The effect of ice sheets and different GHG concentrations on the state of the glacial AMOC in a coupled climate model*

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1. Introduction

There are large differences in the state of the Atlantic Meridional Overturning Circulation (AMOC) during the Last Glacial Maximum (LGM) between climate models and reconstructions but also between different models [1,2]. Many models fail to simulate the shoaling of the upper overturning cell which is indicated by the reconstructions [3,4]. This indicates a lack of understanding regarding the mechanisms which determine the state of the glacial AMOC. Very few studies addressed the effects of the glacial forcings on the AMOC in a coupled model framework [5,6], but none of them analysed the effects of all three glacial forcings and none of them addressed the effects on the deep Atlantic water masses. We therefore address the following questions:

1. What is the response of the AMOC and deep water masses to the individual glacial forcings?
2. What is the sensitivity to different greenhouse (GHG) gas concentrations?

2. Experiments

We use the Max Planck Earth System Model (MPI-ESM) in the coarse resolution configuration.

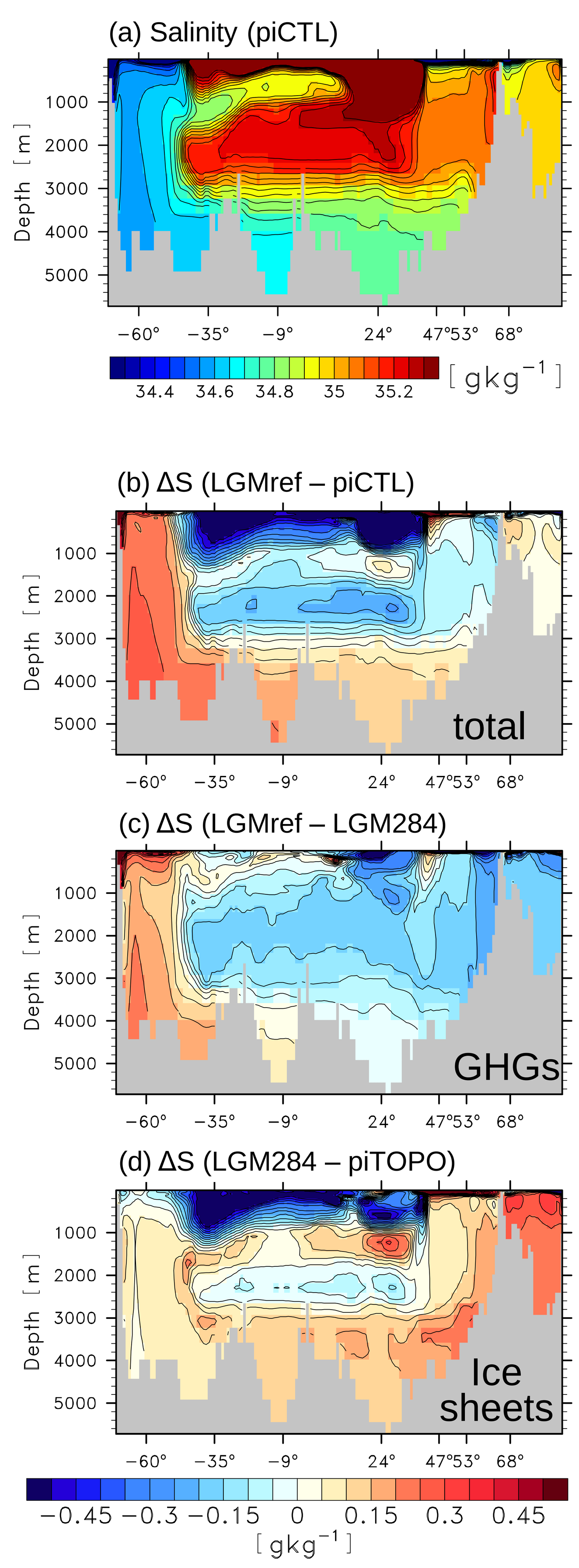
Forcings which can be varied are
- Topography, ice sheets, land-see mask
- Orbital forcing
- GHG concentrations

All simulations are in quasi-equilibrium, and we analyse a mean over the last 300 years of each simulation.

pCO2 [ppm]	0k ice sheets, 0k orbit	0k ice sheets, 21k orbit	21k ice sheets, 21k orbit
353			LGM353
284	piCTL	piTOPO	LGM284
230			LGM230
185			LGMref
149			LGM149

Tab. 1 Experiments and their respective setups. '0k' denotes preindustrial conditions, '21k' denotes glacial conditions.

