Millennial scale evolution of the Southern Ocean chemical divide

Christopher D. Charles\textsuperscript{a,*}, Katharina Pahnke\textsuperscript{b}, Rainer Zahn\textsuperscript{c,d}, P.G. Mortyn\textsuperscript{d,e}, Ulysses Ninnemann\textsuperscript{f}, D.A. Hodell\textsuperscript{g}

\textsuperscript{a}Scripps Institute of Oceanography, UCSD, La Jolla, CA 92037-0244, USA
\textsuperscript{b}Department of Geology and Geophysics, University of Hawaii, 1680 East-West Road, Honolulu, HI 96822, USA
\textsuperscript{c}Institució Catalana de Recerca i Estudis Avançats, ICREA, E-08193 Bellaterra, Spain
\textsuperscript{d}Universitat Autònoma de Barcelona, Institut de Ciencia i Tecnologia Ambientals, ICTA, Edifici Cn, Campus UAB, 08193 Bellaterra, Spain
\textsuperscript{e}Department of Geography, Universitat Autònoma de Barcelona, Bellaterra 08193, Spain
\textsuperscript{f}Bjerknes Center for Climate Research, UIB, Allegaten 55, 5007 Bergen, Norway
\textsuperscript{g}Godwin Laboratory for Paleoclimate Research, University of Cambridge, Downing Site, Cambridge CB2 3EQ, UK

ARTICLE INFO

Article history:
Received 20 January 2009
Received in revised form 18 September 2009
Accepted 24 September 2009

ABSTRACT

The chemical properties of the mid-depth and deep Southern Ocean are diagnostic of the mechanisms of abrupt changes in the global ocean throughout the late Pleistocene, because the regional water mass conversion and mixing help determine global ocean gradients. Here we define continuous time series of Southern Ocean vertical gradients by differencing the records from two high deposition rate deep sea sedimentary sequences that span the last several ice age cycles. The inferred changes in vertical carbon and oxygen isotopic gradients were dominated by variability on the millennial scale, and they followed closely the abrupt climate events of the high latitude Northern Hemisphere. In particular, the stadial events of at least the last 200 kyr were characterized by enhanced mid-deep gradients in both $\delta^{13}C$ (dissolved inorganic carbon) and $\delta^{18}O$ (temperature). Interstadial events, conversely, featured reduced vertical gradients in both properties. The glacial terminations represented exceptions to this pattern of variability, as the vertical carbon isotopic gradient flattened dramatically at times of peak warmth in the Southern Ocean surface waters and with little or no corresponding change $\delta^{18}O$ gradient. The available evidence suggests that properties of the upper layer of the Southern Ocean (Antarctic Intermediate Water) were influenced by an atmospherically mediated teleconnection to high latitude Northern Hemisphere.

1. Introduction

Deep sea sediment cores demonstrate that a defining characteristic of the late Pleistocene glacial episodes was the repeated development of a “chemical divide” that separated the intermediate and deep ocean. The origin of this feature of cold climate intervals has yet to be resolved, despite its prominence and potential importance to the climate system (Toggweiler, 1999). If it were an expression of an altered geometry of deep ocean circulation—perhaps accompanying or even caused by reduced meridional overturning—then this “chemical divide” would necessarily imply a nearly global oceanic involvement in the abrupt climate shifts. Though the divide appears to varying extent in several sedimentary tracers (e.g. Herguera et al., 1992; Marchitto and Broecker, 2006), the mid-to-deep separation effect is best expressed in benthic foraminiferal stable carbon isotopic records from the Atlantic Ocean (Curry and Oppo, 2005). However, not all sedimentary tracers that should be sensitive to variable deep ocean circulation exhibit the same structure over the course of the late Pleistocene climate cycles (e.g. Yu et al., 1996; Piotrowski et al., 2004, 2008); the difference among tracers raises the possibility that factors other than deep ocean circulation (air–sea and land–sea exchange of carbon, for example) might dominate the stable carbon isotopic distribution in the ocean. Furthermore, one could conceive of a number of nutrient and carbon trapping schemes to explain the “chemical divide” (e.g. Boyle, 1988) that would not necessarily involve the variable rates of (physical) overturning of the water (Legrand and Wunsch, 1995). Consequently, the physical significance of one of the most prominent aspects of the ice age ocean remains in question.

