Prospects for the Large Scale Reconstruction of Past Ocean Circulation

SCOR/IMAGES Working Group on Past Ocean Circulation (PACE)

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Past Ocean Circulation

I-TASKS AND RECOMMENDATIONS

I-1. INTRODUCTION

Investigations of past climate over the last several tens of millennia have shown that climate can change quite rapidly. For example, at the end of the Younger Dryas temperature jumped about two-thirds of the way from glacial to interglacial values in only a decade. Because of their ability to store and transport heat, the oceans are an integral part of the climate system. It has been postulated that the rapid climate changes inferred from the paleo-climate data result from changes in the Atlantic ocean circulation [e.g. *Alley and Clark*, 1999; *Rahmstorf*, 2002; *Sarnthein, et al.*, 1994].

This hypothesis was supported by data from the shell chemistry of foraminifera from deep-sea sediments which suggested that nutrients were arrayed differently in the Atlantic over the course of these climate changes. However, even for the Last Glacial Maximum the existing nutrient data appears insufficient to quantify an alternative ocean circulation state [e.g., *Legrand and Wunsch*, 1995]. When we turn to the rapid climate change events that occurred during the last glaciation and over the course of the deglaciation, the circulation scenarios based on nutrient reconstructions only become more poorly constrained.

However, there are several less widely applied methods for assessing rates of paleo-ocean circulation. These methods include assessing deep water residence times from Pa/Th ratios in sediments, assessing deep ocean ventilation from radiocarbon measurements in benthic corals and foraminifera, reconstructing geostrophic flows using density gradients inferred from oxygen isotope measurements and reconstructing the strength of near bottom current speed from physical properties of deep sea sediments.

The SCOR/IMAGES Working Group on Past Ocean Circulation was established to bring together experts in paleoceanography, physical oceanography and ocean modeling to determine what is necessary for an effective and realistic research plan which will lead to a robust reconstruction of past ocean circulation. The group was charged with the following terms

1. *Assess the existing paleoceanographic methods for reconstructing the history of ocean circulation over the past 120,000 years.* Are the existing methods sufficient for a robust reconstruction of past ocean circulation? Are existing chronological tools sufficient to reconstruct distinct ocean circulation states? If not, what developments are necessary?

2. *Assess the available paleoceanographic data for reconstructing the history of ocean circulation over the past 120,000 years.* Can robust conclusions on past ocean circulation be drawn from existing data? For what time periods and locations?

3. *Develop recommendations for future approaches to quantitatively assess the hypothesised changes in ocean circulation over the same time scale.* Identify a

minimum array of global locations and data types that would help to constrain uncertainties concerning changes in ocean circulation linked to major climate changes, bearing in mind the potential for collecting appropriate geological material as well as the size of the expected circulation signal relative to uncertainties in the methods.

The working group organized a Workshop on Past Ocean Circulation which took place from March 20 to March 23, 2005 at the Georgia Institute of Technology in Atlanta. A total of 45 participants attended this workshop, among which were 10 members of the working group, 11 invited speakers, 10 students and post-docs and 11 other participants. Different scientific communities were represented in this group with scientists involved in paleo-data acquisition, modeling or physical oceanography. The workshop enabled the working group to use the expertise and input of the broader community in order to better answer the charges set out above. This report summarizes the findings of the working group as informed by the 2005 workshop.

We have focused on the possibility for the reconstruction of the large scale circulation of the deep and intermediate waters of the world ocean. While the circulation of surface waters is a significant part of the climate system, the reconstruction of subsurface flows seems more feasible given the status of currently available paleoceanographic materials and proxies. In addition, the surface to deep overturning circulation of the Atlantic is thought to play a major role in the abrupt climate changes observed during cool climates. Paleoceanographic reconstructions of this circulation are clearly needed to test this hypothesis as well as to assess the likelihood of similar changes occurring in the future. We also chose to focus on methods and data that address ocean circulation history over the last 40 kyr. This period of time is long enough to include some circulation states which appear to be dramatically different from today, yet is recent enough to assure broad geographic coverage and allow for the use of radiocarbon as a dating tool and tracer.

I-2. WORKING GROUP FINDINGS

Detailed summaries of the currently available techniques and data coverage available for the reconstruction of past ocean circulation can be found in Sections II and III of this document.

I-2.1. Are the currently available techniques adequate for reconstructing past ocean circulation?

We believe that our current understanding of the paleoceanographic proxies at our disposal is sufficient to determine whether the Atlantic MOC has been substantially different during the LGM. Reconstructing this same quantity on millennial time scales over the last 40 kyr will be more challenging, but we still believe that it is possible with some modest increase in the understanding of our proxies. Ocean margin density can give us a fairly direct measure of the shear in the MOC. The accuracy of such a reconstruction will depend primarily on our ability to relate the $\delta^{18}O$ in benthic foraminifera to density, which will depend on the T-S-$\delta^{18}O$ relationship in the water column. For the LGM, this relationship can be assessed using reconstructions from pore waters. For millennial time scales, we can at least partially constrain these changes if we can make further developments on a benthic paleo-temperature proxy. Mg/Ca and Sr/Ca ratios in benthic foraminifera show promise, but this calibration needs to be more fully defined. In addition, attention needs to be paid to instrument calibration to improve the accuracy and inter-lab reproducibility of benthic foraminiferal $\delta^{18}O$ measurements. Pa/Th provides a complementary measure of the residence time of deep water. A better understanding of the particle reactivity of these elements will increase the utility of this tracer even further.

In addition there are a variety of tracers that measure water mass properties such as stable isotopes and trace metals in foraminifera. These have the advantage of having widespread coverage and well understood errors. Radiocarbon in benthic foraminifera and deep-sea corals can also tell us about water masses. There are some promising new water mass tracers (such as Nd isotopes), but we need a better understanding of the mechanisms by which the sea water and sedimentary signals are set. We believe that the use of multiple water mass tracers can improve our understanding of which aspects of the reconstructions are the most reliable. Constraining the water mass properties near their point of origin will provide information on the importance of and modes of formation in different deep water formation regions. It will also allow for the use of radiocarbon measurements in benthic foraminifera and deep sea corals to quantify rates of ocean circulation.

While it would be difficult to incorporate them directly into a quantitative reconstruction of past ocean circulation, semi-quantitative tracers of flow speed and pathways provide an important check on the realism of any scenario.

Radiocarbon dating can provide a common time framework on millennial time scales for the last 25 kyr for the open ocean in mid-latitudes where the potential for high reservoir ages is limited. Changes in the strength of the geomagnetic field can be used to correlate records in areas where radiocarbon dating is not possible.

I-2.2. Are the currently available data adequate for reconstructing past ocean circulation?

A few conclusions can be made from the existing data. The LGM Atlantic (and global) ocean was chemically stratified, with distinctive properties in the intermediate depths and the deep ocean. Export of subsurface waters continued to some degree, so the Atlantic MOC cannot be considered to have been "off" during the LGM. Reconstructions of the global circulation are limited by a lack of Southern Ocean and Pacific data in part due to fundamental limitations on the availability and quality of sediments and in part due to limited previous focus on these regions. On millennial timescales the Atlantic MOC was variable and probably much weaker than today at a time associated with Heinrich Event 1.

In order to improve our assessment of ocean circulation in the LGM Atlantic we need better coverage of water mass proxies in areas of potential water mass formation (Nordic Seas), and the chemistry and physical data in the locations of the modern overflows. In addition there is a particular need for better constraint of water mass properties in the Southern Ocean. Additional proxies such as Zn/Ca and Cd/Ca would improve this situation, as would better geographic coverage of Pa/Th to assess the evolution of different water masses within the Atlantic. Existing limited ocean margin density data suggest a different circulation in the South Atlantic during the LGM, and should be expanded to provide more robust estimates of the shear in the MOC. Florida Straits boundary density also shows a reduction in shear during the LGM, although it is difficult to distinguish among various circulation scenarios consistent with this data.

At this point there are only a limited number of sediment cores that have high enough sedimentation rates (>8 cm/kyr) and have been adequately dated to resolve the millennial scale changes in circulation over the deglaciation. These studies, involving a number of different paleocean circulation proxies suggest that there were significant changes on these time scales. However, many of these records are in the North Atlantic, and more data will be required to portray the changes in water mass structure as they have for the LGM.

I-2.3. Recommendations

I-2.3.1 *LGM Data Compilation and Interpretation Working Group*

We recommend that a working group be formed to compile existing data of ‘paleocirculation proxies’ for the last glacial maximum. If the EPILOG/MARGO program is already planning such an effort, we fully support this. If not, it would be extremely valuable for this effort to be led by someone who was involved in the MARGO effort, so that the experience acquired by the MARGO group can benefit the circulation compilation. Although we already know that the existing data is strongly biased towards the North Atlantic, it is felt that the production of a global database would be valuable. Any data type that was interpreted so far as an indicator of the paleocirculation will be included in the database. The working group will define the time interval for the last glacial maximum based on criteria used in earlier programs (EPILOG, MARGO). In the compilation contributors will be asked to provide an uncertainty estimate of the proxy value building on the experience of these earlier programs. Uncertainties in both the age data points and in the proxy value will be included. For each record a core-top value for each proxy will also be reported. We would suggest one workshop supporting this data compilation effort.

We would suggest another workshop in the second year, in which forward and inverse models will be used in order to interpret the compiled LGM database. This will involve some model development, i.e., the incorporation of tracers into circulation models. It is felt that the models could be run in ‘equilibrium’ mode, that is, the simulations will assume that the tracers that have proxies in the sediment were in equilibrium with the circulation at the LGM. This working hypothesis is felt as necessary in order to make any progress feasible. Thus, the problem of reconstruction the circulation during the LGM will be considered as a ‘time-independent’ problem. In forward models tracer simulations will be compared to the proxy data, whereas in inverse models proxy data and models will be combined quantitatively from the outset. In both modeling efforts, close attention will be paid to the uncertainties in the data and in the models.

Both forward and inverse models can provide explicit recommendations as to the type of information that has the largest potential to provide quantitative constraints on the paleocirculation. That is, model results could provide some guidance about (1) the locations of the data, (2) the minimum uncertainty that proxy data should have, and (3) the type of data, that would be necessary in order to make firmer inferences about the paleocirculation.

I-2.3.2. *Paleocean Circulation Experiment (PACE)*

We propose a focused observational effort to reconstruct changes in the Atlantic MOC over the last 25 kyr. The Atlantic MOC is a leading candidate to explain abrupt climate changes observed in the paleoclimate record (YD/BA oscillation and DO events). Climate models suggest that there may be changes in the

Atlantic MOC in the future, and it is important to document the extent and impact of past changes in the AMOC. There are also high accumulation rate sediments containing adequate carbonate in the North Atlantic from which well resolved and dated records can be generated.

