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North Atlantic intermediate to deep water circulation and chemical stratification during the past 1 Myr

B. P. Flower,[1] D. W. Oppo,[2] J. F. McManus,[2] K. A. Venz,[3] D. A. Hodell,[3] and J. L. Cullen[4]

Abstract. Benthic foraminiferal carbon isotope records from a suite of drill sites in the North Atlantic are used to trace variations in the relative strengths of Lower North Atlantic Deep Water (LNADW), Upper North Atlantic Deep Water (UNADW), and Southern Ocean Water (SOW) over the past 1 Myr. During glacial intervals, significant increases in intermediate-to-deep $\delta^{13}C$ gradients (commonly reaching >1.2‰) are consistent with changes in deep water circulation and associated chemical stratification. Bathymetric $\delta^{13}C$ gradients covary with benthic foraminiferal $\delta^{18}O$ and covary inversely with Vostok CO_2, in agreement with chemical stratification as a driver of atmospheric CO_2 changes. Three deep circulation indices based on $\delta^{13}C$ show a phasing similar to North Atlantic sea surface temperatures, consistent with a Northern Hemisphere control of NADW/SOW variations. However, lags in the precession band indicate that factors other than deep water circulation control ice volume variations at least in this band.

1. Introduction

Conversion of warm surface waters to North Atlantic Deep Water (NADW) is a major source of heat to the North Atlantic and surrounding areas [e.g., *McCartney and Talley*, 1984]. Warm surface water flow to the subpolar North Atlantic and Nordic Seas (Greenland, Iceland, and Norwegian Seas) is tied to NADW production through deep convection. In the present day, deep convection in the Nordic Seas is followed by deep water flow through Denmark Strait and over the Wyville-Thompson Ridge and the Iceland-Scotland Ridge. These flows join with deep water from the Labrador Sea to form NADW, the lower limb of the North Atlantic thermohaline circulation cell [e.g., *Broecker*, 1991]. Variations in the position and strength of NADW formation have occurred on glacial-interglacial time scales during the Pleistocene [e.g., *Broecker and Denton*, 1989; *Broecker*, 1991; *Imbrie et al.*, 1992, 1993].

Benthic foraminiferal carbon isotope records have provided important evidence in reconstructing intermediate to deep water circulation history. Because deep waters gain remineralized low $\delta^{13}C$ organic carbon from overlying surface water productivity during their oceanic transit, a $\delta^{13}C$ gradient develops along the deep water flow path. Young, nutrient-depleted deep waters such as NADW have relatively high $\delta^{13}C$ values, while older, nutrient-enriched deep waters exhibit lower $\delta^{13}C$ [e.g., *Broecker and Peng*, 1982]. Low $\delta^{13}C$ values of glacial age benthic foraminifera from the deep Atlantic indicate a reduction of NADW production [*Boyle and Keigwin*, 1982; *Oppo and Fairbanks*, 1987; *Curry et al.*, 1988]. Inferences based on Atlantic carbon isotope distributions generally agree with those based on Cd/Ca and Ba/Ca nutrient tracers, although these tracers differ significantly for other oceans [e.g., *Boyle*, 1992].

Numerous studies have demonstrated that NADW was probably still produced during Pleistocene glaciations but generally reached depths <2 km [*Boyle and Keigwin*, 1987; *Oppo and Fairbanks*, 1987; *Curry et al.*, 1988; *Duplessy et al.*; 1988, *Lehman and Keigwin*, 1992a, b; *deMenocal et al.*, 1992; *Labeyrie et al.*, 1992, 1995; *Sarnthein et al.*, 1994; *Oppo and Lehman*, 1993; *Oppo et al.*, 1995, 1997; *Bertram et al.*, 1995; *Curry*, 1996a; *Zahn et al.*, 1997; *Venz et al.*, 1999]. In keeping with physical oceanographic terminology, we use upper NADW (UNADW) for northern source water masses shallower than 2 km and lower NADW (LNADW) for depths >2 km. During interglaciations when open ocean convection occurred in the Nordic Seas, surface waters became sufficiently dense to contribute to LNADW. During glaciations, $\delta^{13}C$ and Cd/Ca measurements on benthic foraminifera suggest that some combination of reduced LNADW/increased UNADW must have occurred. The locus of UNADW production was probably in the boreal Atlantic south of the polar front. The production of UNADW results in less heat release per unit deep water formed than LNADW [e.g., *Lehman and Keigwin*, 1992a, b] and hence deep water variations may influence North Atlantic regional climate. Chemical stratification associated with reduced ventilation of SOW may also influence atmospheric CO_2 levels [*Toggweiler*, 1999].

A late Neogene perspective indicates decreased LNADW strength was associated with the development of progressively larger Northern Hemisphere ice sheets, supporting a link between deep ocean circulation and ice growth. LNADW was reduced relative to Southern Ocean Water (SOW) from 80 to 20% during late Pliocene to Pleistocene glaciations [*Raymo et al.*, 1990], while UNADW may have increased by 10% (from ~80 to 90%) during glaciations of the same interval [*deMenocal et al.*, 1992; *Oppo et al.*, 1995]. However, the magnitude of LNADW

[1]Department of Marine Science, University of South Florida, St. Petersburg.
[2]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.
[3]Department of Geology, University of Florida, Gainesville
[4]Department of Geological Sciences, Salem State University, Salem, Massachusetts.

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Table 1. Site Information

Site	DSDP/ODP Leg	Latitude, N	Longitude, W	Depth, mbsl	Location
982	162	57°31.0'	15°52.0'	1134	Rockall Plateau
980	162	55°29.1'	14°42.1'	2168	Feni Drift
607	94	41°00.0'	32°58.0'	3427	Mid-Atlantic Ridge
925	154	4°12 2'	43°29.3'	3040	Ceara Rise
664	108	00°06'	23°14'	3806	central equatorial Atlantic
849	138	0°11 0'	110°31.0'	3851	eastern equatorial Pacific

Note: mbsl is meters below sea level.

reduction apparently does not match the severity of associated glaciations during the Pleistocene [*Raymo et al.*, 1990, 1997]. For example, the interval of most reduced LNADW/increased UNADW occurred during marine isotope stage 12 (MIS 12), yet this glaciation was of similar magnitude to MIS 2, 6, and 16 [*Raymo et al.*, 1990]. In this paper, we explore whether deep water circulation and chemical stratification could have controlled global ice volume variations.

We use new and published data from the North Atlantic, deep equatorial Atlantic, and deep Pacific oceans to examine variations in deep water circulation proxies during the past 1 Myr.[1] Our results confirm that Atlantic deep circulation is linked to subpolar North Atlantic sea surface temperature (SST), as noted by many studies. We show that several indices of deep water circulation exhibit similar phasing with respect to ice volume and suggest that this phasing (including a lag at the 23 kyr period) indicates that North Atlantic deep water variations cannot control global ice volume. Further, we show that although a chemical stratification index covaries with Vostok CO_2, a lag in the precession band weakens the case for chemical stratification as a driver of atmospheric CO_2 changes.

2. Site Locations

Recent ocean drilling in the North Atlantic by Ocean Drilling Program (ODP) Leg 162 [*Jansen et al.*, 1996] has provided important new sites for examining North Atlantic intermediate to deep water circulation history. ODP Site 982 on the Rockall Plateau (57°31'N, 15°52'W; 1134 m below sea level (mbsl)) and Site 980 on the Feni Drift (55°29'N, 14°42'W; 2168 mbsl), together with Deep Sea Drilling Project (DSDP) Site 607 on the western flank of the Mid-Atlantic Ridge (41°0'N, 32°58'W; 3427 mbsl), form a depth transect in the North Atlantic basin (Figure 1 and Table 1). In the present day, these sites lie within NADW above the diffuse mixing zone between NADW and Lower Circumpolar Deep Water (LCDW). During the Last Glacial Maximum (LGM) the northeast North Atlantic was bathed by UNADW to ~2000 m (Figure 2), while deeper portions of the North Atlantic contained SOW [*Boyle and Keigwin*, 1987; *Oppo and Fairbanks*, 1987; *Curry et al.*, 1988; *Duplessy et al.*, 1988; *Oppo and Lehman*, 1993; *Oppo et al.*, 1997].

Rockall Plateau Site 982 is ~1200 m shallower than Site 552 [*Shackleton and Hall*, 1984], the site used as a northern source end-member by many previous studies [e.g., *Raymo et al.*, 1990, 1992, 1997; *deMenocal et al.*, 1992; *Oppo et al.*, 1995]. Because of its shallower depth relative to the strong bathymetric $\delta^{13}C$ gradients observed in Pleistocene glaciations, Site 982 is a better NADW end-member record than Site 552. Benthic foraminiferal $\delta^{13}C$ records from Rockall Plateau Site 982 [*Venz et al.*, 1999], Feni Drift Site 980 [*Oppo et al.*, 1998, *McManus et al.*, 1999; this paper], and Mid-Atlantic Ridge Site 607/CH82 composite record (hereafter Site 607) [*Boyle and Keigwin*, 1985; *Ruddiman et al.*, 1989; *Raymo et al.*, 1990] are used to reconstruct deep water variability in the subpolar North Atlantic. In the absence of a suitable long, high-resolution $\delta^{13}C$ record from the Southern Ocean, Site 849 in the deep eastern equatorial Pacific [*Mix et al.*, 1995] is used as a southern source end-member. Benthic foraminiferal $\delta^{13}C$ data from Ceara Rise Site 925 [*Curry*, 1996b; *Bickert et al.*, 1997; W.B. Curry, manuscript in preperation, 2000] and from eastern Mid-Atlantic Ridge Site 664 [*Raymo et al.*, 1997] enable us to compare LNADW/SOW variations derived in the North Atlantic to those in the deep equatorial Atlantic. Each of these deep sites accurately records the $\delta^{13}C$ of ΣCO_2 and is not significantly influenced by respiration of organic matter [e.g., *Mackensen et al.*, 1993; *Bickert and Wefer*, 1996]. In particular, $\delta^{13}C$ in Site 664 in the eastern equatorial Atlantic tracks $\delta^{13}C$ in nonupwelling core GeoB 1112 [*Bickert and Wefer*, 1996], indicating Site 664 accurately monitors the $\delta^{13}C$ of ΣCO_2.

