Deepwater Variability

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Today, warm, salty surface and near surface waters from the South Atlantic cross the equator, eventually flowing northward into the subpolar North Atlantic. In transit, this water becomes progressively colder, as it releases heat to the overlying colder atmosphere. By the time this water reaches the North Atlantic, its density has increased, and it descends to great ocean depths in a process termed "deepwater formation" or "meridional overturning circulation (MOC)". If less deepwater is formed, less warm water flows northward to replace the descending water, and there is a reduction of heat released to the overlying atmosphere. This affects the climate of the surrounding landmasses. Because changes in the intensity of deepwater formation can affect climate, it is important to understand how much and why it has changed in the past.

Examination of the last 10,000 years (also referred to as the Holocene) is particularly relevant to understanding how the intensity of deepwater formation may change in the future. Boundary conditions throughout this interval following the last Ice Age were similar to today, so deepwater variations documented during this period may be more relevant to the present and future than periods with large ice sheets. Furthermore, this period includes intervals when the hydrologic cycle may have been stronger than today, as might also be the case as the planet warms due to greenhouse gases.

There are many complementary approaches for reconstructing past deepwater variability during the last 10,000 years, each with its own strengths and weaknesses. In this study, we utilize tracers for nutrients, as waters that descend in the North Atlantic have different nutrient signatures than waters that sink near Antarctica. Following the line of reasoning that, when the sinking of waters in the North Atlantic is reduced, the warm water that feeds that sinking water remains in the subsurface farther south, we also reconstructed the subsurface temperature field. Using the same rationale, we reconstructed surface temperatures; a reduction of deepwater formation in the North Atlantic should cool the North Atlantic and warm the South Atlantic.

Our results are described below:

I. We documented (Oppo et al., submitted), for the first time, that carbon isotope variations in sediment cores bathed by Iceland Scotland Overflow Water and Labrador Sea Water were approximately synchronous during the Holocene. This observation suggests that deepwater masses formed in the Nordic and Labrador Seas experienced nearly synchronous, multi-century variability during the past 8,000 years. If correct, this implies regional-scale climate forcing resulted in the similar timing of surface buoyancy changes in the two water mass formation regions, a response that contrasts with the antiphase behavior of these same regions today on interannual to decadal time scales (the North Atlantic Oscillation), but is consistent with the possibility that longer-term persistence of one mode of the North Atlantic Oscillation would affect the meridional overturning circulation (MOC). The apparent coordinated in-phase behavior of the two deepwater formation regions during the Holocene, although far less dramatic, is reminiscent of the wholesale weakening of the MOC in response to abrupt episodes of massive ice discharge into the Atlantic during Heinrich events of the last glacial cycle.

II. The results described above were partially based on a shallow core that lies predominantly within ISOW, but also contains a small portion of warmer, shallower Subpolar Mode Water. Thus, our results should be confirmed with a work on cores lying entirely within ISOW. The OCCI grant funded preliminary stratigraphic analyses of North Atlantic gravity cores collected in 1993, and identified several having accumulation rates in excess of 20 cm/kyr. All of these cores are on the eastern flank of the northern portion of the Reykjanes Ridge. The deeper sites are fully within ISOW. I have submitted a proposal to NSF to carry out detailed work on these cores.

III. This proposal also funded most of the analyses for JP student Rosemarie Came's thesis (Came, 2005), which focused on understanding the linkage between deepwater variability and surface tropical and North Atlantic hydrography during the Holocene. She generated a Mg/Ca-based sea surface temperature (SST) record for the North Atlantic. This record shows a sharp cooling and possible freshwater anomaly at the time of the 8.2 kyr event, a regional cooling associated with freshwater discharge from Hudson Bay (Came et al., 2004a; in prep-a.). Her results also show a long-term warming and decreasing salinity trend over the course of the Holocene, and high amplitude variability, as large as the 8.2 k event during the late Holocene, when there were no residual ice sheets to force those oscillations. To complement this record, Rose also generated Holocene SST and salinity estimates from a Caribbean Sea core, and a subtropical western North Atlantic core. Together with a South Atlantic record that I worked on with funds from this OCCI grant, we have the good beginning to a North-South transect that will help us address the mechanisms for freshwater redistribution during the Holocene.