We suggest that a planning group be formed which will in the first year 1) Compile existing millennial scale data in the Atlantic and 2) Work to define which types of data and geographic coverage will required of a reconstruction of the Atlantic MOC for Heinrich Event 2, Last Glacial Maximum, Heinrich Event 1, Bolling-Allerod, Younger Dryas, Early Holocene, Middle Holocene, and Late Holocene. A compilation of downcore records of 'paleocirculation proxies' for the last 25 kyr will be produced. Again any sedimentary data that has been interpreted as a 'paleocirculation proxy' will be included in the database. It was felt that focusing on the last 25 kyr is a reasonable approach as this period is within the time span (1) for which the precision of radiocarbon dates is sufficient for millennial scale reconstructions, (2) for which there is a calibration between radiocarbon age and calendar age and (3) that includes rapid climate changes such as the onset and terminations of Heinrich events 1 and 2, the Bolling-Allerod, and the Younger Dryas as well as the Holocene. Data contributors will be asked to provide uncertainty estimates for their records to the best of their knowledge.

An attempt will be made to use models so as to provide guidance about the observational strategy (e.g., location, uncertainty, and type of data that would have the largest potential to provide quantitative constraints on the Atlantic MOC). The time dependence of the response of each proxy to circulation changes will be considered.

The planning group will then design an observational program, taking into consideration the data compilation and model recommendations about observational strategy. In particular the compilation will permit the identification of the major gaps in the datasets both in the spatial domain and in the time domain. Investigators would have to meet in order to agree about the core locations and the nature of the proxies that could/should be measured in the core.

After the data is collected and analyzed, forward and inverse models will be used in order to extract from the sediment records quantitative information about the temporal variability of the circulation between 25-0 ka BP. Thus, the interpretation of the records will be viewed as a time-dependent problem, unlike the interpretation of glacial data. Limitations here would come from (1) the computational costs of the simulations (but the cost would be relatively small if focus is on a specific rapid climate change – i.e., the onset of the Bolling or the termination of the Younger Dryas) and (2) the fact that the inverse methods that can address the time-dependent problem are at a much less advanced stage than for the time-independent problem (but tools already exist and are employed to study the time variability of the circulation in the modern ocean – cf. EPOC program).

I-4. OTHER WORKING GROUP PRODUCTS

1. A set of synthesis papers is being published in the AGU journal, *Geochemistry, Geophysics, Geosystems* under the Theme on Past Ocean Circulation. (See Section IV for list of papers)

2. A review written by the working group has been submitted to *Science* documenting the state of our knowledge of the Atlantic Meridional Overturning Circulation.
3. A set of downloadable overheads (pdf) will be available on the IMAGES/PAGES website pending publication of the figures in the review paper.

II-EXISTING METHODS AND DATA FOR RECONSTRUCTING PAST OCEAN CIRCULATION

II-1. SEDIMENT TRANSPORT FROM PHYSICAL PROPERTIES

II-1.1. Magnetic properties

Among the different proxies developed over the past 20 years for reconstructing past changes in the oceanic circulation, the magnetic properties of sediments is playing an increasing role. Beyond the simple measurement of the low field magnetic susceptibility which allows inter-correlations of cores, regional variations in rock magnetic properties (nature, size and concentration of magnetic particles) enable tracking of different particles fluxes.

Full magnetic analyses of cores taken from different parts of the North Atlantic Ocean have proven the ability of the magnetic analyses to detect and trace rapid oceanic circulation changes (Figure 1). Depending on the location of the cores, different modes of re-distribution of the detrital fraction of the sediment among which the magnetic grains have been distinguished [e.g. *Kissel*, 2005]. In the Ruddiman belt between 40°N and 55°N, the Heinrich layers are characterized by a significant increase in both the relative concentration and the grain size of magnetic particles [*Stoner et al*., 1996; 2000; *Robinson et al*., 1995; *Weeks et al*., 1995; *Moreno et al*., 2002; *Thouveny et al*., 2000]. This is the expression of abrupt vertical delivery by the icebergs of magnetic "sand" mixed with the main lithogenic sand. In this area, the background magnetic level is so weak compared to the Heinrich peaks that any other source than ice rafted magnetic particles is negligible. *Robinson et al.* [1995] have used these magnetic characteristics of IRD compared to those of the core tops to define the general trends of the surface currents driving the iceberg trajectories during the LGM.

By contrast, along the path of the North Atlantic Deep Water, the magnetic content of the cores is rather uniform in grain size and changes in the magnetic concentration are the dominant ones. The origin and the pathways of these magnetites are different from those invoked for the Ruddiman belt. Their source area is the basaltic region of Iceland and the Faeroe islands and their transport is controlled by the bottom current associated to the overflow waters [*Kissel et al.*, 1999]. Variations in magnetic concentration along the NADW path are associated with atmospheric changes over Greenland with enhanced (respectively reduced) strength of the bottom currents transporting more (respectively less) magnetic material to the sites during relatively warm (respectively cold) periods. This interpretation was recently confirmed by further clay and grain size analyses conducted on the same cores [*Ballini et al.*, 2006].

The use of the magnetic properties of marine sediments is a powerful tool for reconstructing past changes in the strength of the bottom currents. Magnetic investigations of core tops conducted both in North [*Watkins and Maher*, 2003] and in south Atlantic [*Schmidt et al.*, 1999] have, however, shown that other mechanisms such as eolian transport, high productivity can also be responsible for the magnetic variations. In order to use this proxy as a tracer of past changes in deep oceanic circulation, it is therefore critical to identify the source area of the magnetites by multiproxy analyses, and to work on sediments drifts along the path of the main bottom water masses. As for many other methods, it is also important to conduct magnetic analyses on multiple cores in order to discriminate the local effects from the regional ones.

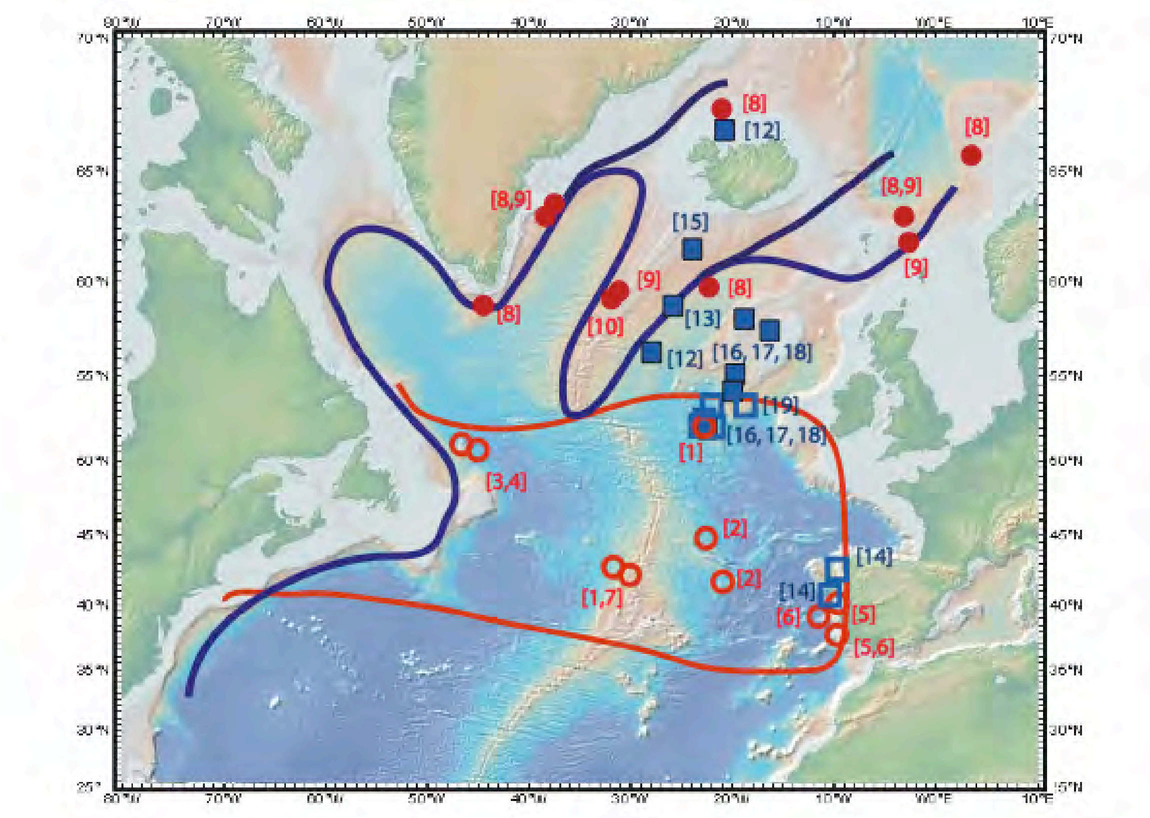

Figure 1: Location of the sites at which a full investigation of the magnetic properties (red) and of the sortable silt (blue) has been conducted for the last glacial stage. The open symbols are for the cores located within the IRD belt and the block symbols are for the cores located along the path of the NADW. [1] *Weeks et al*., 1995; [2] *Robinson et al*., 1996; [3] *Stoner et al*., 1996; [4] *Stoner et al*., 2000; [5] *Moreno et al*., 2002; [6] *Thouveny et al*., 2000; [7] *Kissel*, 2005; [8] *Kissel et al*., 1999; [9] *Ballini et al*., 2006; [10] *Snowball and Moros*, 2003; [11] *Andrews et al*. 2003; [12] *Bianchi and McCave*, 1999; [13] *Giraudeau et al., 2000*; [14] *Hall and McCave*, 2000; [15] *Hall et al. 2004*; [16] *Manighetti. and McCave*, 1995 [17] *McCave et al*., 1995; [18] *McCave et al*., 1995; [19] *Robinson and McCave*,1994.

II-1.2 Size sorting of marine muds for palaeocurrent reconstruction.

Geologists have long related particle size to the speed of the depositing or eroding flow. In the great majority of cases this has been for non-cohesive sands and gravels via grainsize and sedimentary structure analysis. Deep-sea bottom currents are seldom able to move quartz sand [*Masson et al*., 2004], but can in places move foraminiferal sand [e.g. *Lonsdale and Malfait*, 1974]. In such situations the fine fraction is resuspended and carried away to leave a foraminiferal lag, with consequent low accumulation rates and lack of stratigraphic resolution. Thus for high temporal resolution palaeocurrent reconstruction, sensitive parameters from rapidly accumulating and continuously deposited fine sediments are required. As these sediments normally show few structures other than biological disturbance, grainsize parameters are needed.

Recent years have seen a lot of work on development and application of a proxy for the speed of deep-sea currents because this is an essential physical oceanographic variable. Progress in this field largely followed the observations made in the 'HEBBLE' area showing that the terrigenous (i.e. biogenic carbonate and silicate removed) grainsize distributions showed a pronounced mode in the part of the grain size spectrum >10 µm in regions and at times when the flow speed was faster [*Hollister and McCave*, 1984; *Driscoll et al*., 1985; *McCave*, 1985]. This is because above about 10 µm, the flocculation factor in flowing water becomes quite small, as many aggregates are broken up by flow in the buffer layer. This means that, under more vigorous flows, this material can be size sorted according to its primary grain size (actually by settling velocity). The terrigenous silt fraction was accordingly divided into two fractions, 2-10 µm cohesive silt and 10-63 µm sortable silt (SS). The mean size of the latter fraction ($\overline{SS}$) was proposed by *McCave et al.*, [1995] as a sensitive indicator of the flow speed of the depositing current – *note that the flow speed usually referred to is the geostrophic speed occurring above the Ekman layer or bottom mixed layer, 20-100 m above the bed*. In addition, the percentage concentration of sortable silt (SS%) in the total <63 µm fraction was suggested as an index of current-controlled coarser grainsize selection / suppression of finer size accumulation. The basis for the 'sortable silt' flow speed proxy has been set out in some detail by *McCave et al*. [1995], and its application and limitations recently reviewed by *McCave and Hall* [2006].