Carbon isotope records from these sites allow a new assessment of LNADW/SOW history during the 0-1 Myr interval. Issues we explore include (1) the timing of circulation and chemical stratification changes relative to ice volume changes and (2) the timing of chemical stratification changes relative to atmospheric CO_2 changes.

3. Methods

Benthic foraminiferal stable isotope data for all sites were based on *Cibicidoides wuellerstorfi* or *C. kullenbergi.* No species corrections were made because these forms have been shown to record the $\delta^{13}C$ values of bottom water in most environments [e.g., *Graham et al.*, 1981]. Published data for Site 980 for the 0-500 kyr interval were generated at Woods Hole Oceanographic Institution (WHOI) on a Finnigan MAT 252 with 70°C acid dropped into single reaction vessels as described previously [*Oppo et al.*, 1998; *McManus et al.*, 1999]. Each sample contained one to three specimens. New data for the 500-1000 kyr interval were generated in the Stable Isotope Laboratory, University of California, Santa Cruz, on a Micromass

[1] Supporting data are available electronically at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303 (phone: (303) 497 - 6280; fax: (303) 497 - 6513, e-mail: paleo@mail.ngdc.noaa.gov, URL. http//www.ngdc.noaa.gov/paleo).

Precision Isotope Ratio Mass Spectrometer (PRISM) with a 90°C common acid bath. Each sample contained 4 to 10 specimens. Both laboratories quote analytical precision better than 0.08 and 0.05‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Sample replicates indicate a reproducibility of better than 0.2‰ for both for $\delta^{18}O$ and $\delta^{13}C$. All isotopic data are expressed using standard δ notation in per mil relative to VPDB based on NBS-19 carbonate standard values (-2.2‰ for $\delta^{18}O$ and 1.95‰ for $\delta^{13}C$). For spectral analysis each series was interpolated to a constant 3 kyr time step, and Blackman-Tukey cross-spectral analysis was conducted using the Analyseries package [*Paillard et al.*, 1996]. A cross-correlation function was calculated using 1/3 lags and a Bartlett window with a bandwidth of 0.005 cycles/kyr.

4. Stratigraphy and Chronology

Paleomagnetic and/or biostratigraphic data provided preliminary age control at each site, including Sites 980 and 982 [*Jansen, et al.*, 1996; *Channell and Lehman*, 1999]. Benthic oxygen isotope records were then used to correlate all sites to the astronomically tuned timescale using Site 849 benthic $\delta^{18}O$ [*Mix et al.*, 1995]. Results are similar for correlation to Site 677 [*Shackleton and Hall*, 1989, *Shackleton et al.*, 1990]. Oxygen isotope records plotted together in Figure 3 demonstrate the robustness of the correlation to the substage level. Cross-spectral analysis of each record versus Site 849 $\delta^{18}O$ indicates the records are in phase (within 2 kyr) in the eccentricity, obliquity, and

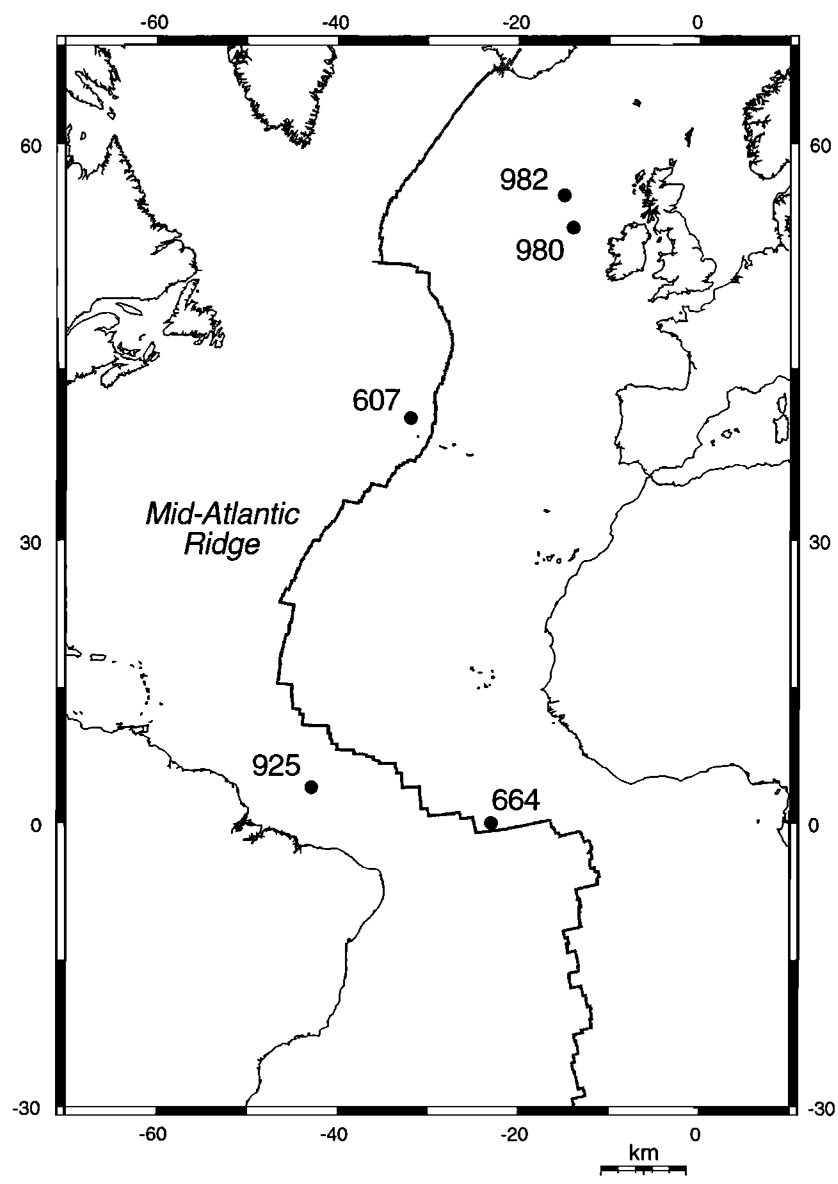

Figure 1. Site map showing locations of DSDP/ODP Sites 607, 664, 925, 980, and 982. Mid-Atlantic Ridge is shown for reference.

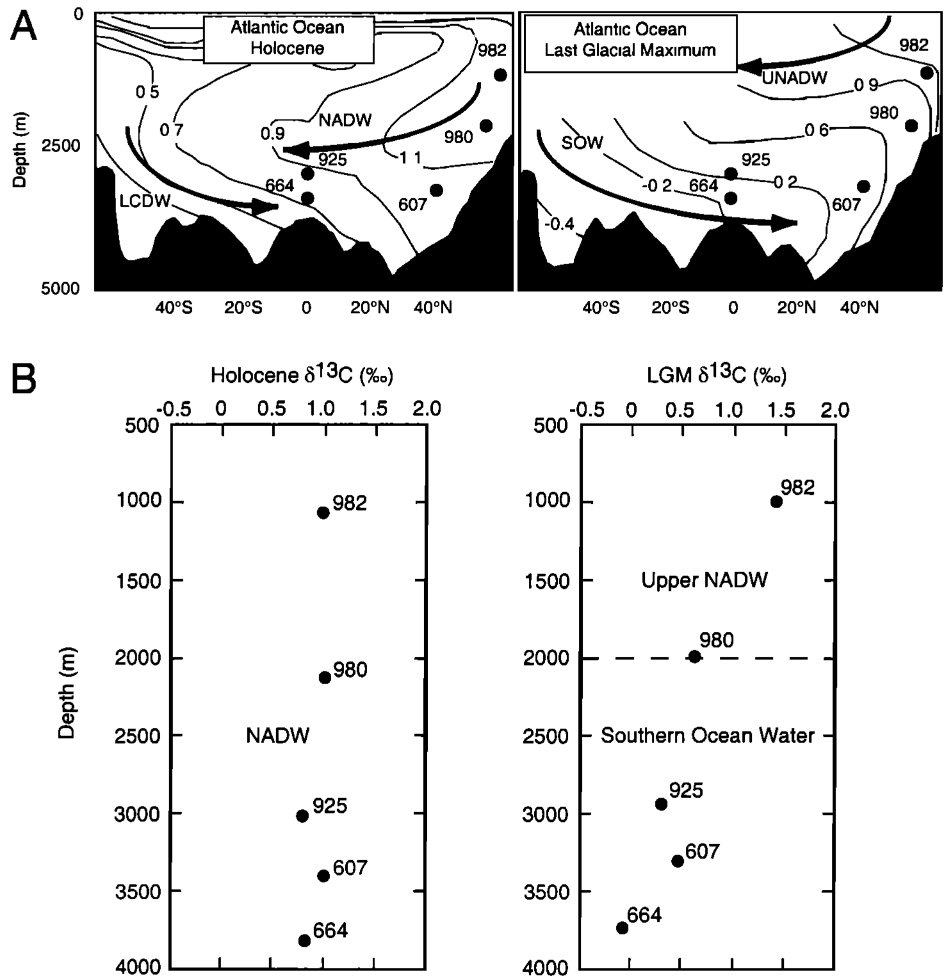

Figure 2. (a) Cross-sectional maps [after *Duplessy et al.*, 1988; *Oppo and Lehman*, 1993] and (b) depth plots of *Cibicidoides* $\delta^{13}C$ data from the North Atlantic for the Holocene and Last Glacial Maximum (LGM). Bathymetric extent of North Atlantic Deep Water (NADW) and Lower Circumpolar Deep Water (LCDW) are shown for the Holocene; Upper NADW and Southern Ocean Water (SOW) are shown for the LGM. Also shown are the locations of Sites 982, 980, 607, 925, and 664 employed in this study. Note strong $\delta^{13}C$ gradient near 2000 m.

precession bands (Table 2). Site 980 data has ~1.2 kyr resolution for the 0-350 kyr interval [*McManus et al.*, 1999], <300 years resolution for the 350-500 kyr interval [*Oppo et al.*, 1998], and ~2.7 kyr resolution for the 500-1000 kyr interval [this paper]. Site 982 resolution is ~2 kyr [*Venz et al.*, 1999], Site 607 resolution is ~3.7 kyr [*Ruddiman et al.*, 1989; *Raymo et al.*, 1997], Site 925 resolution is ~2.2 kyr [*Curry*, 1996b; *Bickert et al.*, 1997; W.B. Curry, manuscript in preparation 2000], and Site 664 resolution is ~3.4 kyr [*Raymo et al.*, 1997].

