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THE END OF THE PRESENT INTERGLACIAL: HOW AND WHEN?

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Abstract—Despite the large decline in Northern Hemisphere summer insolation during the last 8000 years, neither sea level nor polar temperatures have as yet undergone any significant downturn. This behavior is consistent with the prediction by Kukla and Matthews (1972) that the Holocene interglacial will terminate suddenly with a jump to another of the climate system's modes of operation. This is what happened at the end of the last period of peak interglaciation. However, complicating the situation is evidence that ice sheet growth during the transition from marine stage 5e to 5d preceded the shut down of the Atlantic's conveyor circulation which is thought to have brought Europe's Eemian to a close. If so, then in the natural course of events, the end of the present interglaciation awaits the onset of ice cap growth. However, it must be kept in mind that the ongoing buildup of greenhouse gases may alter the natural course of events. In particular, the warming and wetting of the planet will gradually reduce the density of surface waters in the regions where deep waters form. As this reduction is not likely to be symmetrical between the northern Atlantic and the margin of the Antarctic continent, the current near balance between deep water production in the north and south may be disrupted causing an abrupt reorganization of the ocean's thermohaline circulation. Based on the paleoclimatic record, such a reorganization would have had a profound impact on the planet's climate. © 1998 Elsevier Science Ltd. All rights reserved.

QSR VIEWPOINT

INTRODUCTION

In 1972 Brown University's R.K. Matthews and Columbia University's George Kukla wrote a letter to then President Richard Nixon warning him that, as the present interglacial had pretty much run its course, the Earth was in danger of being plunged into yet another period of glaciation. Further, based on Kukla's studies of loess deposits in Czechoslovakia and Austria these Cassandras predicted that this transition would be an abrupt one (Kukla and Matthews, 1972). Nixon's staff passed this letter along to the State Department from whence it went to the National Academy of Sciences. Interestingly enough, the Academy then sent it to John Imbrie (at Brown) and me (at Columbia) for comment. I do not remember exactly what we said, but, as both of us were at that time enamored with the gradual ramp-like declines from full interglacial to full glacial conditions, I suspect that we attempted to defuse this dire warning. However, had this incident occurred in 1996 instead of 1972, I certainly would have taken it more seriously. The reason is that over the last decade, we have come to the realization that, during the course of the last ice age, the Earth's climate was punctuated by a series of abrupt changes which bounded alternating millennia of extreme cold and intermediate cold conditions (known as Dansgaard-Oeschger events). Not only were the differences in climate between these states very large (i.e. comparable to perhaps one third to one half of the full glacial to full interglacial change), but they have now been shown to have been global in extent. With this new information in hand, three questions come to mind.

(1) Were previous intervals of peak interglaciation terminated by abrupt global coolings?
(2) How close are we to the end of the present interval of peak interglaciation?
(3) Will the ongoing buildup of greenhouse gases alter the natural sequence of events?

Question 1: Were previous intervals of peak interglaciation terminated by abrupt global coolings?

The answer to this question is part of a more general one. What fraction of the climatic change experienced by the Earth over the last million years was the result of gradual shifts within one of its modes of operation and what fraction was associated with jumps from one of these modes to another? Imbrie *et al.* (1992, 1993) opted for a world in which climate follows smooth sinusoids. While recognizing that abrupt changes occurred, they relegate them to a minor role. By contrast, Broecker and Denton (1990) opted for a world in which climate is dominated by jumps from one mode of operation to another. While these authors acknowledged that trends in past climate correlate with orbitally-induced seasonality cycles, they attribute this correlation to an orchestration of the preferred operational modes. Another way of stating this difference in outlook is that Imbrie *et al.* point to the ^{18}O records preserved in benthic foraminifera as typifying the record of global climate while Denton and I point instead to the record preserved in Greenland ice. As can be seen in Fig. 1, the difference between these records is stark. Clearly, the truth must lie somewhere between these extremes.

As no firm answer can be given to the more general question, let us retreat to a specific one. How do interglacials end? I lean toward the Kukla–Matthews point of view that they end abruptly. One reason is that neither the Holocene trend in sea level nor that in the oxygen isotope composition of polar ice provides any hint that Earth climate is responding to the decrease in summer insolation change which occurred in the Northern Hemisphere over the last 10,000 years (see Fig. 2). Since the excess ice from the last glaciation melted away, sea level has remained very nearly constant. During the last 6000 years, it has dropped by only about 1 m. Nor has the $\delta^{18}O$ for Greenland ice shown any tendency toward the cooling expected in response to the decline in summer insolation at high northern latitudes. To me this suggests that through the course of the Holocene, climate has remained locked in one of its operational modes and that the range of conditions within this mode has been remarkably small. The implication is that the passage of Earth climate out of the present interglacial conditions will be an abrupt one involving a jump to another of its other modes of operation.