The role of the MOC in abrupt climate variability during the last Glacial to Holocene period is well documented [e.g. *Clark et al.*, 2002]. As highlighted in Fig. 1 considerable effort has been focused on rapidly-deposited sedimentary sequences located beneath the major bottom waters of the North Atlantic. These studies have successfully utilized the SS proxy to detect and trace physical evidence for oceanic circulation changes at a variety of timescales associated with past climate change.

One common, but often mistakenly, cited objection to inferring current speeds from grain size is the presumed dominant influence of source. For fine sediments this is far less of a problem than for sands. Work on particle sizes of suspended sediment record a wide range, and it is poorly sorted both at fluvial source and in the sea [see *McCave and Hall* and refs therein]. Mixing of several meters to tens of meters thickness of failed sea bed in systems of sediment delivery to the deep sea (turbidity currents, debris flows), results in elimination of systematic source effects on at least short time scales (order of at least 100 ka, maybe to 1 Ma) [*Embley & Jacobi*, 1977; *Weaver & Thomson*, 1993]. Only in cases where sediment with a distinct sorted size spectrum is delivered to a relatively quiescent deep e.g. loess, beach sand, aeolian dunes spilling offshelf, will there be a strong source signature in the deposit.

Early in SS investigations of flow speed it was recognized that there might be time intervals and areas where variations in size were due to input variations, independent of variation in bottom currents, and that these would be most likely in sites of slow accumulation where vertical input was dominant [*Manighetti & McCave*, 1995 and *McCave et al*, 1995]. Parts of the abyssal glacial North Atlantic, particularly within the Ruddiman belt between 40°N and 55°N, are such regions, receiving variable input of ice-rafted detritus (IRD). The problem of current inference in this setting has been approached by first identifying the characteristics of the input flux through time at a site which was argued to be unaffected by current winnowing or focusing. Grainsize changes in sortable silt from current-influenced sites were then calculated by difference from the input flux time-series. The resulting variation in differential grainsize was attributed to fluctuating current speed [*Manighetti & McCave*, 1995]. Such an approach is fraught with difficulties and on balance probably doesn't justify itself as a robust procedure for palaeocurrent reconstruction. In such situations it might be better treated by the end-member analytical methods of *Weltje* [1997]; and *Weltje and Prins,* [2003].

II-2. WATER MASS TRACERS

II-2.1. Carbon isotopes in benthic foraminifera.

The nutrient distributions for times in the past are reconstructed by measuring the carbon isotopic composition ($^{13}C/^{12}C$) of fossil shells of benthic foraminifera buried in the sediments. Primary producers in the surface ocean take up both nutrients and carbon, discriminating against the heavy isotope of carbon as they do so, leading to high $^{13}C/^{12}C$ ratios in surface waters and low nutrient water masses and lower values in high nutrient water masses that have collected nutrients and carbon from the decay of organic matter transported to depth in particulate and dissolved forms. The carbon isotope ratio in benthic foraminifera, to a large extent, reflect the ratio in the overlying water mass, but the degradation of organic material on the sea floor and within the sediments can also impact the isotopic ratio, particularly in high productivity environments.

The long-standing tradition of stable isotopes as a tool in paleoceanography, combined with the advent of fully-automated gas preparation devices and mass spectrometers about 20 years ago enabling fast sample throughput, has made benthic $\delta^{18}O$ and $\delta^{13}C$ the workhorse of paleocirculation studies. Our understanding of regional to basin-wide circulation patterns is almost entirely derived from the synoptic mapping of meridional benthic $\delta^{18}O$ and $\delta^{13}C$ gradients. Since the landmark summaries of glacial Atlantic water mass distribution of *Duplessy et al.* [1988] and *Sarnthein et al*. [1994] much progress has been made using the carbon isotope proxy, including extending the glacial water mass identification into the Southern Ocean [*e.g., Bickert and Mackensen,* 2004] and a better refinement of the water mass distribution at intermediate water and deep water locations of the western Atlantic [*Oppo and Lehman*, 1992; *Curry and Oppo,* 2005]. Two new syntheses [*Bickert and Mackensen,* 2004; *Curry and Oppo*, 2005] document that a LGM North Atlantic water mass was found at and above 2000 m water depth and penetrated to at least 30º S in the western basin (Figure 2). The recent synthesis by *Curry and Oppo* [2005] for the western basins (Figure 3) also identified an intermediate water mass of southern origin (much like today's Antarctic Intermediate Water) flowing northward at about 1000 m water depth. Fine-scale benthic $\delta^{13}C$ data tracing intermediate water ventilation at a high-latitude southern hemisphere core site indeed suggest that AAIW plays a variable role in upper-ocean ventilation on orbital and millennial time scales [*Pahnke and Zahn,* 2005]. Thus it is increasingly becoming apparent that the glacial Atlantic contained at least three major water masses with different end member compositions and that the geographic and bathymetric gradients found in the Atlantic are dominated by mixing among these water masses.

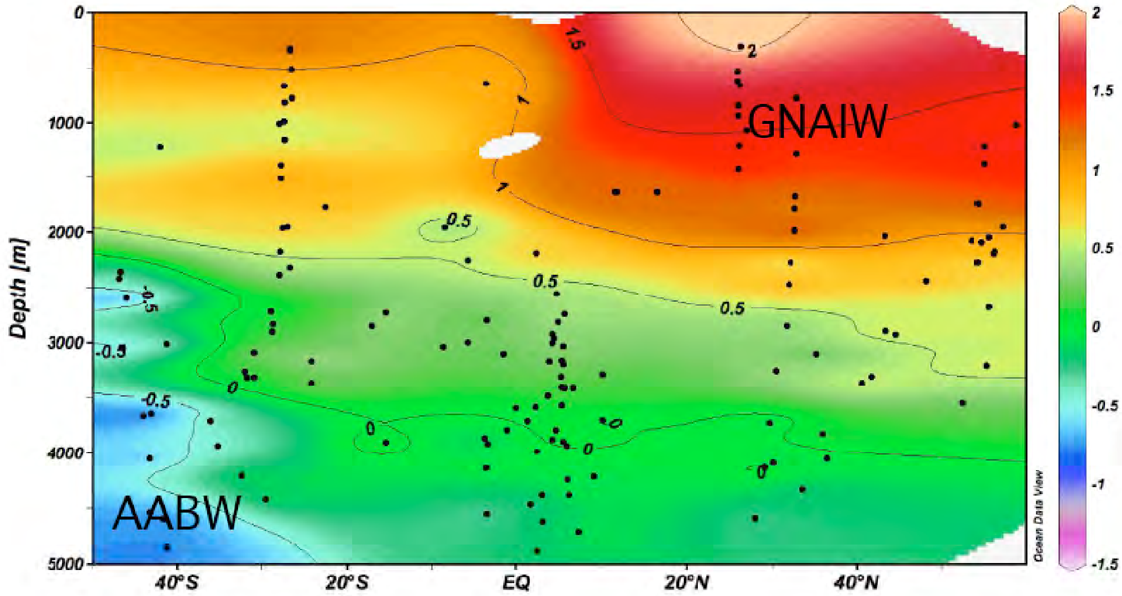

Figure 2: Carbon isotope composition of LGM benthic foraminifera from the Western and Central Atlantic including the data in *Curry and Oppo* [2005] and *Bickert and Mackensen* [2004].

II-2.2. Trace metals in benthic foraminifera.

Past nutrient distributions have also been reconstructed from the ratio of Cd to Ca in the shells of the benthic foraminifera. Like the major nutrients, Cd is taken up by organisms at the sea surface and released at depth as the organic material is decomposed. This benthic proxy has advanced to become a well understood tool but remains underutilized because of its intricate analytical procedure. The early recognition that cadmium has an oceanic distribution similar to that of the labile nutrient phosphate has led to benthic foraminiferal Cd/Ca being introduced as a deep water tracer at about the same time that $\delta^{13}C$ was first applied in paleoceanography [*Boyle*, 1980]. Benthic Cd/Ca was therefore instrumental in codifying the view of a glacial-age shoaling and northward expansion of nutrient-rich Antarctic Bottom Water (AABW) into the North Atlantic [*Boyle and Keigwin*, 1987]

Figure 4 shows that there is now reasonably good meridional and depth coverage for the LGM Atlantic if multi-taxa Cd/Ca data from both east and west of the Mid-Atlantic Ridge are combined. The resulting section, with a strong nutricline (GNAIW/AABW boundary) between 2 and 2.5 km depth in the North Atlantic, generally agrees with reconstructions based on $\delta^{13}C$. The most notable difference is in the deep South Atlantic, where Cd/Ca implies less glacial nutrient increase than $\delta^{13}C$. This apparent discrepancy likely reflects differential behavior of $\delta^{13}C$ and Cd in seawater (air-sea exchange *vs.* water column nutrient cycling), or some parameters that limit the fidelity of benthic foraminifera as water mass paleonutrient recorders. Particularly the air-sea exchange influence on $\delta^{13}C$ allows for some separation of water mass mixing and biogeochemical aging that is not available from only one tracer. Possible artifacts for Cd/Ca include undersaturation with respect to $CaCO_3$ and