5. Results and Discussion

5.1. Carbon Isotope Records From a Depth Transect

Carbon isotope records from the depth transect of Sites 982, 980, and 607 at 1134, 2168, and 3427 mbsl, respectively, trace the evolution of bathymetric $\delta^{13}C$ gradients during the past 1 Myr (Figures 4a and 4b). As expected, the shallowest Rockall Plateau Site 982 generally has the highest values, and the deepest (and more southerly) Site 607 generally has the lowest values. This relation reflects the greater proportion of remineralized carbon in deeper waters. Generally, high $\delta^{13}C$ values at intermediate-depth Site 982 attest to relatively continuous production of UNADW during both glacial and interglacial intervals [*Venz et al.*, 1999]. At Site 607, minimum $\delta^{13}C$ values commonly reach deep Pacific $\delta^{13}C$ values, suggesting incursion of SOW into the deep North Atlantic basin during glacial intervals [*Raymo et al.*, 1990, 1997]. Site 980 $\delta^{13}C$ values covary with Site 607 $\delta^{13}C$ values but are consistently intermediate between the shallower and deeper sites during most glaciations, suggesting that this site lay within the UNADW/SOW mixing zone. Intermediate-to-deep bathymetric $\delta^{13}C$ gradients reach minima of <0.3‰ during interglacial intervals, while gradients commonly reach maxima of >1.2‰ during glacial intervals. Deglaciations are exceptions to this pattern; lower $\delta^{13}C$ values at Site 982 compared to deeper Site 607 suggest SOW influence at intermediate depths during glacial terminations [*Venz et al.*, 1999].

5.2. Percent NADW in the North Atlantic

To assess the relative strengths of Atlantic source waters in the deep Atlantic, we calculate the proportion of northern component water at a given site relative to southern component water (percent NADW) using $\delta^{13}C$ records [*Oppo and Fairbanks*, 1987; *Raymo et al.*, 1990, 1997; *deMenocal et al.*, 1992; *Oppo et al.*, 1995]. We compare $\delta^{13}C$ values at Atlantic Sites 980, 607, 925, and 664 with $\delta^{13}C$ values at North Atlantic and Southern Ocean end-member sites. New data from an improved NADW end-member (Site 982) are used to define northern component water [*Venz et al.*, 1999]. Low $\delta^{13}C$ values on glacial

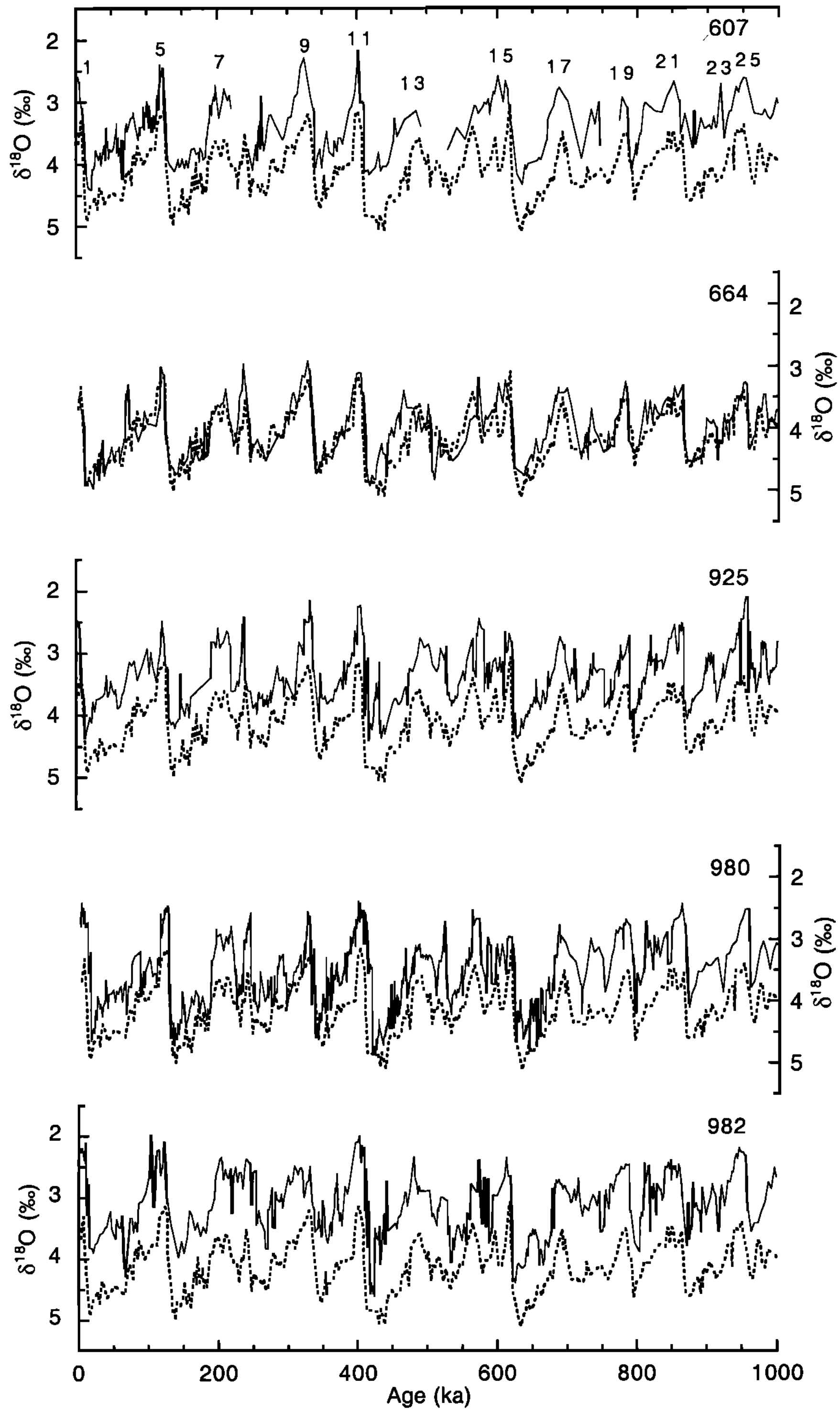

Figure 3. Benthic foraminiferal oxygen isotope data versus age for Sites 607 [*Ruddiman et al.*, 1989; *Raymo et al.*, 1997], 664 [*Raymo et al.*, 1997], 925 [*Curry*, 1996b; *Bickert et al.*, 1997], 980 [*Oppo et al.*, 1998, *McManus et al.*, 1999, this paper], and 982 [*Venz et al*, 1999] (solid lines) compared to Site 849 data [*Mix et al.*, 1995] (dotted line) on each plot. Comparison shows excellent correlation between sites, confirmed by cross-spectral analysis (Table 2).

Table 2. Results of Cross-Spectral Analysis of Benthic Foraminiferal $\delta^{18}O$ Records (Local Versus Deep Pacific Site 849)

	Band, kyr					
	100		41		23	
$\delta^{18}O$ 982 versus $\delta^{18}O$ 849						
Coherence	0 98		0.87		0 44	
Phase, deg	-5 24	$\pm$3 70	12.78	$\pm$12.08	-13.29	$\pm$57.25
Kiloyears	-1.46	$\pm$1 03	1.46	$\pm$1.38	0.85	$\pm$3 66
$\delta^{18}O$ 980 versus $\delta^{18}O$ 849						
Coherence	0 97		0.96		0.80	
Phase, deg	-3 83	$\pm$5 05	1.69	$\pm$5 78	-8.36	$\pm$16.89
Kiloyears	-1.06	$\pm$1.4	0 19	$\pm$0.66	-0.53	$\pm$1.08
$\delta^{18}O$ 607 versus $\delta^{18}O$ 849						
Coherence	0 96		0.89		0.74	
Phase, deg	1.40	$\pm$5 77	14 67	$\pm$11.00	2.85	$\pm$21.55
Kiloyears	0.39	$\pm$1.60	1.67	$\pm$1.25	0.18	$\pm$1.38
$\delta^{18}O$ 925 versus $\delta^{18}O$ 849						
Coherence	0.95		0.93		0 88	
Phase, deg	-4.54	$\pm$6.64	-2.42	$\pm$8.01	-12.88	$\pm$11.48
Kiloyears	-1.26	$\pm$1.84	-0.28	$\pm$0.91	-0.82	$\pm$0.73
$\delta^{18}O$ 664 versus $\delta^{18}O$ 849						
Coherence	0 94		0.95		0.84	
Phase, deg	-0.34	$\pm$7.62	5.56	$\pm$6.55	6.29	$\pm$13.85
Kiloyears	-0.10	$\pm$2.12	0.63	$\pm$0.75	0.40	$\pm$0.89
Vostok $\delta^{18}O_{atm}$ versus $\delta^{18}O$ 849						
Coherence	0 94		0.89		0 88	
Phase, deg	21.91	$\pm$8.07	-17.27	$\pm$11.51	1.66	$\pm$12.26
Kiloyears	6.09	$\pm$2.24	-1.97	$\pm$1.31	0.11	$\pm$0.78