In this regard, it is of interest to look at the climate record kept in ice and sediment to see how the last period of peak interglacial conditions ended. Unfortunately, the undisturbed portion of the record kept in Greenland ice does not extend back that far. Rather, it extends to only about 110,000 years B.P., about 5000 years shy of the end of the 5e period of pronounced warmth (Johnsen *et al.*, 1992). Although 200 m of ice older than 110,000 years were cored by the GRIP and GISP groups, tilting and folding of individual layers in this basal ice and the lack of correlation between the basal portions of the two Summit ice cores strongly suggest that this portion of the record is seriously disturbed. Perhaps the Greenland ice cap was reduced in size during the Eemian. Such a reduction would help to explain the observation that during the peak of the last interglacial warm interval sea level stood several meters higher than now (Picket, 1981). If so, one could postulate that the ^{18}O-enriched portions of the basal ice in the Summit cores accumulated at a lower elevation and then after the close of the Eemian when the cap was rejuvenated, this ^{18}O-enriched ice was shuffled together with remnants of the stage 6 ice (^{18}O-depleted), creating the alternating sequence of ^{18}O-rich and ^{18}O-poor ice which constitutes the lower portions

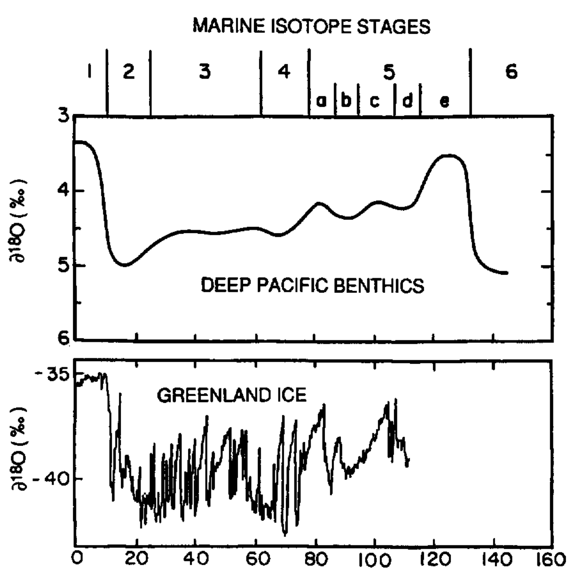

FIG. 1. Contrast between the record of ^{18}O in deep Pacific benthic foraminifera (Shackleton *et al.*, 1983) and that in Greenland ice (Johnsen *et al.*, 1992). The undisturbed portion of the latter record extends back only to marine isotope stage 5d.

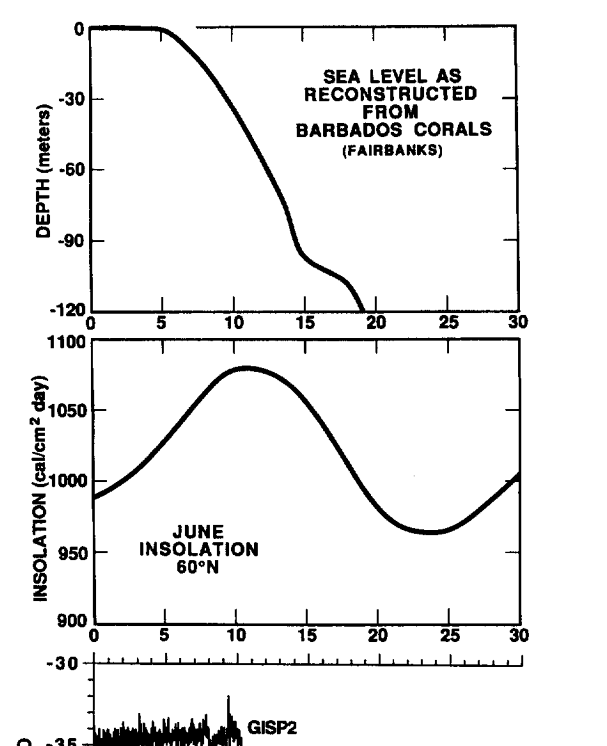

FIG. 2. Comparison of the records for sea level (Fairbanks, 1989; Bard *et al.*, 1990) and $\delta^{18}O$ in polar ice with that for June insolation at 60°N over the last 30,000 years. As can be seen, while over the last 10,000 years insolation has steadily dropped, there is no evidence for re-initiation of ice growth or for a decline in Greenland air temperature. The correlation between the Greenland (GISP2) and Antarctic (Byrd) ice cores is modified after Sowers and Bender (1995).

