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Climate connections between the hemisphere revealed by deep sea sediment core/ice core correlations

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Abstract

Correlation of Southern Ocean deep sea sediment core records with ice core records of polar climate delineates with unprecedented detail the relationship between high latitude climate and the ocean's thermohaline circulation over the last 80,000 years. Our observations suggest that, while North Atlantic Deep Water variability manifests itself clearly in Southern Ocean nutrient proxy records over periods as short as 500 yr, this deep water variability did not promote a direct link between climate variability in the high latitudes of the two hemispheres on millennial timescales. In particular, the proxy records indicate that, on average, northern hemisphere climate fluctuations lagged those of the southern hemisphere by 1500 yr.

Keywords: Antarctic Ocean; paleoclimatology; North Atlantic Deep Water; ice cores; deep-sea sedimentation

1. Introduction

A popular paradigm for interpreting the Pleistocene record of climate change is the notion that a climate response can originate in the North Atlantic and subsequently propagate globally by the varying flux of North Atlantic Deep Water (NADW) [1–4]. This 'conveyor belt' paradigm is appealing because it can explain the otherwise perplexing distribution of phases in the response to long period variations in incident radiation (the so-called Milankovitch variability) [4], while at the same time accounting for the more rapid oscillations observed in, among other places, the Greenland ice cores [2]. The fact that North Atlantic deep sea sediments show fluctuations akin to those found in the Greenland ice sheet offers partial support of the conveyor belt hypothesis [5,6]. Yet a comprehensive test of the hypothesis on all timescales is difficult, because very few deep sea sediment cores have sufficient resolution, and, furthermore, the chronology and interpretation of climate proxies derived from deep sea sediments is often too ambiguous to allow global comparisons.

Bender et al. ([7]; but see also [8]) made a significant advance in this pursuit, placing ice core records from two hemispheres in a common chronological

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framework by aligning globally synchronous shifts in the isotopic composition of molecular oxygen. As a result, portions of the Greenland and Antarctic ice cores now provide firm targets for extra-regional correlation of the deep sea sediment archive, and it is possible to address issues relating to the interhemispheric timing of climate change, such as the beginning of deglaciation in both poles [8]. However, for millennial oscillations over the last glacial cycle — the interval particularly relevant for understanding the 'conveyor belt' reorganizations — even this new ice core correlation tool is not entirely definitive because of the large, potentially variable difference between the age of the gas (the basis for correlation) and the age of the ice (which contains most of the climate proxies) in Vostok, the best developed Antarctic ice core.

Here we report that a single Southern Ocean deep sea core may provide a means of circumventing the fundamental chronological limitations which hamper attempts to delineate short-lived (millennial scale) global climate events. In this core, deep ocean circulation changes and surface ocean temperature changes, recorded in the isotopic composition of benthic and planktonic foraminifera, bear striking resemblance to the climate oscillations captured in the Greenland and Antarctic ice cores, respectively. From this similarity, we infer that both northern and southern hemisphere climate change are represented in a single sedimentary sequence, and therefore the 'stratigraphy' of interhemispheric climate change can be determined directly, even on millennial timescales. Our results not only support the new ice core stratigraphy [7,8], but also add new information on the