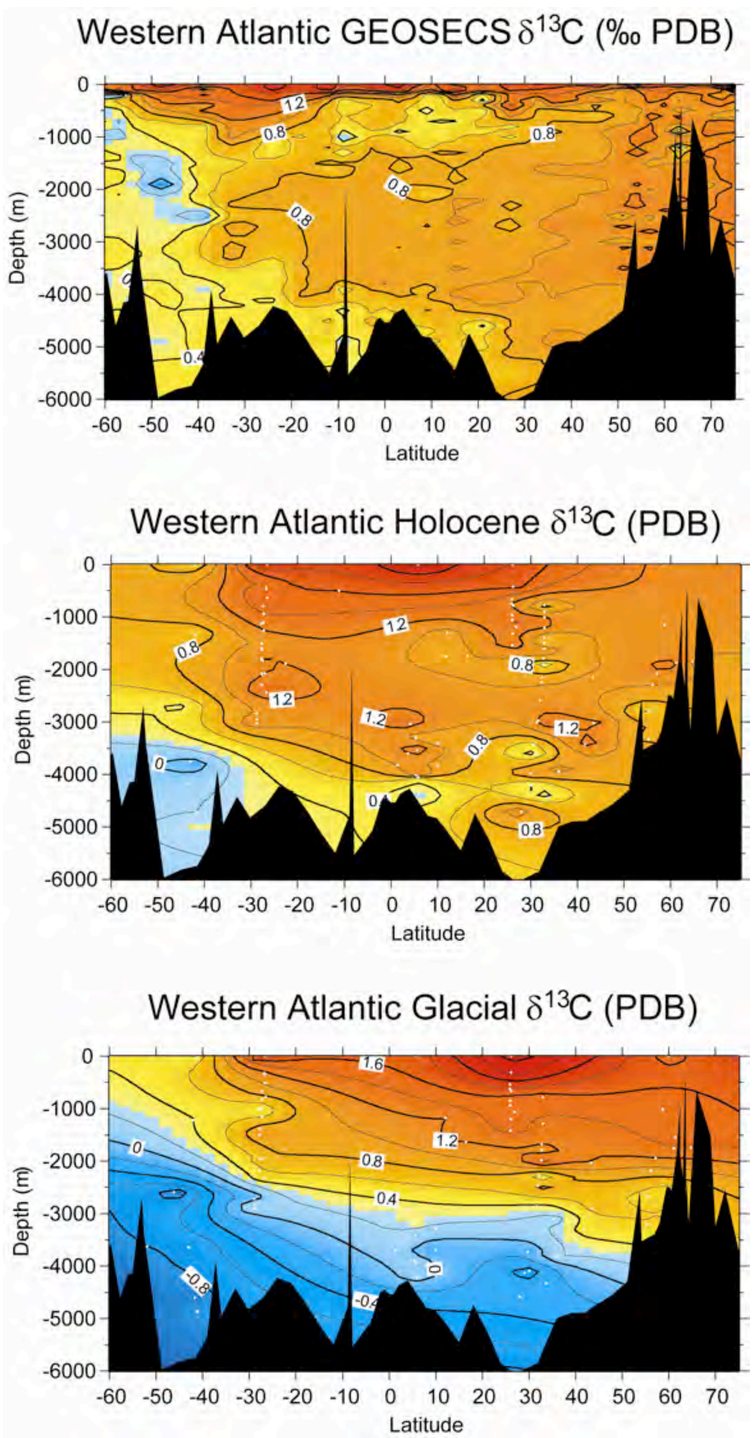

Figure 3. Modern distribution of carbon isotopes in seawater (top), isotopic composition of Holocene age benthic foraminifera (middle) and isotopic composition of LGM benthic foraminifera (bottom) in the Western Atlantic from *Curry and Oppo* [2005].

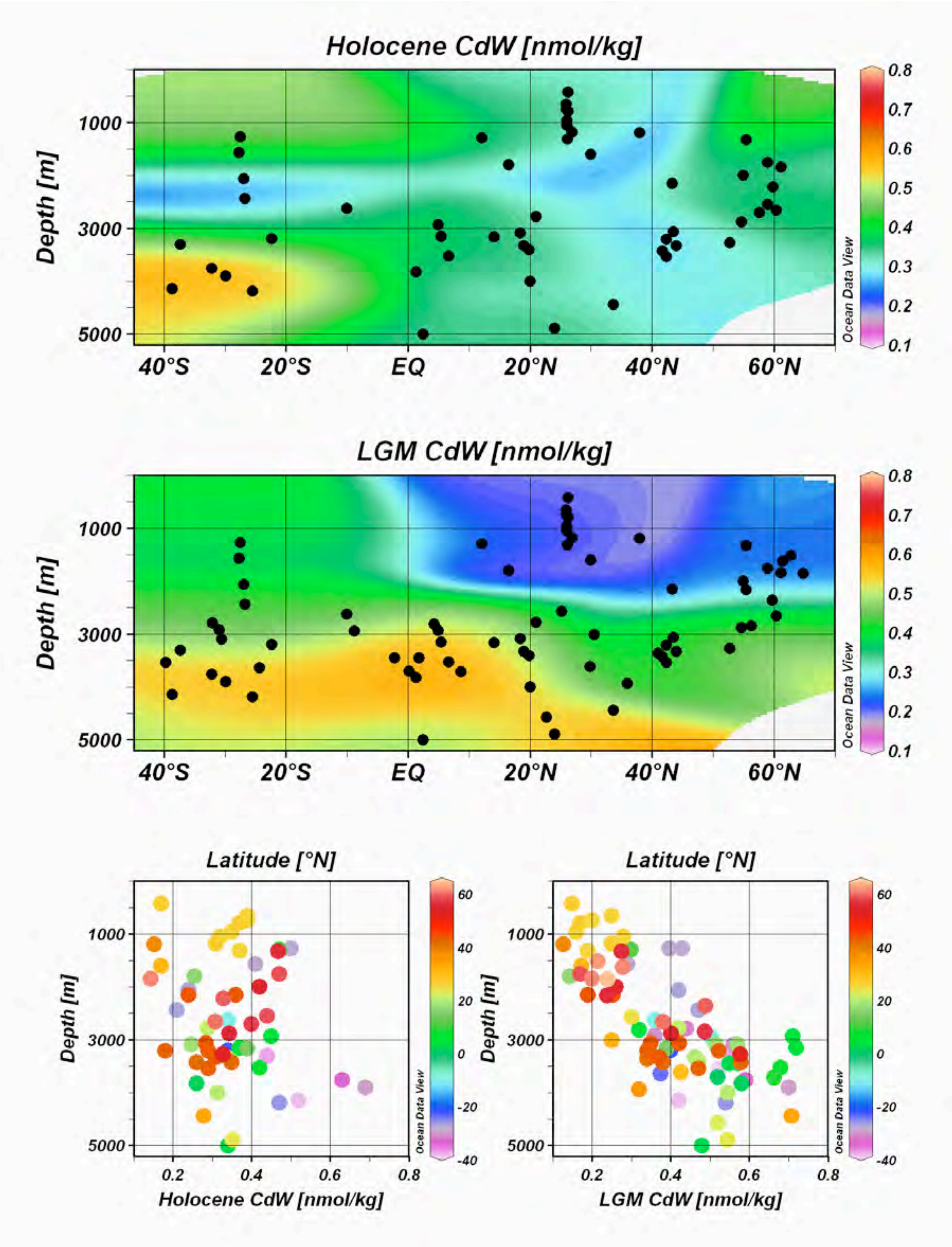

Figure 4: Meridional sections of inferred seawater dissolved Cd (CdW) for the Holocene (top) and LGM (middle) Atlantic Ocean from *Marchitto and Broecker* [2006]. Also shown are composite vertical profiles of for the Holocene (bottom left) and LGM (bottom right), where colors indicate core latitude.

pore water microhabitat effects. Cd/Ca evidence for millennial scale changes in deep Atlantic circulation exists from relatively few sites. This includes apparent deep water nutrient enrichment (AABW expansion) during MIS 3 stadials and intermediate depth enrichment during Heinrich events [*Marchitto et al.*, 2002]

II-2.3. Combined nutrient tracers.

Additional constraints may be placed on water mass mixing and biogeochemical cycling by combining Cd/Ca and $\delta^{13}C$ with other trace metal paleonutrient proxies, namely Zn/Ca and Ba/Ca [*Marchitto, et al.*, 2002]. This approach takes advantage of the differential behavior of these tracers in seawater: zinc and barium have deeper regeneration profiles than Cd, and Ba exhibits less surface ocean depletion than Cd and Zn, so their oceanic distributions respond differently to biogeochemical cycling and deep circulation. Ba/Ca and Zn/Ca strengthen the case for an LGM expansion of AABW.

A second line of paired stable isotope – trace element application involves the benthic $\delta^{13}C$-Cd/Ca couple that has been successfully used to separate physical circulation (i.e., water mass mixing) signals from those mediated by biological nutrient cycling and isotope fractionation during air-sea gas exchange [*Boyle*, 1995; *Elderfield and Rickaby*, 2000; *Lynch-Stieglitz and Fairbanks*, 1994; *Lynch-Stieglitz, et al.*, 1996; *Rickaby and Elderfield*, 2005; *Zahn and Stüber*, 2002]. However, such studies are limited and warrant a wider application.

II-2.4. Nd isotopes

Benthic foraminiferal $\boldsymbol{\varepsilon_{Nd}}$ is under development as a deep-circulation proxy and will provide a valuable tool to derive water mass end members and end member mixing patterns. The deep water masses of the ocean have distinctive neodymium isotope ratios that are recorded both in manganese nodules [*Alberede and Goldstein*, 1992, *Alberede et al.*, 1997] and dispersed manganese-iron oxides in deep sea sediments [*Rutberg et al., 2000*]. Precisely how the water masses acquire their neodymium isotope ratios is still unresolved [*Albarede et al.*, 1997]. The Nd isotope ratio is neither a conservative nor a nutrient water mass tracer. Nd is unaffected by biological cycling in the ocean, but there are both sources and sinks of Nd beneath the sea surface, particularly at the sediment water interface where it is mobilized from detrital material, and is precipitated in metallic crusts. The Nd isotope ratios in North Atlantic Deep Water are high, reflecting the addition of Nd from the predominantly old continentally derived detrital material, and the Nd isotope ratios in the North Pacific are low reflecting the influence of recent volcanic activity. In regions where there is active mixing between these water masses (the Atlantic Ocean and the Southern Ocean) the seawater (and Fe-Mn precipitates) have intermediate values, as is the case for the nutrient and conservative water mass tracers [*Rutberg et al.*, 2000]. This technique is just beginning to be applied towards the reconstruction of water mass changes on millennial time scales [*Piotrowski et al*., 2004; 2005].

II-2.5. Benthic foraminifera species distribution

Benthic foraminifera are one of the most abundant, diverse and ubiquitous meiofaunal group found throughout the world oceans. Their changing assemblage patterns with depth in the ocean were originally interpreted in terms of depth zonations [*Bandy, 1961*; *Phleger*, 1964; *Bandy and Rodolfo*, 1964; *Bandy and Chierichi*, 1966; *Saidova*, 1965]. Application of statistical factor analysis techniques showed some consistent assemblage patterns on regional scales which were further interpreted in terms of water mass distributions in the Atlantic Ocean [*Streeter*, 1973; *Schnitker*, 1974]. These authors interpreted the observed changes in benthic foraminiferal assemblages during the last Glacial in North Atlantic deep-sea sediments as a response to a reduction in the formation of NADW, an interpretation that was later supported by other geochemical tracers [*Boyle and Keigwin*, 1982, 1986-7]. However, the precise relationship between deep-sea benthic foraminifera and the water mass properties that controls them is still elusive, and while on regional space scales some deep-water masses can be differentiated by their benthic foraminiferal assemblages, the species proportions do show some important variability between ocean basins. Thus while AABW is commonly associated with the presence of *E. umbonifera* in the Atlantic, in the Indian Ocean the latter is commonly found together with *C. wüllerstorfi*, while in the Pacific the same species is found together with *E. exigua* and *G. subglobosa* (*Lohmann* 1978, *Corliss* 1979; *Burke*, 1981; *Bremer and Lohmann*, 1982; *Lutze and Colbourn*, 1984; *Mackensen et al*. 1985; 1995), and the variability found in deep and intermediate waters is even greater than those found in the bottom waters (*Douglas and Woodruff*, 1981). The tight correlations between the different deep water physical and chemical variables (eg dissolved oxygen and $CaCO_3$ saturation levels) and the benthic foraminiferal assemblages in the present ocean are the main difficulty to assign specific water properties with relative changes in species assemblages and limits their value as paleotracer and circulation proxies.

