Enhanced mid-depth southward transport in the Northeast Atlantic at the Last Glacial Maximum

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Abstract

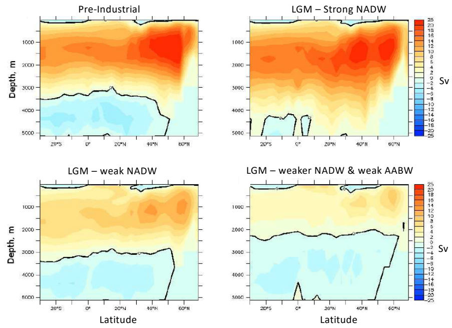
While previous studies consistently suggest that North Atlantic Deep Water (NADW) was shallower at the Last Glacial Maximum (LGM) than at pre-industrial, its strength is still controversial.
Here, using a series of LGM experiments, we show that proxy records are consistent with a shallower and ~40% weaker NADW, associated with a ~3º equatorward shift of the sea-ice edge and convection sites in the Norwegian Sea. A shoaling and weakening of NADW further allow penetration of Antarctic Bottom Water (AABW) in the North Atlantic, despite its transport being reduced by ~40%. While the deep western boundary current in the Northwest Atlantic weakens with NADW, the mid-depth southward flow in the Northeast Atlantic can strengthen, consistent with paleo-records. This Northeast Atlantic intensification is due to a change in density gradients associated with enhanced AABW incursion into the North Atlantic. This weaker LGM oceanic circulation would have reduced the atmospheric CO_2 concentration.

Method

A series of LGM experiments are performed with the Earth System Model LOVECLIM, which includes carbon isotopes and ε_{Nd}. NADW and AABW transports are modulated by meltwater input into the North Atlantic and Southern Ocean, as well as by weakening the Southern Hemispheric westerly winds.

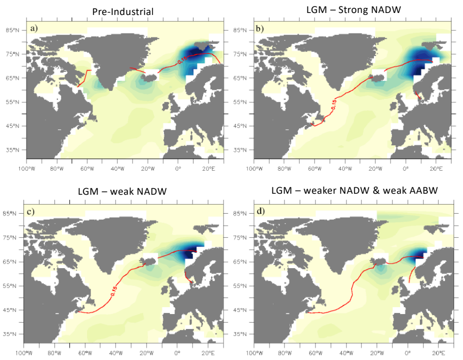
Experiment	Climate	North Atlantic meltwater	Southern Ocean meltwater/ westerlies
PI	Pre-industrial	-	-
LGM – Strong NADW	LGM	-	-
LGM weak NADW	LGM	0.1 Sv	-
LGM weaker NADW & weak AABW	LGM	0.1 Sv	0.07 Sv / -20%

Atlantic Meridional Overturning Streamfunction



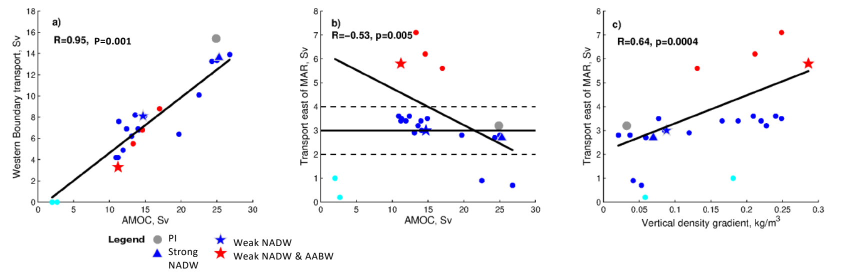
Convection sites and sea-ice

Winter mixed layer depth (m, shaded) and 15% sea-ice concentration contour (red line)



- As the AMOC weakens (b to d), the convection site and sea-ice edge shift southward
- No deepwater formation in the Labrador Sea at the LGM

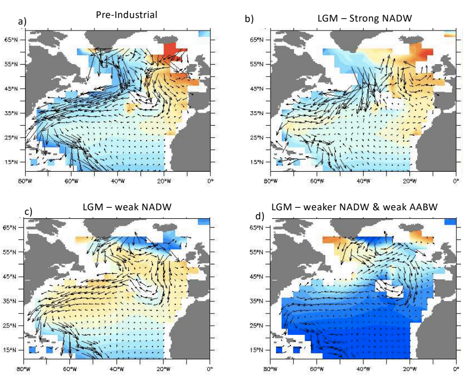
Relationships between AMOC, deep western boundary currents and stratification



(a) As the AMOC weakens, so does the deep western boundary current
(b) However, the mid-depth southward transport on the east side of the Mid-Atlantic Ridge (MAR) strengthen as the AMOC weakens and NADW becomes shallower
(c) This strengthening on the east side of the MAR is associated with an increase in vertical density gradient

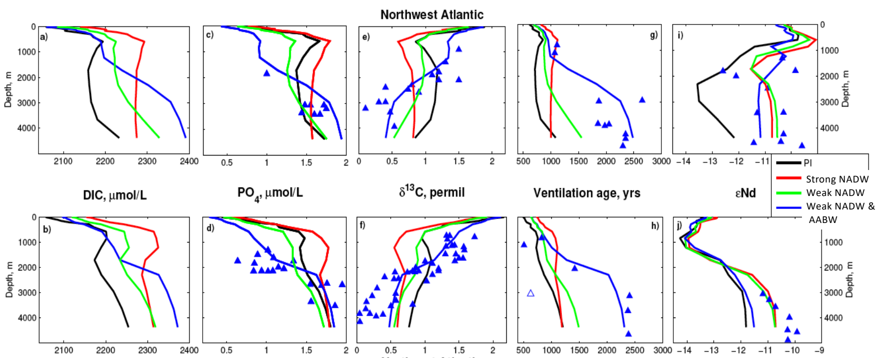
Mid-depth currents

Mid depth (1450-2600m) potential vorticity anomalies ($m^{-1}.s^{-1}$, shaded) and ocean currents



(a,b) Strong zonal potential vorticity gradient at ~50N inhibits the zonal flow and directs the flow towards the deep western boundary current.
(d) The zonal potential vorticity gradient at ~50N is weak, thus allowing the NADW to flow on the east side of the Mid-Atlantic ridge.

Vertical tracer profiles and comparison with proxy records



The blue triangles indicate LGM (c,d) PO4 estimates from Cd/Ca measurements (Marchitto et al., 2006), (e,f) benthic $\delta^{13}C$ (Peterson et al., 2014), (g,h) ventilation age estimates from benthic foraminifera (filled triangles from Skinner et al., (2017) and empty triangle from Balmer & Sarnthein (2018)), and (i,j) ε_{Nd} data (Foster et al., 2007, Gutjahr et al., 2008, Roberts et al., 2010, Bohm et al., 2015, Howe et al., 2016, Lang et al., 2016, Lippold et al., 2016, Howe et al., 2017).

- Best agreement between modelling results and paleoproxy records is obtained for a LGM simulation with weaker NADW and AABW (~-40%)
- As NADW becomes weaker and shallower, AABW can reach into both the Northwest and Northeast Atlantic , despite AABW being weaker

Conclusions

- The strength of the deep western boundary current decreases with the AMOC;
- The mid-depth southward transport on the eastern side of the MAR will weaken only when the AMOC is off;
- Shoaling the NADW - AABW boundary, further away from bottom topography, reduces mixing and increases stratification;
- Paleoproxy records from the North Atlantic indicate a strong vertical stratification, that is best simulated in the LGM experiment featuring a weaker NADW and AABW than in pre-industrial;
- A weak oceanic circulation at the LGM leads to a greater deep ocean carbon content