

# Antarctic Stratification, Atmospheric Water Vapor, and Heinrich Events: A Hypothesis for Late Pleistocene Deglaciations

Daniel M. Sigman

*Department of Geosciences, Princeton University, Princeton, New Jersey, USA*

Agatha M. de Boer<sup>1</sup>

*Cooperative Institute for Climate Science, Princeton University, Princeton, New Jersey, USA*

Gerald H. Haug

*GeoForschungsZentrum, Telegrafenberg, Potsdam, Germany*

We have previously argued that the Antarctic and subarctic North Pacific are stratified during ice ages, causing to a large degree the observed low CO<sub>2</sub> levels of ice age atmospheres by sequestering respired CO<sub>2</sub> in the ocean abyss. Here, we suggest a mechanism for the major deglaciations of the late Pleistocene. The mechanism begins with freshwater discharge to the North Atlantic, as evidenced by a Heinrich event, that shuts down North Atlantic overturning. Because of a global requirement for deep ocean ventilation, the North Atlantic shutdown drives overturning in the Antarctic, which, in turn, releases CO<sub>2</sub> to the atmosphere and reduces Antarctic sea ice extent. The resulting increase in atmospheric CO<sub>2</sub> and decrease in albedo then drive global warming and deglaciation. As a control on the timing of deglaciations, we look to the sensitivity of atmospheric freshwater transport to low latitude temperature, which is a natural antagonist to Antarctic stratification under cold climates. While Antarctic stratification is proposed to develop early in a glacial period, continued cooling through the glacial period may reduce the poleward atmospheric freshwater transport and thus may prepare the Antarctic halocline for collapse. Deglaciations may coincide with obliquity maxima because a reduced low-to-high latitude insolation gradient decreases the net poleward freshwater transport and perhaps also because increased polar insolation can warm the deep ocean and shift the westerly winds poleward, all of which should work to weaken Antarctic stratification. Precession minima may encourage Antarctic destratification by biasing tropical water vapor transport toward the northern hemisphere. Finally, obliquity and precession may work together to encourage the circum-North Atlantic freshwater discharge event that initiates the deglacial sequence.

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<sup>1</sup>Currently at School of Environmental Science, University of East Anglia, Norwich, NR4 7TJ, UK.

## INTRODUCTION

Over the past ten years, evidence has been assembled that the Southern Ocean and the subarctic North Pacific are more strongly stratified during colder climates of the last 3 million years. Both of these polar regions appear to stratify at the onset of intense Northern hemisphere glaciation 2.7 million years ago [Haug *et al.*, 2005; Haug *et al.*, 1999; Sigman *et al.*, 2004], and both regions subsequently appear to be more strongly stratified during the Pleistocene glacial maxima than during interglacials [Francois *et al.*, 1997; Jaccard *et al.*, 2005; Narita *et al.*, 2002; Robinson *et al.*, 2004; Sigman *et al.*, 1999]. In addition, there are measurements that suggest reduced ventilation of Southern Ocean deep water since 2.7 million years ago [Hodell and Venz-Curtis, 2006] and during recent ice ages [Keigwin, 2004; Robinson *et al.*, 2005a; Sikes *et al.*, 2000]. Uncertainties remain in the tools that have been used to reach these conclusions, and there is not community consensus that such stratification and reduced ventilation is the correct interpretation for the available data. Nevertheless, we find the evidence in hand compelling. This drives us to consider what factors might lead to the purported polar ocean changes and what their implications would be for atmospheric CO<sub>2</sub> and climate. We focus here on the Antarctic Zone of the Southern Ocean, given its importance for air/sea CO<sub>2</sub> partitioning [Marinov *et al.*, 2006].

At least two plausible physical mechanisms exist for stratification of the Antarctic during cold climates. Upon cooling, the westerly winds may move equatorward and weaken, both of which would reduce Ekman divergence and its associated upwelling in the Antarctic, allowing the Antarctic halocline to strengthen [Sigman and Boyle, 2000; Toggweiler and Bjornsson, 2000; Toggweiler *et al.*, 2006; Toggweiler and Samuels, 1995]. An alternative mechanism involves the lower sensitivity of density to temperature at low temperatures, referred to below as the “equation of state” (or “EOS”) mechanism [Sigman *et al.*, 2004]. In polar regions such as the Antarctic, wintertime temperatures are coldest at the surface, encouraging vertical mixing and, in the extreme cases, overturning; salinities are lowest at the surface, working against this effect. In the EOS mechanism, global ocean cooling reduces the effect of temperature on polar ocean density structure, allowing the freshness of the Antarctic upper ocean to drive stratification. The wind-shift and EOS mechanisms are not mutually exclusive and may have worked in rough concert to drive stratification over glacial cycles.

We have conducted experiments with a numerical model of the ocean/atmosphere system to develop a better understanding of these mechanisms and their plausibility as drivers of change in polar ocean overturning and stratification [de Boer *et al.*, 2007; de Boer *et al.*, in review]. While results from the simulations support the original hypotheses, certain aspects

of the results involving the North Atlantic were not anticipated (although perhaps they should have been). When combined with key paleoclimate observations, they have led us toward an explanation for glacial terminations that has many motivating aspects. Most parts of this deglacial mechanism work equally well in the context of the EOS or wind-shift mechanism for glacial Antarctic stratification, as described below. Because we have more thoroughly investigated the EOS effect, it is emphasized below.

We begin with an ice age ocean in which the Antarctic and the subarctic North Pacific are strongly stratified. In this mode, CO<sub>2</sub> is efficiently sequestered in the deep ocean due to the rain of organic debris out of the low latitude ocean and minimal venting of this CO<sub>2</sub> back to the atmosphere through the Antarctic. North Atlantic overturning, while presumably reduced in rate and reaching shallower depths than during peak interglacials, is hypothesized to be of greater relative importance in fulfilling the global ocean interior’s requirement for new dense water.

The deglacial sequence begins with a disturbance to this North Atlantic overturning, in the form of a freshwater input. In the case of the last deglaciation, this is represented in the sediment record by Heinrich event 1 at ~17.5 ka [McManus *et al.*, 2004]. The shutdown in ventilation from the North Atlantic removes the glacial ocean’s greatest source of dense water, while the wind-driven upwelling in the Southern Ocean and the downward mixing of buoyancy from the low latitude thermocline continue to remove the ocean’s dense deep water. The buoyancy of the deep ocean increases until overturning is initiated in the Antarctic, releasing biologically sequestered CO<sub>2</sub> back into the atmosphere, which then leads to global warming. A second potential factor in the deglaciation is sea ice extent in the Antarctic. With initiation of overturning in this region, sea ice extent may be reduced, lowering Earth’s albedo and thus providing an additional push toward deglaciation.

In essence, this basic mechanism is a wedding of the Antarctic stratification hypothesis for glacial CO<sub>2</sub> reduction [Francois *et al.*, 1997] with the aspect of “bipolar seesaw” [Crowley, 1992; Stocker *et al.*, 1992] that involves Southern Ocean overturning, in which, subsequent to a North Atlantic overturning shutdown, “the continuing downward mixing of heat from the warm surface ocean [and Ekman divergence in the Antarctic, not noted by author] creates a density ‘vacuum,’ which allows dense surface waters in the Southern Ocean to penetrate into the deep sea [Broecker, 1998].” Previous deglacial seesaw hypotheses did not conceive of a stratified Antarctic during the last ice age, nor did they consider the North Atlantic to be a significant ventilator of the ocean interior during that time. This led to a focus on aspects of the climate record other than the initiation of deglaciation, such as the Younger Dryas event. Our premise of glacial Antarctic stratification has caused us to focus on Heinrich 1,

which coincides with the first clear steps in Antarctic warming and atmospheric CO<sub>2</sub> increase.

To this hypothesis, we add corollaries as to what sets the timing of deglaciations. The tendency for prolonged ice ages, in which multiple freshwater inputs to the North Atlantic occur (as evidenced by Heinrich events) before one of these drives deglaciation, is hypothesized to result from the need for Antarctic stratification to be weakened before our deglacial mechanism can be initiated. We turn to the net poleward transport of fresh water through the atmosphere, which feeds the haloclines of the Antarctic and subarctic North Pacific. Cooling in the tropical to temperate regions should reduce this transport, weakening the haloclines. During the ice ages, progressive cooling of the lower latitude atmosphere and surface ocean (e.g., subsequent to stage 5d) may be required to bring Antarctic stratification to the point of collapse.

