Atlantic Ocean Circulation During the Last Glacial Maximum Simulated by PMIP3 Climate Models

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PMIP3 model output of the meridional streamfunction in the Atlantic Ocean were obtained for the GISS, MIROC, FGOALS, CNRM, MRI and MPI Earth System Models, and 50-year time averages were made. We used simulations from two time periods, the Last Glacial Maximum (LGM, ~20,000 years ago) and the Pre-Industrial Control (P-I C) runs. We evaluated the predicted difference between both time periods, by calculating the value of the streamfunction in the North Atlantic at 30° N, at the depth of maximum transport, and observed a conspicuous increase for the LGM, which averaged over all models results in (8 ± 4) Sv (1 Sv = 10^6 m³/s) (Muglia & Schmittner (2013)[1]). See Table 1 for more detail. The result of a stronger Atlantic Meridional Overturning Circulation (AMOC) in the LGM contradicts some previous inferences based on paleoclimate data from the sea floor, like McManus et al. 2004[2], where ^{231}Pa/^{230}Th is used as proxy and Lynch-Stieglitz et al. (2006)[3], where δ^{18}O is used as proxy.

Methods:

- We define contrast as the difference between the east and west side values of a variable in a predefined zonal region.

- North Atlantic: Strength of the upper branch of the AMOC linked to transport of the Gulf Stream as it moves northward off the coast of Florida.
- Transport of the Gulf Stream proportional to negative tilt of the isopycnals along the zonal direction and the meridional velocity.
- We studied the density and meridional velocity fields along the 30° N parallel between 80 and 65° W.

- South Atlantic: Northward flow associated with the AMOC spread in the upper depths of the whole ocean basin.
- Denser waters over the east side of the South Atlantic Ocean.
- Changes in density contrast between coasts lead to variations in the volume of northward transported water.
- We studied vertical density profiles at each side of the ocean basin at 30° S.

- Comparisons between P-I C and LGM were made.