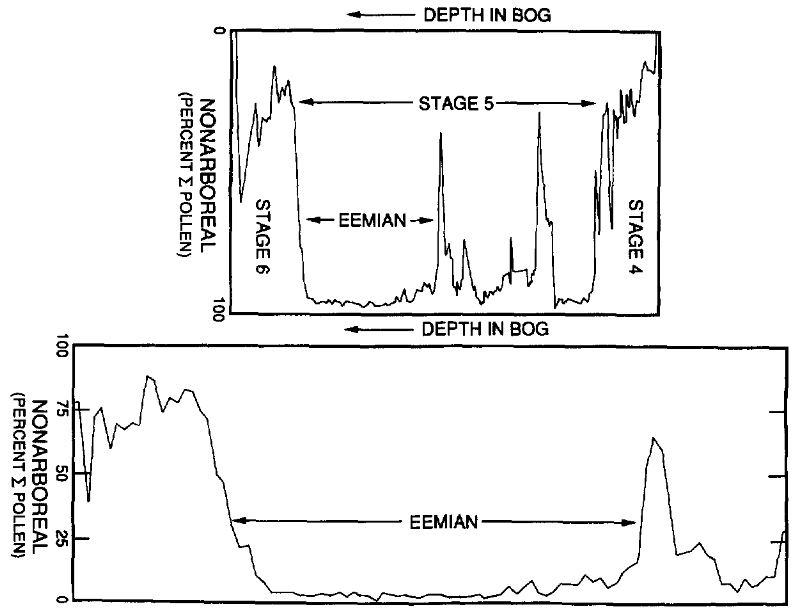

FIG. 3. Pollen record obtained by Woillard (1978) for a peat bog in northeastern France (44°N 7°E). The portion of the record reproduced on the left covers the entire interglacial interval (i.e. marine isotope stage 5) and that on the right covers only the initial third of this interval (i.e. the Eemian).

of the GRIP and GISP ice cores. In any case, we must look elsewhere for evidence regarding the nature of the demise of the last period of peak interglaciation.

Two detailed records from the region strongly impacted by the Younger Dryas cold event (and hence presumably sensitive to the strength of the conveyor) suggest that the European Eemian came to an abrupt close. One is Woillard's (1978) pollen record from northeastern France (48°N). As reproduced in Fig. 3, a sharp rise in the percentage of non-arboreal pollen grains from less than 15% to about 65% of the total grains marked the end of the Eemian. The other is the McManus *et al.* (1994) marine record from 54°N in the eastern Atlantic. As reproduced in Fig. 4, ice-rafted debris (absent during marine stage 5e) suddenly reappears and *N. pachyderma* (left coiling) planktonic foraminifera (rare during marine isotope stage 5e) suddenly jump to prominence. This evidence suggests that, at least in the northern Atlantic basin, the end of the peak warm conditions of the last interglaciation came suddenly (Kukla *et al.*, 1997), implying that climate jumped from one to another of its operational states. This strengthens the case that the Holocene is likely to come to an abrupt close.

Question 2: How close are we to the end of the present interval of peak interglaciation?

In order to estimate how long it will be before the present period of interglacial warmth comes to an end, we first have to estimate how long previous periods of extreme warmth lasted. Our best indicator is ^{18}O records in benthic foraminifera. In these records, the periods of extreme warmth appear to be roughly one half of a precession cycle (i.e., $\sim$ 11,000 yr) in duration. Furthermore, all but one of the Terminations, which brought the major 100,000-yr-duration glacial cycles to a close, occurred during peaks in northern hemisphere summer insolation. Because of this, the bulk of opinion has held that the peak interglacial conditions which followed on the heels of these Terminations lasted only as long as did this seasonality extreme (i.e. for about one half of a precession cycle). However, the duration of these intervals of peak warmth were not likely to have been exactly 11,000 yr. Take, e.g. the duration of the present warm period. Depending on one's definition as to when it started, it has already lasted somewhere between 17,000 calendar years and 11,500 calendar years. The 17,000-year estimate would place the onset just after Heinrich event #1, when a rapid retreat of the ice sheets commenced. If, instead, the onset is pegged at the beginning of the Bölling warm interval, then its current duration would be about 14,500 calendar years. Finally, if the Younger Dryas cold punctuation is assumed to lie within the glacial period, then the current duration would be about 11,500 calendar years. But, regardless of the choice among these definitions, the present interglacial has already lasted at least one half of an insolation cycle.