As a region of both intermediate and deep water formation, the Southern Ocean is obviously an especially pivotal region for understanding the phenomenon. And previous results from the high latitude Southern Hemisphere suggest a clear separation.
between the characteristics of mid-depth and deep ocean during cold periods (Ninnemann and Charles, 2002; Hodell et al., 2003). Thus, it is appropriate to consider the evolution of the vertical structure of Southern Ocean isotopic gradients in as much detail as possible. Here we refine and extend the observations of the vertical gradients in the carbon isotope composition of the Southern Ocean over the last 200 ka, as one step toward deeper mechanistic understanding of the separation between shallow and deep layers throughout the global ocean. We construct time series of vertical carbon and oxygen isotopic gradients by means of simple subtraction of records from a deep South Atlantic and an intermediate depth Pacific sedimentary sequence. The distinction of these new gradient time series is that the constituent records resolve the millennial scale evolution of Southern Ocean isotopic distribution, while also extending beyond the limits of typical millennial scale resolution piston core records—most notably, through the penultimate deglaciation. The features of these quasi-continuous indices are comparable to various other measures of global climate variability and illustrate Southern Ocean processes that may contribute to the manifestation of the ocean’s chemical divide on suborbital timescales.

2. Methods and core chronologies

As with other large scale climatic indices that exploit the difference between time series (such as the Southern Oscillation Index), the purpose of our reconstructions is to highlight most effectively the depth-dependent changes by eliminating any possible shared variability in Southern Ocean isotopic records. It is generally recognized that benthic foraminiferal carbon isotopic time series may result from the combined influence of ocean circulation, surface ocean productivity and the air–sea exchange of carbon (Broecker and Peng, 1982). And any given carbon isotopic record from Southern Ocean sediments no doubt may be subject to
this potential complexity of processes: in fact, reasonable cases have been made to support a major role for all of these factors in determining benthic foraminiferal δ13C variability over ice age cycles (Martin, 1990; Charles and Fairbanks, 1992; Mackensen et al., 1993; Stevens and Keeling, 2000). Our premise here is that the influence on δ13C from some of these processes—the remineralization of organic matter produced in the surface ocean, for example—should not have a variable expression with depth (below the thermocline). Thus, while the cancellation of the common isotopic variability should more precisely describe the evolution of any “chemical divide” than is possible with any individual time series alone (illustrated in Fig. 1), the accurate construction of vertical gradients would also constrain the possible interpretations of the basic regional carbon isotopic variability. The same general logic extends to the intermediate-deep difference in oxygen isotopic composition of benthic foraminifera, and, in fact, the relationship between the vertical gradient time series (δ13C and δ18O) offers additional clues to the processes that might separate the different layers of the ocean in warm or cold climates.

Though this principle is straightforward enough, the difficulty lies in: (i) finding appropriately resolved records from the different water depth ranges; and (ii) correlating the individual sequences in the absence of a continuous radiometric clock. For these reasons, depth transects of sediment cores are usually constructed from cores within a confined region, where surface signals should be in common and therefore useful for correlation. For our purposes here, however, MD97-2120 from the mid-depth South Pacific (Pahnke and Zahn, 2005) and ODP Site 1089 from the deep South Atlantic (Hodell et al., 2002) provide the best available opportunity for creating continuous time series of vertical isotopic gradients (Fig. 1). Despite the geographic separation of the cores, they underlie roughly equivalent surface circumpolar ocean regimes (in the Northern Sub-Antarctic) and are characterized by approximately the same sedimentation rate (the sediments corresponding to the Last interglacial period lie at about 16 and 20 m subbottom depth, respectively). As a result, if the surface water variability in the Pacific and Atlantic sectors of the Sub-Antarctic zone evolved in concert, then the sedimentary sequences should be correlated with one another on the basis of the independent surface water tracers such as isotopic records from the planktonic foraminifer Globigerina bulloides.