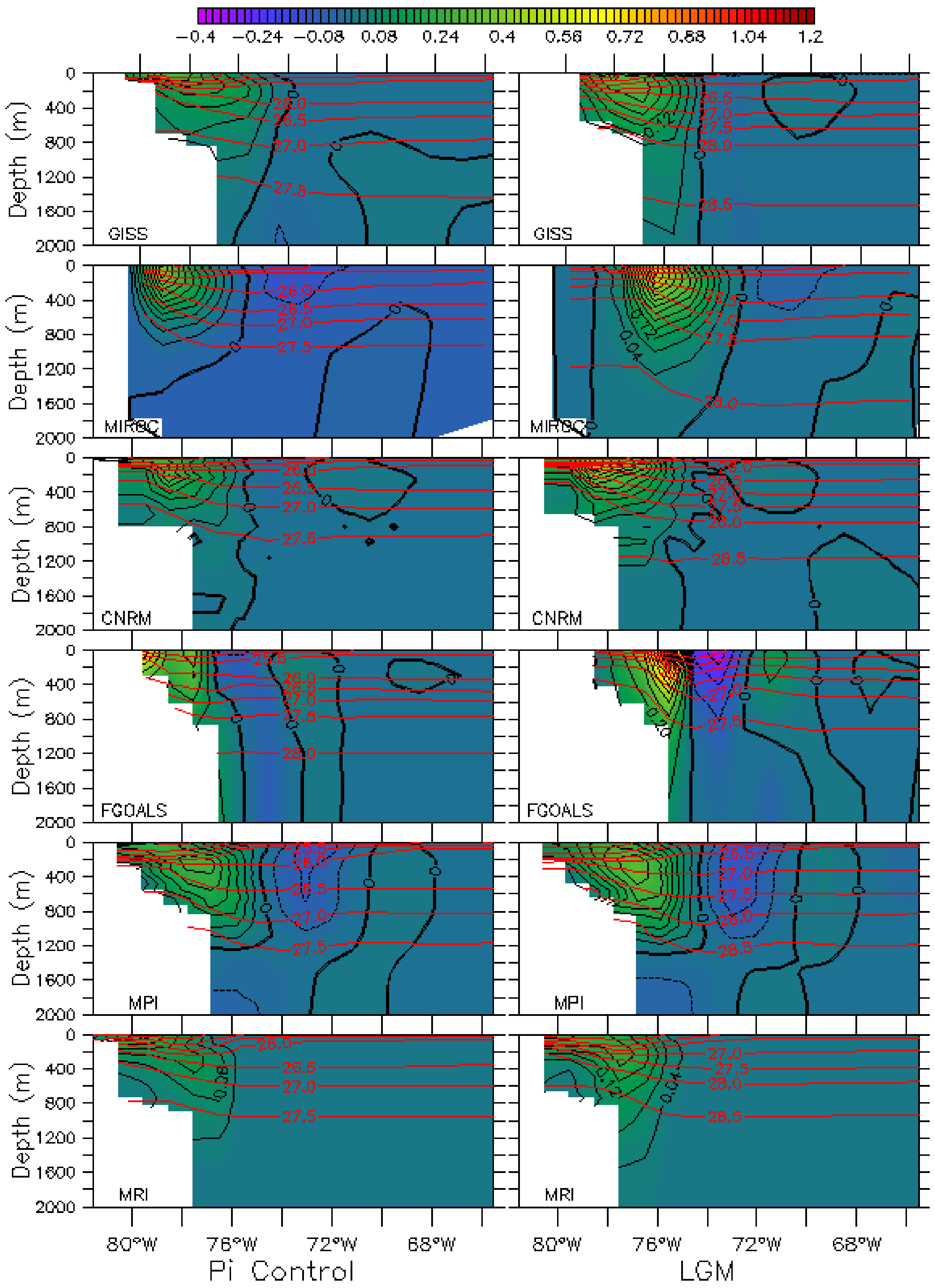

Figure 1: Meridional velocity at 30° N off the coast of Florida. Model results for the P-I C and LGM as indicated. Shading and black contours are meridional velocity values in m/s. Red contours are potential density values in kg/m³.

Results:

- Off the coast of Florida: Increase in the tilt of the isopycnals (red contours in Figure 1) and the meridional velocity (Shading colors and black contours) for all the PMIP3 models studied.

- South Atlantic: Difference between densities at both sides of the basin stronger in the LGM (Figures 2 a and b). Indicates larger northward flow in the LGM than in the control runs.
- Largest difference between periods at shallow and deep waters, where gradient is stronger for the LGM than for the P-I C (Figure 2c).

- Model results are contrary to observations by Lynch-Stieglitz et al. (1999, 2006), where δ^{18}O data was used to infer a decrease in the density gradient in the Florida Strait[4] and the South Atlantic Basin[5].
- Cited observations would lead to a decrease in the transport of the AMOC, while our model results suggest an increase in the transport of the AMOC.