What about the duration of the previous period of peak interglaciation? How long was its interval of extreme warmth? Based on the ^{18}O record in benthic foraminifera, marine geologists refer to this period as stage 5e. One question in this regard is whether the duration of marine isotope stage 5e is the same as that of Europe's Eemian. There is a suggestion in the results published by McManus *et al.* (1994) that the onset in the rise of $\delta^{18}O$ for benthic foraminifera predates the reappearance of ice-rafted debris and *N. pachyderma* (left coiling) foraminifera (see Fig. 4). According to the SPECMAP chronology for the deep sea ^{18}O record

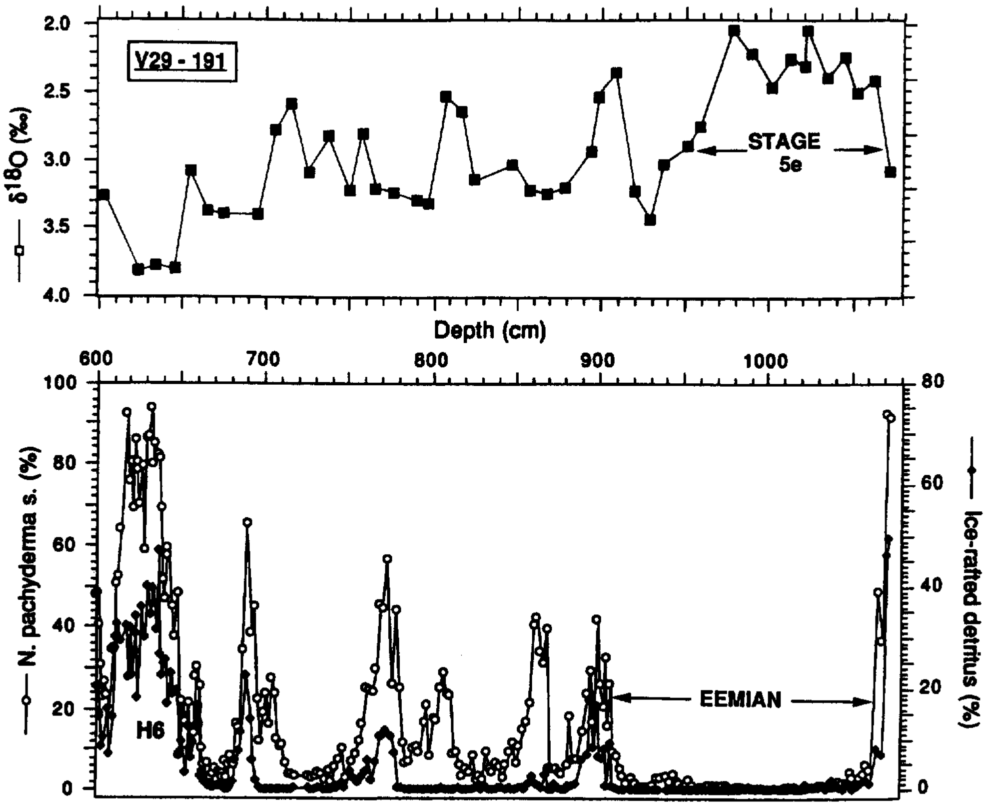

FIG. 4. Record from McManus *et al.* (1996) of northern Atlantic climate from deep sea core V29-191 (54°N, 17°W, 2.4 km). Shown in the upper panel is a depth plot of ^{18}O in benthic foraminifera shells covering the generally warm interval (marine isotope stage 5) between the end of the penultimate glaciation (marine isotope stage 6) and the beginning the last glaciation (marine isotope stage 4). In the lower panel are shown the records of ice-rafted debris (weight percent of dry sediment) and of *N. pachyderma* left coiling (percent of total planktonic foraminifera population). As pointed out by Kukla *et al.* (1997), the duration of the interglacial interval recorded by benthic ^{18}O (marine isotope stage 5e) is shorter than the warm surface ocean interval as recorded by the species of planktonic foraminifera (i.e. the Eemian).