These interpretations of benthic foraminifera in terms of water mass proxies have been further challenged by studies that showing that benthic foraminiferal assemblages were mirror the overlying surface waters primary productivity patterns [*Gooday*, 1988; *Herguera and Berger*, 1991; *Loubere*, 1991; *Herguera*, 1992]. A considerable number of observations reported during the last two decades support the contention that deep-sea benthic foraminifera biomass and standing stock below open ocean environments are limited and shaped by the amount and quality of food raining on the sea-floor [*Gooday*, 1993; 1996; 2003; *Jorissen et al*., 1992, 1995; *Loubere*, 1996; *Fariduddin and Loubere*, 1997; *Schmiedl et al.*, 1997; *Wollenburg and Mackensen,* 1988; *Altenbach et al*., 1999; *Licari et al*., 2003; *Licari and Mackensen,* 2005]. This introduces problems especially when trying to reconstruct bathymetric gradients of deep-water properties using benthic foraminifera assemblages on basin boundaries. Continental margin environments characteristically show enhanced biological productivity and export rates that leave a much stronger imprint in the benthic foraminiferal assemblages than any water mass signature, thus compounding the difficulty of dilucidating the biological productivity controls from the water mass ones.

Our present inadequate understanding of the ecology of deep-sea benthic foraminifera poses important limitations to interpret their assamblage patterns solely in terms of faunal-environmental correlations, and becomes a formidable challenge if we want to interpret the observed changes in the geological record in terms of paleocirculation proxies, although they can help to support different scenarios in addition to other geochemical proxies.

II-2.6. Tracing surface circulation using planktonic species distribution

Planktonic foraminifera are considered to be sensitive indicators of surface water masses, and specific circulation features (especially boundary currents and upwelling). Several planktonic foraminiferal species are widely used to evaluate upwelling intensity (*G. bulloides* for coastal upwelling and *G. glutinata* for open-ocean upwelling), mixed layer depth, thermocline level (*N. dutertrei*), deeper mixing related to stronger winter monsoon in the Indian and Pacific oceans (*G. truncatulinoides*), and lateral subsurface water advection (*G. inflata*). Variations in the assemblages are used to trace temporal shifts in frontal zones.

In addition the presence of some species can be used to indicate the input of water from other regions. For example, in the Arctic Ocean and Western Arctic seas, the occurrence of planktonic foraminiferas and some benthic foraminiferal species in the Holocene sediments indicate a Atlantic water input, most likely related to enhanced Atlantic MOC [*Polyak and Solheim*, 1994; *Ivanova*, 2003 and references therein]. A similar approach has been used to trace the input of lower latitude surface waters into the high North Atlantic [*Bauch et al.*, 2001; *Hebbeln et al.*, 1994; *Kandiano and Bauch*, 2002,*Bauch*, 1992; *Dokken and Hald*, 1996]. *Peeters et al.* [2004] investigated the history of Agulhas leakage and intensity of THC return branch and *Holbourn et al.* [2005] investigated changes in the Indonesian throughflow by looking at the abundance of planktonic foraminifera species.

II-3. T-S-δ^{18}O-DENSITY

Temperature, salinity, and δ^{18}O are also water mass tracers which can be reconstructed for the subsurface ocean from chemical and isotopic measurements on foraminifera in order to investigate the sources and mixing of deep water masses. However, we will consider these tracers separately because the accurate reconstruction of seawater density (a function of temperature and salinity) also provides a dynamical constraint on subsurface ocean circulation.

The distribution of temperature and salinity determine the density at the sea surface which, in part, determines the formation of subsurface water masses. The major currents of the upper ocean are reflected in the surface and subsurface density gradients, and the density gradients in the subsurface ocean are linked to the velocity through the geostrophic balance.

II-3.1. Sea Surface Temperature

Planktonic foraminiferal assemblages. Planktonic foraminifera have been widely used for a number of years to reconstruct SSTs [e.g. *Climap*, 1981, 1984; *Pflaumann et al.*, 1996; *Kucera et al.*, 2005] applying different transfer function techniques (IKM, MAT, RAM, ANN etc.) Several global and large regional coretop databases (db) are available via PANGAEA and NOAA web sites for SST reconstructions. However, the planktonic foraminifera assemblages reflect other environmental variables besides sea surface temperature and transfer function approaches have also been used to assess thermocline depth [*Andreassen and Ravelo*, 1997] and productivity [*Mix*, 1989]. A better knowledge of the modern ecology of foraminifera from plankton tow and sediment traps studies, oxygen isotope measurements in living foraminifera and experiments in species cultivation will help in the interpretation of the fossil assemblages.

Assemblages of diatoms and Radiolaria. In high latitudes estimates of sea surface temperature are mainly based on assemblages of diatoms and Radiolaria. Progress has been made with respect to taxonomy and autecology of siliceous microfossils through water- column and sediment trap studies [e.g. *Abelmann and*

Gowing 1996, *Zielinski and Gersonde* 1997]. This information has been used in new transfer functions for both groups. A problem is that both diatom and radiolarian assemblages may be affected by dissolution which biases particularly diatom assemblages towards more strongly silicified species [*Zielinski and Gersonde,* 1997].

Another important parameter that can be reconstructed through diatoms is the distribution of sea ice. *Crosta et al.* [1998] suggested a quantitative reconstruction of sea ice (number of months with sea-ice coverage per year) by applying the Modern Analogue Technique (MAT). The results of *Gersonde and Zielinski* [2000], however, show that the diatom sea-ice signal preserved in the sediment record is produced under austral summer open water conditions from diatom blooms that have been seeded from sea-ice to open water, which may preclude a quantification of sea ice cover [*Gersonde and Zielinski*, 2000].

Alkenones. Alkenones are a very valuable paleoceanographic tool due to their abundance throughout the word ocean and their presence for much of the stratigraphic record. The use of alkenones, however, is associated with two main problems: First, the UK37 values from surface sediments are higher than from the overlying water column in many regions. This deviation can best be explained by a seasonal or vertical bias of alkenone production as well as differential degradation of 37:3 and 37:2 alkenones in the sediments [*Conte et al.* 2006]. Secondly, alkenones can have a significantly higher age than other components (i.e. Foraminifera) from the same depth interval [*Mollenhauer et al.* 2003]. This indicates that there might be contaminations with older reworked organic material which may also affect the SST reconstructions through UK37 in some ocean areas.

Mg/Ca, oxygen isotope and calcium isotope ratios of planktonic foraminifera. Sea surface temperature is recorded in Mg/Ca, oxygen isotope and calcium isotope ratios of planktonic foraminiferal shells. The understanding of how SST is recorded in these parameters has been improved during the last decade [see references in *Waelbroeck et al.* 2005, *Gussone* 2005, *Barker et al.* 2005]. However, these proxies also share some of the same inherent problems. For example it is clear that the vertical and seasonal distribution of foraminiferal carbonate production exerts a strong control on the temperature recorded by a foraminiferal population on the sea floor. This is especially important since biological processes in planktonic foraminifera are sensitive to changes in sea surface temperature [e.g. *Bjima et al*. 1990]. For this reason, it is unlikely that the temperature recorded by a foraminiferal population always reflects the same niche under different environmental conditions [e.g. *Mulitza et al*. 1998]. However, combined Mg/Ca-δ^{18}O or Ca-isotope-δ^{18}O measurements from the same sample guarantee a common source for δ^{18}O and temperature signals and hence probably allow a better extraction of the δ^{18}O seawater [*Barker et al.* 2003].

Time slice reconstructions. Since CLIMAP several attempts have been made to improve the techniques for sea surface temperature reconstruction and the stratigraphic synchrony of the LGM time slice. *Mix et al.* [1999] developed a new calibration strategy, which uses the past variability of faunal assemblages to circumvent the problem of "no-analog faunas". This technique reveals an ice age cooling of 5-6°C in the eastern equatorial current systems. A new gridded SST data set for the glacial ocean is available at 2° spatial resolution [*Hostetler and Mix*, 1999].

The GLAMAP-Project presented new reconstructions of sea surface temperature at the Last Glacial Maximum (LGM) for the Atlantic only [*Sarnthein et* *al.* 2003]. In this project reconstructed SSTs were averaged for two different LGM definitions, at 21,500–18,000 years B.P. and 23,000–19,000 years B.P. (as defined by the EPILOG working group; see *Mix et al.* [2001]). The GLAMAP reconstructions used 275 sediment cores between the North Pole and 60°S with carefully defined chronostratigraphies and an assessment of the stratigraphic quality. An interpolated version of the GLAMAP data at 1° resolution (using GLAMAP in the Atlantic and CLIMAP for the rest of the ocean) has been produced by *Paul and Schäfer-Neth* [2003].

The MARGO Project [*Kucera et al.* 2005] made a new attempt to produce a global synthesis of sea surface temperature and sea ice extent for the glacial ocean. Their approach was not only confined to faunal and floral based SST reconstructions (foraminifera, Radiolaria, diatoms, dinoflagellates), but also included alkenones, Mg/Ca and oxygen isotopes ratios of planktonic foraminifera for the time slice 23,000–19,000 years B.P. Instead of producing one interpolated map, this group decided to collect the data as raw as possible to allow for a later assessment of the differences among proxies and signal carriers.

II-3.2. Sea Surface Salinity

Because the $\delta^{18}O$ of foraminiferal calcite reflects both the $\delta^{18}O$ of the seawater in which it calcifies and the temperature of calcification, we can combine this information with a sea surface temperature measurement to reconstruct patterns in salinity. Detailed reconstructions have been made for the North Atlantic region over the deglaciation [*Duplessy et al.* 1991,1992; *Sarnthein et al.*, 2003]. Combining measurements of Mg/Ca with oxygen isotope in foraminifera shows particular promise for the reconstruction of surface water $\delta^{18}O$ because they are imprinted on the same shell and therefore represent the same depth and season. This technique has been primarily used to reconstruct surface water conditions in the tropics where the Mg/Ca paleothermometer has the most sensitivity [e.g. *Schmidt et al*. 2004, *Stott et al.*, 2002]. However, care must be taken when interpreting the absolute salinity value from such a combined approach [*Schmidt*, 1999]. Salinity has also been inferred on the basis of the assemblage of dynoflagelates in the high latitude North Atlantic [e.g. *de Vernal et al.*, 2005].

II-3.3. Upper ocean density from $\delta^{18}O$ of planktonic foraminifera

Different species of foraminifera calcify at different depths in the water column. It is not necessary to separate the effects of temperature and seawater $\delta^{18}O$ (related to salinity) to infer density. Oxygen isotopes in surface calcifying foraminifera have been used to reconstruct sea surface density gradients [*Billups and Schrag*, 2000]. Oxygen isotope ratios in planktonic foramifera have been used to deduce the vertical stratification of the water column [e.g. *Farrell et al.*, 1995; *Cannariato and Ravelo*, 1997; *Mulitza et al.*, 1997] as well as the lateral density gradients of the subsurface ocean which reflect the patterns of ocean currents [*Matsumoto and Lynch-Stieglitz*, 2003; *LeGrande et al.*, 2004]. Isotopic measurements on surface calcifying foraminifera are widespread for the LGM [*Waelbroeck et al*., 2005], but measurements for deep calcifying foraminifera are less widespread and the efforts to use these measurements to map the upper ocean circulation patterns have been limited.

