Last Glacial Maximum ocean thermohaline circulation: PMIP2 model intercomparisons and data constraints


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The ocean thermohaline circulation is important for transports of heat and the carbon cycle. We present results from PMIP2 coupled atmosphere-ocean simulations with four climate models that are also being used for future assessments. These models give very different glacial thermohaline circulations even with comparable calculations for present. An integrated approach using results from these simulations for Last Glacial Maximum (LGM) with proxies of the state of the glacial surface and deep Atlantic supports the interpretation from nutrient tracers that the boundary between North Atlantic Deep Water and Antarctic Bottom Water was much shallower during this period. There is less constraint from this integrated reconstruction regarding the strength of the LGM North Atlantic overturning circulation, although together they suggest that it was neither appreciably stronger nor weaker than modern. Two model simulations identify a role for sea ice in both hemispheres in driving the ocean response to glacial forcing. Citation: Otto-Bliesner, B. L., C. D. Hewitt, T. M. Marchitto, E. Brady, A. Abe-Ouchi, M. Crucifix, S. Murakami, and S. L. Weber (2007), Last Glacial Maximum ocean thermohaline circulation: PMIP2 model intercomparisons and data constraints, Geophys. Res. Lett., 34, L12706, doi:10.1029/2007GL029475.

1. Introduction

Reconstructing the strength and structure of the North Atlantic overturning circulation at the LGM is not a simple task — it is difficult enough to do for the present climate. Various paleonutrient tracers, including benthic foraminiferal $\delta^{13}$C [Curry and Oppo, 2005; Duplessy et al., 1988], Cd/Ca [Boyle, 1992; Marchitto and Broecker, 2006], Ba/Ca [Lea and Boyle, 1990], and Zn/Ca [Marchitto et al., 2002], indicate that the boundary between North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) was substantially shallower during the LGM than today. The glacial form of NADW, named Glacial North Atlantic Inter-

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boundary conditions used [Hewitt et al., 2003; Kim, 2004; Kitoh et al., 2001; Peltier and Solheim, 2004; Shin et al., 2003b; Weber et al., 2007]. The second phase of the Paleoclimate Modeling Intercomparison Project (PMIP2) adopts standard forcings and boundary conditions to allow model-model and model-data comparisons for the LGM [Braconnot et al., 2006].

[6] For the PMIP2 LGM simulations, all of the models used the most recent reconstruction of LGM continental ice sheets, ICE-5G [Peltier, 2004], the same change from pre-industrial levels of atmospheric concentrations of carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O), the specification of additional land due to a lowering of sea level, and the change to insolation resulting from a slightly different Earth’s orbit. The presence of the extensive glacial ice sheets accounts for over half of the total radiative forcing of the troposphere [Hewitt and Mitchell, 1997], and the lowering of greenhouse gas concentrations (primarily the CO$_2$) accounts for most of the remaining radiative forcing [Otto-Bliesner et al., 2006], with small contributions from the additional land and insolation changes.

[7] In this paper, we include results from four coupled climate models which have contributed PMIP2 simulations for LGM – CCSM (the National Center for Atmospheric Research CCSM3 model), HadCM (the UK Met Office HadCM3M2 model), MIROC (the CCSR/NIES/FRCGC MIROC3.2.2 (medres) model), and ECBilt-CLIO (the KNMI ECBilt/Louvain-la-Neuve CLIO intermediate complexity model) – models also used for the IPCC AR4 simulations of future climate change.

3. Results
3.1. North Atlantic Meridional Overturning Circulation

[8] These models simulate a similar modern Atlantic meridional circulation with maximum overturning strength (below 500 m) in the North Atlantic of 13.8–20.8 Sv, within the range of observational estimates of 18 ± 3–5 Sv [Talley et al., 2003] (Figure 1). The CCSM and MIROC models show comparable depth penetration of this overturning, to 3800 m and 3500 m, respectively, at 45°N, while the HadCM3 and ECBilt simulated depth is shallower – all somewhat too shallow compared to observed estimates of ~4200 m. AABW fills the deep Atlantic below the NADW with the Atlantic portion of AABW flow of 3–4 Sv at 30°S in all models.

[9] At LGM, the four PMIP2 simulations indicate reduced (enhanced) areas of deep convection in the Nordic Seas (south of Greenland). Proxies also suggest that most GNAIW was likely formed south of Iceland [Duplessy et al., 1988; Pflaumann et al., 2003]. The responses of the strength of the Atlantic meridional overturning circulation differ dramatically among the models. CCSM has a modest weakening (~20%) of North Atlantic overturning strength [Otto-Bliesner et al., 2006] and HadCM has only a small change in strength, while ECBilt and MIROC have increases (~20–40%) in strength. Changes in the depth of the North Atlantic overturning circulation at 45°N also show model differences. CCSM with the greatest depth at modern simulates the largest shoaling of this cell at LGM. MIROC deepens the depth of this cell at LGM to the entire depth of the model. The North Atlantic overturning cell encompasses the entire Atlantic north of 30°S in ECBilt. The HadCM model with weaker penetration of NADW at modern shows modest decreases in depth at LGM. LGM Atlantic AABW at 30°S increases in CCSM and HadCM, decreases in MIROC, and disappears in ECBilt.

