PP31A-1733 Quantifying the effects of changes in ocean circulation and endmember composition on variability in Late Pleistocene $\delta^{13}C$

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Abstract

Benthic $\delta^{13}C$ has a long history as a proxy for ocean circulation change. However, several recent studies [e.g., *Rutberg and Peacock*, 2006; *Raymo et al.*, 2004] have suggested that variations in endmember $\delta^{13}C$ values could confound reconstructions of glacial watermasses or even dominate variability in benthic $\delta^{13}C$. We analyze 17 Atlantic benthic $\delta^{13}C$ records to quantify what percent of variance in the data is associated with changes in endmember composition versus watermass distribution. We illustrate a typical sequence of change in $\delta^{13}C$ for a Late Pleistocene glacial cycle. Then we estimate changes in NADW distribution by assuming that the $\delta^{13}C$ composition of NADW and AABW are recorded by North and South Atlantic sites, respectively. Three possible models of glacial-interglacial $\delta^{13}C$ change are compared to the data to test our interpretation of change in NADW distrubution. These models simulate $\delta^{13}C$ change using one of three assumptions about Atlantic glacial cycle responses: 1) only the distribution of NADW changed, 2) only the $\delta^{13}C$ of NADW and AABW changed, or 3) both the distribution and $\delta^{13}C$ of NADW/AABW changed. The models are evaluated with respect to the variance predicted for the 17 Atlantic sites and the first two principal components of the data. We find that assumption 3 best describes the variance in Atlantic $\delta^{13}C$ with respect to both criteria. In particular, no variance is found in the second principal component unless both circulation and $\delta^{13}C$ composition change, suggesting that at least 10% of the variance in Atlantic $\delta^{13}C$ is associated with changes in NADW distribution. Although watermass geometry cannot directly address the question of overturning rates, the spatial extent of $\delta^{13}C$ gradients across boundaries can provide constraints on rates of production relative to mixing.

Introduction

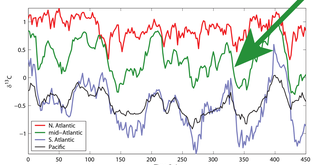
Does mid-Atlantic $\delta^{13}C$ variability reflect changes in circulation or endmember $\delta^{13}C$? (or both?)

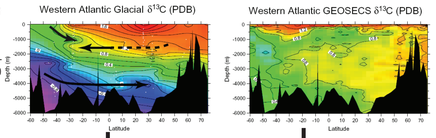
Traditionally glacial cycles in the benthic $\delta^{13}C$ of mid-Atlantic sites have been interpretted as changes in the ratio of North Atlantic Deep Water (NADW) to Antarctic Bottom Water (AABW) caused by changes in the formation rate or density of deep water [e.g., *Duplessy et al., 1988*]. However, calculations of the percent NADW at a site are subject to error due to uncertainty in the $\delta^{13}C$ composition of NADW and AABW through time.

Rutberg and Peacock [2005] recently suggested that the variance in mid-Atlantic $\delta^{13}C$ may result primarily from changes in the $\delta^{13}C$ composition of deepwater endmembers and that deepwater circulation may have remained constant throughout Late Pleistocene.

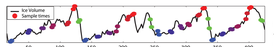
We compare the results of three models of $\delta^{13}C$ change (caused by circulation change only, endmember $\delta^{13}C$ change only, or a combination of both) with the benthic $\delta^{13}C$ records of 17 Atlantic sites to determine whether these data are sufficient to distinguish between the three models.

By interpretting mid-Atlantic $\delta^{13}C$ variability as circulation change, many studies [e.g., *Curry et al.*, 1988; *Duplessy et al.*, 1988; *Raymo et al.*, 1997; *Bickert et al.*, 1997] have concluded that NADW shoals during glacial times, with lower NADW disappearing and upper NADW increasing. This transformation is easily visible in high-resolution reconstructions (below) of western Atlantic $\delta^{13}C$ in the modern and at the LGM [*Curry and Oppo*, 2005]. (Deepwater formed in the North Atlantic is always more enriched in $\delta^{13}C$ than southern source water.)

