



# Surface wind-stress threshold for glacial Atlantic overturning

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## 1. Introduction

Investigating the response of the Atlantic meridional circulation (AMOC) at the last glacial maximum (LGM, ca. 21 kyr BP) requires assessing its driving mechanisms, surface winds and vertical mixing [Kuhlbrodt et al., 2007], at the time. Glacial wind-stress is presently poorly constrained. Here we assess the impact of this uncertainty on the glacial AMOC strength (Montoya and Levermann 2008).

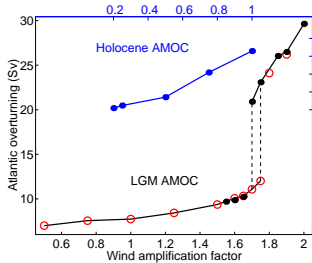
## 2. Glacial simulation

The model used is CLIMBER-3 $\alpha$  [Montoya et al., 2005]. For the LGM, the PMIP2 boundary conditions were imposed (insolation changes, an equivalent atmospheric CO<sub>2</sub> concentration of 167 ppmv, the Peltier [2004] ICE-5G ice-sheet reconstruction, and land-sea mask changes), plus a global salinity increase of 1 psu.

The model was integrated to equilibrium with the Trenberth et al. [1989] surface wind-stress climatology multiplied globally by a factor  $\alpha \in [0.5, 2]$  (LGM $\alpha$ ). To assess the potential of multiple stable states, equilibrium simulations with either  $\alpha = 1$  or  $\alpha = 2$  (LGM $\alpha$ -weak and LGM $\alpha$ -strong, respectively) were used as initial conditions.

## 3. AMOC threshold behavior

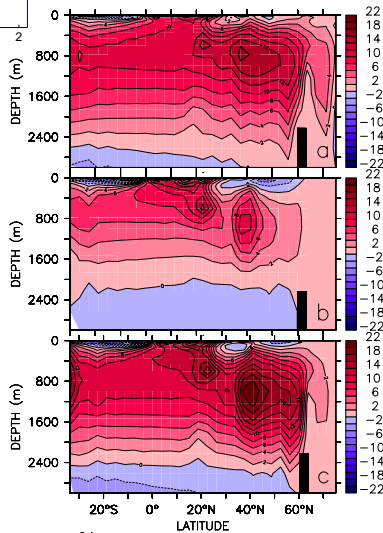
For  $\alpha < 1.7$ , the AMOC strength increases continuously with the surface wind-stress. At  $\alpha = \alpha_c \approx 1.7$  a threshold, associated with an AMOC increase of more than 10 Sv, is observed for the LGM (Figures 1, 2). In the vicinity of this threshold ( $\alpha = 1.7-1.75$ ) the AMOC exhibits two stable states, with weak and strong circulation, respectively. For HOLO, in contrast, the overflow increases continuously with wind-stress and the AMOC strength increase with the wind-stress is roughly linear.



**Figure 1**  
AMOC strength (in Sv) as a function of wind-stress amplification factor  $\alpha$

For  $\alpha < 1.7$ , the simulated glacial AMOC strength of up to 11 Sv (Figure 2b) is consistent with paleodata indicating glacial AMOC rates ranging from up to 30% lower to slightly larger than present [Marchal et al., 2000]. Deep water formation (DWF) takes place south of the Greenland-Scotland ridge.

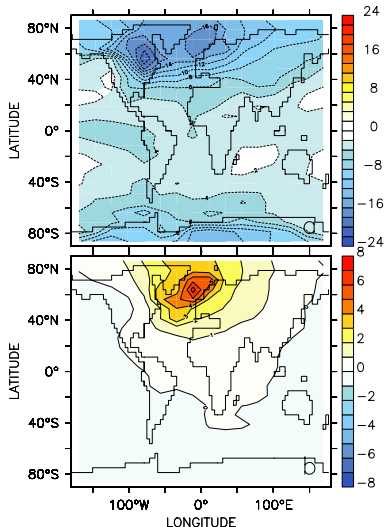
**Figure 2**  
AMOC for a) HOLO, b) LGM1.7-weak, c) LGM1.7-strong (in Sv).