Blackman-Tukey cross-spectral analysis was conducted with the Analyseries program [*Paillard et al.*, 1996] using 1/3 lags and a Bartlett window with a bandwidth of 0.005 cycles/kyr. Coherence is significant at the 80% level (k=0.40; k =0 64 for Vostok $\delta^{18}O_{atm}$ versus $\delta^{18}O$ 849). Negative phase (given in degrees and kiloyears) indicates the given parameter leads benthic foraminiferal $\delta^{18}O$

terminations and extending into some interglaciations indicate even this shallow site is not a perfect northern end-member record. For example, low $\delta^{13}C$ values extending into MIS 5 and MIS 9 (Figures 4a and 4b) complicate our assessment of deep water changes relative to the associated terminations. However, Site 982 is the best record available, and the importance of these excursions is reduced because our analysis covers the past 1 Myr. Because no suitable long $\delta^{13}C$ records are available from the Southern Ocean, we use eastern equatorial Pacific Site 849 to trace southern component water (see discussion by *Raymo et al.*, [1997]). New data from Site 980 allows detailed examination of NADW strength in the middepth Atlantic. After interpolation to a constant time interval of 3 kyr, percent $NADW_{980}$ is calculated as follows:

$$\text{Percent } NADW_{980} = [(\delta^{13}C_{980} - \delta^{13}C_{849}) / (\delta^{13}C_{982} - \delta^{13}C_{849})]\ 100\%$$

The relative contribution of NADW at middepth Atlantic Site 980 is generally greater during interglaciations than glaciations (Figure 5). Lowest values of percent $NADW_{980}$ are observed during MIS 10, 12, 16, 20, and 22. These observations are consistent with results from Site 607 [*Raymo et al.*, 1997], which we recalculate as percent $NADW_{607}$, replacing Site 552 with Site 982 as the northern component end-member (Figure 4). Percent $NADW_{607}$ values are generally lower than percent $NADW_{980}$ values during glaciations but similar during interglaciations. This difference is expected because Site 607 lies "downstream" of Site 980 and is ~1250 m deeper and hence is more influenced by NADW/SOW variations (as are Sites 925 and 664). However, the low percent NADW values at both sites during glacial intervals indicates that the UNADW/SOW mixing zone commonly reached depths as shallow as ~2200 m in the northeast Atlantic, as during the Last Glacial Maximum (~2000 m [*Oppo*

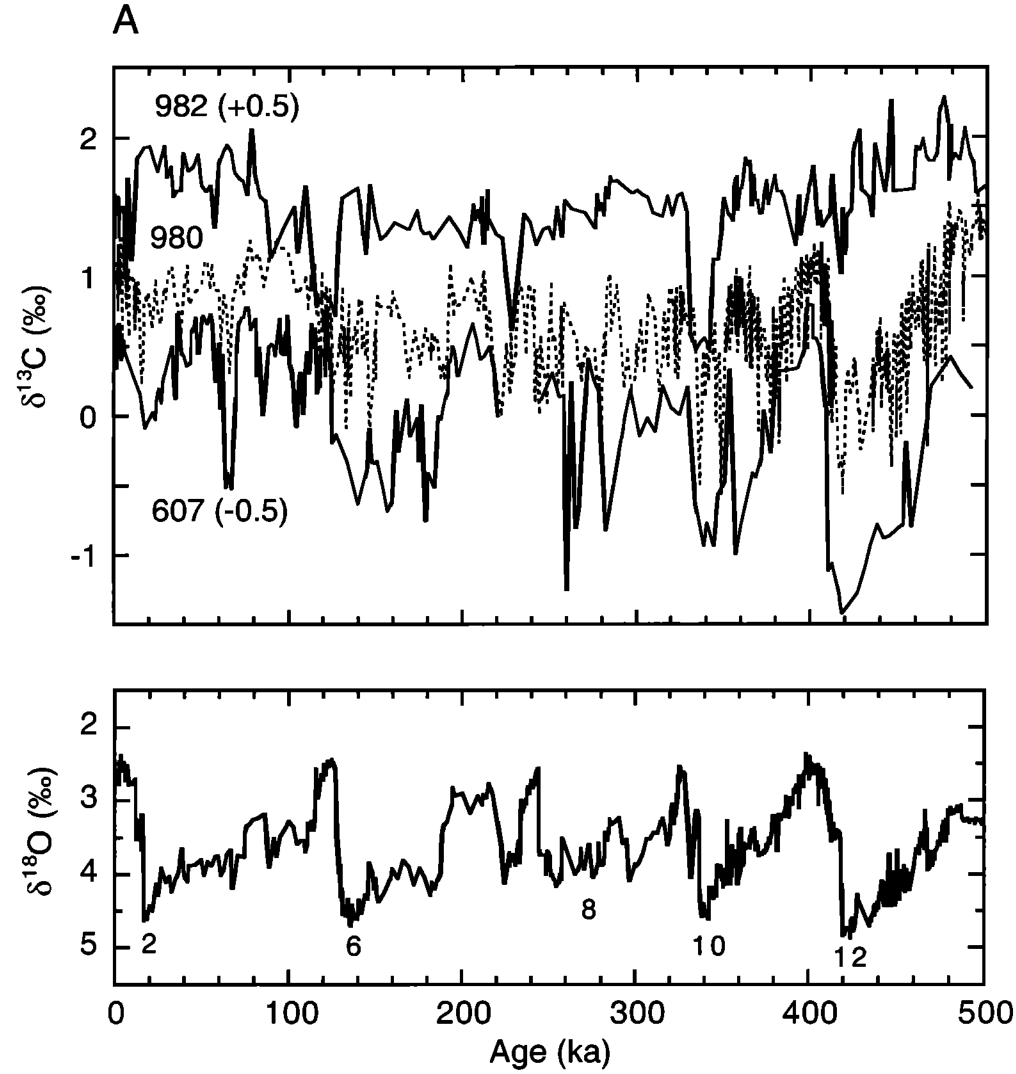

Figure 4. Carbon isotope data versus age for Sites 982, 980, and 607 for the (4a) 0-500 kyr and (4b) 500-1000 kyr intervals. Site 982 data (+0 5‰) and Site 607 data (-0.5‰) have been adjusted for figure clarity. Site 980 benthic $\delta^{18}O$ is also shown for comparison, with selected glacial marine isotope stages (MIS) labeled. Note large intersite $\delta^{13}C$ gradients during glacial intervals.

and Lehman, 1993]). Lower percent NADW values relative to the LGM suggest a shallower UNADW/SOW mixing zone during many earlier glaciations.

The percent NADW proxy at Sites 980, 607, 925, and 664 (Figure 5) also confirms long-term trends in deep circulation over the past 1 Myr [*Raymo et al.*, 1990, 1997]. Minima in glacial percent NADW are found ca. 880, 790, and 420 ka. Maxima in glacial percent NADW are found ca. 970, 540, and 20 ka (LGM). At shallower Site 982, two long-term trends involving reduced suppression of UNADW on terminations are observed during the past 1 Myr [*Venz et al.*, 1999]. Taken together, these records confirm long-term trends in Atlantic deep water circulation, including increasing NADW strength over the past ~420 kyr [*Curry*, 1996a; *Raymo et al.*, 1997]. These long-term trends are not apparent in benthic foraminiferal $\delta^{18}O$ records, indicating a decoupling between ice volume and deep water circulation [*Raymo et al.*, 1990, 1997].

5.3. Intermediate to Deep $\delta^{13}C$ Gradients

Bathymetric $\delta^{13}C$ gradients in the North Atlantic complement percent NADW as a measure of deep water circulation changes. After interpolation to a constant time step of 3 kyr, calculation of the $\delta^{13}C$ difference normalizes the effects of basinwide $\delta^{13}C$ changes. Differencing two $\delta^{13}C$ records is also subject to lesser correlation errors than using three $\delta^{13}C$ records in the calculation of percent NADW, which involves the ratio of two differences. Variations of the bathymetric $\delta^{13}C$ gradient between northern component water Site 982 and Site 607 (~1100-3400 m; $\Delta\delta^{13}C_{982\text{-}607}$, a $\Delta\delta^{13}C_{NCW}$ index) strongly covary with $\delta^{18}O$ (Figure 6a). In particular, glacial-interglacial transitions exhibit near-synchronous $\Delta\delta^{13}C$ decreases, confirming earlier suggestions that terminations were characterized by rapid resumption of LNADW flow to at least ~3400 m [*Broecker and Denton*, 1989; *Raymo et al.*, 1990; *Oppo et al.*, 1997]. Similarly, the $\delta^{13}C$ gradient between Site 982 and deep equatorial Atlantic

Sites 925 and 664 $\Delta\delta^{13}C_{982\text{-}925}$ and $\Delta\delta^{13}C_{982\text{-}664}$) confirms this main observation: remarkable covariance between intermediate-to-deep $\delta^{13}C$ and $\delta^{18}O$ throughout the past 1 Myr (Figures 6b and 6c). Changes in bathymetric $\delta^{13}C$ gradients (Figure 6) more closely match $\delta^{18}O$ variations than does the percent NADW circulation index (Figure 5).

Cross-spectral analysis of the $\Delta\delta^{13}C_{NCW}$ index at Sites 607, 925, and 664 versus local $\delta^{18}O$ allows assessment of this covariance in the frequency domain (Table 3). The analysis shows that bathymetric $\delta^{13}C$ gradients are coherent with $\delta^{18}O$ in the 100, 41, and 23 kyr bands (at the 80% confidence interval). These results confirm the strong covariance observed in the time domain and indicate the two variables ($\Delta\delta^{13}C_{NCW}$ and $\delta^{18}O$) are tightly linked on average throughout the past 1 Myr.