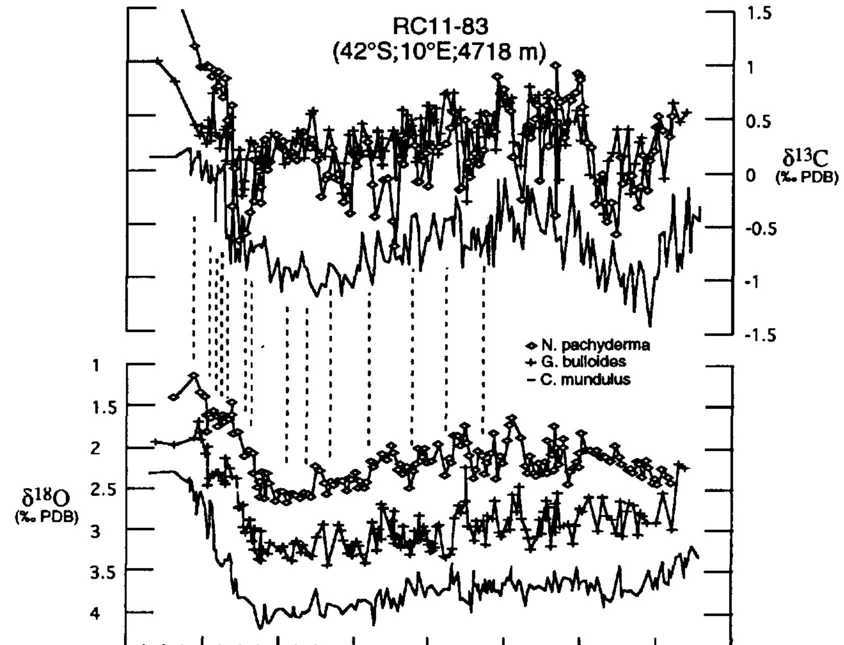


Fig. 1. Isotopic records from South Atlantic deep sea core RC11-83. The planktonic values (*N. pachyderma* and *G. bulloides*) were generated at S.I.O. using the Carousel-48 automatic carbonate device coupled to a Finnigan MAT 252 mass spectrometer. The benthic values (*C. mundulus*; previously assigned to *P. wuellerstorfi* in [14]) were generated at LDEO using the same carbonate device coupled to a Finnigan MAT 251 mass spectrometer [33]. Reproducibility of the measurements is better than 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$. For clarity, we have added +1‰ to the *N. pachyderma* carbon isotopic record. The vertical lines are the AMS ^{14}C dated levels for the core, which are listed in Table 1. Missing values in the planktonic foraminiferal records (for example, the top and the bottom of the core) reflect intervals of extremely low carbonate content in the core.

global manifestation of the 'conveyor' over a range of climate conditions and frequencies.

2. Ice core and marine core sequences

Fig. 1 shows the different isotopic records derived from South Atlantic core RC11-83 (41°36′S; 9°48′E; 4718 m). AMS radiocarbon dates on 14 separate levels of RC11-83 constrain its chronology for the last 40 kyr (Table 1). A polynomial fit of the resulting age–depth curve allows construction of isotopic time series but, in order to compare these deep sea time series with ice core records, the radiocarbon ages must be converted to calendar years. This conversion involves correcting for the apparent ^{14}C reservoir age (which we take as a constant 600 yr [9]), then applying a ^{14}C age–U/Th age calibration (in this case, based on paired analyses given in Bard et al. [10] and several newer, unpublished analyses). For the portion of RC11-83 covering the last deglaciation, we conservatively estimate the calendar year chronology to be good to within ±500 yr. However, before about 25 kyr, there are a limited number of calibration points for converting radiocarbon ages to calendar ages, so our assumed correction is largely an extrapolation and is highly uncertain (probably at least ±1500 yr). To assign ages older than 40 kyr in RC11-83, we define one distinctive oxygen isotope event — the Stage 4/3 boundary — and ascribe its age based on the SPECMAP chronology [11]. The bottom of RC11-83 lies somewhere in the isotope Stage 5/4 transition, and therefore any age assignment before 65 kyr is completely arbitrary. Overall, the error in our chronology probably falls between 2% and 5%, with the smaller error in the youngest part of the record. This range of errors is actually fairly comparable to that for the ice cores. Bender et al. [7] derived their Greenland ice core chronology (which we adopt throughout this paper) for the last 50 kyr through annual layer counting (in other words, it is a calendar age chronology to this level) and, for the older portions, through the mapping of distinct events in the $\delta^{18}O_{atm}$ record into the SPECMAP chronology. In the Vostok ice core, the Bender et al. chronology comes from correlation of the $\delta^{18}O_{atm}$ record to the SPECMAP record [26].

