainties), that $\delta^{13}C$ "decreases during every stadial event, consistent with reduced production of the deepest component of North Atlantic Deep Water and shoaling of its interface with Antarctic Bottom Water" (p. 164) (and with little dating uncertainty between benthic water-mass records and planktonic surface-temperature records), and that the Cd:Ca measurements made across one interstadial support this interpretation.

Keigwin (2004) combined paired benthic-planktonic ^{14}C ages of foraminifera from Bermuda Rise to trace the boundary between deeper waters with characteristics consistent with southern-sourced water and shallower waters with northern-source character. He found that the boundary was shallower during the LGM and the YD than today or just before or after the YD (also see Boyle & Keigwin 1987, Keigwin et al. 1991).

Based on paired uranium-series disequilibrium and ^{14}C ages of deep-water corals, Robinson et al. (2005) documented rapid switches between ^{14}C-enriched and ^{14}C-depleted waters in the deep western North Atlantic. The ^{14}C-enriched (northern-sourced) waters were present in the deep ocean during times when the North Atlantic surface was warm, replaced by depleted waters during surface cold times, consistent with the bipolar see-saw; intermediate waters showed more variability.

Skinner & Shackleton (2004) compared radiocarbon ages of benthic and planktonic foraminifera shells from a deep core in the northeast Atlantic, cross-dated the core to Greenland ice-core records using assumed synchrony of cooling in Greenland and in surface waters at the site, and also assessed deep-water temperature and carbon- and oxygen-isotopic composition. Skinner & Shackleton (2004) found clear evidence for reduced deep water ventilation during the LGM, increase with the Bolling-Allerod warming, and reduction with the YD cooling, consistent with varying dominance by northern-sourced (North Atlantic deep water) versus southern-sourced water (Antarctic bottom water). They stated, "The fact that deglacial changes in the deep water radiocarbon content of the northeast Atlantic run parallel to opposite changes in atmospheric radiocarbon content and in parallel with Greenland temperature fluctuations unequivocally implicates changes in ocean circulation in deglacial climate evolution and illustrates the capacity for the deep ocean to respond and contribute to abrupt climate change" (abstract).

Because of carbon cycle coupling between ocean and atmosphere, the Broecker et al. hypothesis implies that atmospheric CO_2 and ^{14}C should have shifted along with the oceanic changes at abrupt climate events. As summarized in the Supplemental Material, many data sets are consistent with this expectation.

At least three additional and independent approaches reach the same results as these geochemical proxies: Gulf Stream transport, deep Atlantic grain sizes, and ^{231}Pa:^{230}Th.

Gulf Stream transport was reconstructed by Lynch-Stieglitz et al. (1999). The oxygen-isotopic composition of benthic foraminifera is heavier in colder or saltier waters. Separating these effects is nontrivial, but because colder or saltier waters are denser, the foraminiferal isotopic composition is a better indicator of water-mass density than of either factor contributing to that density. Vertical profiles of density across Florida Strait for a time slice allow geostrophic calculation of the Gulf Stream flux, consisting of MOC and wind-driven components. Reduced transport is reconstructed for the LGM, consistent with reduced MOC (Lynch-Stieglitz et al. 1999). That data set lacked sufficient time resolution to test changes across the YD or other abrupt events, but it does provide evidence of reduced MOC transport at a time when North Atlantic records of ^{14}C, $\delta^{13}C$, and Cd:Ca also indicate reduced MOC transport, suggesting that the interpretation of similar changes in $\delta^{13}C$, ^{14}C, and Cd:Ca over shorter intervals is also accurate. Furthermore, in an abstract, Lynch-Stieglitz & Curry (2003) reported higher time-resolution results, indicating reduced Gulf Stream transport through Florida Strait during the YD.

Deep-current strengths associated with the MOC were estimated from grain-size data in a depth transect of sediment cores from the northeastern Atlantic (50–60°N, 15–25°W, 1100–4045 m depth) by McCave et al. (1995). They found weaker deep flows during colder times of the LGM, H1, and the YD, with strengthened intermediate-depth flows, indicating shallowing of the deep flows of the MOC with surface cooling. Comparison to previously published data from the western North Atlantic showed much agreement. McCave et al. interpreted this to indicate "(t)emporal patterns of circulation reassuringly similar to some of those inferred from isotopic and chemical indicators" (p. 151).