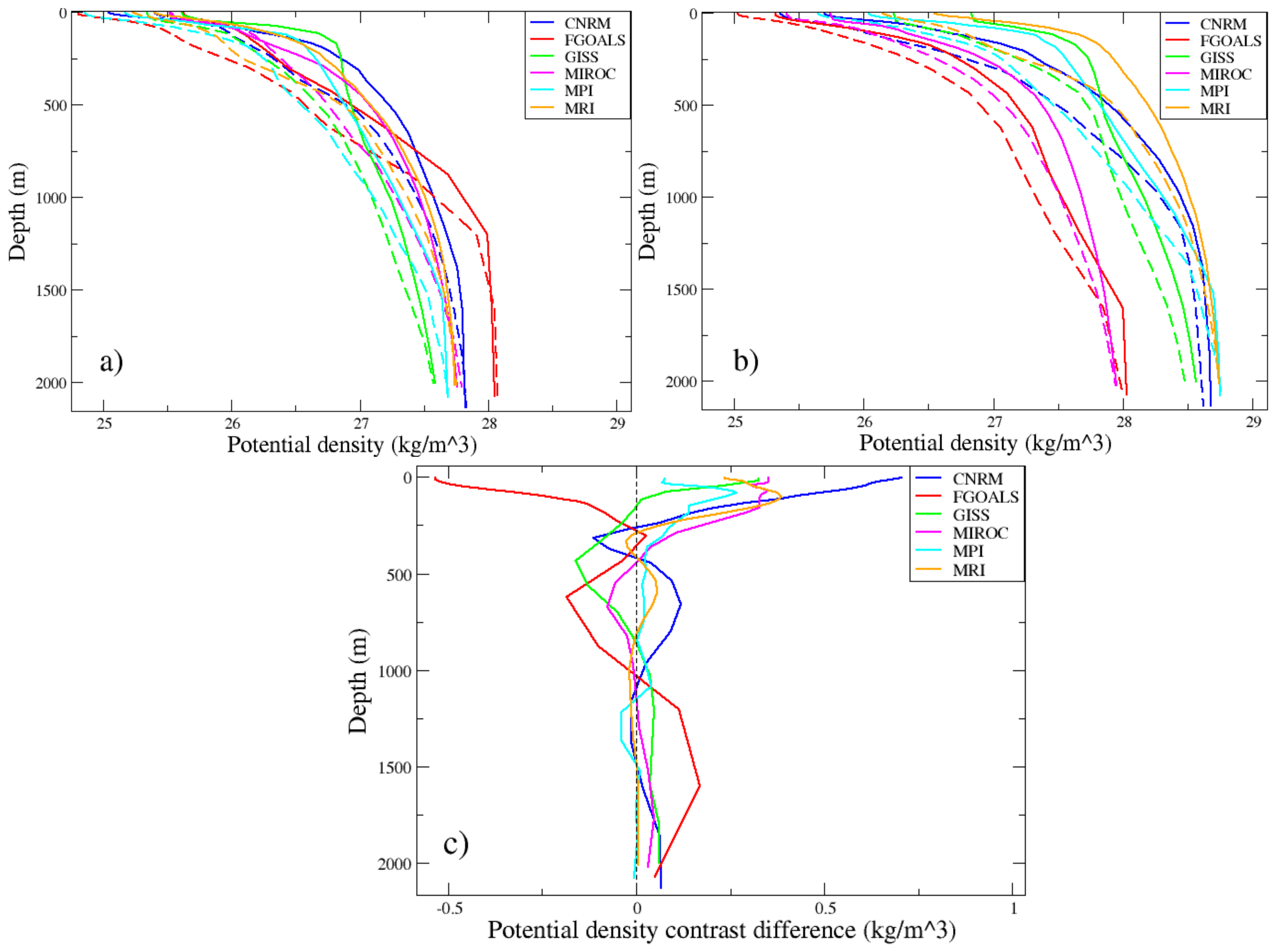

Figure 2: a) Potential density profiles at both sides of the South Atlantic for the P-I C runs. Full lines correspond to the east side and dashed lines correspond to the west side of the basin. For each model, a larger separation between full and dashed lines correspond to a stronger density contrast. b) Same as a) but for the LGM runs. c) Profiles of potential density contrast in the LGM minus potential density contrast in the P-I C. Potential density contrast is defined, for each depth, as the potential density at the east side of the basin minus the potential density at the west side of the basin.

Integrated steric height:

- A quantifiable measure of the different features of the AMOC is needed.
- ISH integrates all the contributions of density anomalies through the water column, and is defined as

$$P(x) = -\int_H^0 \int_H^z \left(\rho(x,z') - \rho_0\right) dz' dz,$$

where ρ is the density at each location, $\rho_\circ$ is the reference density value (taken as 1028 kg/m³), and H is a reference depth level.
- Zonal gradient of ISH across west-east section is proportional (with opposite sign) to magnitude of meridional transport across that section (thermal wind relation).
- Steeper tilts in isopycnals leading to sharper ISH zonal gradients produce larger meridional water transports.
- North Atlantic: We calculated ISH contrast in the Gulf Stream at 30° N between 79 and 76° W. Reference level is 1000m.
- South Atlantic: We calculated ISH contrast between the edges of the whole ocean basin at 30° S. Reference level is 2000 m.

