PP33A-1554

Multiple Modes of Orbital-Scale Change in Thermohaline Circulation?

Interpreting $\delta^{13}C$ Gradients

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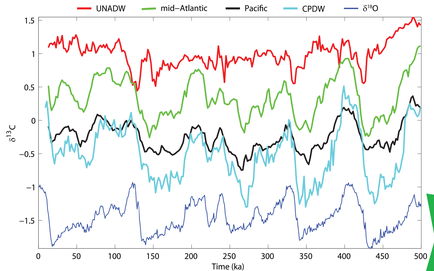
Abstract

Principal component analysis of Late Pleistocene benthic $\delta^{13}C$ records from 24 globally distributed marine sites reveals two independent modes of change associated with different orbital frequencies. Most paleoclimate studies of deep ocean circulation have either reconstructed only a few points in time (e.g., comparing the Last Glacial Maximum and the Holocene) or have examined the temporal evolution of relatively few paleoceanographic records. These techniques have produced a simple model of circulation change in which North Atlantic Deep Water (NADW) shoals during glacial conditions and is replaced at depth by Circumpolar Deep Water (CPDW) formed in the Southern Ocean. Our analysis is consistent with NADW shoaling proportional to ice volume change over the last four glacial cycles. However, we also observe a second, independent mode of change in $\delta^{13}C$ with more precession power. Many sites in the Atlantic record have strong precession responses, with lighter $\delta^{13}C$ values in phase with summer insolation maxima. More analysis is needed to determine whether this precession response is caused by changes in the $\delta^{13}C$ of NADW (at the time of formation or due to aging effects) or by changes in the NADW-CPDW boundary.

Introduction

Benthic $\delta^{13}C$ acts as a tracer of deep water masses because deep water formed in the North Atlantic has higher $\delta^{13}C$ values than deep water formed in the Southern Ocean. We place 24 benthic $\delta^{13}C$ records on a common timescale by graphically aligning their benthic $\delta^{18}O$ records to the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). Then we analyze changes in $\delta^{13}C$ values and water mass boundaries. Regional stacks or averages of $\delta^{13}C$ are interpreted below. In the results section, principal component analysis is used to extract the primary modes of variability in the $\delta^{13}C$ data. A simple model shows that the first component and some aspects of the second component can be explained by the shoaling of North Atlantic Deep Water in response to increases in ice volume (as measured by benthic $\delta^{18}O$). However, the second component also reveals a strong precession response in some Atlantic $\delta^{13}C$ records.

Regional $\delta^{13}C$



Records have been grouped based on their geographic distribution and the similarity of their time series. Sites whose response deviates from these four typical time series were not included in the stacks (averages).

North Atlantic

Sites: DSDP 552, ODP 982, ODP 983. These sites record the $\delta^{13}C$ composition of Upper North Atlantic Deep Water (1145-2300 m). These sites were probably not affected by CPDW in the Late Pleistocene. The light excursions near glacial terminations may indicate that the production of UNADW weakened at these times and produced light $\delta^{13}C$ by "aging"(Venz et al., 1999).

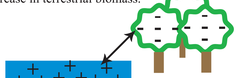
Mid-Atlantic

Sites: 607, 659, 664, 925, 927, 929, 1088, GeoB1034
These sites lie between 41S and 41N with water depths of 2000-4300 m. The $\delta^{13}C$ values of these sites are most strongly affected by the movement of the boundary between NADW and CPDW during the glacial cycle. These sites are nearly 100% NADW during interglacials and less than 50% NADW during glacials.

Pacific Deep Water

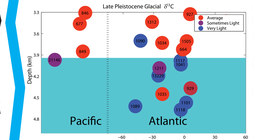
Sites: ODP 677, ODP 846, ODP 849, RC13-110

Deep Pacific water reflects the average $\delta^{13}C$ value of the ocean. This value changes due to the input of isotopically light terrestrial carbon during glacial times when widespread aridity and cooler temperatures lead to a decrease in terrestrial biomass.



Circumpolar Deep Water

Sites: ODP 1089, ODP 1090, RC13-229. These are primarily bathed in CPDW even during interglacials. These sites suggest that the $\delta^{13}C$ composition of CPDW became much lighter during glacial times. An alternate interpretation is that $\delta^{13}C$ values are corrupted by high organic carbon fluxes (Mackensen et al., 1993). However, the consistent presence of extremely light glacial $\delta^{13}C$ values in most cores below 4000 m depth, suggests that the true $\delta^{13}C$ of CPDW is accurately recorded (e.g., Venz and Hodell, 2002; Curry and Oppo, 2005).

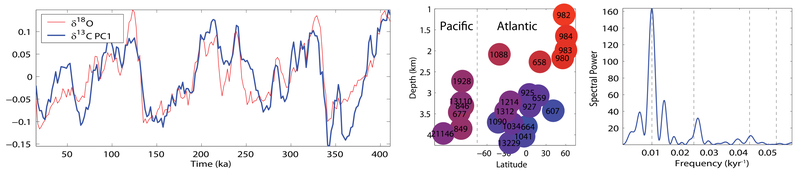


Results

The time series of $\delta^{13}C$ are processed in several ways before principal component analysis is performed. First, the mean value as a function of time is subtracted so that only the values relative to mean $\delta^{13}C$ are considered. Then the records are normalized to zero mean and unit standard deviation. Therefore, the analysis reflects correlations in the temporal pattern of change rather than the variance or mean of $\delta^{13}C$ at each site.