Our best attempt at such a stratigraphic exercise (Fig. 2) consists of iterative optimization of the correlation between time series that are, to varying degrees, independent of one another. First, we assumed a chronology (discussed in more detail below) for MD97-2120 and used this chronology as the benchmark for correlation. The choice of the reference sequence was important, because, of the two sites, the MD97-2120 sequence is the more continuous. (As a single piston core, MD97-2120 is not subject to coring gaps as the spliced ODP sequence might be, and, furthermore, because it was recovered in shallower water, it was less influenced by carbonate dissolution.) Second, we anchored the timing of the most distinctive “abrupt” events in ODP 1089 planktonic δ18O records to that of their apparent counterparts in the MD97-2120 record. Most of these events are undoubtedly the same as those recognized in the Antarctic ice cores, an observation that suggests the circumpolar extent of the anomalies. We then fine-tuned the chronology of Site 1089 to maximize the correlation between the respective planktonic δ18O records. This step was necessary, because there were intervals in the planktonic δ18O records that could not be tied together reliably. There are also some intervals for which planktonic δ13C variability is clearly correlated with planktonic δ18O, and, for these intervals, the match of δ13C simply insures stratigraphic consistency. Finally, we used the benthic foraminiferal δ18O as a cross-check on the correlation achieved from the planktonic records. A significant fraction of that benthic δ18O signal must be shared at both sites, and any egregiously spurious correlation between the planktonic records should result in a fundamental discrepancy between these benthic δ18O records. However, no adjustments were necessary to accommodate the shared benthic δ18O variability, because the optimization of the correlation between planktonic foraminiferal records did not violate the constraints of benthic foraminiferal δ18O variability at any point in the sequence.

This full process resulted in slight modifications to the published chronologies for both sequences (Fig. 3), and, in the case of Site 1089, the comparison with MD97-120 indicated the presence of previously unrecognized coring gaps (these gaps do not materially affect the conclusions drawn in previous papers; however they are significant for our purposes here). Though both records extend for several ice age cycles, the gaps in the 1089 sequences make it increasingly difficult to achieve a consistent correlation prior to about 200 ka. As a result, we truncated our comparison at this horizon.

The reference chronology we adopted for MD97-2120 takes advantage of the strong 23 kyr periodicity evident in the planktonic foraminiferal Mg/Ca SST record. We tuned this 23 kyr variability to the 23 kyr component of Northern Hemisphere summer insolation, following the logic of Huybers and Denton (2008): the high latitude Southern Hemisphere surface temperatures should be sensitive to the duration of Southern Hemisphere summer, which is in turn highly correlated with the intensity of Northern Hemisphere summer insolation. This approach is relatively coarse, because we anchor the ordinal points of the filtered sea surface temperature record (every 5–6 kyr) to the astronomical timescale. The assumption of zero phase offset between Sub-Antarctic SST and boreal summer insolation is entirely compatible with the independent radiocarbon dating of the upper 50 ka of the MD97-2120 record (Pahnke et al., 2003). This assumption of zero phase is also generally compatible with the other possible strategy for marine core chronological development—namely, the transferal (via “wiggle matching of temperature proxies”) of the chronology from Dome Fuji, an ice core record for which the O2/N2 ratio in air.

Fig. 2. Result of iterative matching (by eye) of the millennial scale features of 
(
G. bulloides
) δ18O and δ13C. The reference chronology for both records is depicted in

Fig. 3. The δ13C data from MD97-2120 was not published previously. All other data come from Pahnke and Zahn (2005) and Mortyn et al. (2003).
bubbles has been tuned directly to overlying insolation (Kawamura et al., 2007). The orbitally tuned chronology adopted here for MD97-2120 does suggest a slight lead of SST with respect to the Dome Fuji δ¹⁸O ice record on the Kawamura time scale (Fig. 3b; see also Huybers and Denton, 2008 for a discussion of this point). Such a lead is not likely to be real, so slight adjustments would have to be made in either the marine or ice core chronologies for stratigraphic consistency. However, the discrepancies between the ice core-tuned chronology and the sediment core-tuned chronology are close to the limits of stratigraphic resolution. And because there are legitimate reasons to favor either approach—the direct orbital tuning of the sediment record vs. the transferral of the orbitally tuned ice core record—further constraints are required to determine whether either is more appropriate.