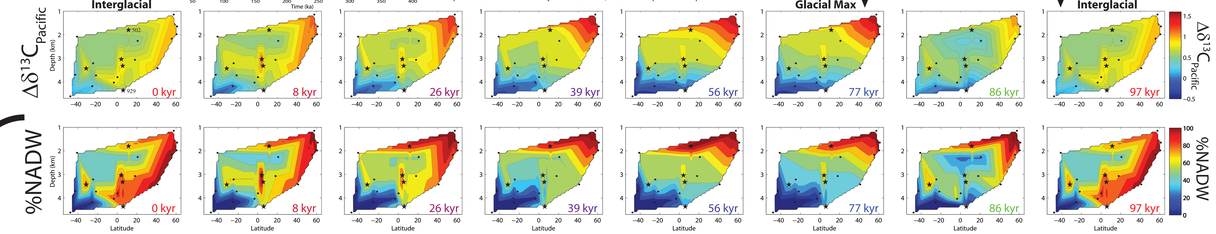




Data



Benthic $\delta^{13}C$ records from 20 Atlantic placed on the age model of *Lisiecki and Raymo* [2005] using graphic correlation of each site's benthic $\delta^{18}O$ record to the $\delta^{18}O$ stack (left) from that study. The $\delta^{13}C$ records are interpolated at a resolution of 2 kyr from 425-15 ka, which is the span of overlap between the sites.



Glacial Cycles in $\delta^{13}C$

$\Delta\delta^{13}C_{Pacific}$ (top row). The distribution of benthic $\delta^{13}C$ in the Atlantic is estimated for seven representative "time slices" in a Late Pleistocene glacial cycle. $\delta^{13}C$ values are plotted relative to the time-varying mean of $\delta^{13}C$ at six Pacific sites; this corrects for cyclic changes in mean $\delta^{13}C$ associated with changes in terrestrial biomass. (The raw data are plotted in the results section.) To reduce noise and describe the $\delta^{13}C$ response during an "average" glacial cycle, each time slice is constructed by averaging the $\delta^{13}C$ for eight different times, two from each of the last four glacial cycles. The times that were averaged together for each timeslice are plotted as different color dots on the ice volume curve above. The time listed for each time slice is the time since the most recent interglacial averaged across the eight times. The location of sites in the west Atlantic are marked by a black star and those in the east Atlantic are marked by a black dot. The average glacial maximum and interglacial $\delta^{13}C$ distributions are quite similar to high-resolution reconstructions of the western Atlantic $\delta^{13}C$ for the modern and LGM [*Curry and Oppo,* 2005].

%NADW (bottom row). We estimate the percent NADW throughout the Atlantic for the same seven timeslices as above. For each site, $\%NADW = (\delta^{13}C_{obs} - \delta^{13}C_{AABW})/(\delta^{13}C_{NADW} - \delta^{13}C_{AABW})$. The time-varying $\delta^{13}C$ composition of NADW is estimated by averaging the $\delta^{13}C$ of ODP Sites 980, 982, and 983. The $\delta^{13}C$ of AABW is taken as the average of $\delta^{13}C$ at RC13-229, ODP 1089, and ODP 1090. The assumptions required for this calculation are that these sites remain in the core of NADW or AABW throughout the last 425 kyr, that no other watermasses are present at each site, and that deepwater $\delta^{13}C$ is accurately recorded and preserved in the benthic foraminifera.

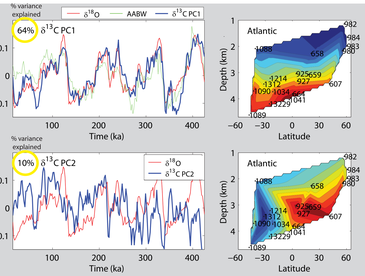
Summary. After interglacials, most change in the distribution of $\delta^{13}C$ occurs fairly rapidly. By 40 kyr after the interglacial, the $\delta^{13}C$ distribution is nearly identical to that at the glacial maximum. During deglaciation, $\delta^{13}C$ values in the South Atlantic respond before those in the deep North Atlantic.

Principal Component Analysis

Preprocessing. First the time-dependent average of all the $\delta^{13}C$ records is subtracted from each site. Then the sites are normalized to zero mean and unit standard deviations. Therefore, the analysis picks out correlations in the timing of $\delta^{13}C$ change at each site rather than differences in mean or variance which are more susceptible to local effects, such as productivity overprints.