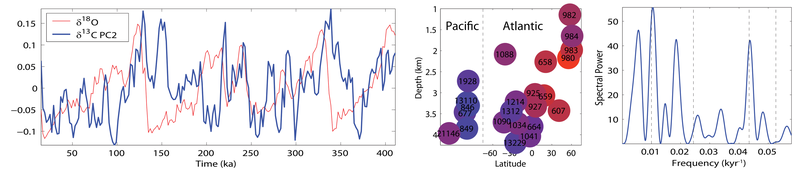
1st Principal Component

This times series correlates strongly with ice volume as recorded by benthic $\delta^{18}O$. It is constructed based on the difference between deep Atlantic sites and intermediate depth Atlantic sites and is best interpreted as changes in the depth of the boundary between NADW and CPDW. (Compare with the model on the right.)



2nd Principal Component

This time series has high values near terminations (producing 200-, 100-, and 50-kyr power) and a strong 23-kyr component. It is constructed by contrasting the core of interglacial NADW with Pacific and southern source waters. Response at the terminations is consistent with changes in the depth of NADW (see model).



Conclusions

- The $\delta^{13}C$ time series of NADW, CPDW, and Pacific deep water are distinct.
- The proportion of NADW to CPDW (or possibly Pacific water) at mid-depth Atlantic sites varies as a function of ice volume.
- Many Atlantic sites display a strong $\delta^{13}C$ response in phase with precession.
- Pacific $\delta^{13}C$ is consistent with a glacial terrestrial carbon source.

References

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Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records, Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071.
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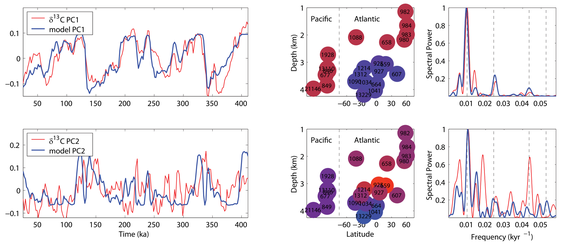
This research was supported by the NOAA Postdoctoral Program in Climate and Global Change, administered by the University Corporation for Atmospheric Research.

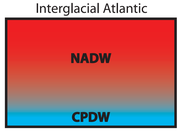
Discussion

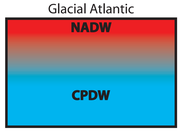
Model

This simple model is constructed by estimating the $\delta^{13}C$ value at each site as a function of time based on simple assumptions. (1) The $\delta^{13}C$ value of NADW is constant. (2) The $\delta^{13}C$ of CPDW is proportional to benthic $\delta^{18}O$ (ice volume). (3) The $\delta^{13}C$ of Pacific sites is the average of NADW and CPDW. (4) The proportion of NADW to CPDW at sites in the Atlantic varies as a function of depth and ice volume. The 100% NADW boundary shifts from 2000 m in the most severe glacial to 3800 m in the warmest interglacial. Percent NADW decreases linearly to 0% from 0-1500 m below the boundary.

The first principal component generated from the model data closely matches the first component of the real data both spatially and as a function of time. The second component of the model resembles the spatial distribution of the second component in the data, and both show peaks centered on terminations. However, the second component of the data also contains a strong precession response which is not predicted by the model. (See below.)







Precession

To study the precession response of the second principal component of the data we construct two $\delta^{13}C$ stacks, an "Atlantic" stack of the most positively weighted sites (980, 984, 607, 659, 925, and 927) and a "Pacific" stack of the most negatively weighted sites (677, 846, 849, 1088, RC13-229). The Atlantic stack contains much more precession power and has a different phase than the Pacific stack. The Pacific stack has a phase lag of 2 kyr relative to ice volume ($\delta^{18}O$) with light values occurring during glacial maxima, consistent with a terrestrial carbon source. The Atlantic stack has a 6 kyr lag relative to $\delta^{18}O$, much too large to be a direct response to ice volume. We propose that these sites are actually in phase with the direct insolation forcing but that their response is opposite in sign to the Pacific response. Atlantic $\delta^{13}C$ is light when precession forcing causes warmer summers and colder winters in the northern hemisphere.

This precession response could either be due to changes in the NADW-CPDW boundary or the $\delta^{13}C$ composition of NADW. A boundary change would require the shoaling of NADW during warm summers, which is the opposite of the observed obliquity response. Therefore, composition changes are more likely. For example, warm summers could cause light $\delta^{13}C$ through slower circulation (producing either an "aging" effect or greater mixing with CPDW), lighter $\delta^{13}C$ in North Atlantic source waters, or a change in productivity. More experiments are needed to distinguish between these options.