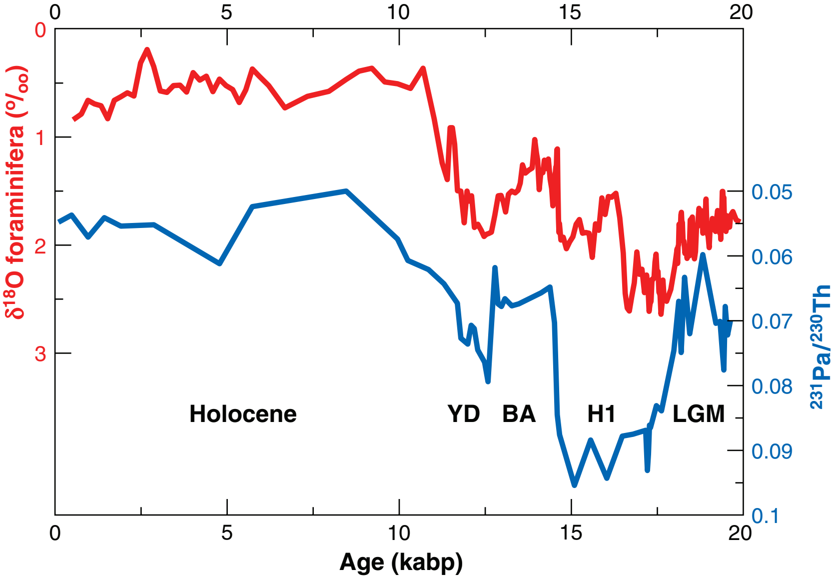

Figure 3

^{231}Pa:^{230}Th (*blue*, calculated for ^{238}U support; ^{232}Th-based calculation results are quite similar) and surface-water temperature indicator (*red*; three-point running average of δ^{18}O of planktonic foraminifera *G. inflata*) for core from 34°N, 58°W, 4.55 km depth in NW Atlantic (from McManus et al. 2004). Note that both scales are inverted, such that downward indicates colder conditions and closer approach to production ratio of ^{231}Pa:^{230}Th, which is 0.093; downward shift is interpreted to be colder surface waters and weaker MOC. Holocene, YD, BA, H1, and LGM are indicated following McManus et al. (2004).

Probably the most interesting development, and the strongest evidence for MOC changes coincident with millennial abrupt changes in the northern Atlantic, comes from the analysis of ^{231}Pa:^{230}Th ratios in North Atlantic sediments (McManus et al. 2004, Gherardi et al. 2005, also see Marchal et al. 2000 and Siddall et al. 2005) (**Figure 3**). Both ^{231}Pa and ^{230}Th are produced in uranium decay series (from ^{235}U and ^{234}U, respectively) from well-mixed species with long residence times. Both Pa and Th adsorb rapidly on particles, but Th has a residence time of 20–40 years in the water column, and Pa has a residence time of 100–200 years. Particle fluxes strip most of the Pa and Th from waters entering the North Atlantic, with opal deposition in the circum-Antarctic belt important. The similarity of residence times of water in the North Atlantic, and of ^{231}Pa in the water, allows the MOC to export a notable fraction of the ^{231}Pa produced in the North Atlantic, whereas almost all of the ^{230}Th produced in the North Atlantic is deposited there. Were the MOC flux to decrease, increasing the residence time of waters in the North Atlantic, then ^{231}Pa:^{230}Th would shift from its vigorous-MOC ^{231}Pa-depleted value toward the production ratio.

Hence, Broecker and colleagues' hypothesis makes a direct prediction, which was not involved in the original hypothesis and not widely measured at that time, about the history of ^{231}Pa:^{230}Th in North Atlantic sediments. Subsequent improvements have allowed sampling to test this hypothesis. The simple answer is that the prediction is borne out (**Figure 3**). As stated by McManus et al. (2004; p. 834), "these results confirm the significance of variations in the rate of the Atlantic meridional overturning circulation for abrupt climate changes." Sampling on both sides of the North Atlantic shows that near-surface cool intervals of the YD and H1 (and, at least for the western North Atlantic, the LGM) were accompanied by ^{231}Pa:^{230}Th ratios shifted toward production values. Subtle differences between the eastern and western North Atlantic signals are quite interesting, but in no way weaken the main observation. The parallel behavior across the basin argues against any odd interpretations of particle fluxes, etc.