3. Response of deep water masses and AMOC to glacial forcings



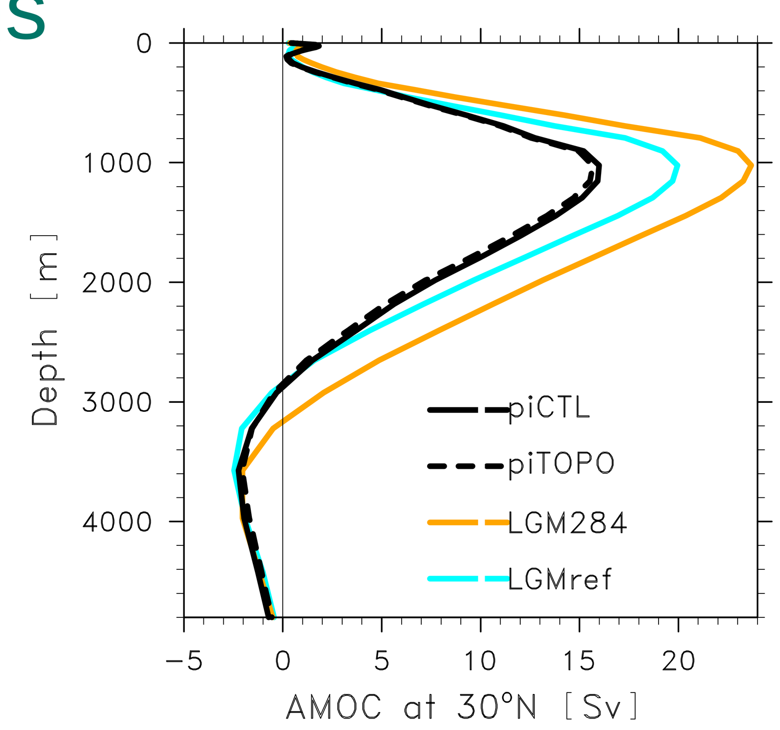


Fig. 2 AMOC profile at 30ºN.

Water masses
Total: Antarctic Bottom Water (AABW) becomes saltier, North Atlantic Deep Water (NADW) becomes fresher (Fig.1b)
GHGs: less NADW below 3000m (Fig.1c)
Ice sheets: more NADW below 3000m (Fig.1d)
Orbit: affects mainly surface properties at high latitudes. Effect is small compared to ice sheets and GHGs (not shown)

AMOC
The AMOC response (Fig. 2) matches the water mass response. The vertical extent of the NADW cell remains almost unchanged in response to the total glacial forcing, the overturning strength increases (compare piCTL and LGMref). This is the result of two larger opposing effects: a shoaling and weakening due to the GHG reduction (compare LGMref and LGM284) and a deepening and strengthening due to the glacial ice sheets (compare LGM284 and piTOPO).

Fig. 1 North-south section from the Weddell Sea to the Nordic Seas of salinity in piCTL and salinity differences in response to the total glacial forcing (LGMref – piCTL), the ice sheets (LGM284 – piTOPO) and the glacial GHG concentrations (LGMref – LGM284). The salinity differences in (b) and (d) are relative to the global-mean glacial salinity increase of 1.21 g/kg.