Table 1
Chronological constraints for core RC11-83

Depth (cm)	Species analyzed	Radiocarbon age (kyr)	Calendar age (kyr)	Comment [a]
189	*G. bulloides*	9.99	11.83	AA5974
221	*G. bulloides*	11.93	13.01	AA5975
231	*G. bulloides*	12.12	13.33	AA5976
248	*G. bulloides*	12.91	14.34	AA5977
262	*G. bulloides*	13.23	14.92	AA5978
298	*G. bulloides*	14.31	16.24	AA5979
335	*G. bulloides*	15.62	17.76	AA5980
426	Mixed planktonics	17.70	20.56	OS3457
477	Mixed planktonics	19.60	22.89	OS3458
546	Mixed planktonics	21.30	23.93	OS3530
644	Mixed planktonics	24.10	27.02	OS3529
756	Mixed planktonics	28.40	32.03	OS3528
844	Mixed planktonics	32.00	36.10	OS3531
943	Mixed planktonics	35.80	41.00	OS3459
1243				Stage 4/3

[a] Code number refers to accession numbers for the Arizona accelerator facility (AA) and the NOSAMS Woods Hole facility (OS).

The resolution and the dating of RC11-83 enables a fairly detailed comparison between deep sea sediment proxies and ice core proxies. Fig. 2a shows the relationship between the time series of benthic foraminiferal $\delta^{13}C$ in RC11-83 and Greenland $\delta^{18}O_{ice}$ [12]. The similarity between the records is obvious; benthic $\delta^{13}C$ shares many of the same characteristics of the Greenland ice core record: an abrupt, episodic glacial–interglacial transition, millennial oscillations in isotopic Stage 3, and bundling of millennial events in longer term cycles. The match between the timing of most individual events is also remarkable, especially considering the chronological uncertainties in both records, which are larger than the total duration of many of the cycles. Perhaps the high degree of correlation ($R = 0.72$ from 10 to 70 kyr) is fortuitous with the present dating, but structural similarities suggest that high latitude Northern Hemisphere climate variability is imprinted on the Southern Ocean nutrient proxy record, even on millennial timescales.

Although an exact match between the Greenland and Southern Ocean records cannot be made because of the age uncertainties, one would expect strong northern hemisphere control on Southern Ocean nutrient proxy records. Benthic $\delta^{13}C$ variability at the site of RC11-83 reflects, for the most part, changes