3. Results

The respective benthic δ¹³C records “float” on the sediment core stratigraphic correlation (Fig. 4a) and are then differenced to produce a vertical gradient time series (Fig. 4b). In making this difference time series, we use a simple subtraction of records to retain the per mil units, but the results would not be different if we were to normalize the records first. The principle feature of this index is the millennial scale variability, which is highlighted at the expense of the longer period fluctuations that are prominent in the constituent records. Spectral analysis of this index (not shown) confirms the lack of power in the orbital frequencies, which were evidently common to the two time series and were therefore cancelled in the differencing. The millennial scale variability of the index is not only characteristic of the well-known “Dansgaard Oeschger” interval of 20–60 ka, but it also dominates intervals of isotopic Stage 6, through to the penultimate deglaciation. In fact, there are only three well-defined intervals of persistently low vertical gradient in δ¹³C—the Holocene, marine isotope Stage 5a (70–80 kyr), and the Last interglacial period. Aside from these intervals, the index jumps abruptly from high to low every few thousand years. And even for the intervals of persistently weak vertical gradient, the development and termination of those intervals were seemingly set off by abrupt events (cf. the end of the Last interglacial episode).

Given the characteristics of this δ¹³C difference time series, one obvious question is whether any particular excursion might be artificial—a product of erroneous stratigraphic correlation or the result of other random errors. This question can be addressed.
The relative timing of the individual records by 1500 years or so. The robustness of the difference series does not necessarily apply to the major ice age transitions, where “edge effects” of miscorrelation can manifest themselves in a significant way (Fig. 4c). However, in general, the observations imply that the context and interpretation (hence the ultimate value) of the reconstructed vertical gradients depend to a large extent on the accuracy of the reference chronology, as opposed to the stratigraphic correlation alone. This accuracy can probably only be judged in comparison with the chronology of other known events of the Earth’s climate record.

One additional systematic issue to consider is the extent to which the two coring sites remained representative of the upper and lower layers of any vertical discontinuity. If water mass boundaries migrated vertically past the fixed depths of the sedimentary sequences, then the reconstructed vertical gradients might be confounded. This “site stationarity” problem is probably most relevant for the MDF97-2120 sequences, because the core site lies near the top surface of Upper Circumpolar Deep Water in the modern ocean (Fig. 1). In fact, the orbital scale variability in common between the mid-depth and deep isotopic records is probably a reflection of the common heavy influence of Circumpolar Deep Water at both sites. However, for the millennial scale, the site stationarity issue is one that requires additional records from various depths to assess properly—a prospect that may be imminent (Ninnemann et al., in prep).

### 3.1. Southern Ocean vertical gradients

Regardless of possible complications and chronological adjustments to the $\delta^{13}$C vertical gradient time series, it seems clear that it bears the typical stamp of Northern Hemisphere climate fluctuations. Over the last 100 ka, the resemblance of this index to the Greenland ice core record of climate is particularly striking, in both timing and scale (Fig. 6a). Using the well-established millennial scale events of the circum-North Atlantic as a reference, the abrupt strengthening of the vertical $\delta^{13}$C gradient in the Southern Ocean (in essence, an increase in the mid-depth $\delta^{13}$C values) seemingly occurred in conjunction with the all the major stadial events in the ice core, especially those also featuring Heinrich events (McManus et al., 1999). This association was emphasized in the original description of the MDF97-2120 $\delta^{13}$C record (Pahnke and Zahn, 2005). On the other hand, the decreases in the $\delta^{13}$C gradient (in essence, an increase in deep $\delta^{13}$C values) seemingly occurred during the transitions to all the interstadial events of the ice core record. Thus, while the association with the abrupt climate events of the last 100 kyr was distinct in the deep (vs. mid-depth) Southern Ocean, the vertical chemical gradient maintained a relatively consistent relationship with canonical records of Northern Hemisphere climate events, in both the cooling and warming phases.