(Martinson *et al.*, 1987), the duration of marine isotope stage 5e was close to 12,000 years. If so, then the record in V29-191 suggests that the duration of warm conditions in the northern Atlantic must have been several thousand years longer. Using ^{230}Th measurements on core V28-82, McManus (Ph.D. thesis, 1996) obtained a sedimentation rate of 3.6 cm 10^{-3} yr^{-1}. for the 50 cm long warm interval, setting its duration at about 14,000 years. So, it appears that the length of the last interval of intense interglacial warmth was similar to that of the present interglacial. Thus, this analogy suggests that we are close to the end of the present period of peak warmth. However, enough uncertainty exists that the time remaining until the end of the present warm could be anywhere from zero to four thousand years. Further, because of the stochastic nature of the endings of these periods of peak warmth, they need not be identical in duration.

One period of peak interglaciation (i.e. that in marine isotope stage 11) does not fit this pattern. Its duration was considerably longer (Oppo *et al.*, 1998). Like the Holocene, this interglacial occurred during a period when the orbital eccentricity (and hence also the precession driven seasonality cycle) was at a minimum. If stage 11 is taken as the analogue, then the present period of extreme warmth should endure much longer than a few thousand years.

Another way to look at this question is to ask whether any forerunner heralded the approach of the Eemian's abrupt end. As can be seen in Fig. 3, at least in northern Europe, a deterioration of conditions set in a thousand or so years before the abrupt cooling occurred. Another clue is provided by the observation that the cooling event which terminated the Eemian was only a thousand or so years in duration. By contrast, the ^{18}O increases associated with marine stages 5d and 5b were about one-half precession cycle in duration. This raises the question as to where to place the brief cold events in the longer periods of ^{18}O increase. If the relationship between the benthic ^{18}O and ice-rafted debris records observed in V29-191 is taken at face value, then the end of Eemian must have been preceded by substantial growth of the Earth's ice caps. As recorded by coral reefs on the island of Barbados, the sea level lowering associated with ice cap growth during marine stage 5d culminated at least 20 m below the + 4 meter stage 5e sea stand (Broecker *et al.*, 1968). If this view of the evidence is correct, then the abrupt cooling which terminated the Eemian must have been preceded by a several thousand-year-long period of ice cap growth (see Fig. 5). However, as sea level decline has not yet begun to decline, then by analogy to the Eemian, the end of the present interglacial lies at least several thousand years in the future.

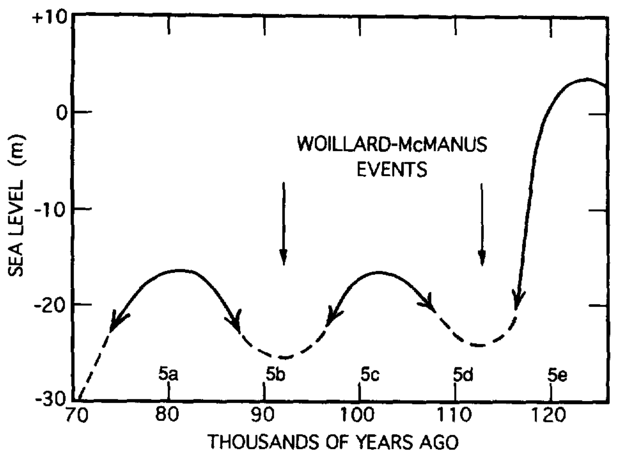

FIG. 5. The short duration coolings which punctuated the last interglacial (i.e. marine stage 5) appear to lie within the longer duration ice growth episodes 5d and 5b. If so, ice growth must have preceded the onset of the dramatic cooling of the region around the northern Atlantic.

Question 3: Will the ongoing buildup of greenhouse gases alter the natural sequence of events?

It is frequently suggested that the warming expected from the buildup of man-made greenhouse gases might be a blessing in that it will counter the natural cooling expected if Earth climate continues to track Milankovitch's insolation cycles. But, if the Earth's climate is destined to undergo an abrupt rather than a gradual cooling, then the likelihood of a compensation by the ongoing greenhouse warming is indeed small. Rather, if the buildup of greenhouse gases is to alter the course of natural events, it will do so by causing a premature jump from one operational state to another. In order to explore this possibility, we have to think in terms of a mechanism capable of pushing the Earth climate system over the brink into a new state.