Model	**AMOC transport (Sv)**			**Gulf Stream transport (Sv)**			**ISH contrast off Florida at 30N (10^-6 kg/m)**			**ISH contrast at 30S (10^-6 kg/m)**		
	P-I C	**LGM**	**Difference**	**P-I C**	**LGM**	**Difference**	**P-I C**	**LGM**	**Difference**	**P-I C**	**LGM**	**Difference**
GISS	17.17	20.31	3.14	23.04	46.61	23.57	0.06	0.07	0.01	-0.21	-0.26	-0.05
MIROC	14.42	23.9	9.48	40.51	59.38	18.87	0.26	0.30	0.04	-0.17	-0.2	-0.04
CNRM	14.34	24.28	9.94	23.09	51.81	28.72	0.12	0.14	0.01	-0.2	-0.27	-0.06
FGOALS	22.18	36.67	14.49	46.2	84.3	38.1	0.03	0.22	0.19	-0.16	-0.27	-0.11
MPI	18.78	21.57	2.79	56.54	68.68	12.14	0.13	0.18	0.05	-0.27	-0.28	-0.01
MRI	14.56	22.39	7.83	17.14	36.63	19.49	0.04	0.10	0.07	-0.17	-0.18	-0.01
Average	16.90	24.85	7.94	34.42	57.90	23.48	0.11	0.17	0.06	-0.20	-0.24	-0.05
1-sigma SD	3.15	5.97	4.45	15.63	16.92	9.02	0.08	0.08	0.07	0.04	0.04	0.04

Table 1: Modeled transport of the AMOC (columns 1-3), and the Gulf Stream (columns 4-6), at 30° N. Modeled ISH contrast (east side minus west side) for the Gulf Stream off Florida at 30° N (columns 7-9) and for the South Atlantic Basin at 30° S (columns 10-12). Values for P-I C and LGM are presented, as well as the difference between periods (LGM minus P-I C). Last two rows are the averaged values between the six models studied, and the 1-sigma standard deviation calculated from the dispersion between values.

Discussion:

- ISH contrasts are predicted as larger in magnitude for the LGM (columns 9 and 12 in the Table 1).
- For the North Atlantic off the coast of Florida, a positive difference between the LGM and P-I C suggests stronger northward flow for the LGM.
- For the South Atlantic, a negative Coriolis parameter makes for a northward water transport via the thermal wind relation for negative contrast values. Thus, negative values in the difference between ages mean a stronger northward flow for the LGM.
- ISH results validated by volume transport of the Gulf Stream and AMOC at 30° N. Both show increase for the LGM (columns 3 and 6 in Table 1).

Conclusions:

- PMIP3 models studied predict a stronger AMOC for the LGM, with steeper density gradients across basins, and larger meridional volume transports.
- Result contradicts cited bibliography, where proxy data was used to determine weaker Atlantic meridional flows during the LGM.
- More knowledge of the forcings acting over the AMOC during the LGM is needed to have a better match between models and observations.
- However, Earth System Model results should be taken into account as a tool for understanding different climate scenarios and their consequence in ocean dynamics.

References:

[1] Muglia, J. and Schmittner, A., *Ocean circulation during the Las Glacial Maximum simulated by PMIP3 Climate Models*, Perspectives across terrestrial and ocean ecosystems, August 6 – 10, 2013, Boulder, CO (Poster presentation).
[2] McManus, J. F., Francois, R., Gherardi, J.-M., Keigwin, L. D., and Brown-Leger, S. (2004), *Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes*, Nature, 428 (6985), 834–7.
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[5] Lynch-Stieglitz, J., Curry, W. B., Oppo, D. W., Ninneman, U. S., Charles, C. D., and Munson, J. (2006), *Meridional overturning circulation in the South Atlantic at the last glacial maximum*, Geochemistry, Geophysics, Geosystems, 7(10).

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