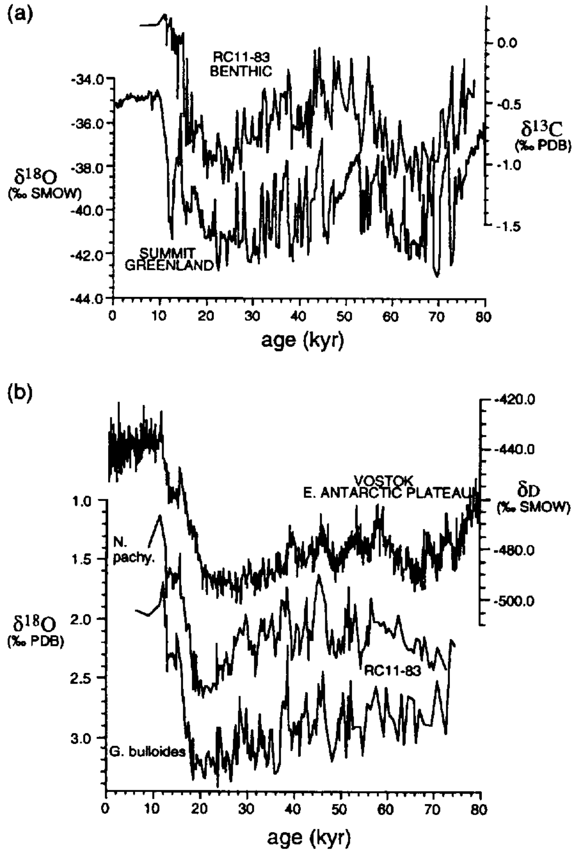


Fig. 2. (a) Time series of benthic foraminiferal $\delta^{13}C$ in core RC11-83 with the Summit $\delta^{18}O_{ice}$ ice time series [7,12]. For the ice core, the age scale is a 'SPECMAP' chronology prior to 50 kyr and 'calendar age' chronology after 50 kyr. For RC11-83, the age scale is a 'SPECMAP' chronology prior to 40 kyr and a radiocarbon-based 'calendar age' chronology after 40 kyr (see text). (b) Time series of $\delta^{18}O$ from two planktonic foraminiferal species (*N. pachyderma* and *G. bulloides*) with the δD_{ice} record of Vostok [7,21]. The Vostok age scale represents a 'SPECMAP' chronology (see text).

in the flux of NADW to Circumpolar Deep Water [13,14]. Maxima in $\delta^{13}C$ indicate increased southward flow of NADW, because this water mass is tagged with high $\delta^{13}C$ (and low nutrients) [15]. The same conditions which promote increased NADW flux also lead to higher temperatures throughout Greenland, and a significant amount of heat is transported poleward directly by NADW formation [2]. Thus, the similarity between benthic $\delta^{13}C$ and Greenland $\delta^{18}O_{ice}$ can be viewed as a predictable consequence of 'conveyor' variability.

Like any proxy record, however, the interpretation of $\delta^{13}C$ is not entirely free of complications. Deep ocean circulation, alone, cannot explain the magnitude of the RC11-83 benthic $\delta^{13}C$ oscillations (one would expect a maximum circulation effect of about 0.5‰, corresponding to shifts from no NADW to modern NADW input), nor the low absolute values during the glacial periods (Southern Ocean values should fall to match those of the glacial Pacific, between $-0.3‰$ to $-0.5‰$, if circulation was the only control) [14,16]. Some other process — but evidently one that is coherent with the northern hemisphere climate — overprints the $\delta^{13}C$ record. The origin of this amplification mechanism is still unknown and subject to debate, but it is perhaps significant that the same overprint (of up to 0.5‰) affects the planktonic foraminiferal records (Fig. 1). Thus, the unexpectedly high amplitude of the benthic foraminiferal record cannot be strictly the result of pore water and sediment/water interface processes. Following Mackensen et al. [17], we consider it likely that latitudinal changes in surface productivity or upper water nutrient cycling amplify the RC11-83 $\delta^{13}C$ time series in some way. A simple positive feedback mechanism might operate, merely increasing the amplitude in all frequencies of the $\delta^{13}C$ spectrum, if NADW variability is the cause of latitudinal productivity changes.

The South Atlantic may be fairly unique in this regard, considering the relatively minor latitudinal disturbance of diatom productivity and planktonic $\delta^{13}C$ in the other sectors of the Southern Ocean. This geographic distinction establishes a natural test for the origin of the high amplitude benthic foraminiferal $\delta^{13}C$ fluctuations. In fact, additional evidence for the deep circulation interpretation of the millennial scale $\delta^{13}C$ variability in RC11-83 comes from the observation that many of the same benthic $\delta^{13}C$ oscillations, while lower in amplitude, can be recognized in a high resolution South Pacific core characterized by a different surface productivity regime [18].