This relationship between the Southern Ocean and Northern Hemisphere climate was not confined to the limits of the Greenland Ice core record. The Chinese speleothem record of monsoon variability is now acknowledged as a precisely dated archive manifesting the influence of high latitude Northern Hemisphere climate change in Southeast Asia; in the speleothem records, anomalous monsoon activity shows a close temporal link to high latitude Northern Hemisphere climate on millennial timescales (Wang et al., 2008). Fig. 6b demonstrates that there is also a relatively close temporal match between the “anomalous” fluctuations in monsoon strength—defined here by the deviations away from the dominant precessional variability—and the Southern Ocean vertical isotopic gradients throughout at least the last 190 ka reflecting that both are linked via atmospheric connections to North Atlantic variability. It is interesting to note, for example, interstadial-like configurations of Southern Ocean $\delta^{13}$C.
at about 135 ka, well in advance of Termination II, in both the monsoon record and the record of Southern Ocean carbon gradient. Both records also subsequently feature strong anomalies during Heinrich event 11 at 130 ka. These comparisons of course depend on the orbitally tuned deep sea sediment chronology and its relationship to the U/Th dated speleothem chronology. However, the match of full records is compelling enough to suggest that millennial scale Northern Hemisphere climatic events may be tied with the Southern Ocean vertical structure over multiple ice age cycles.

Aside from the temporal signature, additional clues to the origin of this Southern Ocean carbon isotopic divide come from comparison to the vertical oxygen isotopic gradient and the proxies for Sub-Antarctic surface temperature. Increases in the strength of the vertical gradient in δ¹³C were generally accompanied by increases in both the overlying surface temperature and increases in the vertical gradient of benthic foraminiferal oxygen isotopes (1). The increased oxygen isotopic gradient during times of heightened carbon isotopic gradient resulted from the fact that the mid-depth foraminiferal δ¹⁸O shifted to lower values while the deep δ¹⁸O remained relatively constant. (The marine isotope Stages 2–4 interval offers perhaps the clearest example of this phenomenon). These foraminiferal δ¹⁸O changes of course could represent either temperature fluctuations or shifts in the isotopic composition of

---

**Fig. 5.** The basic characteristics of the vertical gradient time series are fairly robust to details of stratigraphic correlation. Top panel (a) illustrates the effects of stratigraphic correlation, as the 1089 time series is arbitrarily lagged +1.5 kyr (red line) and −1.5 kyr (gray line) away from the “best guess” correlation (black line). Middle panels (b, c) show an expanded view of the time series in (a) for Terminations I and II. Bottom panels (d, e) illustrate the effect on the correlation with MD97-2120 planktonic foraminiferal δ¹⁸O reference series (black line), assuming an arbitrary lag of the 1089 time series by +1.5 kyr (blue line) for Terminations I and II. The orange line in both (d) and (e) represents our “best guess” correlation, as in Fig. 2.
It is important to establish whether the enhanced vertical gradients in the Southern Ocean also preconditioned the other ocean basins to heightened divides. This issue is difficult to assess empirically, because high deposition rate records that can be correlated with the Southern Ocean sequences are rare; and we should be clear that we are referring here to the millennial scale changes in gradients, as opposed to the vertical structure of “time slices” such as the LGM. Thus, full assessment of the issue must await a more extensive network of records. In any case, records from the Brazil margin (Cane et al., 2003), the Coral Sea (Bostock et al., 2004), and the Arabian Sea (Jung et al., 2009) feature comparable isotopic evolution as MD97-2120, though the radiocarbon chronologies are difficult to align with sufficient precision. And at least one additional Northern Indian Ocean record (published in Naqvi et al., 1994) displays carbon and oxygen isotopic trends that are virtually identical to that of MD97-2120, despite the fact that the absolute values of the $\delta^{18}O$ and $\delta^{13}C$ are quite different (Fig. 8). The Southern Ocean is the only plausible source for ventilation of mid-depth Indian Ocean water that fills the Andaman Basin, which has an effective sill depth of 1500 m (Naqvi et al., 1994); thus, the similarity between sedimentary sequences from these two regions indicates that Southern Ocean processes made an imprint on the characteristics of the bulk interior of the ocean.

4. Discussion

One common conception of vertical temperature and nutrient (carbon) gradients in the ocean’s interior over ice age cycles is that the main changes must have resulted from the variable operation of the Atlantic meridional overturning circulation. The logic is that as overturning in the north weakened, the upper layer would come to be dominated by warm, salty and nutrient poor northern source water just as cold salty and nutrient rich southern source water invaded a greater area of the deep ocean (e.g. Alley and Clark, 1999). In some formulations of the ice age ocean (e.g. Stevens and Keeling, 2000) the separation between the upper and lower layers would lie at about 2700 m, the effective sill depth of the Drake Passage. These general “conveyor” concepts seem especially applicable to the distribution of sedimentary tracers in the Atlantic (Curry and Oppo, 2000; Marchitto et al., 2002). But they have also been applied to the changes observed in other ocean basins as well (e.g. Waelbroeck et al., 2006).