Clearly, one would like to have multiple indicators of water-mass distribution and current strength across the full bestiary of events, whereas at present most indicators are restricted to the deglacial sequence (although some data extend into stage 3), and three-dimensional mapping is not available for many. Nonetheless, the Broecker et al. hypothesis of involvement of the MOC in millennial oscillations has led to qualitatively (and often quantitatively) successful predictions about a host of indicators, including trace-element, stable and radioactive carbon-isotopic changes, grain-size and water-isotopic distributions in the ocean, and coupled atmospheric-carbon changes. Although there clearly are cases in which data or model are not in full agreement with Broecker and colleagues' hypothesis (e.g., see Stocker & Marchal 2000), I know of no strong cases in which important predictions of the MOC/millennial-climate hypothesis were extensively tested and found to fail consistently, whereas consistent successes are now common.

CHALLENGES AND OPPORTUNITIES

The basic success of Broecker and colleagues' hypothesis is clear as a predictive as well as explanatory idea. Yet large gaps exist in our data, models, and understanding of the system, and the changes that happened, and these gaps surely impact our interpretation of possible future changes.

The MOC, and in particular the northern Atlantic portion, can operate in multiple modes. Depending on the model used, and the mean state of the climate, there may be up to several modes, and one or more may be stable. The two-mode ("on-off") model is a useful thought experiment but is clearly too simple. The three-mode picture is supported by some evidence (Sarnthein et al. 1995, Alley & Clark 1999, Alley et al. 1999, Stocker 2000, Rahmstorf 2002). In this view, the presence or absence of wintertime sea ice in the GIN seas has important impacts on Greenland climate and broad regions of the Northern Hemisphere, but relatively subtle influences on oceanic circulation and linked climate beyond the North Atlantic; wintertime sea ice growth in the GIN seas is linked to southward shift of sinking for the MOC, and perhaps with shallowing or decreased vigor of the sinking, but MOC sinking continues. The additional cooling shift to the Heinrich or "off" mode involves shallowing and reduction of the remaining sinking, linked with Heinrich events, and has a relatively larger impact on the MOC flux, and hence the Southern Hemisphere, but a relatively smaller impact on sea ice, hence the Northern Hemisphere, than does the mode switch involving the GIN seas. This almost certainly still oversimplifies reality, but may be a useful starting point for additional research.

The background climate state rather clearly affects the preferred mode of operation of the system, based on models and data. The GIN seas likely became "stuck" with wintertime sea ice during the LGM, with persistent cold conditions recorded in Greenland. Generation of wintertime sea ice in the warmer Holocene climate is not as easy, with persistently warmer conditions in Greenland and the GIN seas. The Holocene GIN seas may have been temporarily shifted toward wintertime sea ice by the largest of the freshwater forcings, the flood from Lake Agassiz just before the 8k event (Clarke et al. 2004), but the condition did not stay beyond a century (Alley & Agustsdottir 2005). When orbital forcing placed the mean climate state intermediate between glacial and interglacial conditions, as in stage 3, oscillations occurred between cold and warm states in the GIN seas. However, despite many insights, I do not believe that we know the functional dependence of the stable state(s) and the hysteresis loops on the orographic effects of the ice sheets (with larger ice in North America favoring more-zonal winds across the Atlantic and thus increased wintertime sea ice formation in the GIN seas), the radiative effects of greenhouse gases, and the orbitally controlled distribution of insolation (with conditions favoring cold GIN seas in turn promoting wintertime sea ice there). The role of brine rejection from sea ice growth and of fresh-water transport linked to sea ice drift also could be elucidated better (e.g., Wang & Mysak 2006), as could the relative importance of surges or floods versus sustained meltwater routing (Meissner & Clark 2006).