II-3.4. Subsurface Temperature from Mg/Ca and Sr/Ca on benthic foraminifera

To firmly establish benthic foraminiferal Mg/Ca as a deep-ocean temperature tool is of particular importance in that independent temperature estimates are urgently needed to more reliably compute deep-water $\delta^{18}O$ from benthic isotope data. Paired benthic $\delta^{18}O$ and Mg/Ca will be essential to making progress on a variety of topics, notably establishing deep-ocean THC patterns and deriving reliable sea level estimates. To date, benthic Mg/Ca is under development with a dedicated focus on gaining better calibration between Mg/Ca of commonly used benthic foraminiferal species (*Uvigerina* spp., *Cibicidoides* spp., *Hoeglondina elegans*, etc.) and ambient bottom water temperature [*Lear, et al.*, 2000; *Martin, et al.*, 2002; *Rickaby, et al.*, 2000]. Sr/Ca in benthic foraminifera also looks promising as a deep water temperature proxy [*Rosenthal et al*., 2006]. At this point the number of down core Mg/Ca and Sr/Ca records on benthic foraminifera are very limited [e.g. *Martin et al.,* 2002; *Marchitto and deMenocal,* 2003; *Skinner and Shackleton,* 2005] and this is likely to remain the case until the calibration issues with this proxy are sorted out.

II-3.5. Subsurface S and $\delta^{18}O$ from pore fluids

The $\delta^{18}O$ and S of the ocean during the LGM has been reconstructed by measuring the diffusive profile of the Chlorinity and $\delta^{18}O$ of pore waters in sediments [*Schrag and dePaolo,* 1993; *Schrag et al*, 2002; *Adkins and Schrag*, 2001]. Combined with $\delta^{18}O$ measurements on nearby benthic foraminifera, the T of the seawater at each location can be inferred as well. These properties can be used as tracers, but also provide insight into the modes of deepwater formation and the density stratification of the deep ocean. This technique can be applied to shorter time scale (e.g. millennial) variability only for the most recent past, due to the nature of a diffusive signal. While this method cannot be used to recover a millennially resolved record of water mass properties over the last 40 kyr, it can be used to fully reconstruct the T-S- $\delta^{18}O$ for the LGM. Currently such measurements exist for a limited number of sites in the deep ocean, but even this limited array suggests that the controls on density stratification in the ocean were significantly different from today [*Adkins et al*., 2002]. At present there are no data from thermocline depths.

II-3.6. Subsurface Density from $\delta^{18}O$ on benthic foraminfera

Because the $\delta^{18}O$ of foraminifera and density both increase in more saline and colder water, foraminiferal $\delta^{18}O$ can be used to estimate the density of past seawater [e.g. *Lynch-Stieglitz et al.,* 1999]. The regional relationships between $\delta^{18}O$ of foraminifera and density are quite strong, but will change in time as the T-S- $\delta^{18}O$ of seawater relationship changes. Pore fluid measurements can be used to establish the T, S and $\delta^{18}O$ of water masses during the past, but the time resolution is limited by the diffusion of the pore fluids and at present there are no data from thermocline depths. However, the T and $\delta^{18}O$ of subsurface water masses can be reconstructed if the relationship between Mg/Ca and Sr/Ca in benthic foraminifera proves to be a reliable indicator of temperature (see above), providing some constraint on the past relationship between $\delta^{18}O$ of benthic foramifera and density.

II-3.7. Using the geostrophy for reconstruction of past ocean circulation.

Density information inferred from the $\delta^{18}O$ in foraminifera can be used to constrain past ocean circulation using the geostrophic method. The concept was first demonstrated in the Florida Straits [*Lynch-Stieglitz et al,* 1999a,b], where a lower density contrast across the Straits was inferred for the LGM, consistent with weaker flow. While this work is currently being extended at millennial timescales over the last 40 kyr, a flow estimate for the Florida Straits will only partially constrain past Atlantic Ocean circulation scenarios. In the more general case, the east-west contrast in ocean margin density reflects the shear in the meridional overturning circulation [*Marotzke et al.*, 1999; *Lynch-Stieglitz*, 2001]. *Hirschi et al.* [in press] showed that the ocean margin density in a high resolution model of the North Atlantic can be used to accurately reconstruct subtle changes in the overturning circulation where there are no strong flows along sloping boundaries. If well chosen, a relatively small number of paleoceanographic measurements can be used to constrain the strength of the MOC in the North Atlantic during the past [*Hirschi and Lynch-Stieglitz*, 2006]. Using a similar idea, *Lynch-Stieglitz et al.* [2006] show that the east-west density contrast across the South Atlantic was reduced during the last glacial maximum. However, these cores cannot resolve circulation changes at millennial time scales, and the results need to be replicated on better dated material. Numerous oxygen isotope measurements on benthic foraminifera have been collected over the last decades. However, to reconstruct the subtle gradients across the entire ocean basin requires careful instrument and inter-laboratory calibration. Measurements on glacial age benthic foraminfera (which have isotopic values far removed from the calibration standard) are particularly susceptible to error.

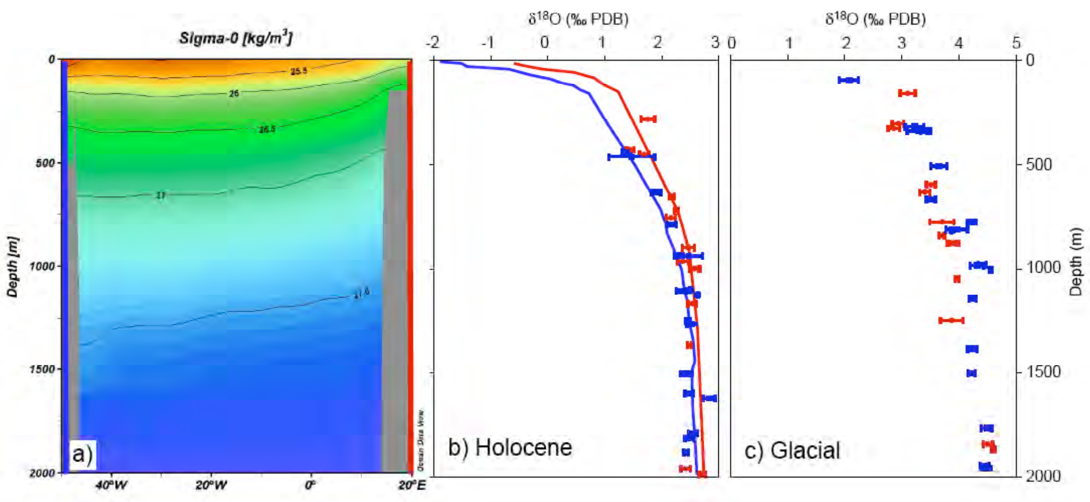

Figure 5: a) The potential density of seawater across the South Atlantic at 30°S. The waters are denser on the eastern side of the basin, reflecting the presence of the meridional overturning circulation. b) The oxygen isotopic composition of the shells of benthic foraminifera ($\delta^{18}O$) in recent sediments on the eastern (red symbols) and western (blue symbols) side of the basin reflect the density contrast across the basin today. The solid lines are the predicted $\delta^{18}O$ based on modern hydrographic data [*Lynch-Stieglitz et al*., 2006] c) The oxygen isotopic composition of the shells of benthic foraminifera for the LGM suggest that the modern density contrast in the upper 2 km was absent or reversed [*Lynch-Stieglitz et al*., 2006].

II-4. RADIOCARBON

In the modern ocean, radiocarbon measurements in dissolved inorganic carbon provide a measurement of the time since deep-water masses last exchanged gases at the surface. The process works as follows. Produced in the stratosphere, ^{14}C oxidizes to CO_2 and provides a "top down" tracer of the ocean circulation. On average, compared to a pre-industrial, pre-nuclear atmospheric standard, there is a 13% deficit of ^{14}C atoms in the modern deep ocean (-130‰ in ^{14}C nomenclature, [*Stuiver and Polach*, 1977]). The only way to account for this loss is through radioactive decay while the deep carbon reservoir is isolated from the atmosphere. With a half-life of 5730 years this, 130‰ deficit is equal to ~1100 years of isolation from the atmosphere. However, this is not the whole story in the modern ocean. NADW and AABW leave the surface ocean with very different "initial" radiocarbon ages. In each case there is not complete equilibrium with the 0‰ atmosphere before these newly forming water masses leave the surface. The situation is most profound for southern source waters because surface water residence times are shorter than the ~10-year exchange time for the carbon isotopes. Modern AABW and NADW have initial $\Delta^{14}C$s of -165‰ and -65‰ respectively [*Broecker, et al.*, 1991]. These initial ages lower the estimated ^{14}C age of the deep ocean from ~1100 years to ~800 years [*Stuiver, et al.*, 1983].

These end-member issues for the ^{14}C age tracer and the subsequent mixing of different deep-water masses in the ocean interior complicate the interpretation of ^{14}C ages in both the modern and past ocean. Theoretically, the concept of a "ventilation age" is not precise and often leads to confusion in the literature [*Hall and Haine*, 2002]. In general, the "age" of any fluid parcel is difficult to define. We would like to know the total transport of mass, heat and carbon by the deep ocean at times in the past. But simply calculating a tracer difference and a ^{14}C age can be misleading. However, even in light of these complications, there is much progress to be made by measuring the ^{14}C content of the past ocean.

From the first measurements of benthic-planktonic age differences in foraminifera, the use of radiocarbon as a past ocean tracer, rather than as a chronometer, has evolved to include several complementary interpretations that are all related to the concept of deep ocean "ventilation age" [*Broecker, et al.*, 1990; *Duplessy, et al.*, 1989; *Shackleton, et al.*, 1988]. Perhaps the simplest way to view deep ocean radiocarbon data is the radiocarbon age difference between contemporaneous benthic and planktonic foraminifera. This "B-P" age is easily incorporated into ocean circulation models that include radiocarbon as a tracer and can therefore provide strong constraints on past ventilation rates [*Meissner, et al.*, 2003]. The approach is straight forward; measure planktonic and benthics down core to generate a time series of deep circulation rate. However, this method is complicated by several factors. First are variations and uncertainty in the same end-member values that complicate the modern interpretation; such that even if the mixing ratio of deep waters in the past are known for a benthic-planktonic pair, the modeled ventilation age is dependent on surface exchange processes at the deep water formation regions. Second, the local planktonic "reservoir age" need not be constant in time either [*Bard*, 1988; *Bard, et al.*, 1994; *Siani, et al.*, 2001; *Waelbroeck, et al.*, 2001]. Several recent studies have used B-P age pairs to provide constraints on the North Pacific [*Ahagon, et al.*, 2003] and the North Atlantic [*Keigwin*, 2004] deep circulation from the LGM through the deglaciation.

Any method that couples an independent calendar age measurement with a deep-water radiocarbon value, can avoid the reservoir age problem. Ash layers from well-dated volcanic events are found in the sediments around New Zeeland [*Sikes, et al.*, 2000]. Benthic ^{14}C ages associated with these ashes can be directly converted into past ocean $\Delta^{14}C$ values and show a very radiocarbon depleted water mass in the deep Pacific at the time of the Kawakawa ash (~22 ka). Similarly, deep-sea corals with independent U-series and ^{14}C dates can provide deep water $\Delta^{14}C$ data with some of the best precision of any method. This method has been confined mostly to the North Atlantic [*Adkins, et al.*, 1997; *Mangini, et al.*, 1998; *Robinson, et al.*, 2005] but there is one data point from the deglaciation in the Drake Passage [*Goldstein, et al.*, 2001]. In general the conversion of B-P ages and other types of benthic radiocarbon data into $\Delta^{14}C$ values for the past deep ocean is probably the best approach. With this number, radiocarbon data can be compared with ^{14}C values in other reservoirs, especially the atmosphere.