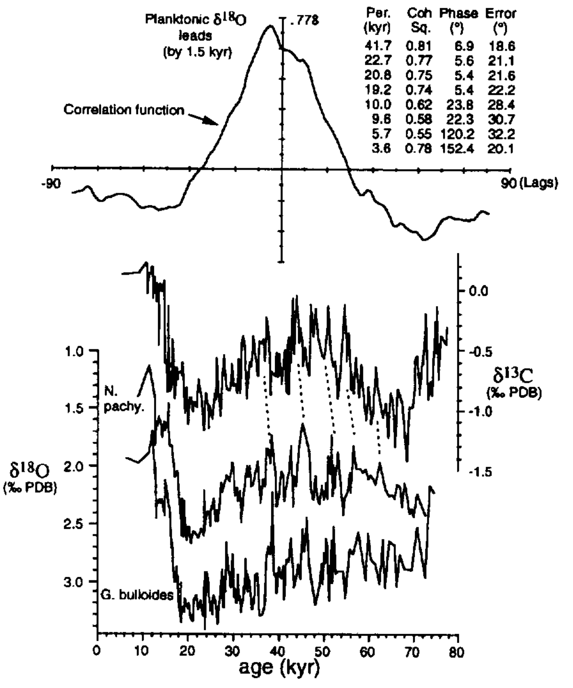
There are, however, several periods when not only the amplitude is in question; the linkage between Greenland climate and Southern Ocean $\delta^{13}C$ breaks down completely. The most obvious example is the Younger Dryas interval from 12 to 11 kyr B.P., but early Stage 3 is equally anomalous. We do not believe the lack of coupling in these intervals undermines the deep sea circulation interpretation of $\delta^{13}C$. (For example, a strong Younger Dryas age anomaly is not observed in any nutrient proxy record, $\delta^{13}C$ or otherwise, in any of the Southern Ocean cores we have examined thus far [19]. If the global thermohaline circulation was perturbed to its glacial mode during this interval, one might expect to see some anomaly in these records.) Rather, it is possible that, by changes in the mode of NADW formation, the flux of nutrient depleted water to the Southern Ocean was strong while the northward flux of heat to Greenland was not [20], or that, through atmospheric circulation changes, the Greenland oxygen isotopes could vary independently of the strength of the 'conveyor'. In any case, these isolated intervals do not erase the implication of the generally strong coupling shown in Fig. 2a: oscillations quite similar in character and timing to those of northern hemisphere climate clearly were felt in the deep ocean of the high latitude Southern Hemisphere, and the 'conveyor' is the most logical explanation for these oscillations.

Fig. 2b shows the comparison between two planktonic foraminiferal $\delta^{18}O$ time series (*N. pachyderma* and *G. bulloides*) with the Vostok δD_{ice} [21] (Bender et al. chronology). The similarity between these time series is striking over the last 70 kyr (for example, $R = -0.86$ considering *G. bulloides* $\delta^{18}O$ and Vostok δD_{ice}). Each of these variables ($\delta^{18}O_{pl.\ foram}$ and δD_{ice}) could be controlled by a number of possible influences. The oxygen isotopic composition of foraminiferal carbonate depends on both the temperature and the isotopic composition of ambient seawater (which itself is governed by whole ocean ice volume effects, local meltwater effects, and local hydrological effects). The isotopic composition of ice at Vostok depends not only on the precipitation site air temperature, but also on the temperature and isotopic composition of the moisture source. However, among these possibilities, regional temperature change is the only explanation for the good anticorrelation between the RC111-83 $\delta^{18}O_{pl.\ foram}$ and the Vostok δD_{ice}, because any changes in the isotopic composition of seawater capable of affecting the planktonic foraminiferal record would either drive the δD_{ice} of Vostok in a parallel direction (for example, in the case of whole ocean effects or meltwater events) or would be too small for detection in the ice core (for example, if sea surface salinity were to change by a few tenths of a per mil.)