The apparent synchronization of deglaciations to maxima in obliquity and minima in precession [*Huybers and Wunsch, 2005; Imbrie et al., 1992; Roe, 2006* and references therein] may also arise from reduced net transport of water vapor from the low to high latitudes. Increasing obliquity will reduce the low-to-high latitude insolation gradient, which may decrease the net poleward transport of water vapor [*Raymo and Nisancioglu, 2003*] that sustained the glacial Antarctic halocline. In addition, increased polar insolation under high obliquity may warm the deep ocean through the polar regions, which would weaken Antarctic stratification through the EOS mechanism. Precession minima (i.e. times when perihelion occurs during northern hemisphere summer) may also affect water vapor transport so as to prepare the Antarctic for overturning. These minima lead to more intense summers in the northern hemisphere but less intense summers in the southern hemisphere, potentially shifting the deposition of tropical water vapor away from the southern hemisphere and thus weakening the Antarctic halocline. Finally, these same extrema in both obliquity and precession may encourage freshwater releases to the North Atlantic [*Imbrie et al., 1992*], initiating the Antarctic overturning cascade.

Below, we justify our hypothesis and its premises, drawing upon previously published data and model results as well as new model experiments. First, we describe the compensatory role that the North Atlantic plays in our simulations of the EOS and wind-driven mechanisms for Antarctic and North Pacific stratification. These simulations suggest that the glacial-age North Atlantic would have worked to satisfy the global ocean requirement for continual subsurface water formation in the face of polar ocean stratification elsewhere. Second, we look to the paleoclimate data for evidence of such a compensatory role. As in previous work [e.g., *Sigman et al., 2004*], we search for perspective on glacial cycles from the evolution of climate over the last 3 million years; in this case, we focus on benthic foraminiferal carbon isotope records over

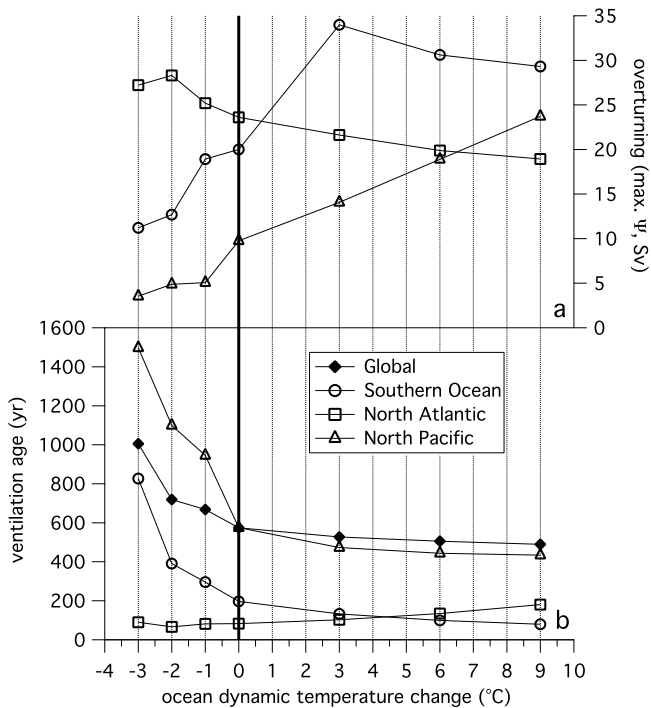
this period [*Hodell and Venz-Curtis, 2006*]. Third, we review previous concepts regarding the storage of CO<sub>2</sub> in the deep ocean, which indicate that continued ventilation from the glacial-age North Atlantic is an important aspect of polar stratification-based hypotheses for lowering atmospheric CO<sub>2</sub> during glacial times. Fourth, we summarize the paleoclimate evidence for a deglacial sequence that begins with a reduction in the North Atlantic overturning and propagates to the Southern Ocean. Fifth, in an effort to understand the timing of deglaciations, we present new model simulations that pit the EOS mechanism for Antarctic stratification against the effect of atmospheric cooling on water vapor transport. We consider the results in the context of both progressive cooling during ice ages and the obliquity and precession cycles.

#### THE GLOBAL OCEAN OVERTURNING CONSTRAINT AND THE NORTH ATLANTIC

To investigate the effect of climate on polar ocean overturning, we have conducted experiments with an ocean general circulation model coupled to a two-dimensional energy moisture balance model for the atmosphere. The ocean model is based on the Geophysical Fluid Dynamics Laboratory's Modular Ocean Model version 4 (MOM4, [*Griffies, 2003*]), using a simplified basin geometry (similar to *Bjornsson [2001]*). The entire coupled model system is described by *de Boer et al. [2007]*.

In our experiments on both the EOS and wind-shift mechanisms, the upper ocean density stratification of the Antarctic is higher in the "cold climate" simulations, and this region thus ventilates the deep ocean more slowly (Figure 1; [*de Boer et al., 2007; de Boer et al., in review*]). Overturning in the Antarctic is particularly efficient at releasing biologically sequestered CO<sub>2</sub> back to the atmosphere [*Marinov et al., 2006; Sarmiento and Toggweiler, 1984*], yielding the potential connection between polar ocean stratification and lower CO<sub>2</sub> during ice ages.

These model studies also bring to the forefront the role that the North Atlantic plays in global ocean ventilation. In our cold climate simulations of both the EOS mechanism and the wind-shift mechanism, because of reduced overturning in the model's Antarctic and North Pacific regions, the global ocean ventilation rate is lower and the mean ocean ventilation age is greater (Figure 1b). However, the global ventilation age increases less, as a proportion of the age in the control simulation, than do the individual ventilation ages in the Southern Ocean and North Pacific [*de Boer et al., 2007; de Boer et al., in review*] (solid diamonds compared to open circles and open squares in Figure 1). In both the EOS and wind-shift experiments, as cooling occurs, a progressively greater fraction of global ocean overturning shifts to the North Atlantic (open triangles in Figure 1).



**Figure 1.** Sensitivity of polar ocean overturning and deep ocean circulation to “ocean dynamic temperature” change in an ocean model, as indicated by the maximum overturning stream function (a) and ventilation age (b) [de Boer et al., 2007; de Boer et al., in review]. The dynamic temperature change is a homogeneous change to ocean temperature at the point in the model code where density is calculated. This approach for studying the effect of ocean temperature on circulation is designed to prevent feedbacks associated with changing fluxes of heat, in particular, across the air/sea interface (see references cited above). The mean ventilation age was calculated for 0.7 to 3 km depth poleward of 56°N in the North Atlantic and North Pacific and for 0.7 km to the bottom poleward of 60°S in the Southern Ocean; the global mean ventilation age is for all water below 0.7 km. As the dynamic temperature is lowered, the Southern Ocean (open circles) and North Pacific (open triangles) decrease their overturning (a), increasing the ventilation age of the ocean interior regions that they feed most directly (b) and resulting in an increase in the ventilation age of the global ocean interior (b, filled diamonds). However, the North Atlantic response (open squares) is of the opposite sense, increasing its overturning upon cooling, such that the global ocean ventilation age change is less than would result from the Antarctic/North Pacific changes alone. In all experiments shown here, no water parcel in the ocean was allowed to drop below the freezing point of seawater ( $\sim 1.9^\circ\text{C}$ ); other simulations indicate that this constraint does not dominate the results [de Boer et al., 2007].

We believe that the increased relative importance of the North Atlantic ventilation in the cold climate simulations in both the EOS and wind-shift experiments results from the fact that the North Atlantic is, among the three polar regions, the least strongly stratified by salinity. At the same time, in

the model and in the real ocean, the North Atlantic does possess a halocline, albeit a weak one, such that regional effects alone would cause the North Atlantic to stratify under cooling [Winton, 1997]. In the wind-shift experiment, the absolute rate of North Atlantic ventilation is indeed lower in the cold climate simulations [de Boer et al., in review], as one might expect [Toggweiler and Samuels, 1995]. However, in the EOS cold climate simulations, North Atlantic overturning is slightly greater than in the control simulation (Figure 1a). Thus, the North Atlantic response in the EOS experiment cannot be driven by local conditions. Rather, it results from a buffering role that the North Atlantic plays in reconciling the regional ventilation changes in the Antarctic and North Pacific with the global requirement for new deep water [de Boer et al., in review]. Potential energy continues to be added to the deep ocean, in particular, by wind-driven upwelling south of the Drake Passage [Toggweiler and Samuels, 1995] and the downward diffusion of buoyancy [Munk, 1966; Munk and Wunsch, 1998], albeit at a lower rate with weaker winds or a homogeneously colder ocean [de Boer et al., 2007; de Boer et al., in review]. In the absence of Antarctic and North Pacific overturning, the North Atlantic overturning works to extract this potential energy so as to yield an energetic steady state for the ocean interior.