Principal Component 1 (PC1). This most dominant component of the data explains 64% of the variance in the data. We propose that the spatial pattern of PC1 is correlated to the amount of AABW found at each site throughout the glacial cycle. For example, the spatial pattern of PC1 in model 2 (far right, blue box) is inversely correlated with the (constant) %NADW at each site. The time series associated with PC1 correlates strongly with benthic $\delta^{18}O$ (ice volume) and the $\delta^{13}C$ of deep South Atlantic sites. We propose that it is largely a function of changes in the $\delta^{13}C$ gradient between NADW and AABW endmembers. Notice the nearly identical time series for PC1 generated by models 2 and 3 (blue and purple boxes) which use northern and southern sites to estimate $\delta^{13}C$ variability in NADW and AABW. Additionally, PC1 includes the effects of circulation changes which correlate with this time series (i.e., those which correlate to ice volume).

Principal Component 2 (PC2). The second strongest orthogonal component of the data explains 10% of the variance. PC2 is positively correlated with deep North Atlantic sites thought to experience the most variability in %NADW over the glacial cycle. Therefore, we propose that this time series is correlated with changes in the %NADW at these sites through time (specifically, circulation changes which do not correlate with PC1).



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Acknowledgments

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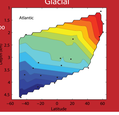
Models

1. Circulation Only

The $\delta^{13}C$ compositions of NADW and AABW are held constant relative to mean Pacific $\delta^{13}C$, and the depth of the boundary between NADW and AABW is inversely proportional to ice volume (benthic $\delta^{18}O$).

We optimize the fit between the raw (unnormalized) data and parameters controlling the maximum and minimum NADW depth, the thickness of the mixing layer between them (modeled as a linear gradient in $\delta^{13}C$), and the rate of decrease in %NADW as a function of latitude. The boundary depth given is the depth at which NADW begins to mix with AABW at 0 degrees latitude. For ODP sites 658 and 1088, we use only half of the modeled %NADW to fit the lower mean $\delta^{13}C$ at these sites. Because these sites are at water depths of 2000-2300 m, we assume that this correction reflects the influence of intermediate water not included in the model.

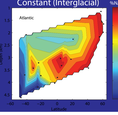
NADW $\delta^{13}C$: Pacific $\delta^{13}C$ + 1.5‰
AABW $\delta^{13}C$: Pacific $\delta^{13}C$
Minimum boundary: 1582 m
Maximum boundary: 2400 m
Mixing zone: 2700 m
N-S gradient: 0.2% per degree



2. Endmember $\delta^{13}C$ Only

The percent of NADW at each site is held constant at interglacial levels, and the $\delta^{13}C$ compositions of NADW and AABW vary.

The $\delta^{13}C$ of NADW is estimated as the average of $\delta^{13}C$ records from North Atlantic ODP Sites 980, 982, and 983. The $\delta^{13}C$ of AABW is estimated as the average of $\delta^{13}C$ records from deep South Atlantic sites RC13-229, ODP 1089, and ODP 1090. If circulation is constant over the glacial cycle, it should be consistent with modern (interglacial) observations. We estimate the modern %NADW at each site by calculating the average %NADW across the four interglacials in our records, using our estimates of the $\delta^{13}C$ of NADW and AABW at each time. The resulting estimates of %NADW for each site (below) are approximately consistent with the modern distribution of NADW and modern $\delta^{13}C$ profiles.

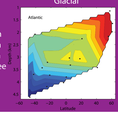


3. Circulation and Endmember $\delta^{13}C$

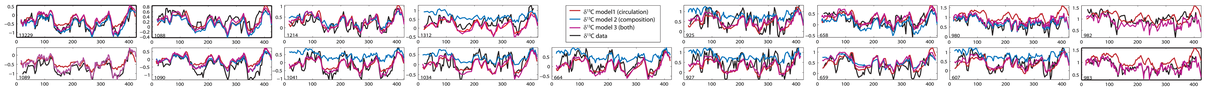
Both the distribution of NADW and the $\delta^{13}C$ of NADW and AABW are allowed to vary. The $\delta^{13}C$ of NADW and AABW are estimated as in model 2, and the depth of the boundary between NADW and AABW is inversely proportional to ice volume as in model 1.