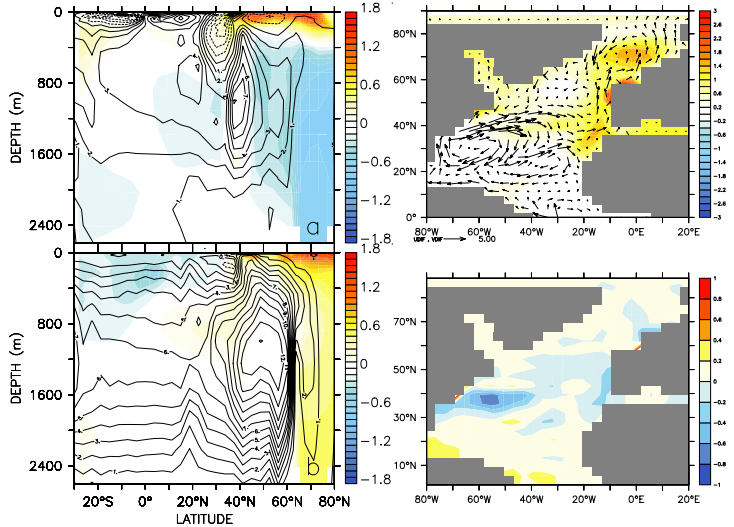
In LGM1.7-weak, surface air temperature (SAT) shows an overall decrease with respect to the HOLO (Figure 1a). In LGM1.7-strong Nordic Seas' SATs increase by up to 8 K relative to LGM1.7-weak (Figure 1b). In the North Atlantic both pattern and magnitude of the simulated temperature difference between strong and weak AMOC states are consistent with those expected during abrupt climate changes of the last glacial period, in particular Dansgaard-Oeschger (DO) events.

**Figure 3**

Mean SAT difference  
a) LGM1.7-weak minus HOLO and b) LGM1.7-strong minus LGM1.7-weak (K).



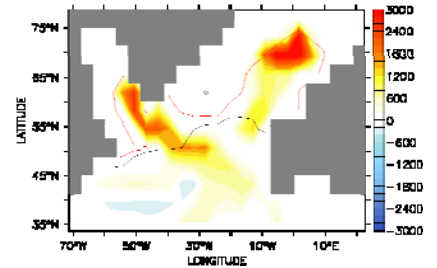
The LGM nonlinear behavior is related to the existence of DWF in the Nordic Seas and a vigorous overflow (Figure 2c). Enhanced surface wind-stress increases the horizontal subtropical and subpolar gyres. More salt is transported from the Tropics to the North Atlantic in the upper ocean layers. The section of salinity difference between LGM1 and LGM1.7-weak (Figure 4a) shows gyres transport more saline waters from the tropics northward of 30N within the upper 350m. Higher subtropical SSTs also result in reduced freshwater flux through enhanced evaporation (Figure 5b) and thereby higher subtropical surface salinities, but the relevant mechanism at high northern latitudes is increased salt transport (Figure 5a).



**Figure 4** Difference in salinity (in psu) and overturning streamfunction (in Sv) in the Atlantic: (a) LGM1.7-weak minus LGM1 and (b) LGM1.7-strong minus LGM1.7-weak. Contour interval is 1 Sv.

**Figure 5** Difference in a) salinity (in psu) and surface currents (in cm/s), averaged over the upper 300m and b) net atmospheric freshwater flux (precipitation minus evaporation plus runoff, in m/yr) (LGM1.7-weak minus LGM1).

For  $\alpha > 1.7$  the gyre salinity transport to the Nordic Seas induces DWF there (Figure 6) and strengthens the AMOC. The enhanced overturning triggers the positive salt-advection feedback. The stronger AMOC is associated with a stronger North Atlantic current and poleward heat transport. Together with the strong decrease in seaice concentration (Figure 6) and the positive sea-ice albedo-temperature feedback this leads to Nordic Seas' SATs increased by up to 8 K relative to LGM1.7-weak (Figure 1b).



**Figure 6** LGM1.7-strong minus LGM1.7-weak difference in maximum mixed-layer depth (in m) locations of 80% winter sea-ice concentration (LGM1.7-weak: black; LGM1.7strong: red)

Additional runs were carried out with  $\alpha = 2$  only in the Northern Hemisphere, North Atlantic mid-high latitudes, or Southern Ocean. Only the first run yielded a relatively strong AMOC of ca. 20 Sv with DWF in the Nordic Seas. Thus, although the role of the winds further south is not negligible, enhanced wind-stress in the whole North Atlantic is critical.

## 4. Conclusions

The glacial AMOC strength increases with the surface winds, exhibiting a threshold behavior with respect to these.

In the North Atlantic both pattern and magnitude of the simulated temperature difference between strong and weak AMOC states are consistent with those expected during DO events.

If the glacial climate were close to a threshold, small changes in surface wind strength might promote DWF in the Nordic Seas and induce large regional temperature anomalies associated with strong sea ice retreat. Our results thus point to a potentially relevant role of surface wind strength changes in glacial abrupt climate change.

## References

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