Given the role of the North Atlantic as a buffer for the global deep ocean ventilation, the absolute change in its overturning will depend sensitively on the change in the global deep water formation requirement relative to the local ventilation changes in the Antarctic and subarctic North Pacific. Thus, we put little weight on the EOS experiment’s subtle increase in North Atlantic overturning during cold climates, which may run contrary to paleoclimate observations [Lynch-Stieglitz et al., 1999; Marchal et al., 2000] and which is affected by how one defines the boundary between North Atlantic- and Antarctic-influenced water in the ocean interior (see Figure 1 caption). However, a robust observation from the experiments for the response of the polar ocean to cooling and/or weakening of the westerly winds is that ventilation will shift in a relative sense to the region with the weakest halocline, that is, the North Atlantic [de Boer et al., 2007; de Boer et al., in review].

#### CARBON ISOTOPE CONSTRAINTS ON THE IMPORTANCE OF NORTH ATLANTIC VENTILATION IN DIFFERENT CLIMATES

##### *The Plio-Pleistocene Cooling*

The distribution of atmospherically derived freshwater among the major polar ocean regions has changed dramatically in response to geologic forcing [Driscoll and Haug, 1998; Haug and Tiedemann, 1998; Haug et al., 2001b], and

it may also change in response to climate. Here, however, we assume that the North Atlantic has persisted as the saltiest polar region over the last 4.5 million years [Haug *et al.*, 2001a; Haug and Tiedemann, 1998; Motoi *et al.*, 2005]. On the basis of this assumption and the model results outlined above, we would expect the polar North Atlantic to become a more dominant source of deep water as climate has cooled over the last 3.6 million years and during the glacial maxima of the last 2.7 million years [Haug and Tiedemann, 1998]. Here, we ask whether there is support for this prediction from the  $\delta^{13}\text{C}$  of benthic foraminifera, the most abundant paleoceanographic measurement intended to reconstruct changes in deep ocean circulation.

From 5 to 2.7 million years ago, deep Southern Ocean  $\delta^{13}\text{C}$  was intermediate between the apparent North Atlantic and deep Pacific end-members, coming closer to the North Atlantic end-member between 3.5 and 2.7 Ma. However, at 2.7 Ma, deep Southern Ocean  $\delta^{13}\text{C}$  dropped sharply toward the deep Pacific end-member (Figure 2). By  $\sim 1.5$  Ma, it had fallen below the deep Pacific. Questions remain regarding the fidelity of benthic foraminifera as recorders of deep Southern Ocean  $\delta^{13}\text{C}$  [Mackensen *et al.*, 1993]. Moreover, the performed  $\delta^{13}\text{C}$  of newly formed Southern Ocean deep water can change markedly with surface conditions (e.g., ice coverage). Nevertheless, we consider a reduction in Southern Ocean ventilation of the abyss to be the most likely explanation for the sharp decrease in deep ocean  $\delta^{13}\text{C}$  [Hodell and Venz-Curtis, 2006]. The coincidence of the Southern Ocean  $\delta^{13}\text{C}$  decrease with the evidence for surface ocean stratification at 2.7 Ma (Figure 2a) fits with the interpretation that the latter changes in open Antarctic surface conditions drove a decrease in the overturning of the Antarctic as a whole [Sigman *et al.*, 2004].

In contrast, the  $\delta^{13}\text{C}$  data over the last 5 million years suggest a continuous role for the North Atlantic in ventilating the ocean interior, albeit with important changes in the depth to which North Atlantic overturning reached. The benthic foraminiferal  $\delta^{13}\text{C}$  gradient between the intermediate/deep North Atlantic and the deep North Pacific as well as indicators of sedimentary carbonate preservation appear consistent with increasing relative importance of the North Atlantic in the ventilation of the ocean interior over the course of Plio-Pleistocene cooling [Haug and Tiedemann, 1998; Ravelo and Andreasen, 2000]. Over the last 5 million years, there has been a  $\sim 0.7\text{‰}$  difference in  $\delta^{13}\text{C}$  between the Atlantic and Pacific (Figure 2b). The history of the gradient over this period depends on whether mid-depth (roughly less than 2.5 km depth) or deep records are considered for the North Atlantic. Mid-depth records suggest a subtle ( $\sim 0.4\text{‰}$ ) increase in the gradient over the 4 to 5 million years. Deeper records suggest a more constant Atlantic/Pacific  $\delta^{13}\text{C}$  gradient from 5 to  $\sim 1.5$  million years ago, after which the deep Atlantic

decreased  $\sim 0.4\text{‰}$  toward deep Pacific  $\delta^{13}\text{C}$ . A fair summary of these changes is that the  $\delta^{13}\text{C}$  gradient has been roughly constant but that the depth of North Atlantic-driven ventilation has shoaled. It seems likely that these changes integrate to less total subsurface water formation in the North Atlantic over the last 1.5 Ma, but the reduction may have been modest.

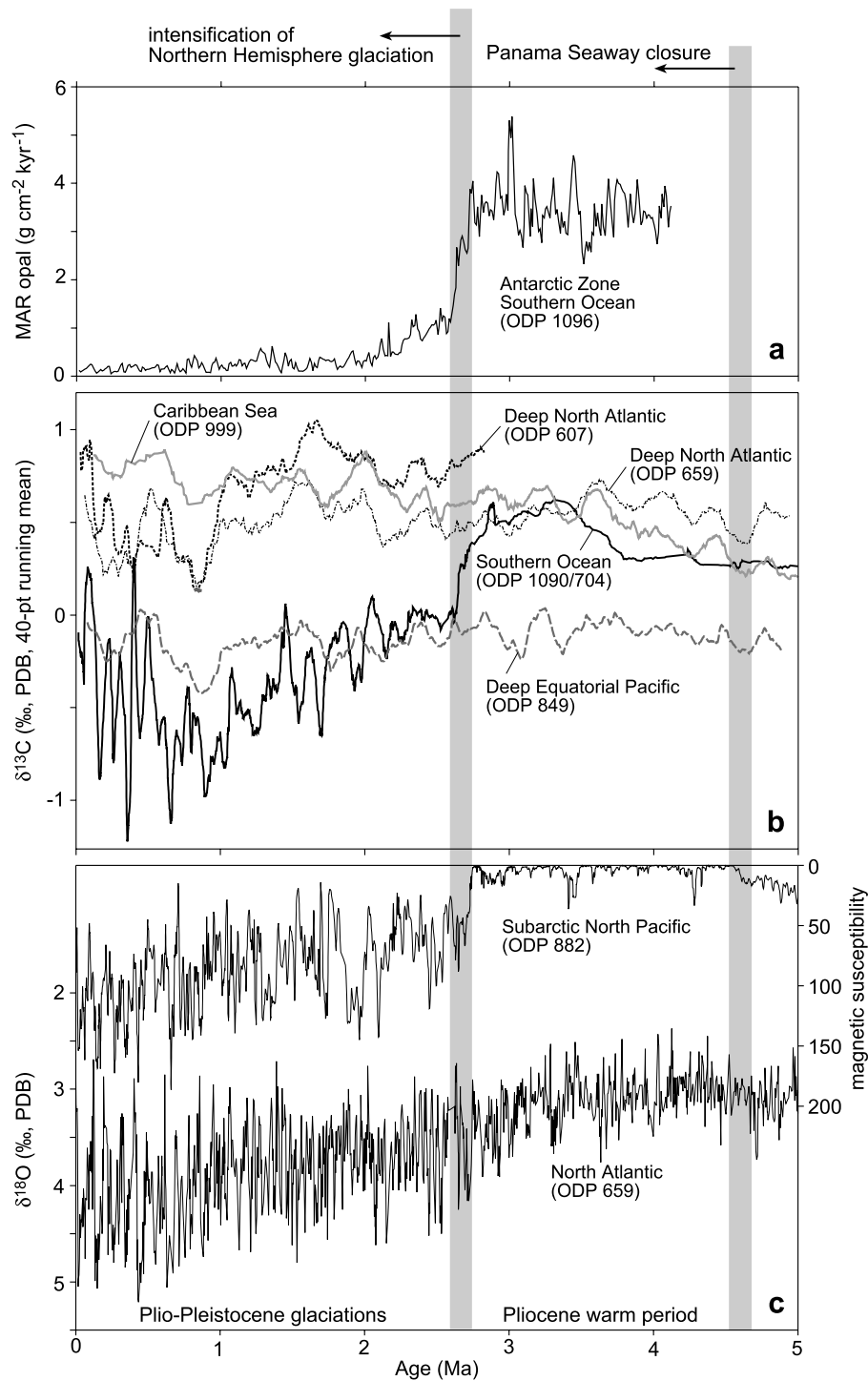
In summary, the cooling over the last 3 million years was apparently characterized by the loss of ventilation from the Antarctic [Hodell and Venz-Curtis, 2006] and possibly also the subarctic North Pacific [Ravelo and Andreasen, 2000], while North Atlantic ventilation continued but shoaled after 1.5 million years ago. If so, over this period, the North Atlantic became progressively more important, relative to the other polar regions, in satisfying the global ocean interior's need for new dense water.