An interesting aspect of the ocean-atmosphere ^{14}C cycle is that the record of $\Delta^{14}C$ in the air is a powerful constraint on the mean ocean overturning rate. On longer time scales the time rate of change in of ^{14}C in the atmosphere can be expressed as the balance between three fluxes:

$$\frac{d^{14}C_{atm}}{dt} = Production - \lambda^{14}C_{atm} - Ocean\ Exchange$$

Because the mass of carbon in the atmosphere is small the second term on the right hand side of this equation is also small. At steady state there is a balance between radiocarbon production in the atmosphere and its subsequent decay in the deep ocean. For the modern carbon cycle the land biosphere also plays an important role in seasonal to interdecadal changes in the atmospheric $\Delta^{14}C$. But for the purposes of PACE we are interested in longer time scales than this and the dominant balance has to be with the ocean. From the above equation it is also apparent that a reduction in the deep ocean’s exchange with the atmosphere (i.e. a change in the MOC strength) will lead to a rapid rise in the 14/12 ratio of the air. Using planktonic radiocarbon dates from the laminated portion of the Cariaco Basin this process has been nicely demonstrated for the start of the Younger Dryas [*Hughen, et al.*, 1998]. Indeed there are several other large and rapid changes in the $\Delta^{14}C$ of the atmosphere that also probably correspond to MOC changes. By placing ocean records on a $\Delta^{14}C$ scale it is possible to directly compare how the ocean compliment to any atmosphere switch in $\Delta^{14}C$ evolves in space and time.

Measurements of radiocarbon in the deep ocean have progressed considerably since the mid 1980’s when Accelerator Mass Spectrometry (AMS) was first implemented in Paleoceanography. Advances in this important analytical tool will continue to improve our understanding of $\Delta^{14}C$ as a tracer of water mass age in the past and we emphatically support efforts to make these measurements more precise, more widely available, and less expensive. Continued improvement in the atmospheric radiocarbon “calibration” data set has also changed how we view ^{14}C in the deep ocean. All measurements of past $\Delta^{14}C$ must measure both the $^{14}C/^{12}C$ content and the calendar age in a single sample. Deep-sea corals accomplish this with coupled U-series and radiocarbon ages. Benthic-planktonic foraminifera pairs can also be used this way, but they require an accurate transformation of the planktonic age into a true calendar age. For these reasons we see it as imperative that both the AMS and U-series dating infrastructure available to paleoclimatologists continue to improve and become more widely available. State of the art multi-collector ICP-MS labs do not currently have the capacity to process the growing samples sets relevant to constraining the past ocean overturning rate using radiocarbon data.

II-5. URANIUM DECAY-SERIES DISEQUILIBRIA (PA/TH)

The contrasting chemical behavior of uranium decay-series nuclides provides a means for assessing the rate of deep circulation. This is due to the chemically distinct behavior of uranium and its radioactive decay products thorium-230 and protactinium-231. Uranium is relatively stable in solution in seawater and thus has a residence time of several hundred thousand years in the ocean. Because this is far longer than the overall oceanic mixing time of a millennium or two, uranium is evenly distributed throughout the ocean, thus providing a constant and homogenous source term for its decay products. By contrast, the radioactive-decay products thorium and protactinium are extremely particle-reactive and are rapidly removed from seawater by settling particles and subsequently buried on the sea floor. The resulting oceanic residence times are on the order of decades for thorium and centuries for protactinium. This chemically distinct behavior maintains a strong departure from secular equilibrium, with an excess of uranium in seawater, and an excess of thorium and protactinium in deep-sea sediments. In addition, while the global combined ocean-sediment system is approximately in balance, persistent intra-basin and interbasin gradients are maintained by sedimentary and oceanic processes. At steady state, the ^{231}Pa and ^{230}Th would be buried at the same 0.093 ratio that they are produced by the radioactive decay of ^{235}U and ^{234}U. Large scale ocean circulation drives an important departure from this ratio in sediments.

The most successful explanation for the removal of Th and Pa from seawater is the reversible exchange model, with differing rate constants for adsorption and desorption on settling particles [*Bacon and Anderson*, 1982]. This model predicts linear increases with depth in the concentrations of both dissolved and particulate nuclides at steady-state. Thorium grows into this steady-state profile much faster than protactinium and the burial of ^{230}Th approximates the water column production over most of the globe [*Henderson et al.*, 199X; *Yu et al.*, 2001; *Hoffmann and McManus*, submitted]. The somewhat less particle-reactive protactinium has not been observed to achieve a steady state profile, indicating significant lateral transport. In the Pacific ocean, the vast extent, large gradients in particle rain, and long residence time of deep water combine to allow transport along isopycnals from the central gyres to the margins where high particle fluxes preferentially remove the particle-reactive elements in a process described as boundary scavenging [*Anderson et al.*, 1983]. In the Atlantic ocean, the short residence time of deep waters caused by the production and spreading of NADW as the lower limb of the meridional overturning circulation limits the effect of boundary scavenging and allows the systematic export of ^{231}Pa from the modern North Atlantic [*Moran et al.*, 2001]. This net export results in burial ratios that are significantly lower than the production ratio of 0.093 in most North Atlantic sediments and significantly higher than the production ratio in the Southern Ocean [*Yu et al.*, 1996].

Past changes in the rate of the MOC would influence the residence time of deep and intermediate waters in the Atlantic, reducing or increasing the preferential export of ^{231}Pa and thus driving variations in the $^{231}Pa/^{230}Th$ in North Atlantic sediments [*Yu et al.*, 1996; *Marchal et al.*, 2000, Siddall et al., 2005, in press]. One approach to past reconstructions would be to map the burial ratios throughout the ocean for a given time slice for comparison with modern, or coretop, measurements. A seminal study using this approach found a similar average ^{231}Pa deficit in coretop and LGM sediments of the entire Atlantic [*Yu et al*., 1996]. This indication of similar modern and LGM export suggested a vigorous glacial MOC that was difficult to reconcile with the interpretation of stable isotope and trace metal data that glacial circulation had been reduced. These results were shown not to be at odds by model experiments that demonstrated the potential decoupling of water mass distributions and rate of MOC [Legrand and Wunsch, 1995]. A subsequent study pointed out the importance of differing regional responses of $^{231}Pa/^{230}Th$ to circulation change, and performed a statistical analysis showing that the North Atlantic LGM dataset allowed a range of $^{231}Pa/^{230}Th$ from a slight increase in export to a 30% reduction [*Marchal et al*., 2000]. One important result from these combined studies was evidence that the LGM climate state was not associated with a shutdown in ocean circulation.

Another approach to reconstructing the past strength of MOC utilizes time series of measurements from selected sediment cores. One such study further support for significant export of deep waters from the North Atlantic during the LGM [*McManus et al.,* 2004]. This study, utilizing the advanced analytical techniques afforded by ICP-MS applied to sediment core GGC5 from 4500 meters water depth on the Bermuda Rise, revealed similar coretop and LGM $^{231}Pa/^{230}Th$ values to those found nearby by *Yu et al.* [1996]. In addition, the high resolution study of GGC5 revealed substantial changes in the rate of MOC in association with abrupt deglacial climate events. At the time of the H1 catastrophic iceberg discharge (Heinrich) event, the $^{231}Pa/^{230}Th$ burial ratio increased to near production ratios as the North Atlantic air and ocean temperatures reached their nadirs. When the burial ratio decreased, indicating renewed MOC, regional temperatures soared. A similar oscillation in MOC, SST and Greenland air temperature accompanied the Younger Dryas. The potential for $^{231}Pa/^{230}Th$ to record such millennial events had previously been predicted in a model experiment [*Marchal et al.,* 2000] and was clearly borne out in the sedimentary data [*McManus et al.,* 2004]. A subsequent examination of a core from a shallower depth (3400 m) on the Iberian margin in the eastern North Atlantic confirmed the findings of an association of variations in MOC inferred from $^{231}Pa/^{230}Th$ and abrupt deglacial climate changes across H1 and the Younger Dryas [*Gherardi et al.,* 2005]. At both locations, the sharpest decreases in the $^{231}Pa/^{230}Th$ burial ratio accompanied the most pronounced deglacial warmings in the region, that of the Bolling/Allerod and the early Holocene. The study from the eastern basin provided important new evidence of a substantial rate of MOC at the LGM, as the glacial $^{231}Pa/^{230}Th$ burial was actually lower than the coretop value [*Gherardi et al.,* 2005]. The difference in response at the two sites, at different water depths, holds the suggestion that a vigorous but intermediate depth MOC can help reconcile disparate views of the glacial ocean. A third study revealed the influence of higher frequency events as well during the deglaciation (Hall et al., 2006).

The existing sedimentary studies show that the $^{231}Pa/^{230}Th$ approach retains great promise for reconstructing past circulation changes. They also point out the importance of additional targeted data, to confirm initial interpretations, and to account for the important information imparted by evidence from different water depths and locations. For the best utilization of sedimentary $^{231}Pa/^{230}Th$, the data should be accompanied by lithologic analyses to monitor potential particle influences, and then interpreted in the context of water column and modeling studies. Previous studies reveal the significant potential influence on sedimentary $^{231}Pa/^{230}Th$ of variations in particle flux [*Kumar et al.,* 1993] and composition [*Chase et al*., 2002]. Existing water column studies, while limited, already provide an important foundation for understanding the influence of ocean circulation on $^{231}Pa/^{230}Th$ in the Atlantic Ocean [*Moran et al*., 2001], the Southern Ocean [*Walter et al.,* 1997] and most recently in the Indian Ocean [*Thomas et al*., 2005]. Model studies have provided the basis for interpreting the behavior of ^{230}Th [*Henderson et al.,* 1999] and ^{231}Pa/^{230}Th [*Marchal et al.,* 2000; *Siddall et al.,* 2005, in press]. Improved understanding of past changes in the rate of MOC will best be achieved if parallel improvements in modern observations, lithological data and mathematical models accompany the required increases in spatial coverage and temporal resolution of sedimentary ^{231}Pa/^{230}Th data.

III-EXISTING CIRCULATION RECONSTRUCTIONS

III-1. FORWARD MODELS

Coupled ocean-atmosphere models can improve our understanding of the present, past and possibly also future climate. For past climates the sparseness of data (both spatially and temporally) means that large scale atmospheric or oceanic conditions have to be estimated from proxy data obtained from relatively few sites. Even with the number of paleotracers available today (see section 2) inferring past oceanic circulations is far from being a trivial task and this is where numerical models can be very useful. Promising applications are the assimilation of sparse proxy data into coupled climate models in order to produce global fields [*Paul and Schäfer-Neth*, 2005] and the simulation of circulation patterns consistent with past climatic conditions such as the ones during the Last Glacial Maximum (LGM). Models of intermediate complexity are particularly suited for long integrations and typically consist of a zonally averaged (2-dimensional) ocean component coupled to an energy balance model (EBM) or to an energy moisture balance model (EMBM). Studies based on that type of model [*Ganopolski et al.*, 1998; *Wang and Mysak*, 2006; *Wang et al.*, 2002; *Winton*, 1997] all indicate a weaker meridional overturning circulation (MOC) in the North Atlantic for LGM conditions. An interesting feature found in the model used in *Wang and Mysak* (2006) is that a stable, weak MOC circulation is only found under very cold conditions (similar to LGM). In a climate that is only moderately cooler than the modern climate the MOC is weakened but it is more likely to exhibit oscillations. This feature is consistent with paleodata that show less variability during the last glacial maximum than during the other phases of the last Ice Age.