As noted by many workers, the ice core data suggest that during at least most of the ice age stadial-interstadial oscillations, the warm interstadials could not be sustained. Large and abrupt warming was followed almost immediately by gradual cooling, leading to more-abrupt cooling. Whether the interstadials were simply unstable or ice melting from the interstadial warmth freshened the North Atlantic and pushed it from an initially stable mode toward an unstable mode remains unclear. Whichever, if the system was destined to switch from a warmer to a colder mode, it is almost guaranteed that a freshwater event (a surge or flood or switch in location of freshwater input to the North Atlantic) served to trigger each cooling, even if the cooling was inevitable in a steady climate, because there were so many surges and floods and switches in freshwater input to the North Atlantic (e.g., Teller & Leverintgon 2004, Donnelly et al. 2005, Rayburn et al. 2005). (By analogy, a mortal body is guaranteed to die, but the death certificate lists a cause; prevention of that cause would have served only to delay the inevitable. Even if the North Atlantic circulation during interstadials was destined to die, something still killed it.) The Broecker et al. (1990) salt oscillator remains intriguing, with a background state (orbits, CO_2, insolation, ice-sheet configuration) in which the North Atlantic could not remain permanently in one steady state, but had to oscillate between two (or more) states around a hysteresis cycle. In the real, noisy climate system, both warmings and coolings would have had "causes," although the cycling was inevitable. However, for glacial background conditions, Ganopolski & Rahmstorf (2001) found only a single, cold steady state that could be perturbed easily to a second, warmer steady state before decaying back (also see Romanova et al. 2004).

The preferred spacing of approximately 1500 years between abrupt warmings is highly intriguing (e.g., Grootes & Stuiver 1997, Alley et al. 2001). Spectral analyses tend to indicate that the existence of true periodicity at this frequency depends on which published timescale is adopted (Hinnov et al. 2002); for example, the GISP2 Meese-Sowers timescale (Meese et al. 1997) gives a clear periodicity (Rahmstorf 2003), whereas some other timescales do not. This tends to support the existence of the periodicity; fortuitous errors are unlikely to have produced the observed precise clock in the GISP2 timescale (Rahmstorf 2003). Nonetheless, as one intimately involved in timescale development (Alley et al. 1993b, 1997b), I find it hard to believe that we could have produced sufficiently accurate results to find such a precise clock, so I remain personally confused.

Regardless of timescale and precision of clock, there does exist a preferred spacing of roughly 1500 years between abrupt warmings, across a range of sampling intervals and definitions of what exactly is an abrupt warming (and a similar result is obtained for coolings) (Alley et al. 2001). Furthermore, there is a suggestion of a preferred spacing of approximately 3000 years, with avoidance of spacings of approximately 2250 and 4250 years. This at least suggests the possibility of elements of stochastic resonance, that a weak "clock" of some sort combines with noise to pace the transitions [Alley et al. 2001, Ganopolski & Rahmstorf 2002; also see Eyink 2005; to the best of my knowledge, no one has suggested that the noise and signal are tuned to optimize stochastic resonance, but Alley et al. (2001) specifically argued against such a tuning, with implications for the hypothesis-testing of Roe & Steig (2004).] A solar clock seems most likely (Bond et al. 2001), if a clock is ticking. Braun et al. (2005), using an intermediate-complexity model, showed how superposition of solar cycles of 87 and 210 years might give rise to a 1470-year spacing of D-O-type events. Unfortunately, given the available dating uncertainties, and the limited length of the records, these questions are difficult to answer at this time (Alley et al. 2001), and new dating and data sets are probably required to make notable headway.

Broecker et al. (1989) presented evidence from Gulf of Mexico sediment cores showing the signature of meltwater drainage from the Laurentide ice sheet down the Mississippi River shortly before and after, but not during, the YD event. Broecker et al. (1989) suggested that eastward diversion of the meltwaters (see Meissner & Clark 2006), likely beginning with a flood, triggered and maintained the YD cold, and perhaps that a southward diversion helped reestablish the MOC in the northern Atlantic and end the YD cold interval. Other cold events have been linked to floods, including the 8k event (Barber et al. 1999) and the Preboreal event just after the end of the YD (Fisher et al. 2002; also see Nesje et al. 2004, Donnelly et al. 2005, and Rayburn et al. 2005, and papers cited therein). The recent work of Aharon (2003) agrees with Broecker et al. (1989) in showing diversion of glacial meltwater away from the Gulf of Mexico during the YD. However, Aharon (2003), Flower et al. (2004), and Lowell et al. (2005) are among recent researchers suggesting that the overall story could prove to be somewhat more complex than previously believed. Refined dating of events is almost certainly needed, especially in the Lake Agassiz basin (Broecker 2006).