IV. The results described above lead to an NSF-funded collaborative proposal (co-PI G. Schmidt, GISS/Columbia U.) that will enable us to integrate most of the surface data generated as part of this grant with modeling experiments specifically designed to understand the role of the hydrologic cycle (including freshwater redistribution within and among the ocean basins) in Holocene climate change. The data generated as part of the OCCI study will form an important component of the validation of the simulated temperature and salinity anomalies. We want to explore the underlying assumption for salinity reconstructions, that regional relationships between surface salinity and seawater $\delta^{18}O$ were constant during the Holocene. In some cases, salinity changes proposed for the Holocene seem large (e.g., on the order of 1-2 psu), and require dramatic changes in the hydrologic cycle. We propose to look at the response of the hydrological cycle, and the isotopic expression of those changes for several aspects of Holocene climate change, including abrupt Holocene events. We will assess whether the response of the tropics to North Atlantic perturbations is consistent with invariant regional salinity-$\delta^{18}O$. We will also assess the affect of sustained modes of tropical climate variability (e.g. ENSO) on North Atlantic climate and isotopic archives, and of sustained NAO modes on tropical climate.

V. Holocene circulation changes were significantly smaller than changes that occurred in association with large and abrupt glacial and deglacial events. Documenting the response to these larger events provides an important framework for interpreting the geologic expression of the smaller Holocene events. To this end, Joint Program student Rosemarie Came measured, benthic Mg/Ca, Cd/Ca, and Zn/Ca in two low-latitude cores from intermediate water depths with OCCI funds. Benthic foraminiferal Cd/Ca from a Florida Current core documents the history of the northward penetration of Antarctic Intermediate Water (AAIW) within the return flow of the Atlantic meridional overturning circulation (MOC). Her results confirm the notion that AAIW is an important component of the return flow for the North Atlantic MOC (Came et al., in prep-b). When the MOC was weak, as during the last glacial maximum and the Younger Dryas, the contribution of AAIW to the Florida Current was weaker than today. Less AAIW in the Florida Current when the MOC was weak suggests that the northward penetration of AAIW is directly related to the strength of the North Atlantic MOC, consistent with the modern view of AAIW's role (e.g., Rintoul, 1991). Mg/Ca-based intermediate-depth temperature changes are consistent with model predictions of temperature redistribution in response to an event of reduced MOC (Came et al., in prep-c).

VI. Finally, results funded by the OCCI motivated a collaborative proposal pending at NSF (co-PIs W. Curry and A. Broccoli -Rutgers U.) that will explore the response of the MOC and AAIW to surface freshwater and ice discharge events in the high-latitudes of the northern and southern hemisphere. The data component of the proposal focuses on the reconstruction of the history of the northward penetration of AAIW into the north Atlantic. The modeling component is set up as sensitivity studies to understand the effect of changes in the MOC on AAIW penetration into all three major ocean basins, as well as to test specific hypotheses (northern versus southern) relating to the proximal forcing for those MC changes. Data-model comparisons are a key aspect of the proposed work.

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Came, R. E., D. W. Oppo, and J. F. McManus, Mg/Ca-derived Holocene sea surface temperature variabilityfrom Site 984 in the high-latitude North Atlantic, ICP Biarritz, France, September, 2004a.

Came, R. E., D. W. Oppo, and W. B. Curry, North Atlantic intermediate-depth circulation during the Holocene: Evidence from simultaneous benthic foraminiferal Mg/Ca and Cd/Ca data, Fall AGU, San Francisco, 2004b.

Came, R. E., Abrupt climate change in the Atlantic ocean during the last 20,000 years: insights from multi-element analysis of benthic and planktic foraminifera and a coupled AOGCM, MIT/WHOI Joint Program in Oceanography Ph. D. Thesis, 2005.

Came, R. E., Oppo, D. W., and McManus, J. F. Amplitude and timing of salinity and temperature variability in the high-latitude North Atlantic. (In prep-a for Nature)

Came, R. E., Oppo, D. W., Curry, W. B., Lynch-Steiglitz J. (in prep-b.), Variability in the influence of Antarctic Intermediate Water in the Florida Current over the last 20,000 years.

Came. R. E., Oppo, D. W., Curry, W. B., A. J. Broccoli, R. J. Stouffer, Lynch-Steiglitz J. (in prep-c.) North Atlantic intermediate depth variability during the Younger Dryas: evidence from benthic foraminiferal Mg/Ca and the GFDL R30 coupled OA-GCM

Oppo, D. W., J. F. McManus, and J. L. Cullen, Palaeo-oceanography: Deepwater variability in the Holocene Epoch, *Nature 422, 277-278,* 2003a.

Oppo, D. W., J. F. McManus, and J. L. Cullen, Holocene North Atlantic Deepwater δ^{13}C Variability, Fall AGU, San Francisco, 2003b.

Oppo, D. W., M. E. Raymo, J. F. McManus, Multi-century oscillations in the subsurface North Atlantic during the Holocene, submitted to Science, October 23, 2005.