Phase estimates at all sites show that changes in bathymetric $\Delta\delta^{13}C_{NCW}$ lead $\delta^{18}O$ in the 100 kyr band (-16.67° to -17.93°, or -4.63 to -4.98 kyr) are nearly in phase in the 41 kyr band (within 2 kyr, except at Site 664) and generally lag $\delta^{18}O$ in the 23 kyr band (Table 3). Similar findings at each orbital period using $\delta^{13}C$ records from three different deep Atlantic sites (also supported by the $\Delta\delta^{13}C_{982\text{-}849}$ results; Table 3) suggest that the central conclusion is robust: $\Delta\delta^{13}C_{NCW}$ leads $\delta^{18}O$ at the 100 kyr period and lags at the 23 kyr period.

Low-$\delta^{13}C$ excursions during glacial terminations at intermediate depth Site 982 [*Venz et al.*, 1999] may complicate the interpretation of the $\Delta\delta^{13}C_{NCW}$ index in the 100 kyr band. It is possible that SOW incursions at Site 982 lead to an early decrease in the intermediate-to-deep $\delta^{13}C$ gradient that does not reflect a resumption of LNADW flow. However, $\Delta\delta^{13}C_{NCW}$ decreases seem to coincide closely with glacial terminations (Figure 6). Furthermore, several deglaciations have minimal $\delta^{13}C$ excursions, e.g., MIS 11/12, 13/14, and 15/16 [*Venz et al.*, 1999], and yet have $\Delta\delta^{13}C_{NCW}$ decreases with magnitudes comparable to other deglaciations. These observations may suggest that SOW incursions during glacial terminations at Site 982 are not primarily responsible for the lead of $\Delta\delta^{13}C_{NCW}$ versus benthic foraminiferal $\delta^{18}O$ in the 100 kyr band.

Similar increases in the intermediate-to-deep water $\delta^{13}C$ gradient are observed during the LGM for the North Atlantic [*Boyle and Keigwin*, 1987; *Oppo and Lehman*, 1993; *Oppo et al.*,

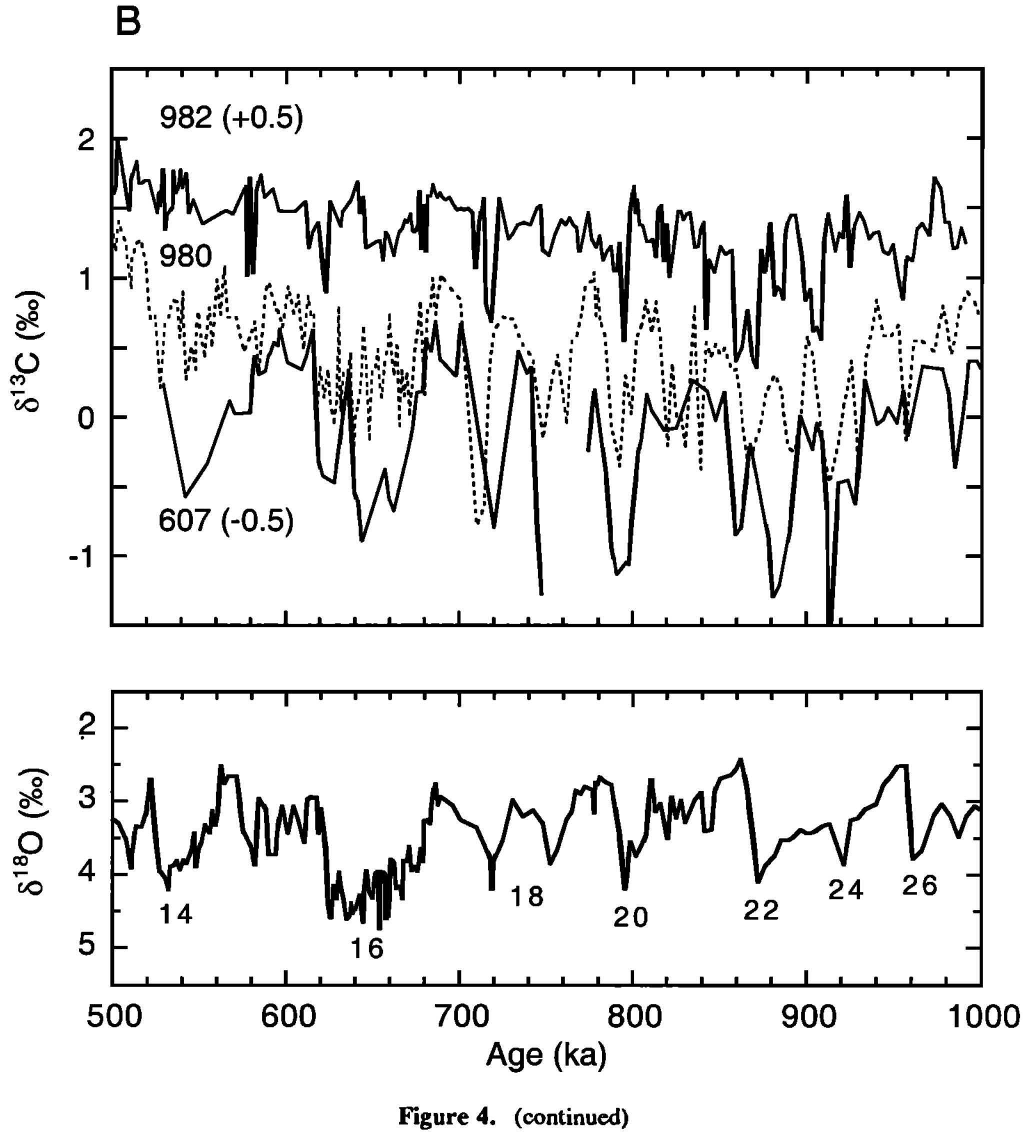

Figure 4. (continued)

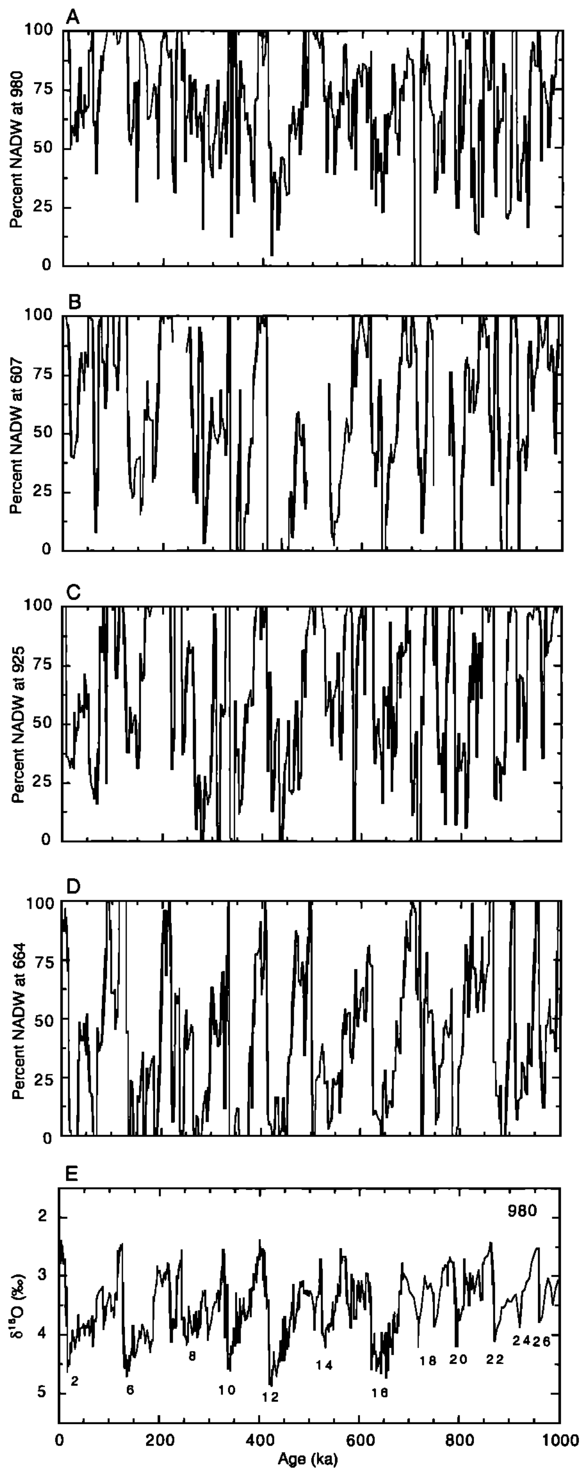

Figure 5. (a-d) Percent NADW at Sites 980, 607, 925, and 664 for the 0-1000 kyr interval. (e) Site 980 benthic foraminiferal $\delta^{18}O$ with selected glacial MIS labeled, shown for comparison. Note long-term increases in glacial percent NADW from ca. 800 to 540 ka, and from 420 to 20 ka.

1997], the Indian Ocean [*Kallel et al.*, 1988], and the western Pacific [*Herguera et al.*, 1991] and smaller increases in the eastern Pacific [*Mix et al.*, 1991]. *Boyle* [1986, 1988] proposed that increased deep nutrient regeneration may have increased the dissolution of carbonate and drawn down atmospheric CO_2 levels. However, this mechanism can only explain a small amount of CO_2 drawdown (10-20 µm [*Boyle*, 1992]). A new box model [*Toggweiler*, 1999] explores an oceanographic mechanism for CO_2 drawdown that does not rely on deep nutrient regeneration. This model treats the NADW/SOW boundary as a chemical divide separating low-CO_2 water above from high-CO_2 water below, derived from the Southern Ocean. Reduced ventilation of Southern Ocean deep waters plus $CaCO_3$ compensation due to reduced $CO_3^{=}$, along with cooler SST, together account for nearly 80 ppm CO_2 reduction [*Toggweiler*, 1999]. Thus covariance between intermediate-to-deep $\delta^{13}C$ and $\delta^{18}O$ over the past 1 Myr may be related to changes in ventilation of SOW and consequent CO_2 variability.