Of course, seawater $\delta^{18}O$ changes must be embedded in the RC11-83 $\delta^{18}O_{pl.\ foram}$ record. The major component of the planktonic foraminiferal signal over periods greater than a few thousand years is the ice volume effect (about 1.3‰ for a full glacial transition) [22]. One could also argue for localized meltwater events at various times, perhaps the best example of which may occur between 30 and 25 kyr [23,24]. These separate influences may be responsible for the occasional mismatches between RC11-83 $\delta^{18}O_{pl.\ foram}$ and Vostok δD_{ice} in Fig. 2a. However, for most of the millennial scale oscillations in these marine and ice core records — where a good correlation can be made — it is reasonable to assume a common temperature change. If they reflect temperature alone, Vostok δD_{ice} and RC11-83 $\delta^{18}O_{pl.\ foram}$ oscillations in marine isotope stage 3 (roughly 20‰ and 0.6‰, respectively) both suggest fluctuations of a few degrees celsius; in this case, the marine/ice core scaling to temperature is compatible. Perhaps the temperature connection between these marine and ice core isotopic records is especially powerful, because the sub-Antarctic region (site of RC11-83) provides the main source of moisture for precipitation over central Antarctica (site of Vostok) [25].

3. Phase relationships

The correlations between the different marine records in RC11-83 and the ice core records from Greenland and Antarctica imply that both northern and southern hemisphere climate signals are present in a single deep sea sediment core characterized by an extremely high sedimentation rate. Thus, we have a unique opportunity to examine explicitly the interhemispheric timing of global climate events through the stratigraphic relationship between RC11-83 benthic foraminiferal $\delta^{13}C$ and $\delta^{18}O_{pl.\ foram}$. Fig. 3 shows that the maximum correlation between these two variables occurs when the $\delta^{18}O_{pl.\ foram}$ time series is lagged by 1,500 yr (in other words, the $\delta^{18}O$ record leads the $\delta^{13}C$ record). This phase relationship can be illustrated graphically by observing that tie lines between similar looking events are seldom perpendicular to the time axis (Fig. 3, below). The average



Per. (kyr)	Coh Sq.	Phase (°)	Error (°)
41.7	0.81	6.9	18.6
22.7	0.77	5.6	21.1
20.8	0.75	5.4	21.6
19.2	0.74	5.4	22.2
10.0	0.62	23.8	28.4
9.6	0.58	22.3	30.7
5.7	0.55	120.2	32.2
3.6	0.78	152.4	20.1

Fig. 3. Cross correlation of planktonic foraminiferal $\delta^{18}O$ (*G. bulloides*) with benthic foraminiferal $\delta^{13}C$ in RC11-83. The vertical axis indicates the degree of correlation. The horizontal axis is the number of lags (time step = 0.25 kyr). There is excellent agreement between the records if the planktonic foraminiferal $\delta^{18}O$ is shifted forward by 1.5 kyr. The phase estimates for significant periods are listed to the right. (Coh sq refers to squared coherency.) These phase estimates can be illustrated graphically with the actual time series by connecting events similar in appearance with tie lines, as shown in the lower figure.

offset of these tie lines is 1,500 yr. Phase estimates by period suggest that the 1,500 yr lag of the benthic foraminiferal $\delta^{13}C$ is fairly constant with frequency: the time series are essentially in phase for periods greater than about 20 kyr, but the phase angle increases monotonically with decreasing period to 180° at about 3 kyr. We can rule out two possibilities for generating this phase offset between the RC11-83 isotopic time series. The influence of bioturbation (which has the potential to create depth offsets between synchronous changes in different sedimentary components) is minor in RC11-83 because the sedimentation rate is so high. Also, substantial changes in the ventilation time of the Atlantic (which could delay any deep water signal with respect to surface water records) are not likely if the radiocarbon ages that link the deep water changes to the times of major northern hemisphere climate change are correct.