#### *Late Pleistocene Glacial Cycles*

Consistent with its evolution over Plio-Pleistocene cooling, the  $\delta^{13}\text{C}$  of Southern Ocean deep water dropped upon the glaciations of the late Pleistocene. During the Last Glacial Maximum (LGM), deep Southern Ocean  $\delta^{13}\text{C}$  reached  $-0.5$  to  $-1.0\text{‰}$  [Charles and Fairbanks, 1992], markedly lower than its modern value of  $0.5\text{‰}$  (keeping in mind an ice age whole ocean decrease in  $\delta^{13}\text{C}$  of  $\sim 0.4\text{‰}$  [Curry *et al.*, 1988]). In the same vein as our interpretation of the 2.7 Ma decrease in Southern Ocean deep  $\delta^{13}\text{C}$ , we attribute this low  $\delta^{13}\text{C}$  to reduced ventilation by the Antarctic. The available radiocarbon data suggest that LGM Southern Ocean deep water in the Pacific sector was much more slowly ventilated than during the Holocene [Sikes *et al.*, 2000], in apparent agreement with the Antarctic stratification hypothesis.

It has long been recognized that the North Atlantic has undergone major changes in its ventilation over glacial/interglacial cycles [Boyle and Keigwin, 1982; Duplessy *et al.*, 1988]. During the last ice age, the deep Atlantic came to be dominated by water that was enriched in nutrients and burdened with low- $^{13}\text{C}/^{12}\text{C}$  inorganic carbon from the breakdown of organic matter. Detailed work connects this change to the glacial-age decrease in the benthic  $\delta^{13}\text{C}$  in the Southern Ocean [Curry and Oppo, 2005]. It is tempting to consider the greater volumetric importance of the southern-sourced water in the deep Atlantic as evidence of rapid southern hemisphere deep water formation flooding the North Atlantic. However, the radiocarbon data suggest that the abyssal water in the LGM Atlantic was extremely "old", with a ventilation age of thousands of years [Keigwin, 2004; Robinson *et al.*, 2005a].

While the North Atlantic did not continuously ventilate the abyssal ocean during the last glacial maximum, benthic foraminiferal Cd/Ca and  $\delta^{13}\text{C}$  data indicate that it did ventilate



**Figure 2.** Compilation of records addressing the relative roles of the North Atlantic and Southern Ocean in ventilating the ocean interior over the past 5 million years. (a) Opal mass accumulation rate (MAR) in the Pacific sector of the Antarctic [Hillenbrand and Fütterer, 2001], suggesting reduced surface/deep exchange in the Antarctic since isotope stage 110/G6 (~2.7 Ma) [Sigman *et al.*, 2004], which ice rafted debris in the North Atlantic and North Pacific and foraminiferal oxygen isotopes associate with intensification of Northern Hemisphere glaciation (left gray bar and panel (c)). (b) Records of benthic foraminiferal  $\delta^{13}\text{C}$  from ODP Site 607 (black dotted line, sampling the western basin of the deep North Atlantic) [Raymo *et al.*, 1990], ODP Site 659 (black dash-dotted line,

the subsurface Atlantic at a shallower level (i.e. as “Glacial North Atlantic Intermediate Water” [Oppo and Lehman, 1993]), extending down to ~2.5 km depth [e.g., Marchitto *et al.*, 1998], with the available  $\delta^{13}\text{C}$  data suggesting some ventilation down to ~3.5 km [Curry and Oppo, 2005].  $^{231}\text{Pa}/^{230}\text{Th}$  data suggest that, during the last glacial maximum, export of subsurface waters from the North Atlantic, presumably mostly as mid-depth water, was reduced by less than 30% relative to the Holocene [Marchal *et al.*, 2000; Yu *et al.*, 1996]. It would also appear that the North Atlantic ventilated to greater depths during the interstadials of the last ice age [Curry *et al.*, 1999; Curry and Oppo, 1997].

To summarize our interpretation of the benthic foraminiferal  $\delta^{13}\text{C}$  data, both on the million year time scale and over glacial/interglacial cycles, the North Atlantic overturning persists as climate cools, while the Southern Ocean source appears to fall away. It remains to be seen how the North Atlantic ventilation changed in absolute rate, but, in a relative sense, it appears to be more important in ventilation of the ocean interior under colder climates. In this regard, it fits the expectations of the EOS and wind-shift experiments. An important caveat is that the shoaling of North Atlantic ventilation under cold climates has uncertain implications for the energy budgets of different depths within the ocean interior. However, one can imagine that glacial North Atlantic Intermediate Water shielded the deeper ocean from the mechanisms by which it currently gains buoyancy.

#### THE ROLE OF NORTH ATLANTIC OVERTURNING IN THE BIOLOGICAL PUMP

Assuming adequately rapid  $\text{CO}_2$  exchange at the ocean’s surface, the strength of the biological pump is characterized by the concentration ratio of preformed to total phosphate in the ocean interior. If the preformed-to-total phosphate ratio is low, then most of the nutrients in the interior were acquired through the respiration of organic matter, as opposed to descending “preformed” into the interior with the water that

left the ocean surface. Thus, a decrease in the preformed-to-total phosphate ratio of the ocean interior increases biological sequestration of  $\text{CO}_2$  in the interior, lowering atmospheric  $\text{CO}_2$  [Ito and Follows, 2005; Sigman and Haug, 2003; Toggweiler *et al.*, 2003], although other dynamics are also important.

The preformed-to-total phosphate ratio of North Atlantic Deep Water is lower than that of the Antarctic Bottom Water. As a result, one mechanism for lowering  $\text{CO}_2$  during ice ages is to reduce Antarctic Bottom Water formation while maintaining North Atlantic overturning [Toggweiler, 1999]. In this framework, the maintenance of North Atlantic overturning as a source of low preformed nutrient subsurface water helps Antarctic stratification to drive a reduction in atmospheric  $\text{CO}_2$ . Thus, there is some consistency between our numerical model simulations that drive Antarctic stratification upon cooling and the hypothesis that Antarctic stratification reduced atmospheric  $\text{CO}_2$  during the last ice age: both call for, or are supported by, continued North Atlantic overturning in the cold climate case. The observations of a shallower (mid-depth) form of ventilation from the North Atlantic during ice ages also supports the needs of the Antarctic stratification mechanism for lowering atmospheric  $\text{CO}_2$ . This change allows dissolved inorganic carbon to accumulate in the abyssal (rather than mid-depth) ocean during ice ages, which efficiently drives a transient seafloor  $\text{CaCO}_3$  dissolution event, increasing ocean alkalinity and thus further lowering atmospheric  $\text{CO}_2$  [Boyle, 1988; Toggweiler, 1999].