We optimize the fit between the raw (unnormalized) data and parameters controlling the maximum and minimum NADW depth, the thickness of the mixing layer between them (modeled as a linear gradient in $\delta^{13}C$), and the rate of decrease in %NADW as a function of latitude. Because endmember $\delta^{13}C$ varies in this model, the optimal parameter values are different than in model 1. The boundary depth given is the depth at which NADW begins to mix with AABW at 0 degrees latitude. As in model 1, we use only half of the modeled %NADW to fit the lower mean $\delta^{13}C$ at ODP sites 658 and 1088.

Minimum boundary: 2261 m
Maximum boundary: 2900 m
Mixing zone: 2100 m
N-S gradient: 0.3% per degree



Results

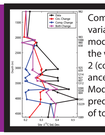


Percent Variance Explained

	Atlantic	mid-Atlantic	mid-Atlantic (site-dependent correction)
Model 1	73%	65%	70%
Model 2	77%	50%	60%
Model 3	83%	68%	73%

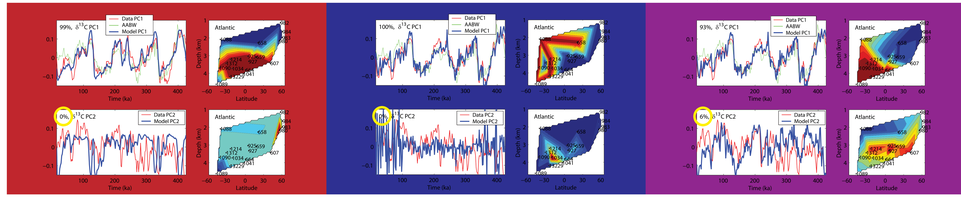
To calculate the percent of variance in all Atlantic $\delta^{13}C$ data collectively, the vector of $\delta^{13}C$ data for all sites at all times is projected onto the predicted $\delta^{13}C$ for each model, and the variance of the projection is described as a percent of total variance in the data. Because model 2 calculates the %NADW for each site explicitly while models 1 and 2 predict $\delta^{13}C$ at each site based only on time, depth, and latitude, we perform an additional calculation in which a correction of up to 0.25 per mil is applied to each site based on its mean $\delta^{13}C$. This allows for differences in %NADW based on longitude and local topography.

In all three cases, model 3 explains a greater percent of data variance than models 1 or 2.



Comparing the observed and predicted variance at each site (left), we see that model 1 (circulation only) underpredicts the variance in deep Atlantic sites. Model 2 (composition only) underpredicts variance in mid-Atlantic sites by a factor of 2. Model 3 (circulation and composition) predicts the magnitude and depth trend of total variance fairly well.

Principal Component Analysis



The strongest evidence in support of changes in both circulation and endmember $\delta^{13}C$ over glacial cycles comes from principal component analysis of the model predictions. When circulation or composition are varied alone, all of the variance in the data is explained by the first principal component. This result is independent of exact time series used for circulation change in model 1 or the spatial distribution of NADW and endmember $\delta^{13}C$ variability in model 2. Model 3 is the only one to generate significant variance in PC2 (6% in the model versus 10% in the data). Additionally, the time series of PC2 in model 3 correlates fairly well with PC2 of the data, particularly since MIS 7 (225 ka).

Conclusions

Most change in the distribution of $\delta^{13}C$ occurs in the first 30 kyr after an interglacial.

By 40 kyr after an interglacial, the $\delta^{13}C$ distribution is nearly identical to that at the glacial maximum.

During deglaciation, $\delta^{13}C$ in the South Atlantic respond before those in the deep North Atlantic.

Modeling changes in both circulation and endmember $\delta^{13}C$ explains more variance in Atlantic $\delta^{13}C$ than either alone.

However, a simple parameterized model in which NADW shoals in response to ice volume is capable of explaining most $\delta^{13}C$ change.

No variance is found in the second principal component unless both distribution and $\delta^{13}C$ composition of deepwater endmembers change, suggesting that at least 10% of the variance in Atlantic $\delta^{13}C$ is associated with changes in NADW distribution.