3.2. Deep Ocean Temperatures and Salinities

[10] The PMIP2 models also predict the three-dimensional temperature and salinity structure of the oceans. Model-ODP comparisons show that the PMIP2 models reproduce relatively well the modern deep ocean temperature-salinity

Figure 1. Atlantic Ocean meridional overturning circulations (Sv) simulated by the PMIP2 coupled atmosphere-ocean models for (top) modern and (bottom) Last Glacial Maximum.
The models simulate warmer and saltier deep waters at Feni Drift in the North Atlantic than at Shona Rise in the Atlantic sector of Antarctica. Seasonally, the largest brine rejection occurs in the subpolar regions, especially during the winter months (Figure 3). CCSM has more extensive winter sea ice in the North Atlantic, especially in the absence of winter ice south of Greenland at LGM allows large heat exchange between the ocean and atmosphere, while the MIROC model exhibits decreases in the thermal contribution and increases in the haline contribution to Southern Ocean WMF at LGM, but CCSM has a much larger haline contribution. The total rate of LGM Southern Ocean WMF is twice greater in CCSM than MIROC and as a result the AABW extends farther northward at LGM in all three basins.

### 3.4. Sea Ice

Sea ice plays an important role for understanding the different responses of the thermohaline circulation to glacial forcing in the CCSM and MIROC models. The thermal contributions are most important for North Atlantic WMF at LGM in both models, but for CCSM this contribution is only about half that of MIROC. WMF due to heat loss occurs in the ice-free regions where high surface densities are coincident with large thermal buoyancy forcing. In the MIROC model, the absence of winter ice south of Greenland at LGM allows large heat exchange between the ocean and atmosphere, especially during the winter months (Figure 3). CCSM has more extensive winter sea ice in the North Atlantic, especially in the western North Atlantic south of Greenland-Iceland-Scotland region. Regions of WMF in CCSM at LGM occur south of Greenland and also in a northward seasonally ice-free region in the Greenland-Iceland-Norwegian Sea but the thermal buoyancy forcing is smaller than in MIROC in these regions.

In the Southern Ocean, brine rejection due to sea ice production increases the densification of the waters around Antarctica. Seasonally, the largest brine rejection occurs...
where sea ice is being formed, i.e. in open ice leads in coastal regions and just off the permanent ice. CCSM has vigorous seasonal sea ice formation and export at LGM around Antarctica. The result is a significant increase in WMF of AABW in the CCSM simulation at LGM as compared to modern. MIROC, on the other hand, has less extensive LGM sea ice and a more modest haline contribution to WMF.

### 4. Summary and Conclusions

[17] The LGM North Atlantic MOC changes in the PMIP2 models fall into three classes: shallower but less confidently weaker (CCSM), no significant changes (HadCM), and deeper and stronger (MIROC and ECBilt). For CCSM and MIROC, the responses are tied to the buoyancy fluxes in the North Atlantic and Southern Ocean. Differences are related to more seasonally extensive sea ice at LGM in CCSM than MIROC. HadCM and ECBilt have more intermediate changes in LGM sea ice extent (auxiliary material), though in neither does density contrast between AABW and NADW play a controlling role in determining the strength of LGM NADW [Weber et al., 2007].

[18] Proxy reconstructions of LGM sea ice and ocean stratification can provide additional constraints on interpre-

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**Figure 3.** The buoyancy forcing \((10^{-6} \text{ kg m}^{-2} \text{s}^{-1})\) at LGM predicted by CCSM and MIROC for (top) northern winter (February) by the thermal contribution in the North Atlantic and (bottom) southern winter (August) by the haline contribution in the Southern Ocean. Regions of high density for each model where deep water mass formation occurs are dotted. The white lines indicate (top) the model LGM February sea ice edge, 50% concentration, representing northern winter extent, and (bottom) LGM February (solid) and September (dotted) sea ice edges, 90% concentration, representing permanent and winter Southern Hemisphere extents.
tation of the LGM Atlantic meridional overturning. LGM AABW forms in coastal leads and just equatorward of permanent sea ice cover due to brine rejection during sea ice production [Shin et al., 2003a]. Southern Ocean summer sea ice extent simulated at LGM by CCSM closely follows the summer sea ice edge in the Atlantic sector as reconstructed by CLIMAP Project Members [1981] and EPILOG [Gersonde et al., 2005]. The CCSM LGM simulation of Southern Hemisphere sea ice and deep Atlantic temperature and salinity as compared to proxy records confirms the interpretation from paleonutrient tracers and previous modeling that the glacial Atlantic Ocean was more stably stratified at high northern latitudes with a shoaling of NADW (i.e. GNAIW), and AABW penetrating much farther into the North Atlantic than present.

[19] The continental ice sheets over North America and the extensive sea ice over the Labrador Sea create a source of cold, dry air which enhances the cooling and evaporation downstream over the North Atlantic. Sea ice extent has been shown to be crucial to modulating the impact of atmospheric forcing and thus water mass formation in the subpolar North Atlantic at LGM in an eddy-permitting ocean model [Yang et al., 2006]. CCSM overestimates proxy evidence of LGM winter sea ice in the region south of Greenland [CLIMAP Project Members, 1981; Sarntthein et al., 2003], a region at modern of large upward heat flux from the ocean to atmosphere, and so may underestimate production of GNAIW. MIROC underestimates proxy evidence of sea ice indicating production of LGM NADW may be overestimated. The model results for the strength of GNAIW and proxy evidence from a variety of tracers suggests GNAIW was not significantly stronger than modern and perhaps not considerably weaker either.

[20] The strength of NADW and suppression of air-sea gas exchange due to glacial sea ice expansion in the Southern Ocean have been suggested as playing possible roles in regulating past atmospheric CO2. In turn, climate model results indicate that lower glacial CO2 can effect substantial changes to sea ice and the glacial thermohaline circulation. Thus, a reconstruction of Atlantic overturning circulation, ocean stratification, and sea ice extent is critical to understanding the biogeochemical and physical feedbacks that regulate the past carbon cycle.

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