#### NORTH ATLANTIC VENTILATION SHUTDOWN AND DEGLACIATION

A remarkable feature of the last deglaciation and of previous deglaciations as well is the occurrence of an early shutdown in all forms of North Atlantic sourced deep water, typically coincident with the rapid deposition ice rafted debris across the high latitude North Atlantic (Heinrich

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sampling the eastern basin of the deep North Atlantic) [Tiedemann *et al.*, 1994], ODP Sites 999/502 (solid gray line, sampling the mid-depth North Atlantic) [Haug and Tiedemann, 1998; Oppo *et al.*, 1995], ODP Site 849 (gray dashed line, sampling the deep Pacific) [Mix *et al.*, 1995], and ODP Sites 1090/704 (solid black line, sampling the deep Southern Ocean) [Hodell and Venz-Curtis, 2006]. For most of these  $\delta^{13}\text{C}$  records, sample spacing is between 5 and 10 kyr; to clarify longer term trends, we smoothed the records with a 40 point running mean. (c) A record of magnetic susceptibility (inverted) from ODP Site 882 in the western Subarctic North Pacific [Haug *et al.*, 1995] indicates a dramatic increase in the input of ice rafted debris at 2.7 Ma, also observed in the North Atlantic at this time [Shackleton *et al.*, 1984], and is interpreted to reflect the intensification of Northern Hemisphere glaciation. In addition, a benthic  $\delta^{18}\text{O}$  record from ODP Site 659 (sampling the deep North Atlantic) [Tiedemann *et al.*, 1994] reflects changes in ice volume and deep ocean temperature over this time period. These records, taken together, suggest that Southern Ocean-sourced ventilation has decreased with progressive cooling and glaciation since 2.7 Ma, while the North Atlantic ventilation has been maintained, albeit with changes in the depth to which that ventilation reached. The effective closing of the Panama Seaway is also shown (right gray bar) [Haug and Tiedemann, 1998; Keigwin, 1978]. This figure and its interpretation derive largely from Hodell and Venz-Curtis [2006].

event 1 in the case of the last ice age) [McManus *et al.*, 2004; Oppo *et al.*, 1997; Oppo *et al.*, 2001; Venz *et al.*, 1999]. A role for this shutdown in driving deglaciation may at first seem unlikely because, in the circum-North Atlantic, it should cause cooling, not warming [Broecker, 1991; Imbrie *et al.*, 1992]. In our hypothesis, despite its effect on regional climate, it drives global warming by triggering deep overturning changes in the Antarctic.

We have described above that, in our model simulations that reduce Antarctic and North Pacific overturning, the North Atlantic acts as a buffer, satisfying the persistent global requirement of dense deep water production; the North Atlantic overturning either increases slightly or decreases much less than does the overturning in the other polar regions. However, local forcing, in particular, a sudden fresh water input associated with the melting of land ice, should be able to stop deep ocean ventilation through the North Atlantic [Manabe and Stouffer, 1995]. This appears to have occurred to a most intense degree at 17.5 ka, when  $^{231}\text{Pa}/^{230}\text{Th}$  data suggest that, immediately following Heinrich event 1, the North Atlantic export of subsurface water ceased completely for a period of  $\sim 3$  kyr (Figure 3c) [McManus *et al.*, 2004]. When this occurred, the role of the North Atlantic as a ventilation buffer would have been lost. As a result, the Antarctic would have been pushed toward overturning to maintain the supply of dense water to the ocean interior. An increase in Antarctic overturning, given a broad range of surface ocean biology responses, would have allowed respired  $\text{CO}_2$  to escape into the atmosphere [Francois *et al.*, 1997; Robinson *et al.*, 2004; Sigman *et al.*, 1999; Sigman and Haug, 2003; Toggweiler, 1999]. The resulting rise in atmospheric  $\text{CO}_2$  would then drive warming and deglaciation on a global basis. The observed timing of  $\text{CO}_2$  rise appears consistent with this scenario (Figure 3e).

The production of new dense water entails the release of heat to the atmosphere in the region where it occurs, especially if it occurs in response to the accumulation of buoyancy in the ocean interior. Thus, while the first deglacial event occurs in the northern hemisphere, the first dramatic deglacial warming would occur in the southern hemisphere, where overturning is initiated (Figure 3d). This aspect of the hypothesis fits observations from ice cores (compare panels b and d in Figure 3) as well as paleoceanographic reconstructions of sea surface temperature indicating that abrupt deglacial warming began in the southern hemisphere [Imbrie *et al.*, 1992; Kiefer and Kienast, 2005; Sowers and Bender, 1995; Visser *et al.*, 2003].

Antarctic sea ice has a non-trivial effect on Earth's global albedo. With the increased Antarctic overturning hypothesized to occur in response to the shutdown in North Atlantic ventilation, Antarctic sea ice extent should have declined. This would represent a second mechanism, in addition to the  $\text{CO}_2$  rise, for Antarctic warming once overturning begins.

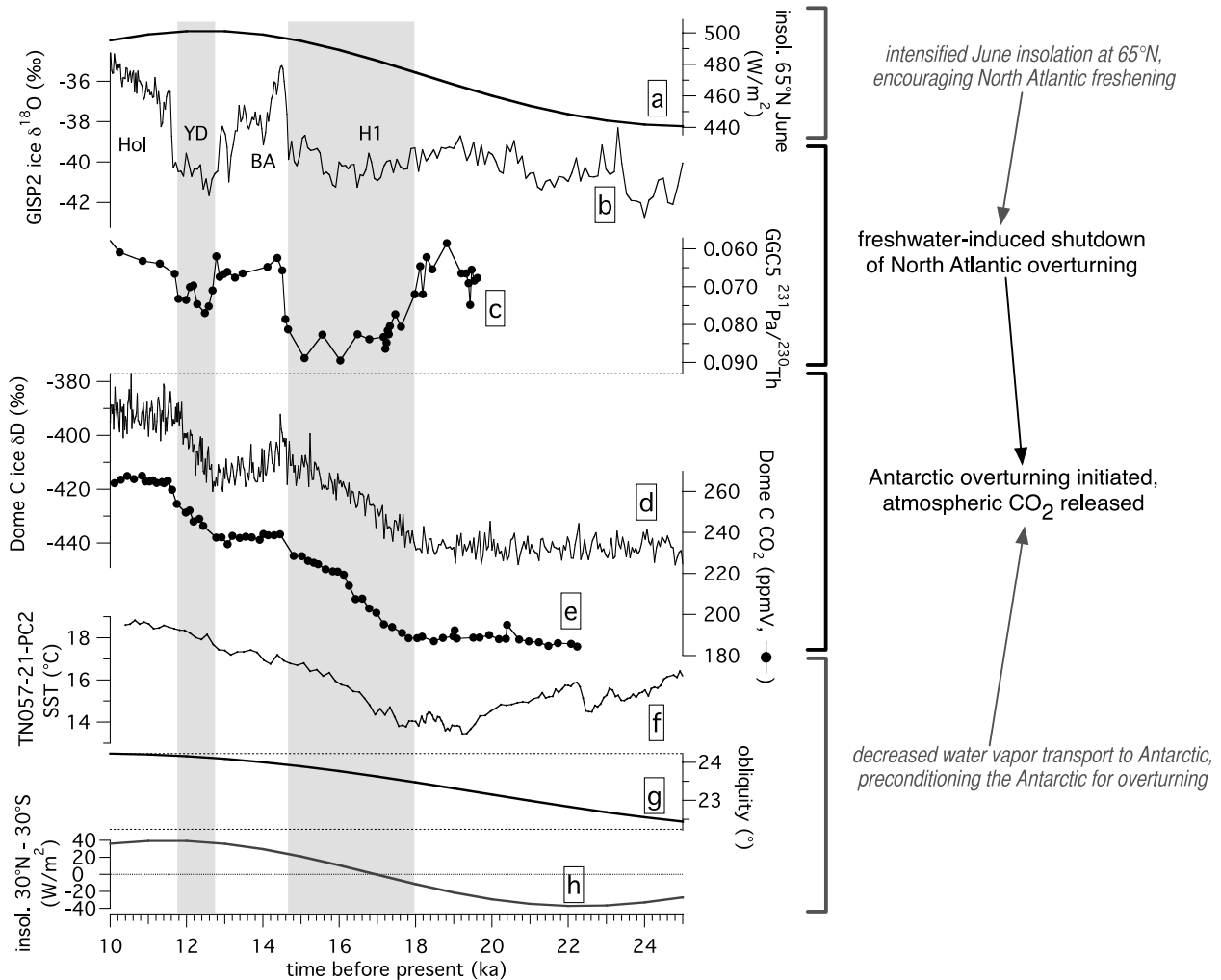
We propose that these first drivers of warming initiated a positive feedback that sustained the shift toward greater Antarctic overturning, through the EOS and/or wind-shift mechanisms.