Not surprisingly, using the Bender et al. chronology, the Greenland and Antarctic ice core climate records ($\delta^{18}O_{ice}$ and δD_{ice}) are characterized by an analogous phase relationship to that deduced from the RC11-83 proxy records. As with the RC11-83 records, the maximum correlation between Vostok δD and Greenland $\delta^{18}O_{ice}$ occurs when the Vostok δD time series is lagged by about 1,250 yr (i.e. Vostok leads), and the lag is constant with frequency. This relatively constant lag of Greenland climate may explain Bender et al.'s observation [7] from the ice core records that, while the brief (< 2000 yr) climate events at the two poles cannot be tied — and may even be out of phase — the bipolar climate events longest in duration appear synchronous; a lag of 1,500 yr can be statistically indistinguishable from zero phase for a 20 or 40 kyr climate cycle, but it becomes increasingly important for cycles of less than 10 kyr in duration.

However, even with perfect correlation between the gas records in Greenland and Antarctica, 1–2 kyr offsets between ice core $\delta^{18}O_{ice}$ and δD_{ice} cannot be proven, because the ice age–gas age difference at Vostok varies between 3 and 7 kyr [26]. This obstacle underscores the power of the stratigraphy of RC11-83. In a single core we can demonstrate unequivocally that a lag exists between benthic foraminiferal $\delta^{13}C$ and $\delta^{18}O_{pl.\ foram}$ because it equates to a 20–40 cm depth offset. Thus, to the extent that the RC11-83 $\delta^{13}C$ and $\delta^{18}O$ records represent northern and southern hemisphere climate, respectively, our results support the Bender et al. chronology. Regardless of chronology, however, by applying the principal of superposition to the RC11-83 records, we infer that a 1–2 kyr northern hemisphere lag characterized much of the last 80 kyr, over both long- and short-lived climate oscillations.

The Younger Dryas event (12–11 kyr B.P.) provides a particularly illustrative case study. The Greenland ice cores feature a large $\delta^{18}O_{ice}$ anomaly, which is often assumed to be connected with a 'turn off' of NADW production [2]. An obvious question is whether correlative anomalies appear globally and, consequently, can be linked to a 'conveyor' mechanism. The Vostok δD_{ice} record does show an oscillation on the last deglaciation, but it is not clear whether this anomaly is in fact the Antarctic counterpart of the Younger Dryas event. Gas records from Greenland and Antarctic ice cores can be correlated firmly during this interval (not only by $\delta^{18}O_{atm}$, but also by methane, which undergoes a particularly distinct Younger Dryas age excursion [27]). By applying this gas stratigraphy with a best estimate for the ice age–gas age difference in Vostok [8], the deglacial anomaly in the Vostok δD record occurs 1200 yr before the true Younger Dryas event in the Greenland $\delta^{18}O_{ice}$. Of course, if one assumed the Vostok ice age–gas age difference was 1,200 yr smaller, one could match both the gas records and the climate records [27]; so with this evidence alone, the relative timing of the Greenland and Antarctic deglacial isotopic anomalies in the ice is still open to question.

Appealing to the RC11-83 record may resolve this issue. Radiocarbon dates clearly show that a deglacial isotopic anomaly in the RC11-83 $\delta^{18}O_{pl.\ foram}$ record, quite similar in appearance to the Vostok deglacial δD oscillation, occurs at least 1000 yr before the Younger Dryas interval. This evidence therefore suggests that the apparent 1200 yr lag of the Younger Dryas in the Greenland ice cores (relative to the Vostok deglacial anomaly) is real and is not the result of an inaccurate estimate of ice age–gas age differences. Sowers and Bender [8] reached the same conclusion by comparing the deglacial sections of Greenland and Antarctic ice cores with very small ice age–gas age differences (GISPII and Byrd). This interhemispheric timing of the 'Younger Dryas' deduced from the ice core stratigraphy and from RC11-83 may be typical of the last 80 kyr as a whole. Despite the fact that there is no large RC11-83 benthic $\delta^{13}C$ anomaly during the Younger Dryas interval, for most other millennial oscillations in isotopic stage 3, a $\delta^{18}O_{pl.\ foram}$ (sub-Antarctic surface climate) anomaly occurs at least 1000 yr before a correlative benthic foraminiferal $\delta^{13}C$ (conveyor) anomaly.