Additional work seems warranted for understanding the mechanisms of deep water formation in the North Atlantic, coupling to sea ice, and controls on sea ice because of the critical role these played in the past changes, and the role they may play in future changes. Although some careful work has been done (e.g., Zhang & Delworth 2005) the mechanisms by which North Atlantic changes affect other features (shifts in ITCZ, monsoonal precipitation, etc.) are often not as well understood as they might be, and enhanced insights should prove useful.

Note added in proof: The study by Seager & Battisti (2007) covers some of the same material reviewed here, and then provides an interesting and useful perspective on atmospheric and oceanic processes in and well beyond the North Atlantic, and on the possible role of tropical or other extra-North Atlantic processes in the abrupt climate changes. Clearly, the reality of the abrupt climate changes, and the success of the Broecker et al. (1985) view in predicting new data sets, do not provide a complete process understanding of the events; much interesting science remains.

SUMMARY

Broecker et al. (1985) combined paleoclimatic data from ice, land records, and deep and shallow marine settings; results from atmospheric and oceanic modeling; and process understanding to present the audacious hypothesis of important paleoclimatic changes in response to mode flips in the MOC in the northern Atlantic. Broecker et al. (1985) noted "the tenuous nature of the information presently available." Since then, in numerous papers (e.g., Broecker et al. 1988, 1989, 1990; Broecker & Denton 1989; Broecker 1994, 1997, 1998), Broecker and colleagues have worked to thicken the tenuous information and to build and join communities to do likewise. Although greatly refined, the basic picture remains essentially unchanged. Too much freshwater in the North Atlantic will slow the MOC sinking or shift it southward, allow sea ice growth in the GIN seas and perhaps elsewhere, and generate important and widespread climate anomalies. Strong feedbacks and hysteresis in the North Atlantic allow abrupt mode switches. The preferred mode(s) depends on the background climate, but modes, hysteresis, and jumps are possible in a broad range of climates. (Clearly, in a climate that is too warm for wintertime sea ice formation in the absence of MOC sinking, cessation of MOC sinking cannot generate wintertime sea ice formation.)

Broecker et al. (1985) provided perhaps the wisest council arising from this understanding: "Thus, if the changes that characterized glacial time and those that will characterize the coming CO_2 superinterglacial time involve mode switches, investigations of the transient climate response have to allow for this possibility. . .we must begin to explore this alternate track. . . . Even given the full use of present resources, it will be several decades before we possess sufficient understanding to predict future climates. Unless we intensify research in these areas, the major impacts of CO_2 will occur before we are prepared fully to deal with them." I can do no better today than to echo this statement.

FUTURE ISSUES

Prediction of future shutdowns inevitably involves details of model performance as well as forcings and requires more space than is available here. A few results seem clear, however:

(*a*) MOC shutdown cannot trigger a new ice age, completely stop the mostly wind-driven Gulf Stream, cause the extinction of humanity or even of Europeans, or exceed the fertile imaginations of Hollywood writers.

(*b*) Although unlikely, MOC shutdown remains possible and important. The strong link between past MOC changes and rainfall in monsoonal regions and elsewhere raises clear concerns about the future; pending better elucidation of the mechanism(s) involved, and whether they are adequately reproduced in model studies, even weakening of the MOC conceivably could be important.

(*c*) Typical coupled-model "global warming" runs over the next century or more usually produce slowing of the MOC without shutting it down or causing net cooling, and thermal as well as salinity effects are important (Gregory et al. 2005, Stouffer et al. 2006).

(*d*) However, some intermediate-complexity models indicate that future freshwater fluxes in a warming world, including possible meltwater fluxes from Greenland, could be sufficient to trigger a shutdown (Rahmstorf et al. 2005; also see Fichefet et al. 2003 and Schlesinger et al. 2006), although a shutdown does not occur in other intermediate-complexity models (also see Ridley et al. 2005).

(*e*) Were a shutdown to occur fairly soon, notable regional climate anomalies, including net cooling over the northeastern Atlantic, would be expected (Fichefet et al. 2003, Wood et al. 2003).

(*f*) Impacts of such a shutdown are expected to be sufficiently large that they merit serious consideration in planning to generate optimal economic response to greenhouse gas emissions (Keller et al. 2000, 2004).

In short, even though a large, rapid, high-impact event seems unlikely based on most of the literature, the nonzero possibility and the potentially large impacts motivate further research, which is likely to pay off in knowledge for policy makers.

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