#### COOLING AND ATMOSPHERIC WATER TRANSPORT

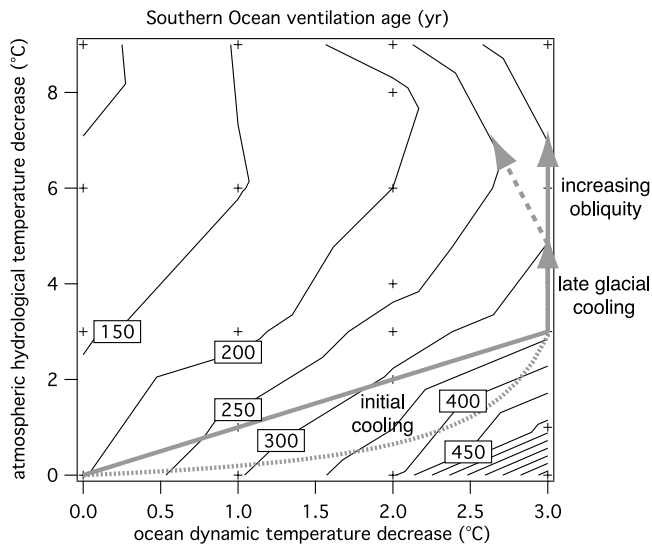
In the hypothesis described above, the H1 event in the North Atlantic is called upon to initiate the most recent deglaciation. This raises the question of why previous Heinrich events did not drive major deglaciations (i.e. deglaciations to conditions akin to the Holocene). Moreover, while there is strong evidence for an orbital trigger for deglaciations [Hays *et al.*, 1976; Huybers and Wunsch, 2005; Imbrie *et al.*, 1992; Roe, 2006], the obliquity and precession cycles are  $\sim 41$  and  $\sim 23$  kyr in period while late Pleistocene glacial terminations occur every 80 to 120 kyr, suggesting that those cycles alone cannot completely explain late Pleistocene deglaciations. In general, one of the great challenges in understanding deglaciations is explaining why they occur at the coldest times; this verges on explaining the origin of the "saw-tooth" [Pollard, 1982].

The haloclines that work to stratify the polar oceans are ultimately supported by the transport of water vapor from the lower latitudes. The effect of tropical and subtropical cooling is to reduce the supply of freshwater to the polar ocean surface regions. This yields a (negative) "water vapor feedback" that works against Antarctic stratification in cold climates [de Boer *et al.*, in review]. When the water vapor effect of atmospheric cooling is pitted against the EOS effect of ocean cooling in our model, equivalent coolings in the ocean and atmosphere yield, in net, less Antarctic overturning (Figure 4). Such a trajectory of equivalent atmosphere and ocean cooling is plausible for the beginnings of ice ages (solid trajectory for "initial cooling" in Figure 4). Alternatively, the impact of ocean cooling may have been effectively earlier than that of the atmospheric cooling (dotted trajectory for "initial cooling" in Figure 4), since the initial stages of glaciation may cool the poles and the ocean interior more than the tropical water vapor sources. In either case, the Antarctic stratifies upon cooling.

However, the water vapor effect may have increased relative to the oceanic effects as a glacial period intensified. Observations generally indicate that the tropical, subtropical, and temperate surface ocean cooled from the early to later phases of the last glacial period [Dannenmann *et al.*, 2003; Herbert *et al.*, 2001; Pahnke and Sachs, 2006]. In contrast, there is evidence that the deep ocean cooled proportionally less over the course of the last ice age (from stage 5d ( $\sim 110$  ka) to stage 2 ( $\sim 20$  ka)) [Cutler *et al.*, 2003; Martin *et al.*, 2002], perhaps because the polar ocean is constrained by the freezing point of seawater [Adkins *et al.*, 2002; Schrag *et al.*, 1996].



**Figure 3.** Compilation of ice core and sediment data across the last deglaciation, demonstrating the possibility that a North Atlantic overturning shutdown at  $\sim 17.5$  ka, presumably in response to a freshwater input associated with Heinrich event 1 (H1), led to an increase in Antarctic overturning, which released  $\text{CO}_2$  to the atmosphere. The GISP2 (Greenland) record of ice  $\delta^{18}\text{O}$  (line b; [Groote and Stuiver, 1997]) and the Dome C (Antarctic) record of ice  $\delta\text{D}$  (line d; [Monnin et al., 2001]) show the Antarctic lead in deglacial warming, with a hiatus in Antarctic warming during the Greenland's Bölling-Allerød (BA) warm period and a resumption of Antarctic warming during Greenland's Younger Dryas (YD) cold period. The  $^{231}\text{Pa}/^{230}\text{Th}$  of North Atlantic sediment core OCE326-GGC5 (line c; [McManus et al., 2004]) indicates a sharp reduction in North Atlantic export of intermediate/deep water beginning at 17.5 ka (marked with a gray interval) and coinciding with H1, with a resumption at the BA, followed by another reduction (marked with a second gray interval) at the onset of the YD and coinciding with H0 (not indicated). The dashed horizontal line under (c) corresponds to the  $^{231}\text{Pa}/^{230}\text{Th}$  “production ratio” that should be observed with no export of subsurface water from the North Atlantic. The two gray intervals noting reduced North Atlantic intermediate/deep water formation appear to coincide with the Antarctic warming (line d) and increasing atmospheric  $\text{CO}_2$  (line e; [Monnin et al., 2001]). Obliquity (line g; [Berger and Loutre, 1991]) increases over the last deglaciation; by 17 ka, it has increased 70% of the way from its minimum at 29 ka (indicated by the lower dashed line below (g)) to its maximum at 9.5 ka (the upper dashed line above (g)). The obliquity increase is used to explain an observed decrease in subtropical South Atlantic sea surface temperature (SST) from 25 to 18–19 ka (line f; [Sachs et al., 2001]). As supported by Antarctic ice core deuterium excess changes [Vimeux et al., 1999], this SST decrease may have reduced the tropical/subtropical water vapor supply to the Antarctic over this period, which may have worked against the predominant Antarctic water column stratification. Precession shifts peak summertime (June/December) insolation from the southern to northern hemisphere over the period from 22 to 11 ka (line h; [Berger and Loutre, 1991]). This may have also worked to reduce poleward water vapor transport to the Antarctic. Finally, the orbital changes together (which are the main components of the  $65^\circ\text{N}$  summer insolation change, line (a)) would have encouraged Northern hemisphere ice sheet melting, which may have spawned the H1 event. The ages for the intervals noted with abbreviations in (b) are according to the GISP2 record, except for H1, which is according to Hemming [2004]. The GISP2 time scale is from layer counting [Meese et al., 1994]. The Dome C  $\text{CO}_2$  and  $\delta\text{D}$  time scales are from Marchitto et al. [in review].



**Figure 4.** Output from an ocean general circulation model demonstrating two opposing effects of cooling on Antarctic stratification. Southern Ocean ventilation age at steady state is contoured as a function of decreases in ocean dynamic temperature (ODT) [de Boer *et al.*, 2007] and atmospheric hydrological temperature (AHT) [de Boer *et al.*, in review]. Individual model experiments run to steady state are indicated by black crosses. A decrease in ODT (to the right) reduces Antarctic overturning through the EOS effect (see text and Figure 1), increasing the ventilation age of the Southern Ocean. A decrease in AHT (upward) is a homogeneous decrease in temperature applied to the atmospheric energy balance model at the point where saturation with water is determined. All else constant, this causes water vapor to be precipitated closer to its source in the low latitudes, reducing the atmospheric freshwater supply to the poles, weakening the Antarctic halocline, causing more overturning, and thus reducing the ventilation age of the Southern Ocean. For the initial cooling associated with glaciation, a plausible envelope of trajectories is given by the solid and dotted gray lines (see text). Decreasing ODT and AHT together by 3°C causes a net decrease in Antarctic overturning. Continued (late glacial) cooling during the evolving glacial period is focused in the atmosphere and low latitude surface ocean (lower upward gray arrow), the deep ocean perhaps approaching the freezing temperature of seawater. With this cooling, Antarctic stratification is weakened. An increase in obliquity may have a similar effect as an AHT decrease, decreasing the net transport of water vapor from low to high latitudes (upper upward gray arrow). Although not included on this plot, a precession-driven shift in the hemisphere of maximum summer insolation (Figure 3h) may have compounded obliquity's effect by shifting water vapor transport away from the southern hemisphere. An obliquity increase may also have a steady state effect similar to an increase in ODT, by warming the deep ocean through the polar surface (dashed gray arrow tilting to the left; see text). The ocean/atmosphere model as well as ODT and AHT change protocols are described fully elsewhere [de Boer *et al.*, 2007; de Boer *et al.*, in review].

Continued tropical and subtropical surface cooling through the glacial period may transform a well-stratified glacial Antarctic into a state in which overturning is imminent (“late glacial cooling” in Figure 4). In this way, gradual climate cooling may be a key process that preconditions the Southern Ocean for its overturning response to interruption of North Atlantic-sourced ventilation.