Furthermore, the variable strength of the meridional overturning circulation relationship is most often invoked to explain the geographic pattern of abrupt surface climate events globally (e.g. Broecker, 2006). For example, the anti-phased warming of the high latitudes of the Northern and Southern Hemisphere has been described as the result of the cross equatorial heat piracy of the North Atlantic overturning (the “bi-polar seesaw”; Crowley, 1992) or as the result of ocean adjustment to freshwater input in the North (the “thermal-freshwater seesaw”; Knutti et al., 2004). For either of these explanations of global abrupt climate change, the gradients of temperature and nutrients in the ocean interior (including the Southern Ocean) should vary in accordance with the perturbations to the sinking of NADW in the north.

Our records of the chemical and thermal divide of the Southern Ocean fit some, but not all aspects of this general conception of the AMOC. For example, the strong resemblance between the Southern Ocean vertical gradient time series and the Greenland ice core record of climate might be taken as evidence for the propagation of anomalies via the “conveyor”. On the other hand, it is important to recognize that the Southern Ocean vertical gradients that we have reconstructed here are actually a composite of two distinct responses that may have separate origins and therefore separate implications: Heinrich events and other strong North Atlantic cooling events were characterized by prominent excursions...
towards higher $\delta^{13}C$ and lower $\delta^{18}O$ (higher temperatures) in the mid-depth South Pacific record, while the warming episodes in the North Atlantic were marked by significant excursions to high $\delta^{13}C$ and modest increases (if anything) in the $\delta^{18}O$ of deep South Atlantic record. These responses of the upper and lower layers of the Southern Ocean were anti-correlated to some extent, but there were prominent exceptions to this rule — notably, during the terminations. During these episodes, the upper Southern Ocean (and the Antarctic continent) warmed when the vertical carbon isotopic gradient flattened dramatically to its modern state, an association of events that is exactly the opposite of expectations from a simple “bi-polar seesaw.”

And though the ocean seesaw concepts seem capable of explaining the millennial scale variability in the cold periods (isotope Stages 2–4, for example), the mechanisms centered solely on the Northern Hemisphere perturbations to the thermohaline circulation fail to explain why the terminations would be different (Wolff et al., 2009). For example, the return to modern vertical gradients in carbon at about 14 ka—if this were a product of the flux and/or geometry of NADW—should have been accompanied by strong cooling in the high southern latitudes. Such a strong response is not observed in either marine or ice core records. Furthermore, it is important to emphasize that, even during the “Dansgaard Oeschger” events of the Stages 2–4, the vertical gradients in both carbon and oxygen isotopes maintained a strong correlation to Sub-Antarctic surface ocean proxy measurements; and sediment cores that record the variations in surface Sub-Antarctic surface water properties during Heinrich events strongly suggest a southward displacement of the influence of subtropical water—i.e. not just heat. Such fluctuations in turn demand either

Fig. 7. (a) The vertical gradient in Southern Ocean oxygen isotopes (black line) follows the reconstruction of Sub-Antarctic SST (gray line) at MD97-2120 on millennial timescales, except during deglaciation. (b) The same is generally true of the vertical carbon isotopic gradient (black line), but the divergence between $\Delta \delta^{13}C$ and SST (gray line) is especially pronounced during the terminations. (c) The relationship between the vertical carbon isotopic gradient (black line) and oxygen isotopic gradient (gray line) over the last 60 ka highlights the difference in pattern between the “Dansgaard Oeschger” interval and Termination I.
a change in the westerly wind field or a change in eddy activity that
determines the balance of subtropical (vs. polar) water near the
frontal zones (Ninnemann et al., 1999; Sachs and Anderson, 2005).