4. Discussion

To summarize, the marine core/ice core correlations suggest that:

1. millennial scale 'conveyor belt' changes are manifested in a Circumpolar Deep Water nutrient proxy record covering the last glacial cycle;
2. the planktonic foraminiferal $\delta^{18}O$ at the site of RC11-83 joins the Vostok ice core record in providing a reflection of high latitude southern hemisphere climate;
3. there is a 1–2 kyr phase lead of these southern hemisphere climate proxies, relative to conveyor-related proxies.

The first of these observations seemingly confirms the success of the conveyor paradigm, because it demonstrates that deep sea circulation changes are nearly global in extent. The last observation qualifies the paradigm severely, because, if correct, climate changes in the southern hemisphere cannot be a direct response to these global circulation changes. Thus, this conclusion is clearly distinct from popular hypotheses which suggest that the Southern Ocean either warms [1] or cools [28] as a consequence of increased NADW production, and we are obliged to explore further the significance of this inference.

The apparent lag in conveyor variability obviously argues against the idea that global climate responds as a wave propagating from the North Atlantic [4], and it would also preclude global climate fluctuations driven solely by internal dynamics of northern hemisphere ice sheets [29]. At the very least, we infer that the circulation changes resulting from NADW flux variability were capable of affecting the nutrient cycling in the Southern Ocean, but did not carry an overriding climatic impact into the southern hemisphere. Taking things further, it is also possible that the lag in the conveyor yields important clues to the origin of millennial scale climate variability in general. A critical assumption, as yet unsubstantiated, involves whether the millennial oscillations in the planktonic foraminiferal $\delta^{18}O$ record (and in Vostok δD) are in fact related genetically to their lagged counterparts in the benthic foraminiferal $\delta^{13}C$ record (and Greenland $\delta^{18}O_{ice}$). If so (if, for example, there was a common process linking the Younger Dryas event and the Antarctic deglacial oscillation occurring 1200 years prior), then the lag implies that the basic control for the strength of NADW production and air temperature in the adjacent continental areas originated outside of the high latitude northern hemisphere.

While it is conceivable that high latitude processes in the southern hemisphere could force a response in the conveyor circulation [30], perhaps a more likely explanation for the observed phase relationship involves tropical temperature variability. Over the last deglaciation, variations in RC11-83 $\delta^{18}O_{\text{pl. foram}}$ and the Vostok δD_{ice} are very nearly synchronous with changes in tropical sea surface temperature recorded in Barbados coral [31]. All three records, for example, show an oscillation occurring 1000 yr before the Younger Dryas interval. The 1–2 kyr lag in the conveyor might then indicate that the mid- to high-latitude southern hemisphere climate reacted directly to tropical temperature fluctuations (through either ocean or atmospheric processes), while the response of the deep North Atlantic Ocean was delayed by the thermal influence of the northern hemisphere ice sheets, or by the ice sheets' influence on the salt balance of the North Atlantic surface layer.

Of course, the significance of this suggestion depends on first documenting the existence of, then explaining, the cause of rapid tropical temperature variability in a glacial climate. Although the average Sr/Ca value for ice age Barbados coral is consistent with a variety of other lines of evidence which imply glacial-age cooling of the tropics, there is still considerable debate on the magnitude and the regional extent of this cooling [32]. Furthermore, even granting tropical climate instability, this scenario would still require complex non-linearities in some aspect of high latitude climate. So the issue of the origin of any of the rapid fluctuations in the conveyor, or in any other part of the system, is not settled by shifting the focus to tropical climate variability. Nevertheless, the phase relationship between proxies from a single core is relatively incontrovertible; if the RC11-83 records are in fact reflections of broad climatic processes, then they force a reconsideration of the conveyor as the major engine of rapid climate change on a global scale.

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