4. Sensitivity to different GHG concentrations

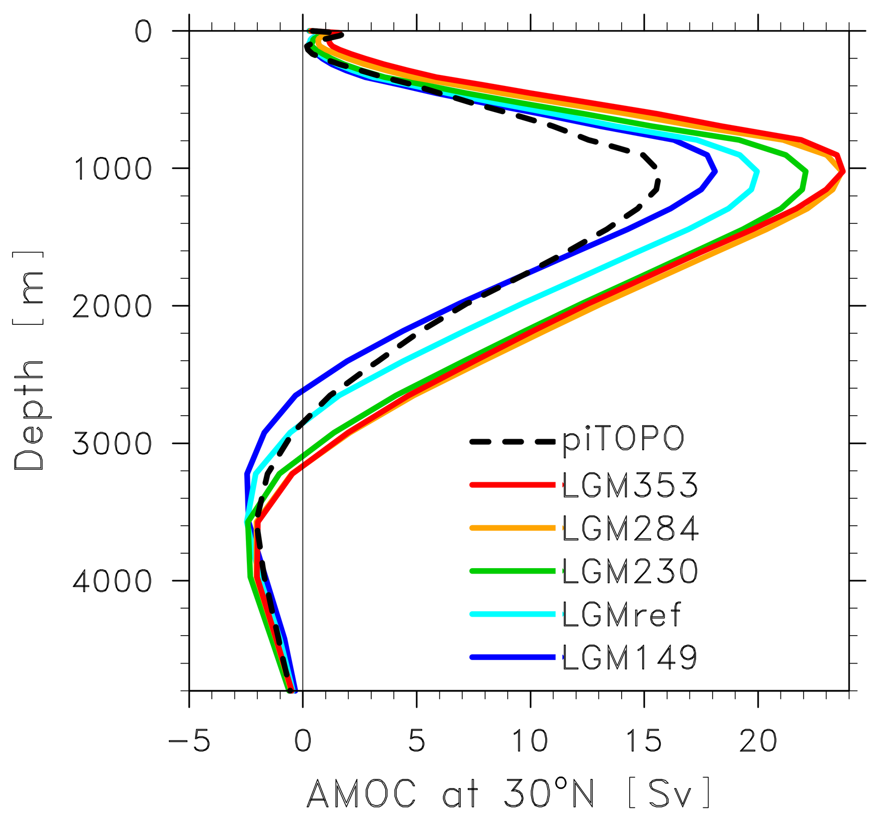


Fig. 3 AMOC profile at 30ºN.

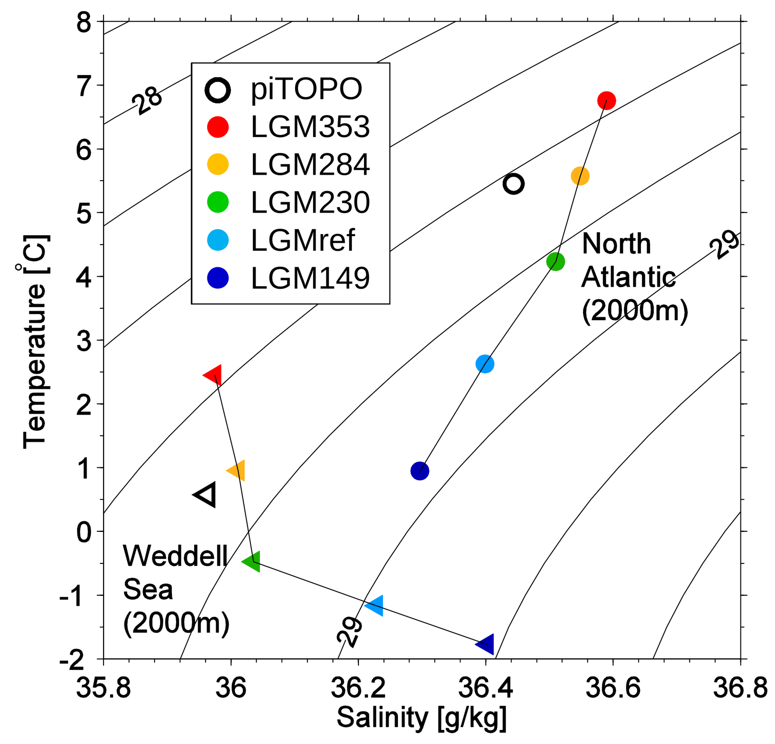


Fig. 4 Temperature and salinity corresponding to the spatial maximum density in the Weddell Sea and the North Atlantic. Contours denote potential density σ_θ.

Below a pCO_2 of 284 ppm, the strength of the NADW cell begins to decrease with decreasing pCO_2 (Fig.3). Shoaling of the NADW cell sets in only below 230 ppm when AABW becomes denser than NADW (Fig.4). A NADW cell which is substantially shallower than for present-day conditions is only simulated with a pCO_2 of 149 ppm. The shoaling coincides with a reversal of the north-south salinity gradient: AABW becomes saltier than NADW.