These considerations lead us to propose an alternative expla-
nation for much of the behavior we observe: that the millennial
scale variability in at least the upper Southern Ocean water masses
was a product of atmospheric teleconnections to the Northern
Hemisphere (depicted in Fig. 9b) as opposed to effects of the AMOC
"conveyor". Chiang and Bitz (2005) demonstrate that the imposi-
tion of sea ice anomalies in the Northern Hemisphere has the
potential to influence winds and pressure patterns in the Southern
Hemisphere, through a southward shift in the convergence zones in
the tropical Pacific. While these and other analogous modeling
experiments (Velinga and Wood, 2002) emphasize the connection
between sea ice in the high northern latitudes and the ITCZ, it is
logical to expect that the ultimate effects would extend to higher
southern latitudes

despecially if the tropical Pacific was affected
strongly (Clark et al., 2007). And though the water mass trans-
formations that produce intermediate water in the Southern Ocean
are not well characterized even for the modern ocean, changes in
wind-driven mixing and gradients near the polar frontal zone, or
large scale meridional shifts in the precipitation-evaporation
balance could certainly give rise to variations in the "preformed"
characteristics of AAIW— including its temperature, salinity,
nutrient content and carbon isotopic composition.

One main advantage of explaining the variability of the upper layer of
the Southern Ocean “chemical divide” as an atmospheric tele-
connection, as opposed to an oceanic propagation, is that the ter-
ninations would pose no contradiction: if the teleconnection depended
on a link between sea ice and the tropical Pacific convergence zone,
then that link could have been overwhelmed by other more direct
influences on the atmospheric circulation during deglaciation.

What would be unique about terminations in this regard? For
one, the exact times of strongest fall/winter [the most critical
season for ENSO development (Clement et al., 1999)] insolation
forcing on the equatorial Pacific were the very same intervals that
the normal anti-correlation between the Northern Hemisphere and
the upper Southern Ocean broke down. Other forces such as large
changes in the sea level could also interfere with the sea ice-ITCZ
link (Bush and Fairbanks, 2003). Direct greenhouse gas forcing in
the high latitudes of both hemispheres might also be strong enough
to dominate any atmospheric teleconnection; in fact, the typical
pattern of correlation in the vertical gradients broke down when
atmospheric carbon dioxide rose to nearly its full interglacial level.

Finally, J.R. Toggweiler (pers. communication) points out another
possible unique aspect of the terminations—that these may have
been times of maximum spin-up of the Antarctic Circumpolar
Current as the westerlies shifted southward to their maximum
extent, in which case, the mixing of heat and carbon at sites just
north of the ACC may appear to be anomalous with respect to other
intervals of less extreme atmospheric forcing. Thus, unlike the

Fig. 8. Comparison between the benthic foraminiferal records over the last deglacia-
tion from MD97-2120 in the Southwest Pacific (Pahnke and Zahn, 2005) and RC12-344
in the Andaman Basin, North Indian Ocean, with an effective sill depth of 1.3 km (Naqvi
et al., 1994). The values in parentheses on the δ13C scale refer to MD97-2120. The
similarities between these oxygen and carbon isotopic sequences suggest that vari-
ability of the Southern Ocean mid-depth propagated northward into the interior of the
ocean (though the amplitude of response is attenuated in the northern core). The RC12-
344 sequence was not radiocarbon dated; its age scale is estimated here on the basis of
the oxygen isotopic variability.

Fig. 9. Flow chart of mechanisms that might account for not only the altered vertical
gradients in the Southern Ocean over millennial timescales but also the temporal
connection with Northern Hemisphere events. The hypothetical oceanic pathway, “A”
is the most popular in published literature (e.g. Waelbroeck et al., 2006; Clark et al.,
2007), but the atmospheric pathway, “B”, deserves serious consideration. These two
pathways need not be mutually exclusive.
AMOC, a variety of atmospheric effects could explain the isotopic manifestation of the terminations in the Southern Ocean. For the most part, these arguments can be applied most easily to the upper layer, but it is conceivable that the isotopic composition of the lower layer of the Southern Ocean would also be affected by atmospheric teleconnections to the Northern Hemisphere. Historically, the coincidence between increases in deep δ13C and Northern Hemisphere stadial/interstadial transition—for example, the Bolling/Allerod transition at about 14.5 ky—has been explained as a consequence of increased NADW input to the Circumpolar Deep Water. This explanation does, however, conflict with other interpretations of δ13C in low-resolution deep Atlantic sediment cores that argue for a minimum flux of NADW during the main stadial/interstadial intervals (Lisiecki et al., 2008). This apparent paradox might be reconciled if one argues that the density of deep water south of the ACC influences the admixture of deep water at sites north of the ACC (i.e. at Site 1089). Then the increases in deep δ13C at Site 1089 would be sensitive to the north/south density contrast as opposed to the flux of NADW, and, consequently, could be subject (through changing Southern Ocean sea ice field) to the same atmospheric teleconnection patterns that we envision for the upper layer.