While this is an attractive model, it is not clear that our data are consistent with it. For example, during the MIS 5/6 transition, CO_2 probably leads ice volume [*Broecker and Henderson*, 1998], while our $\Delta\delta^{13}C_{NCW}$ records do not. Although there is some uncertainty in the relative timing of atmospheric CO_2, ice volume, and $\Delta\delta^{13}C_{NCW}$, it is hard to imagine that we have miscorrelated to hide a 6 kyr lead [*Broecker and Henderson*, 1998] at the MIS 5/6 transition. Thus our data are consistent only if either (1) CO_2 leads ice volume by much less than 6 kyr or (2) our miscorrelations allow for a much larger lead by $\Delta\delta^{13}C_{NCW}$ or CO_2 over ice volume.

5.4. Comparison to Vostok Atmospheric CO_2 Record

Comparing our $\Delta\delta^{13}C_{NCW}$ index with the Vostok atmospheric CO_2 record [*Petit et al.*, 1999] provides a further test of the *Toggweiler* [1999] model. If chemical stratification directly influences atmospheric CO_2, it should be nearly in phase with CO_2 changes in the orbital bands. CO_2 data on the Vostok extended glaciological timescale (EGT) cannot be directly compared to the deep-sea chronology because of significant differences prior to ~150 ka [*Petit et al.*, 1999]. To make this comparison, we first correlated the Vostok atmospheric $\delta^{18}O$ record (hereafter $\delta^{18}O_{atm}$) with Site 849 $\delta^{18}O$ (Figure 7), assuming $\delta^{18}O_{atm}$ closely tracks global ice volume [*Sowers et al.*, 1991, 1993; *Bender et al.*, 1994; *Broecker and Henderson*, 1998]. The $\delta^{18}O_{atm}$ is not strictly an ice volume proxy because it reflects photosynthesis processes (e.g., the Dole effect) in addition to the $\delta^{18}O$ of seawater. However, it seems to respond within 2 kyr of the $\delta^{18}O$ of seawater during the last two deglaciations [*Sowers et al.*, 1991; *Sowers and Bender*, 1995; *Broecker and Henderson*, 1998], so we tentatively use it for correlation to deep-sea $\delta^{18}O$ records (following *Sowers et al.*, [1991, 1993]). This correlation should not be considered an absolute age model for the Vostok ice core, but it is consistent with the Vostok EGT within the limits of its ice flow model [*Lorius et al.*, 1985; *Jouzel et al.*, 1996], which is better than $\pm$15 kyr at 414 ka [*Petit et al.*, 1999].

Cross-spectral analysis confirms that we have adequately correlated Vostok $\delta^{18}O_{atm}$ and Site 849 $\delta^{18}O$. Phasing between Vostok $\delta^{18}O_{atm}$ and Site 849 $\delta^{18}O$ (Figure 7 and Table 2) demonstrates that these records are in phase (within 2 kyr) in the precession and obliquity bands but that $\delta^{18}O_{atm}$ lags Site 849 $\delta^{18}O$ in the eccentricity band. The latter relationship may be an artifact of comparing only four eccentricity cycles. Indeed, Figure 7 shows that we have correlated Vostok $\delta^{18}O_{atm}$ precisely to Site 849 $\delta^{18}O$ at glacial terminations. Next, because our chemical stratification index was also correlated to Site 849 $\delta^{18}O$, we can compare $\Delta\delta^{13}C_{NCW}$ and Vostok CO_2 in the time and

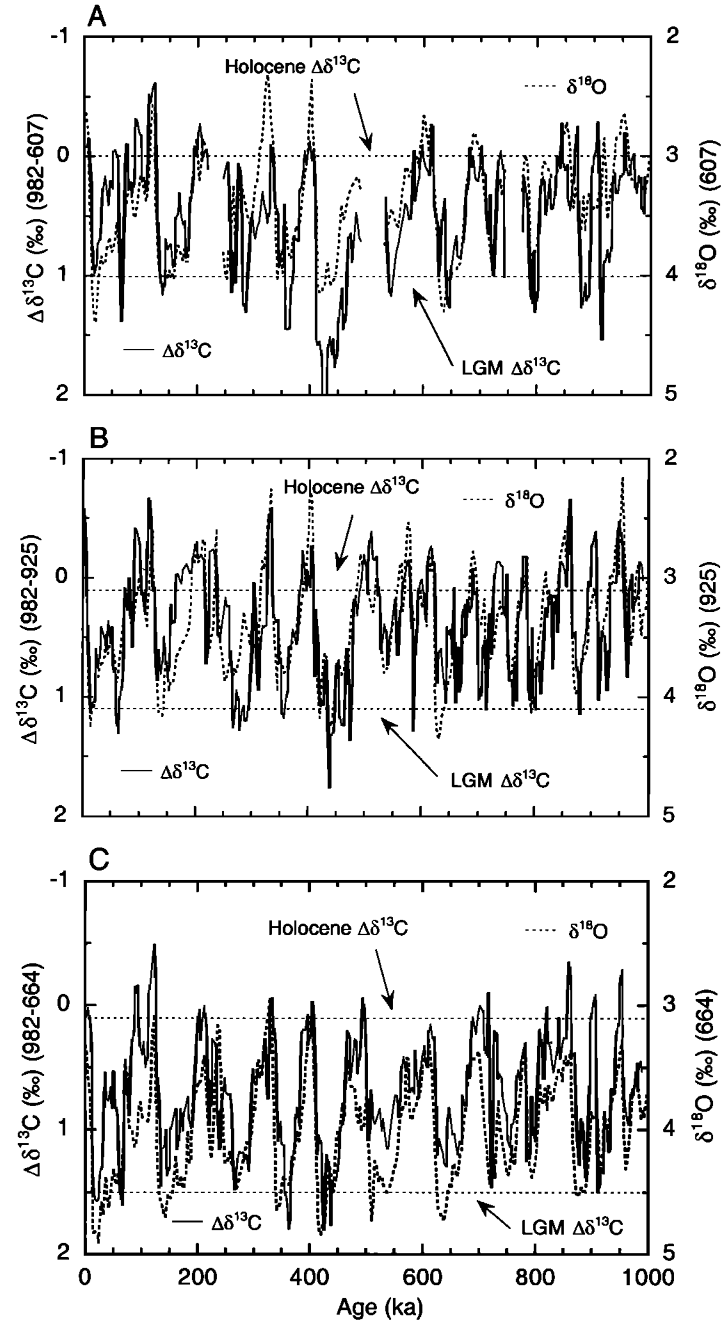

Figure 6. Bathymetric carbon isotope gradients ($\Delta\delta^{13}C_{NCW}$) covary with benthic foraminiferal $\delta^{18}O$ for the 0-1000 kyr interval. North Atlantic intermediate-depth Site 982 (~1100 m) is compared to (a) North Atlantic Site 607 ($\Delta\delta^{13}C$ 982-607), (b) western equatorial Atlantic Site 925 ($\Delta\delta^{13}C$ 982-925), and (c) central equatorial Atlantic Site 664 ($\Delta\delta^{13}C$ 982-664). Oxygen isotope record for each deep site is shown as a dotted line on each plot. Dashed lines indicating Holocene and LGM $\delta^{13}C$ gradients [after *Duplessy et al*, 1988; *Oppo and Lehman*, 1993] are also plotted.

frequency domains (Figure 7 and Table 4). There is no need to account for the gas age/ice age difference in the Vostok records because both $\delta^{18}O_{atm}$ and CO_2 are measured on gas samples. Cross-spectral analysis reveals that $\Delta\delta^{13}C_{NCW}$ is coherent with Vostok CO_2 in the orbital bands but not consistently in phase. In particular, $\Delta\delta^{13}C_{NCW}$ lags CO_2 in the precession band (Table 4), weakening the case for chemical stratification control of atmospheric CO_2. Further, $\Delta\delta^{13}C_{NCW}$ clearly lags Vostok CO_2 on glacial terminations (Figure 7).

However, our $\Delta\delta^{13}C_{NCW}$ index may respond later than CO_2 variations because it is also affected by subpolar North Atlantic processes, while CO_2 in the *Toggweiler* [1999] model is controlled only by Southern Ocean processes. Similarly, $\Delta\delta^{13}C_{NCW}$ decreases at glacial terminations are larger than

Table 3. Results of Cross-Spectral Analysis of $\Delta\delta^{13}C_{NCW}$ Index (Site 982 $\delta^{13}C$ Minus Local $\delta^{13}C$) Versus Benthic Foraminiferal $\delta^{18}O$

	Band, kyr					
	100		41		23	
$\Delta\delta^{13}C$ 982-980 versus $\delta^{18}O$ 980						
Coherence	0.81		0.80		0 51	
Phase, deg	-17.13	±15.61	16.30	±15.91	67.25	±38.95
Kiloyears	-4.76	±4.34	1.86	±1.81	4 30	±2 49
$\Delta\delta^{13}C$ 982-607 versus $\delta^{18}O$ 607						
Coherence	0 89		0.78		0.65	
Phase, deg	-16.67	±10 68	-4.78	±17 25	17.38	±25.35
Kiloyears	-4.63	±2 97	-0.54	±1.96	1.11	±1.62
$\Delta\delta^{13}C$ 982-925 versus $\delta^{18}O$ 925						
Coherence	0.88		0 83		0.63	
Phase, deg	-17.93	±11.26	-9.15	±14 17	49.91	±27.01
Kiloyears	-4.98	±3.13	-1 04	±1 61	3.19	±1.73
$\Delta\delta^{13}C$ 982-664 versus $\delta^{18}O$ 664						
Coherence	0 94		0.78		0.70	
Phase, deg	-16.87	±7 29	-23 26	±17 23	24.76	±21.93
Kiloyears	-4.69	±2.03	-2.65	±1.96	1.58	±1.40
$\Delta\delta^{13}C$ 982-849 versus $\delta^{18}O$ 849						
Coherence	0 89		0.75		0.41	
Phase, deg	-41.13	±11 11	-13 93	±19.25	23.28	±56.07
Kiloyears	-11.43	±3.09	-1.59	±2 19	1 49	±3.58

Blackman-Tukey cross-spectral analysis was conducted as described in Table 2 Coherence is significant at the 80% level (k=0.40). Negative phase (given in degrees and kiloyears) indicates the given parameter leads benthic $\delta^{18}O$.

expected from CO_2 sequestration by SOW [*Toggweiler*, 1999] because of increases in UNADW ventilation. Finally, our phase results rest on the assumption that Vostok $\delta^{18}O_{atm}$ tracks Site 849 $\delta^{18}O$. If this is wrong, then the phasing of $\Delta\delta^{13}C_{NCW}$ relative to CO_2 will have to be revised. Therefore it may be premature to rule out chemical stratification changes as a direct cause of CO_2 variations recorded in the Vostok ice core during the past 400 kyr In any case, chemical stratification may have acted as a reinforcer of climatic change induced by other processes.