More complex models consisting of three-dimensional components based on primitive equations for both the atmosphere and the ocean have also been used to simulate the LGM climate [*Hewitt et al.*, 2001; *Hewitt et al.*, 2003; *Kim et al.*, 2003; *Kitoh and Murakami*, 2001; *Otto-Bliesner et al.*, 2006]. In *Kim et al.* (2003) the reduction of atmospheric CO_2 to LGM values leads to a decrease in global surface air and sea surface temperatures by 10ºC and 5.6ºC, respectively. Especially in the tropics the cooling for the tropical regions is more severe than the one found in the CLIMAP SST reconstruction. However this cooling is in better agreement with the GLAMAP SST reconstruction [*Sarnthein et al.*, 2003]. For the oceanic circulation the strength of the subtropical gyre circulation (Gulf Stream, Kuroshio) increases in an LGM climate. There is also a marked decrease of the North Atlanic MOC which becomes much shallower while AABW fills much of the deep ocean (also in the North Atlantic). In comparison *Otto-Bliesner et al.* (2006) find a more moderate cooling in their LGM simulation with a global drop in temperature of about 4.5ºC compared to preindustrial conditions. The tropical SSTs are only cooled by about 1.7ºC, a value which is close to the one found in the CLIMAP SST reconstruction. The North Atlantic MOC is much shallower in the LGM climate but its strength is only slightly reduced. As before the production of AABW increases and the deep ocean is largely dominated by waters of Antarctic origin.

The weakening of the MOC is in contrast with the simulations described in *Kitoh and Murakami* (2001) and *Hewitt et al.* (2003) which show a strengthening of the North Atlantic MOC under LGM conditions. Compared to numerical simulations with reduced MOC strength, the studies of *Kitoh and Murakami* (2001) and *Hewitt et al*. (2003) are characterised by relatively "mild" LGM climates (drops in global surface air temperature of less than 4ºC compared to 10ºC in *Kim et al*, 2003). A nonlinear response of the MOC to global cooling was suggested by Wang et al. (2002). It is found that only beyond a certain cooling threshold there is a significant weakening of the MOC. For moderate drops of the global temperature the MOC strength increases. A similar nonlinear behaviour in more complex models might explain the different MOC responses and the apparent disagreement between different model studies. A question that remains is why the LGM climate varies so much between different models.

In a series of "hosing" experiments undertaken with the Community Climate System Model (CCSM) the sensitivity of the MOC to freshwater forcing was tested for Holocene and LGM conditions [*CCSM*, 2005]. It is found that the cooling induced in the North Atlantic by the freshwater discharge (1Sv during 100 years) is more pronounced for the Holocene circulation but the interhemispheric response is larger for the LGM state even if the North Atlantic cooling due to the discharge is smaller. The LGM circulation is also characterised by a longer recovery time for the MOC which has not returned to its original strength at the end of the simulation (541 years). For the Holocene state the MOC recovers to its initial strength within 400 years.

III.2. INVERSE METHODS

Paleoceanographic data can be combined with ocean circulation models using inverse methods in order to test precise hypotheses regarding these data (for a discussion of inverse methods and their application to oceanography see, e.g., *Wunsch*, [1996, 2006]). Only a few studies applied inverse methods to paleoceanography. *LeGrand and Wunsch* [1995] (hereafter LW95) used the method of total inversion [*Tarantola and Valette*, 1982; *Mercier*, 1986] in order to combine paleoceanographic data with a circulation model. The combination permitted the test of hypotheses about the abyssal circulation in the North Atlantic during the last glacial maximum (LGM, a time interval near 21 ka BP). Two different types of data were used: benthic $\delta^{18}O$ and benthic $\delta^{13}C$. The $\delta^{18}O$ data were used to constrain bottom water densities, assuming that the benthic $\delta^{18}O$ gradients reflect primarily temperature gradients that in turn would dominate density gradients. On the other hand, $\delta^{13}C$ was considered as a conservative tracer. LW95 argued that omitting the effect of remineralization on $\delta^{13}C$ in the deep North Atlantic is a reasonable approximation and would increase the capability of $\delta^{13}C$ to yield information about the circulation . The model used by LW95 is a simplified representation of the physics of the ocean circulation (geostrophic model). The model domain is the Atlantic from 10^oN to 50^oN and 1 km to 5 km. Its resolution is 10^o x 10^o x 1 km. Several boxes with higher horizontal resolution are added along the western boundary of the basin to simulate the Deep Western Boundary Current.

The study of LW95 comprised two major steps. First, they combined their model with climatologic data of temperature (T), salinity (S), and dissolved phosphorous, in order to produce a modern, reference circulation. Second, they conducted two inversions in order to evaluate whether the glacial benthic $\delta^{18}O$ and $\delta^{13}C$ data are consistent with (i) the reference circulation; and/or (ii) another circulation characterized by a southward flux of North Atlantic Deep Water (NADW) reduced by half. They concluded that these data are consistent with both circulations. They argued that these data would actually be consistent with an infinite number of circulation states because such data do not allow one to constrain the *rates* of water motion. In the modern ocean, density data are used to constrain geostrophic transports from the so-called “thermal wind” relations that relate the vertical variation of the horizontal velocity components to the horizontal variations of density. LW95 contended that in the glacial ocean, density gradients cannot be estimated because T gradients are poorly determined and S gradients are unknown, i.e., the interpretation of benthic $\delta^{18}O$ in terms of seawater density is ambiguous. Likewise, they argued that the benthic $\delta^{13}C$ data do not provide much information about the paleocirculation.

Winguth et al. [2000] used the adjoint method to combine benthic $\delta^{13}C$ and Cd/Ca data for the LGM with a global ocean circulation model including a description of biogeochemical processes. This model is more complete than the basin-scale model of the abyssal circulation considered by LW95. The physical component of the model is a large-scale geostrophic circulation model. The biogeochemical component includes the processes of organic matter production in the surface layers and remineralization at depth, as well as the air-sea gas exchange for the C isotopes. The model horizontal resolution is about 3.5^o x 3.5^o, with 11 vertical layers. *Winguth et al.* concluded that the southward flow of NADW was shallower at the LGM and was accompanied by a strong source of Glacial North Atlantic Intermediate Water - consistent with a prevailing interpretation of benthic $\delta^{13}C$ and Cd/Ca records from the North Atlantic [e.g., *Duplessy et al.* 1980; *Curry and Lohmann,* 1982; Boyle and *Keigwin*, 1982; *Duplessy et al.*, 1988; *Curry et al.*, 1988]. In some sense, they and LW95 obtained a similar result: the paleodata are consistent with an assumed glacial circulation. A major difference between both studies, however, is that LW95 also showed that the paleodata are consistent with the modern circulation.

Huybers et al. [2006] used the method of total inversion to combine idealized paleoceanographic observations (paleodensity estimates, $\delta^{13}C$, and $\Delta^{14}C$) with the geostrophic model adopted by LW95. The model domain is a rectangular basin in a single hemisphere, extending from 0^o-35^o in longitude, 10^o-50^o in latitude, and 1-4 km in depth. Its resolution is 10^o x 10^o x 1 km; higher horizontal resolution is used along the western boundary. The authors concluded that (i) determining a change by a factor of two in the MOC from the paleoceanographic ‘data’ requires much better accuracy than presently available; and (ii) the joint use of different data types in the inferential process (‘multi-proxy approach’) improves estimates of the MOC.

Finally, *Gebbie and Huybers* [2006] combined measurements of benthic $\delta^{18}O$ from along the margins in South Atlantic with the thermal wind and mass balances in order to explore whether the glacial values require a MOC different from the modern one. The model domain is a single section along 30^{o}S with a horizontal resolution of 1^o and a vertical resolution of 120 m. The authors found that (i) both the Holocene and glacial $\delta^{18}O$ values are consistent with an estimate of the modern MOC; and (ii) the glacial $\delta^{18}O$ values demand a MOC different from the modern one only after several assumptions are made (e.g., the relationship between seawater $\delta^{18}O$ and salinity is invariant and the glacial temperatures along the margins are known to within 1^{o}C).

Whereas the studies summarized in this section provided important insight, it is worth being explicit about their limitations. (1) Both LW95 and Huybers et al. neglected the effect of organic matter remineralization on $\delta^{13}C$. A reduced ventilation of the deep sea should lower the $\delta^{13}C$ of bottom water, owing to the ongoing oxidation of isotopically light organic carbon [e.g., *Marchal et al*., 1998]: by omitting this so-called ‘aging effect’, the capability of $\delta^{13}C$ data to constrain the ventilation might be altered. (2) In contrast to LW95, *Winguth et al*. did not report whether the paleodata they considered are also consistent with some estimate of the modern circulation (3) Confining the model domain to only a fraction of the water depth [LW95; *Huybers et al*., 2006] implies that the depth-averaged transport is left unconstrained (4) Not the full range of paleoceanographic observations that can potentially constraint the paleocirculation has been considered. Work is underway (i) to produce an updated compilation of benthic $\delta^{18}O$ data and nutrient proxy data ($\delta^{13}C$, Cd/Ca, and Zn/Ca) in the Holocene and glacial Atlantic and (ii) to combine these data with a circulation model on the basis of an inverse method [*Marchal and Curry*, 2006]; supplementary information about the paleocirculation such as provided by $^{231}Pa/^{230}Th$ and ^{14}C will be eventually incorporated in the analysis. (5) Finally, the information provided by the temporal variability that is present in sediment records has not been fully exploited yet. For example, earlier and ongoing studies envision~~ed~~ the problem of inferring the glacial circulation as a time-independent problem: given a dataset that is assumed to be 'synoptic', which is (are) the time mean circulation(s) that is (are) consistent with the data? However, the interpretation of sediment records is a time-dependent problem by its very nature. Whereas inverse methods exist that permit the combination of time-dependent data (time series) with a dynamical model (for an application to paleoclimatology see *Marchal* [2005]), the application of such methods to the interpretation of such records awaits future investigations.

IV: G-CUBED THEME ON PAST OCEAN CIRCULATION CONTENTS

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III-2. INVERSE MODELS

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VI. ACKNOWLEDGEMENTS

We would like to thank the participants in the Workshop on Past Ocean Circulation who contributed their ideas and expertise to this document. In particular, we'd like to thank Tom Marchitto and Bill Curry who contributed text and figures to Section II. We thank SCOR and IMAGES for providing funds and leadership for these activities. Ed Urban, Ralph Schneider and Laurent Labeyrie provided support in many ways. We thank the NSF MESH Office from providing additional support for the Workshop.