While we cannot say for sure what triggered past mode switches, only one viable mechanism has been identified, i.e., the reorganization of the ocean's thermohaline circulation system. Currently, deep waters generated in two regions of the ocean vie for dominance (Broecker, 1997). One of these source regions lies in the northern Atlantic and the other along the perimeter of the Antarctic continent. While the deep water produced in the northern Atlantic is several degrees warmer, its higher salt content gives it a density only slightly lower than that for its southern counterpart. These two source waters are blended as they swing round and round the circum-Antarctic raceway. The mix so generated floods northward through deep topographic passages ventilating both the Indian and the Pacific Oceans. Under today's climate conditions, these two sources of deep water are nearly equal in strength, each supplying about 15 million cubic meters of water per second to the circum-Antarctic mixmaster (Broecker *et al.*, in press).

A number of ocean models have been used to study the stability of this circulation scheme. These studies have one important conclusion in common; i.e., the deep water circulation system has more than one quasi stable mode of operation (see Rahmstorf, 1995, for a summary). At least in the models, these modes act as strange attractors. The present circulation pattern in the model oceans can be disrupted and replaced on a time scale of decades by an alternate mode. These alternate modes have in common a 'weakening' of deep water formation in the northern Atlantic. As the supply of water destined for transformation into new deep water is delivered by the upper (i.e. warm) limb of the Atlantic's conveyor circulation, this weakening results in a diminishment of ocean heat transport into the northern regions of the Atlantic and hence a cooling of the surrounding land masses. Indeed, evidence from sediment cores in the Atlantic is consistent with the conclusion that during glacial time the strength of deep water formation in the northern Atlantic was considerably diminished allowing deep waters of southern origin to gain the upper hand.

If indeed the trigger for global climate changes resides in the ocean's thermohaline circulation, then the key to answering question 3 must lie in the factors which influence the density of surface waters in the deep water source regions. The favorite means employed by modellers to induce shutdowns of the Atlantic's conveyor circulation is to add excess fresh water to the high latitude sector of the northern Atlantic. The consequent freshening lowers the density of ambient surface water until it can no longer sink. In their quest for an explanation for the alternation between millennial-scale intervals of extreme cold and intermediate cold which dominated the glacial portion of the Greenland ice core record, they opt for salinity-induced rather than temperature-induced density reductions. The reason is that the presence of large ice caps offered a means to alternately store and release fresh water.

During periods of peak interglaciation, this excess ice is absent. Thus it might appear that the release of fresh water by ice melting cannot be called upon to bring interglaciations to an end. But, as we have already seen, substantial ice growth appears to have occurred before the warm conditions of the Eemian were terminated. As much of this ice growth is likely to have occurred in eastern Canada, it is possible that release of fresh water from a newly formed ice cap in this region was responsible for a shutdown of the Atlantic's conveyor. If this scenario is correct, then as regrowth of an ice sheet has yet to commence, one might conclude that there is little chance that the ongoing buildup of manmade greenhouse gases will accelerate the natural sequence of events leading to the end of the Holocene. Rather, the extra greenhouse gas may instead retard the growth of ice sheets, and hence delay the end of the present interglacial.

More likely, however, is the possibility that the buildup of greenhouse gases may by itself trigger a reorganization of the ocean's thermohaline circulation system (Manabe and Stouffer, 1994; Stocker and Schmittner, 1997). The global warming produced by this buildup will tend to decrease the density of all surface waters. Further, the intensification of the hydrologic cycle on a warmer planet may deliver more fresh water to the oceans in the high latitudes. As it is unlikely that the impacts of the greenhouse buildup will be identical in the northern Atlantic and in the Southern Ocean, a possibility exists that the current balance between deep water production at the two extremities of the planet might be upset.

This being the case, one of the major initiatives of research programs concerned with future climates must be to monitor the state of health of the present-day deep water formation system. We have a long way to go before we can do this properly. For example, we can currently account for the source locale for only about one quarter of the ventilated deep water being formed in the Southern Ocean (Broecker *et al.*, in press). Hence, in order to do this evaluation, we must first learn more about where and how deep water forms. Further, while the current generation of ocean general circulation models form more or less the right amount of deep water in the Southern Ocean, this model production occurs well away from the continental margin while, in reality, deep water forms beneath floating ice on the narrow shelves or in polynas formed in the surrounding sea ice pack.

Of course, it might be argued that a greenhouse-induced reorganization of the thermohaline circulation would not classify as an interglacial ending event. Clearly, as shown by both Manabe and Stouffer (1994) and Stocker and Schmittner (1997), the Earth would have to be warmed by 4–5°C before such a change would be triggered. Hence, it is not at all clear that the climate induced by such a reorganization would be on the average cooler than that we now enjoy. In other words, we would remain in what would have to be classified as interglacial conditions.

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