Figure 4 specifically compares the water vapor effect against the equation of state effect. However, a similar dynamic may arise if the wind shift mechanism is responsible for Antarctic stratification at the onset of a glacial period. As the southern hemisphere westerly winds initially move equatorward and out the Drake Passage early in an ice age, their tendency to weaken the Antarctic halocline would be lost [Toggweiler *et al.*, 2006; Toggweiler and Samuels, 1995], and further equatorward migration of the westerlies would have little effect. Thus, as with the EOS effect, migration of the westerlies may provide a mechanism for initial Antarctic stratification that would, with continued climate cooling, become susceptible to the increasingly potent opposing effect of reduced water vapor supply, thus preparing the glacial Antarctic for overturning.

What, though, is our mechanism for the gradual atmospheric cooling that progressively reduces the water vapor supply? The time scale of ice sheet growth has long been prominent in glacial hypotheses [Imbrie *et al.*, 1993; Pollard, 1982]. We turn to this idea here, focusing on the effect that ice sheets have on global temperatures. First, more extensive ice sheets drive cooling by increasing albedo, both directly and through its effect on the terrestrial biosphere [Bender, 2003 and references therein]. Second, there is some evidence that atmospheric dust fluxes increase gradually through the course of the last ice age [Bender, 2003; Petit *et al.*, 1999; Wolff *et al.*, 2006] and that iron fertilization of the Subantarctic Zone in the Southern Ocean follows this dust flux history, becoming progressively more important as ice sheets grow and climate cools [Kohfeld *et al.*, 2005; Robinson *et al.*, 2005b]. Third, as described by Peacock *et al.*, [2006], other previously hypothesized biogeochemical mechanisms for lowering CO<sub>2</sub> become relevant as sea level falls in the later stages of a glacial period. These include increasing ocean alkalinity due to reduced shelf calcium carbonate deposition [Berger, 1982] and increasing ocean phosphate content due to weathering of continental margin sediments [Broecker, 1982], both of which are most plausible when called upon to explain only a fraction of glacial/interglacial CO<sub>2</sub> change.

While much recent progress has been made in the reconstruction of tropical and subtropical sea surface temperature over the last glacial cycle, a consensus view is not yet apparent for the details of mid-glacial cooling. For example, while some western tropical to subtropical Pacific records show

minimal cooling after stage 4 (at ~70 ka) [Lea *et al.*, 2000; Oppo and Sun, 2005], other records from the region appear to indicate cooling through to stage 2 (at ~20 ka) [Dannenmann *et al.*, 2003; Pelejero *et al.*, 1999; Stott *et al.*, 2002]. While a recent compilation suggests that progressive cooling is commonly evident in tropical and subtropical records for the interval from stage 5d (~110 ka) to mid-stage 3 (~45 ka) [Pahnke and Sachs, 2006 and references therein], it is not clear that tropical temperatures were colder at stage 2 (~20 ka) than at mid-stage 3 (~45 ka). The records with highest temporal resolution show oscillations over this period that likely have an orbital cause [Pahnke and Sachs, 2006; Sachs *et al.*, 2001], which we discuss next.

### ORBITAL PACING

Orbital pacing has long been recognized as a dominant control on deglaciations [Hays *et al.*, 1976]. Obliquity and precession have both been investigated in terms of their direct effects on ice sheets [Huybers, 2006; Huybers and Wunsch, 2005; Paillard, 1998]. However, such ice sheet-based explanations do not explain atmospheric CO<sub>2</sub> changes, nor do they explain why the first rapid deglacial warming occurs in Antarctica before it occurs in Greenland (Figure 3). In the deglacial mechanism proposed above, a freshening-driven cessation of the North Atlantic overturning represents a polar northern hemisphere trigger for deglaciation that would not cause early North Atlantic warming. However, this virtue of the hypothesis begs the question, what role do orbital changes play in the deglacial sequence? We propose that increasing obliquity and precession help to prepare the system for deglaciation by weakening Antarctic stratification, and they may also encourage the North Atlantic freshening event that begins the cascade of oceanic changes.

An increase in obliquity weakens the meridional gradient in insolation, warming the poles at the expense of the tropics, which may reduce the net poleward transport of water vapor [Raymo and Nisancioglu, 2003]. There is support for an obliquity forcing on southern subtropical/temperate sea surface temperature in both the Atlantic [Sachs *et al.*, 2001] and the Pacific [Pahnke and Sachs, 2006], with temperatures decreasing from ~30 to ~18 ka as obliquity increases (Figures 3 f and 3 g). Moreover, Antarctic ice core records of deuterium excess indicate that higher obliquity leads to a colder source temperature for the water vapor source of Antarctic ice [Vimeux *et al.*, 1999], consistent with reduced water vapor supply from the low latitudes. Such a reduction would work to weaken the Antarctic and North Pacific haloclines (solid upward arrow labeled “increasing obliquity” in Figure 4). Thus, obliquity maxima would build upon the reduced poleward water vapor transport of cold climates to push the Antarctic and subarctic North Pacific toward overturning.

While still less certain, an obliquity maximum may also weaken Antarctic and North Pacific stratification by warming the polar ocean. Once the polar warming has been transported to the deep ocean, the EOS mechanism would tend to increase the rate of overturning in these halocline-bearing polar regions (dashed arrow tilting leftward labeled “increasing obliquity” in Figure 4) [de Boer *et al.*, 2007]. This effect would need to overcome the initial opposing effect of warming the polar ocean surface relative to the deep ocean, which would transiently push the Antarctic and North Pacific toward stronger stratification, as observed in model simulations of anthropogenic warming [Haywood *et al.*, 1997; Manabe and Stouffer, 1993; Manabe *et al.*, 1991]. A polar role for obliquity can also be imagined in the case of the westerly wind shift mechanism for glacial Antarctic stratification, with increased mean annual insolation at higher latitudes causing the winds to shift poleward, weakening the Antarctic halocline.

However, if obliquity were the only relevant parameter, deglaciation arguably should have occurred at ~45 ka, when obliquity was at a maximum and low latitude sea surface temperatures were perhaps equivalently cold as during the LGM [Pahnke and Sachs, 2006]. Deglaciations also appear to be associated with precession minima [Imbrie *et al.*, 1992], times when perihelion occurs during northern hemisphere summer. These minima lead to more intense summers in the northern hemisphere but less intense summers in the southern hemisphere (Figure 3, panels a and h). This may shift the deposition of tropical water vapor away from the southern hemisphere and thus weaken the Antarctic halocline, making it vulnerable to breakdown. An assumption here is that the summer season is the most important for meridional water vapor transport. The apparent effect of precession on the annual mean location of the intertropical convergence zone [Haug *et al.*, 2001a] argues that this assumption is reasonable.

A second proposed role for obliquity and precession in our deglacial mechanism, in addition to weakening Antarctic stratification, would be to encourage abrupt melting events such as is represented by H1. Obliquity maxima represent maxima in mean annual polar insolation, while precession minima yield intense northern hemisphere summertime insolation; the combination of the two yield the 65°N summertime insolation maxima that have been linked to deglaciations (Figure 3a) [Imbrie *et al.*, 1992 and references therein]. Both may enhance summer melting and hasten northern hemisphere ice sheet reductions, some of which can occur in abrupt events. Given the central position of the North Atlantic to the potential drainages of the northern hemisphere ice sheets and the small size of the basin, North Atlantic overturning is susceptible to interference from freshwater inputs [Driscoll and Haug, 1998; Manabe and Stouffer, 1995].