5. Brine release in the Southern Ocean

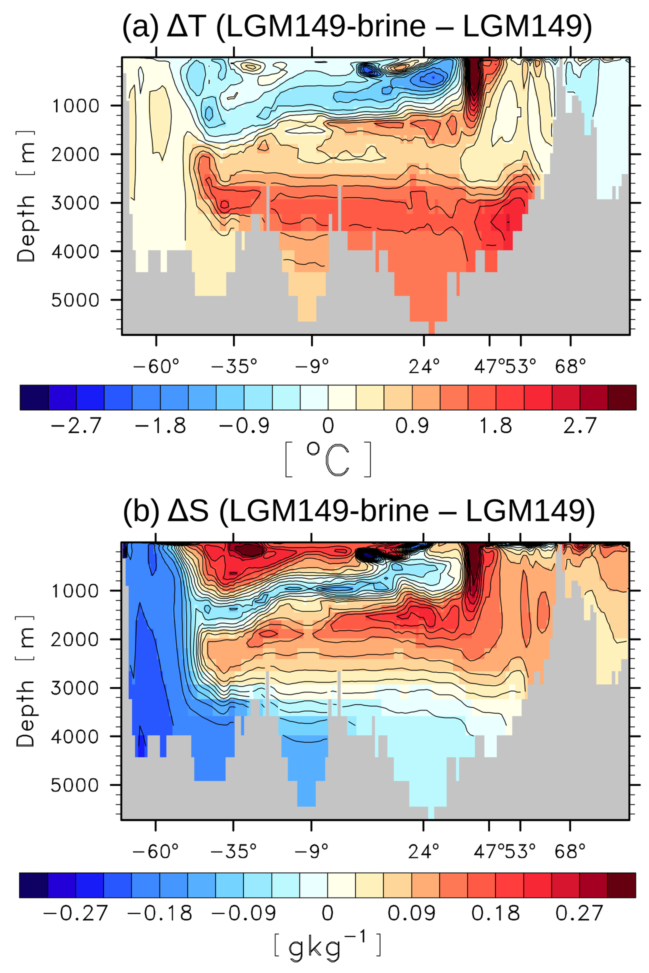


Fig. 5 North-south section of temperature and salinity differences induced by the reduced brine release (LGM149 -brine – LGM149).

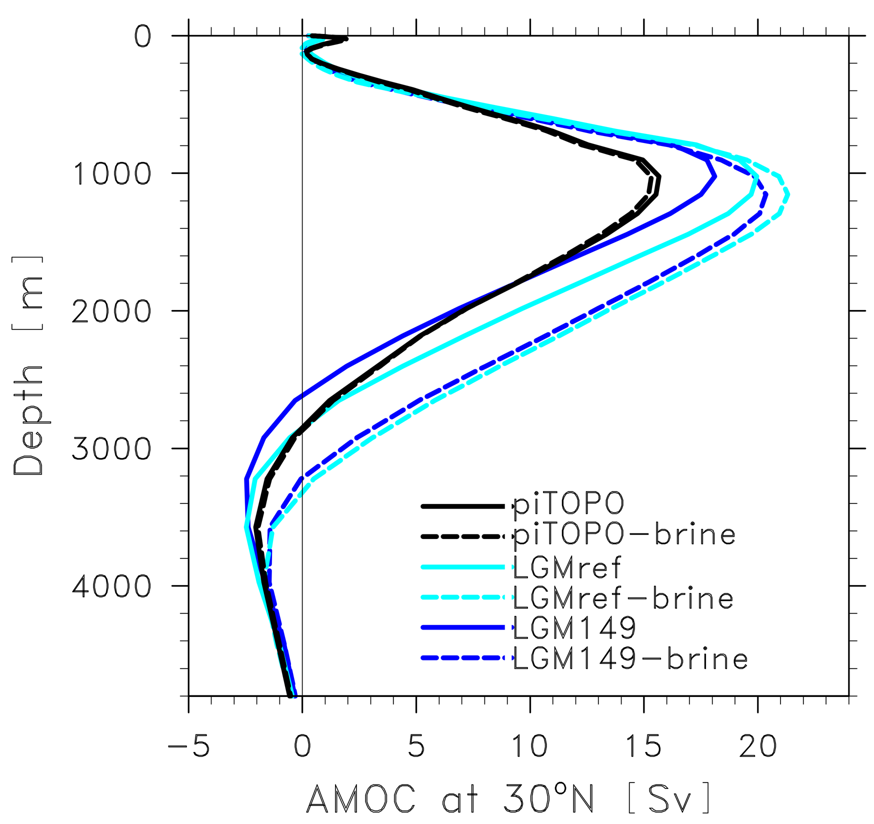


Fig. 6 AMOC profile at 30ºN. Simulations with reduced brine release are indicated by the dashed lines.

The salinity increase in the Weddell Sea below a pCO_2 of 230 ppm is caused by increased brine release and shelf convection (not shown). Sensitivity experiments in which the brine release in the Southern Ocean has been reduced by approximately 50 % show that brine release is key to the shoaling of the NADW cell in low pCO_2 environments.
With reduced brine release, the fraction of NADW below 3000m in the North Atlantic increases (Fig.5). This goes together with a deepening and strengthening of the NADW cell and a weakening of the AABW cell (Fig.6). At higher pCO_2, the effect of the reduced brine release on the overturning is small (compare piTOPO and piTOPO-brine in Fig.6).

6. Conclusions

- The small net effect of the total glacial forcing on the vertical extent of the NADW cell is the result of two larger opposing effects: shoaling in response to the low GHG concentrations and deepening in response to the ice sheets.
- A NADW cell which is substantially shallower than today can be simulated with a pCO2 of 149 ppm.
- Brine release in the Southern Ocean is key to the shoaling.

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* Read the full story in:
Klockmann et al, The effect of greenhouse gas concentrations and ice sheets on the glacial AMOC in a coupled climate model, *Clim. Past Discuss.*, in review, 2016.

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[2] Muglia and Schmittner (2015), *GRL*, 42
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