5.5. Comparison to Other Deep Circulation Indices

In order to examine how deep circulation may have influenced climate in ways other than through CO_2 sequestration, we now compare two other measures of deep circulation, percent NADW (described above) and $\Delta\delta^{13}C_{SCW}$. For the $\Delta\delta^{13}C_{SCW}$ index, deep Pacific Site 849 $\delta^{13}C$ was subtracted from each $\delta^{13}C$ record to measure enrichment relative to southern component water values (following *Curry* [1996a]). To determine whether the phase relationships we derived for the $\Delta\delta^{13}C_{SCW}$ index and $\delta^{18}O$ are robust, we also compare the phasing for percent NADW and $\Delta\delta^{13}C_{SCW}$. As noted above, the $\Delta\delta^{13}C_{NCW}$ index (Site 982 $\delta^{13}C$ minus local $\delta^{13}C$) is coherent with and significantly leads ice volume variations in the 100 kyr band at all sites (Table 3). Also, the phase lead is relatively constant (~4.8 ±3.1 kyr). However, this lead is not observed for the other indices (Tables 5 and 6). Therefore we cannot rule out the possibility that SOW incursions during glacial terminations at Site 982 are responsible for early $\Delta\delta^{13}C_{NCW}$ decreases in the 100 kyr band.

In the 41 kyr band, phasing for all three indices exhibits a meridional trend, in which the southernmost Site 664 leads $\delta^{18}O$, while northernmost Site 980 lags $\delta^{18}O$ (Tables 3, 5, and 6). At low to middle-latitudes (Sites 925 and 607), all three indices are in phase with $\delta^{18}O$. This pattern reflects a consistent south-to-north progression in deep circulation indices. Evidence for a meridional trend relative to ice volume variations complements previous work demonstrating a depth-dependent relation in the equatorial Atlantic. A depth transect of Ceara Rise cores shows that the $\Delta\delta^{13}C_{SCW}$ index (local $\delta^{13}C$ minus Site 849 $\delta^{13}C$) leads $\delta^{18}O$ in the 41 kyr band in the deeper cores [*Curry*, 1996a, b]. This result is confirmed for each of the primary orbital bands over the past 1 Myr by $\delta^{13}C$ [*Bickert et al.*, 1997] and by a dissolution index [*Harris et al.*, 1997] and interpreted to indicate that Circumpolar Deep Water is an early responder to Northern Hemisphere insolation changes. The meridional and depth-dependent trends we observe may reflect the progressive withdrawal of NADW from southern regions during 41 kyr glaciations.

In the 23 kyr band the three indices lag $\delta^{18}O$ at all sites. Furthermore, northernmost Site 980 exhibits the greatest lag (as well as the only lag in the 41 kyr band), suggesting that deep water changes are recorded in the northeast Atlantic significantly after the deep and southern Atlantic. This is because Site 980 is close to northern deep water sources and is the last site to encounter the mixing zone with SOW as the northern source retreats.

Obliquity and eccentricity are in phase in the two hemispheres, so the phasing of NADW/SOW indices at the 100 and 41 kyr periods is consistent with either Northern Hemisphere or Southern Hemisphere processes as early responders to Northern Hemisphere orbital forcing. Because precession is out of phase in the two hemispheres, the timing of deepwater changes at the 23 kyr period can be used to distinguish between Northern and Southern Hemisphere forcing. The lag of deep water circulation indices relative to ice volume variations in this band is consistent with deep water changes forced by Northern Hemisphere processes, as relevant climate variables in the Southern Hemisphere (such as SST) clearly lead ice volume [*Hays et al.*, 1976; *Imbrie et al.*, 1992]. In fact, deep water changes parallel SST changes in the subpolar North Atlantic, with SST nearly in phase with ice volume at the 100 and 41 kyr bands and lagging at the 23 kyr band [*Ruddiman and McIntyre*, 1981, 1984; *Imbrie et al.*, 1992]. The SST lag (+6 kyr) may be greater than the deep circulation lag (0 to +6 kyr), but these patterns suggest that linked processes may be controlling both North Atlantic SST and deep circulation, including the conversion of subpolar surface waters to NADW.

In contrast, Southern Ocean SST lead ice volume (by ~1.5-13 kyr) in all three orbital bands during the past 400 kyr [*Imbrie et al.*, 1992, 1993]. Other Southern Hemisphere processes (including Antarctic air temperatures and dust flux) also lead ice volume (based on benthic foraminiferal $\delta^{18}O$ and the $\delta^{18}O$ content of O_2 in the Vostok ice core) by ~ 2-8 kyr during the past 150 kyr [*Broecker and Henderson*, 1998]. If NADW/SOW variations were responding to Southern Ocean SST variability,

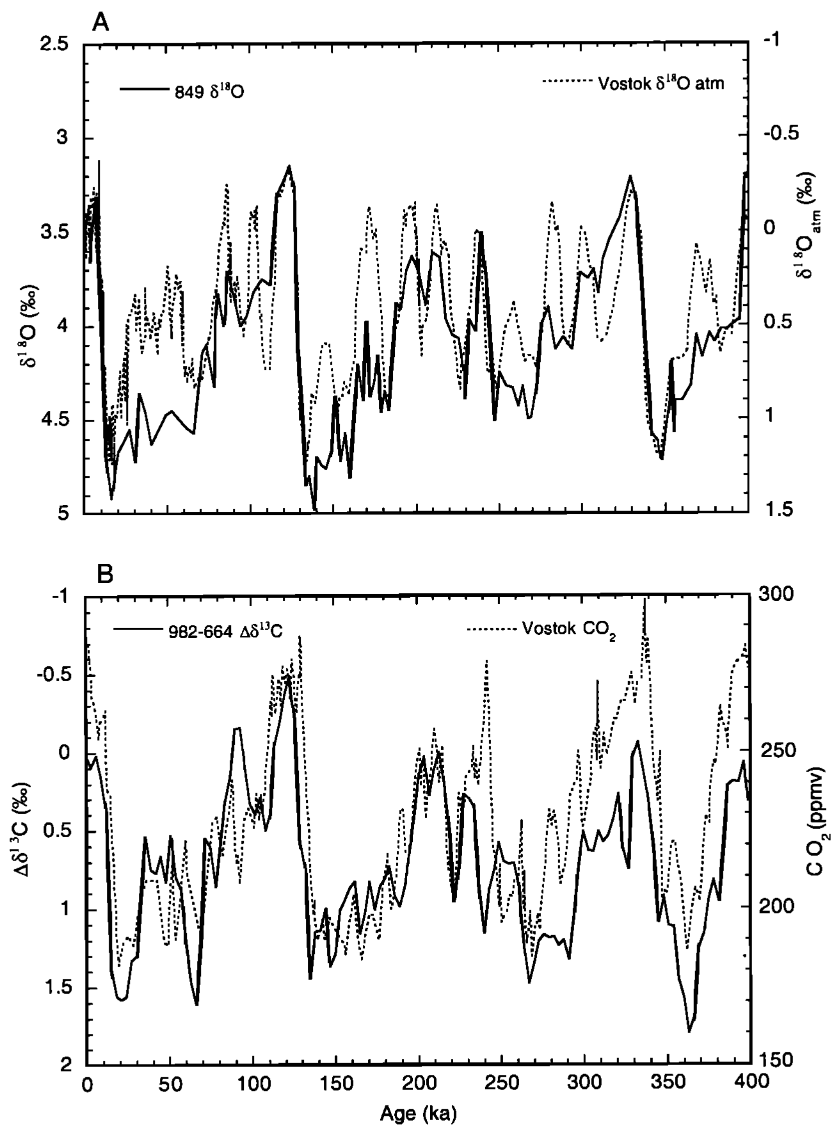

Figure 7. Comparison of Vostok ice core records with our bathymetric $\delta^{13}C$ index for chemical stratification Figure 7a shows our correlation of the Vostok $\delta^{18}O_{atm}$ record to Site 849 benthic foraminiferal $\delta^{18}O$ Cross-spectral analysis confirms excellent correlation in the 41 and 23 kyr bands (Table 2). Figure 7b shows that ($\Delta\delta^{13}C_{NCW}$ covaries inversely with Vostok CO_2. However, a lag in the precession band (Table 4) weakens the case for chemical stratification as a driver of CO_2 changes.