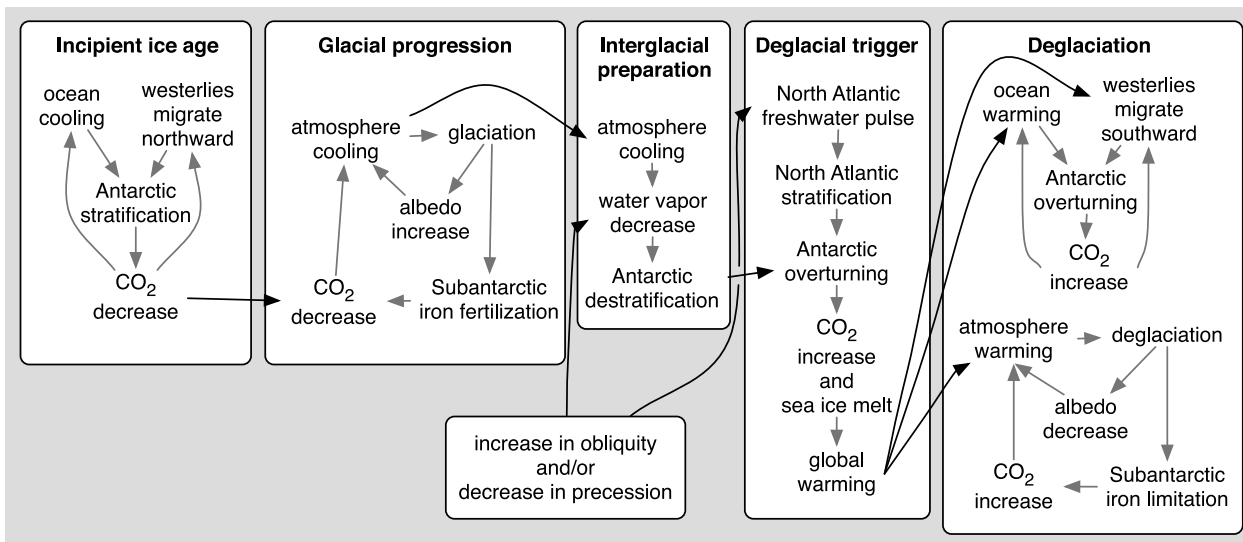
If insolation did play a role in the freshwater input associated with H1, then one should expect some evidence of Northern Hemisphere warming and ice melting in advance of H1. Indeed, there are early signs of modest warming and deglacial processes in the northern hemisphere (e.g., the small GISP2  $\delta^{18}\text{O}$  increase ~24 to 18 ka, Figure 3b) [Alley *et al.*, 2002; Bender, 2003 and references therein].

Heinrich events in general cannot be explained solely as the result of high northern hemisphere insolation. Nevertheless, it seems fair to imagine that an insolation-driven melting event would be recorded in North Atlantic sediments as something like the deposits of H1. Previous Heinrich events may have been associated with comparable rates of freshwater input to the polar North Atlantic. It may be that they did not lead to deglaciations because Antarctic stratification was still too strong to break down entirely in the face of a brief cessation in North Atlantic overturning. We would argue that H0, the event associated with the onset of the Younger Dryas, occurred after Antarctic overturning had been initiated. Nevertheless, the ensuing North Atlantic cold interval was again associated with accelerated Southern hemisphere warming and a second rapid increase in atmospheric  $\text{CO}_2$

(Figure 3d and e; [Monnin *et al.*, 2001]), suggestive of a repetition of the Antarctic ventilation increase associated with H1 [Broecker, 1998].

#### SUMMARY AND CONCLUDING REMARKS

The hypothesis proposed above can be (albeit somewhat artificially) separated into several stages, composed of periods dominated by feedbacks and event cascades (Figure 5). We begin in the midst of an ice age, when salinity-based stratification of the Antarctic and subarctic North Pacific is in place. This stratification works to cool the globe through reducing atmospheric  $\text{CO}_2$  (storing it in the abyss) and by increasing polar albedo through encouraging extensive sea ice (“Incipient ice age” in Figure 5). As cooling intensifies due to the albedo effect of ice sheet growth and possibly the progressive fertilization of the Subantarctic with iron (“Glacial progression” in Figure 5), the atmospheric supply of freshwater to the polar regions is reduced, rendering the glacial Antarctic and North Pacific haloclines susceptible to collapse (“Interglacial preparation” in Figure 5). In addition, by similar effects on the atmosphere’s water vapor



**Figure 5.** Diagram of stages and events that compose our hypothesis for the cause of glacial terminations. The black arrows provide the linkages that cause one stage or event to lead to the next. The entrance of obliquity and precession into these feedbacks to affect the timing of deglaciation is also indicated (see text). Glaciation provides the long time scale ( $\geq 10$  kyr) component that causes the slow development of glacial periods, as proposed in many previous hypotheses for glacial cycles. Peacock *et al.* [2006] suggest processes other than Subantarctic iron fertilization that would also yield  $\text{CO}_2$ -based positive feedbacks that would apply to the Glacial progression. The causal links under Interglacial preparation and Deglacial trigger could be combined to yield a negative feedback associated with low-to-high latitude water vapor transport. Our separation of this feedback into sequential events is tantamount to an assertion that Antarctic overturning is vulnerable to thresholds similar to those demonstrated for North Atlantic overturning. The feedbacks indicated under Deglaciation are the same as those under Incipient ice age and Glacial progression, but they are not temporally separated because ice sheet collapse occurs more rapidly than ice sheet growth.

transport, the obliquity maxima every 41 kyr and precession minima every ~22 kyr may also weaken Antarctic stratification (black arrow from “obliquity and/or precession decrease” in Figure 5).

In this oceanographic regime, a melting-associated freshwater input to the North Atlantic occurs, possibly encouraged by a maximum in obliquity and/or a minimum in precession (“Deglacial trigger” in Figure 5). This shuts off North Atlantic ventilation of the abyss. The buoyancy of the interior then rises until the Antarctic stratification, already weakened, breaks down, allowing deep water to the Antarctic surface. This allows the deeply sequestered CO<sub>2</sub> to escape into the atmosphere and reduces sea ice extent, both of which cause global warming and initiate rapid deglaciation (Deglaciation in Figure 5). The deglaciation is associated with the same positive feedbacks as in glaciation (compare Deglaciation with Incipient ice age and Glacial progression in Figure 5). However, we assume that the loss of ice sheets occurs much more rapidly than their growth, such that there is no important temporal separation of the feedbacks in the case of deglaciation.

We have found that the hypothesis of stratification of the ice age Antarctic yields new implications for “seesaw”-like overturning feedbacks between the North Atlantic and Antarctic [*de Boer et al.*, 2007]. In their context, the correlations among North Atlantic overturning shutdown, Antarctic warming, and CO<sub>2</sub> rise beg a simple North Atlantic mechanism for initiating the global warming at the end of the last ice age. The proposed circulation changes have a clear connection to previous hypotheses based on inverse behavior in the North Atlantic and Southern Ocean [e.g., *Gildor and Tziperman*, 2001; *Knutti et al.*, 2004; *Stocker and Marchal*, 2000]. In our case, this behavior arises from the energy budget of the ocean interior, specifically, the need for continued ventilation in the face of a shutdown in North Atlantic overturning.

Deglaciations in the late Pleistocene appear to be encouraged by the occurrence of an extreme ice age [*Pollard*, 1982; *Tziperman and Gildor*, 2003] and by maxima in obliquity and minima in precession [*Huybers and Wunsch*, 2005; *Imbrie et al.*, 1992; *Roe*, 2006]. The first two conditions have in common the tendency to reduce the tropical supply of water vapor to the poles [*Raymo and Nisancioglu*, 2003], while precession minima are likely to bias water vapor supply toward the northern hemisphere and away from the Southern Ocean. To this point, the effect of cooling on water vapor transport was seen largely as a weakness of the argument that Antarctic stratification is associated with cold (not warm) climates [*Sigman and Boyle*, 2001]. Thus, an interesting aspect of our hypothesis is that it embraces the dependence of Antarctic stratification on freshwater transport as an explanation for the timing of deglaciations.

Our hypothesis has clear areas of weakness, but some of these also point toward important questions for future research. As a first example, most of our arguments regarding climate-driven water vapor changes and polar halocline formation are untested. The role of water vapor transport in glacial cycles is a rich and important question, and it is becoming increasingly tractable as a target for investigation. Second, our arguments regarding the timing of deglaciations focus on the evolution of Antarctic conditions. We have not explored the climate-dependent conditions of the North Atlantic [*Winton*, 1997], which may, for example, control whether a given Heinrich event is able to shut off North Atlantic overturning. Third, while we have posited a threshold response from Antarctic overturning, where weakened stratification gives way upon North Atlantic perturbation, we have not demonstrated that such a threshold response would indeed occur. Finally, and on a more general note, hypotheses such as ours beg for improved reconstructions of upper ocean conditions in the Antarctic across major deglaciations.

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A.M. de Boer, School of Environmental Science, University of East Anglia, Norwich NR4 7TJ, UK.

G.H. Haug, GeoForschungsZentrum, Telegrafenberg, Potsdam D-14473, Germany.

D.M. Sigman, Princeton University, Department of Geosciences, Guyot Hall, Princeton, New Jersey 08544, USA. (sigman@princeton.edu)