In any case, this atmospheric teleconnection hypothesis for the upper layer is testable on a number of respects, because if it were responsible for altering the characteristics of AAW, then, by extension, it may explain much of the appearance of the upper layer of the chemical divide during Heinrich events. For one thing, such a mechanism allows for significant decoupling between δ13C and other nutrient or water mass tracers in the upper layer of the "chemical divide", because gas exchange imports a significant influence on δ13C in the Sub-Antarctic zone (Lynch-Stieglitz et al. 1995; Charles et al., 1993). Second, the mechanism might actually predict a decoupling between the normal (modern) association of physical tracers such as sortable silt and nutrient tracers in the mid-depth ocean (Hoogakker et al., 2007). Third, significant variability in the carbon isotopic composition of intermediate water formed in the Southern Ocean should impart a signature in the atmosphere as well (for example, during Heinrich events, this mechanism should lead to relative depletion of atmospheric radiocarbon or carbon-13)—especially, if, as implied by the records in Fig. 7, the Southern Ocean processes influenced a substantial volume of the upper ocean. Finally, the characteristics of specific intervals of the ice age cycles should be diagnostic of mechanism. For example, the initial changes in Southern Ocean vertical gradients across Terminations I and II bear strong resemblance to those of the MIS 4/3 boundary, yet an anti-phased pattern of warming in the Southern Ocean upper layer (relative to Northern Hemisphere climate) was ultimately maintained during the Stage 4/3 transition, unlike during Terminations I and II.

This last point serves as a reminder that the Southern Ocean vertical gradients we have reconstructed here have effectively filtered out the longer period (orbital scale) fluctuations in properties that are common to the depths of these specific sedimentary sequences. The gradient records are therefore blind to possible changes in the vigor or geometry of the thermohaline circulation on these longer timescales that might have driven mid-depth and deep Southern Ocean in parallel. Furthermore, with only two sites, we obviously cannot claim that the behavior we observe captures all aspects of the "chemical divide"—for example, its expression between 2000–3000 m water depth in time slice reconstructions of the LGM (Marchitto and Broecker, 2006). Nevertheless, it is worth considering the processes that gave rise to the changes we observe and the extent to which they should operate in the same way on various timescales. Given that the Southern Ocean millennial scale variability analyzed here is demonstrably different from longer period behavior; and given that the terminations are apparently unique (in their pattern of associations) from the rest of the ice age cycle, the evolution of Southern Ocean vertical gradients must have been a product of more than just the variable operation of the North Atlantic thermohaline circulation.

Regardless of origin, changes in the vertical gradients in the Southern Ocean would certainly influence the appearance of water mass mixing in sensitive regions of the world ocean (Skinner et al., 2003), the heat storage and therefore the sensitivity of the climate system to perturbation (Adkins et al., 2005), and the CO2 balance in the atmosphere (Toggweiler, 1999; Sigman and Boyle, 2000). Thus the time series created here provide a necessary step toward integration of these various aspects of "abrupt change". Furthermore, the comparison between the Southern Ocean "chemical divide" and the U/Th dated speleothem record (Wang et al., 2008) suggests that a unified chronology of abrupt events throughout much of the ocean/atmosphere system may be achievable.

**Acknowledgements**

This work was an outgrowth of projects supported previously by NSF and the Ocean Drilling Program (grants to CDC and DAH). We thank numerous colleagues for discussion, including Ralph Keeling, Jess Adkins and Jeff Severinghaus. We also thank Robbie Toggweiler and an anonymous reviewer for their especially helpful comments on an earlier draft.

**References**