Table 4. Results of Cross-Spectral Analysis of $\delta^{13}C_{NCW}$ Index (Site 982 $\delta^{13}C$ Minus Local $\delta^{13}C$) Versus Vostok CO_2

	Band, kyr					
	100		41		23	
$\delta^{13}C$ 982-980 versus Vostok CO_2						
Coherence	0.64		0.74		(0.59)	
Phase, deg	-7.70	±30.60	7.38	±21.87	65.39	±36.20
Kiloyears	-2.14	±8.50	0.84	±2.49	4.18	±2.31
$\delta^{13}C$ 982-607 versus Vostok CO_2						
Coherence	0.76		0 85		(0.57)	
Phase, deg	14.92	±27.40	6.02	±14.36	91.46	±35.17
Kiloyears	4.15	±7.61	0.69	±1.64	5.84	±2.25
$\delta^{13}C$ 982-925 versus Vostok CO_2						
Coherence	0.69		0.73		0.71	
Phase, deg	13.81	±25.94	22.24	+22 20	97.47	±24.83
Kiloyears	3.84	±7.21	2.53	±2.53	6.23	±1 59
$\delta^{13}C$ 982-664 versus Vostok CO_2						
Coherence	0.89		0.81		0.72	
Phase, deg	8.06	±11 75	-5 32	±17.44	59.81	±23 22
Kiloyears	2.24	±3.26	-0.61	±1.99	3.82	±1.48
$\delta^{13}C$ 982-849 versus Vostok CO_2						
Coherence	0.87		0 94		0.67	
Phase, deg	-13.85	±17.25	24.28	±10.69	81.02	±34.87
Kiloyears	-3.85	±4.79	2.76	±1.22	5.18	±2.23

Blackman-Tukey cross-spectral analysis was conducted as described in Table 2. Coherence is significant (except where indicated by parentheses) at the 80% level (k=0.64). Negative phase (given in degrees and kiloyears) indicates the given parameter leads benthic $\delta^{18}O$.

one might expect Atlantic deep circulation indices to share this lead at all periods. However, the absence of a lead at the 23 kyr period is inconsistent with Southern Hemisphere processes primarily controlling NADW/SOW variability.

Although these findings support the suggestion that Northern Hemisphere processes (including NADW formation) are important early responders to Northern Hemisphere orbital forcing in the 41 and 100 kyr bands, the lag at the 23 kyr period indicates that deep water changes themselves do not drive global ice volume. These results contrast with those of *Imbrie et al.* [1992] who use the $\delta^{13}C$ difference between South Atlantic and Pacific records to suggest a lead of deep water at all Milankovitch periods. The particular South Atlantic $\delta^{13}C$ record they used has been shown to record processes other than deep water variability [*Bickert and Wefer*, 1996]. These processes may have affected the timing of $\delta^{13}C$ change relative to deep water circulation change. Our finding of a lag in the precession band in three cores using three deep water $\delta^{13}C$ indices strongly suggests that deep water is not necessarily a leading factor in orbital-scale climate change but rather responds at approximately the same time as subpolar North Atlantic SST, similar to that observed on millennial time scales [*Charles et al.*, 1996]. This link between North Atlantic SST and deep water is expected as the strength of NADW controls the heat transport in the upper limb of the global ocean conveyor.

6. Conclusions

Carbon isotope records from a depth transect in the North Atlantic of Sites 982, 980, and 607 (1134, 2168, and 3427 mbsl) trace the evolution of intermediate-to-deep $\delta^{13}C$ gradients during the past 1 Myr. Interglaciations exhibit similar $\delta^{13}C$ values, confirming earlier evidence for NADW in intermediate to deep waters. Significant increases in bathymetric $\delta^{13}C$ gradients during glacial intervals (commonly reaching >1.2‰) often exceed that observed for the Last Glacial Maximum. Bathymetric $\delta^{13}C$ changes indicate some combination of increased UNADW, decreased LNADW, increased SOW, and associated chemical stratification in deep waters.

Site 980 $\delta^{13}C$ values covary with Site 607 $\delta^{13}C$ values but are consistently intermediate between the shallower and deeper sites during glaciations, suggesting that this site (~2200 m) lay within the mixing zone between UNADW and SOW. Using an improved NADW end-member record (Site 982 [*Venz et al.*, 1999]), percent NADW records support earlier work noting a decoupling of Pleistocene ocean circulation and ice volume variations. The general similarity of percent NADW records from Sites 980 and 607 suggests that SOW may have influenced substantial volumes of the deep Atlantic, reaching depths as shallow as ~2200 m. Regardless of which end-member is used, the large percent NADW variations of the past 1 Myr [*Raymo et*

Table 5. Results of Cross-Spectral Analysis of Percent NADW Versus Benthic Foraminiferal $\delta^{18}O$

	Band, kyr					
	100		41		23	
Percent NADW at 980 versus -$\delta^{18}O$ 980						
Coherence	0.78		0.79		0.48	
Phase, deg	-9.13	±17.24	29 36	±16 96	68 65	±44 30
Kiloyears.	-2.54	±4.79	3 34	±1 93	4 39	±2.83
Percent NADW at 607 versus -$\delta^{18}O$ 607						
Coherence	0.87		0.79		0.70	
Phase, deg	-10.24	±11 92	-3 03	±16.95	16.16	±22.03
Kiloyears	-2.84	±3 31	-0.34	±1.93	1.03	±1.41
Percent NADW at 925 versus -$\delta^{18}O$ 925						
Coherence	0.83		0 85		0.63	
Phase, deg	-4 76	±14 17	-0.32	±13.21	56.95	±27.04
Kiloyears	-1 32	±3 94	-0.04	±1.50	3.64	±1.73
Percent NADW at 664 versus -$\delta^{18}O$ 664						
Coherence	0.92		0.79		0.67	
Phase, deg	-10 12	±8.90	-26.72	±16.66	32.55	±23.72
Kiloyears	-2.81	±2.47	-3.04	±1.90	2.08	±1.52

Blackman-Tukey cross-spectral analysis was conducted as described in Table 2. Coherence is significant at the 80% level (*k*=0 40) Negative phase (given in degrees and kiloyears) indicates the given parameter leads benthic foraminiferal $\delta^{18}O$

Table 6. Results of Cross-Spectral Analysis of $\Delta\delta^{13}C_{SCW}$ Index (Local $\delta^{13}C$ Minus Site 849 $\delta^{13}C$) Versus Benthic Foraminiferal $\delta^{18}O$

	Band, Kyr					
	100		41		23	
980-849 $\Delta\delta^{13}C$ versus -980 $\delta^{18}O$						
Coherence	0.45		0.55		(0 31)	
Phase, deg	72.58	±53.05	59 82	±38.53	86.08	±70.53
Kiloyears	20 16	±14.74	6 81	±4.39	5 50	±4.51
607-849 $\Delta\delta^{13}C$ versus -607 $\delta^{18}O$						
Coherence	0.71		0 62		0 48	
Phase, deg	9.38	±21 95	13.37	±27.64	7.91	±40.12
Kiloyears	2.61	±6.10	1.52	±3.15	0.51	±2 56
925-849 $\Delta\delta^{13}C$ versus -925 $\delta^{18}O$						
Coherence	0.63		0 65		0.66	
Phase, deg	7 61	±27.38	-2.65	±25.18	58 76	±24.66
Kiloyears.	2.11	±7.61	-0.30	±2.87	3.75	±1.58
664-849 $\Delta\delta^{13}C$ versus -664 $\delta^{18}O$						
Coherence	0.90		0.57		0 53	
Phase, deg	5.23	±10.15	-32.49	±32.54	31.40	±34.79
Kiloyears	1.45	±2.82	-3.70	±3.71	2.01	±2.22

Blackman-Tukey cross-spectral analysis was conducted as described in Table 2. Coherence is significant (except where indicated by parentheses) at the 80% level (*k*=0 40). Negative phase (given in degrees and kiloyears) indicates the given parameter leads benthic $\delta^{18}O$.

al., 1990, 1997] are confirmed. Lower percent NADW values relative to the LGM suggests a shallower UNADW/SOW mixing zone during most earlier glaciations. Furthermore, long-term changes in percent NADW confirm a growing body of evidence for long-term trends in Atlantic Ocean circulation during the past 1 Myr.

An intermediate-to-deep stratification index ($\Delta\delta^{13}C_{NCW}$) more strongly covaries with benthic foraminiferal $\delta^{18}O$ than percent NADW. The $\Delta\delta^{13}C_{NCW}$ index leads in the 100 kyr band but not in the other bands. Incursion of SOW during glacial terminations at intermediate Site 982 may account for early $\Delta\delta^{13}C_{NCW}$ decreases in the 100 kyr band. We also use the $\Delta\delta^{13}C_{NCW}$ index to test a new model for oceanographic control of atmospheric CO_2 by chemical stratification in the deep ocean [*Toggweiler*, 1999]. We find that $\Delta\delta^{13}C_{NCW}$ is coherent with atmospheric CO_2 in the orbital bands but not consistently in phase. Still, we cannot rule out that chemical stratification changes led to the CO_2 variations recorded in the Vostok ice core during the past 400 kyr, in part because of uncertainties in correlation of ice core records to the deep sea chronology. In any case, chemical stratification may have acted as a reinforcer of climatic change induced by other processes.

In the 41 kyr band, phasing for three indices ($\Delta\delta^{13}C_{NCW}$, percent NADW, and $\Delta\delta^{13}C_{SCW}$) exhibits a meridional trend, in which the southernmost Site 664 leads $\delta^{18}O$, while northernmost Site 980 lags $\delta^{18}O$. This pattern reflects a consistent south-to-north progression in deep circulation indices relative to ice volume variations, complementing similar evidence for a depth-dependent lead in the equatorial Atlantic [*Curry*, 1996a,b; *Harris et al.*, 1997; W. B. Curry, manuscript in preparation, 2000]. Similar phasing of deep water and subpolar North Atlantic SST relative to ice volume, in particular the lag at the 23 kyr period, suggests that Northern not Southern Hemisphere processes control deep water variability. This lag also suggests that other factors may control ice volume variations to a greater degree than deep ocean circulation.

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J. L. Cullen, Department of Geological Sciences, Salem State University, Salem, MA 01970.

B. P. Flower, Department of Marine Science, University of South Florida, St. Petersburg, FL 33701 (bflower@seas.marine usf edu)

D. A. Hodell and K. A. Venz, Department of Geology, University of Florida, Gainesville, FL 32611

D. W. Oppo and J. F. McManus, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

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