Does Southern Ocean surface forcing shape the global ocean overturning circulation?

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Background

- Upper overturning circulation: clockwise (AMOC)
- Lower overturning circulation: anticlockwise; below ~3000m depth

Lumpkin and Speer, 2007
Background

At the **LGM**:  
- Shoaling of NADW  
- Expansion of AABW  

Reduced CO$_2$ outgassing and stronger carbon sequestration at the LGM (e.g., Watson et al., 2015)

Modified from Curry and Oppo, 2005
Background

Theoretical arguments suggest that the AMOC depth is dynamically linked to the sea ice extent in the Southern Ocean (Ferrari et al., 2014; Burke et al., 2015; Watson et al., 2015).
Background — AMOC in PMIP3

- All models in PMIP3 except for CCSM4 simulate a deeper AMOC despite consistently equatorward extension of Antarctic sea ice coverage in the LGM simulations.

Muglia and Schmittner, 2016
Does Southern Ocean surface forcing shape the global ocean overturning circulation in a comprehensive climate model?
Experimental design

NCAR CESM in ocean-only configuration:

- **Active**: ocean
- **Specified** from output of previous coupled runs: atmosphere, sea ice, land runoff
  - Surface forcing for ocean is specified
Experimental design: surface buoyancy flux

Ocean-only simulations:

PI : Surface forcing from a coupled Pre-Industrial run ($F_{\text{PI}}$)

LGM : Surface forcing from a coupled LGM run ($F_{\text{LGM}}$)

Test : Surface forcing from LGM south of 40°S (purple dashed line) and PI north of 30°S
Results: AMOC depth

Definition of the boundary $\sigma_{bc}(y)$ between the two overturning circulation cells:

$$\psi(y, \sigma_{bc}(y)) = 0$$
Results: AMOC depth

In contrast to previous expectations, the AMOC in the **Test** run shoals only about **half** as much as in the **LGM** run.
The control of Southern Ocean surface buoyancy forcing on the AMOC depth is based on two assumptions:

- Same isopycnal slope in modern as in LGM: \( s \simeq \tau / (\rho_0 f K) \)
- Approximately adiabatic — overturning circulation streamfunction follows isopycnal
Results: Constant isopycnal slope? — Yes!

- **Isopycnal slope does not change substantially** among these three simulations.
Results: Adiabatic? — No!

- **Overturning circulation does not follow isopycnals** in the Southern Ocean
- Zero contours of the streamfunction in Test and LGM start at the same place at base of surface mixed layer but **drift away from each other with depth**.
Results: Adiabatic? — No!

- Overturning circulation does not follow isopycnals in the Southern Ocean
- Zero contours of the streamfunction in Test and LGM start at the same place at base of surface mixed layer but drift away from each other with depth.
Results: Influence of diapycnal mixing on the AMOC depth

Conceptual model (brief overview):

- Stratification: \( N^2 = N_0^2 \exp\left(\frac{z}{H}\right) \)
- Constant isopycnal slope
- Constant diapycnal diffusivity
- Overturning circulation streamfunction at base of mixed layer in the Southern Ocean:

\[
\psi(y, 0) = \psi_s(y) = -\psi_0 \sin(2\pi \frac{y + L_s}{L_s})
\]

Streamfunction at northern boundary of the Southern Ocean:

\[
\psi(0, z) = \psi_s\left(-\frac{z}{s}\right) + \frac{L_x \kappa z}{H s} \sqrt{1 + s^2} \approx \psi_s\left(-\frac{z}{s}\right) + \frac{L_x \kappa z}{H s}
\]
Results: Influence of diapycnal mixing on the AMOC depth

The AMOC gets deeper for stronger diapycnal mixing.
Results — diapycnal diffusivity in observations

- Enhanced diapycnal mixing over rough topography in vast regions of the Southern Ocean could diminish the influence of Southern Ocean surface forcing on the AMOC depth.

- Diagnosed diapycnal diffusivity within the range of observations (e.g., Waterhouse et al., 2014)
Summary: Schematic diagrams

Adiabatic (Ferrari et al., 2014) vs. Diabatic (this study)

(a) Adiabatic:
- PI
- 80S to 40S
- 70N
- NADW
- AABW

(b) Diabatic:
- PI
- 80S to 40S
- 70N
- NADW
- AABW

(c) LGM
- PI
- 80S to 40S
- 70N
- NADW
- AABW

(d) LGM
- PI
- 80S to 40S
- 70N
- NADW
- AABW
Summary

- We tested the influence of Southern Ocean surface buoyancy forcing on the AMOC depth in a state-of-the-art climate model

- Applying LGM surface forcing in the Southern Ocean shoals the AMOC only about half as much as previously expected

- Diapycnal mixing in the Southern Ocean renders the circulation more diabatic than previously assumed in some idealized studies
Diapycnal mixing: physical or numerical?

Profiles of the model-reported diapycnal diffusivity (60°S-40°S)

- Diapycnal diffusivity profile in PI and Test appears to be within the range of observations (e.g., Waterhouse et al., 2014)
- Different diapycnal diffusivity between LGM and Test could account for the different diapycnal mixing between these two simulations
Diagnosed diapycnal transport between 60S and 40S: 6.4 Sv, 7.4 Sv, 9.4 Sv.

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Diapycnal mixing: physical or numerical?

Effective diapycnal diffusivity:

\[ \mathcal{W} \frac{\partial \sigma_2}{\partial z} = \frac{\partial}{\partial z} \left( \kappa_{\text{eff}} \frac{\partial \sigma_2}{\partial z} \right) \]

<table>
<thead>
<tr>
<th>Run name</th>
<th>( \kappa_{\text{eff}} ) (( \times 10^{-4} \text{m}^2/\text{s} ))</th>
<th>( \kappa_{\text{reported}} ) (( \times 10^{-4} \text{m}^2/\text{s} ))</th>
<th>( \kappa_{\text{eff}} / \kappa_{\text{reported}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.88( \pm 0.09 )</td>
<td>0.52( \pm 0.24 )</td>
<td>1.67</td>
</tr>
<tr>
<td>Test</td>
<td>1.73( \pm 0.09 )</td>
<td>0.80( \pm 0.44 )</td>
<td>2.16</td>
</tr>
<tr>
<td>LGM</td>
<td>2.10( \pm 0.08 )</td>
<td>0.72( \pm 0.36 )</td>
<td>2.90</td>
</tr>
</tbody>
</table>

* Calculated on isopycnals in the last slide and averaged between 60°S and 40°S

- Uncertainties exist in the estimate of effective diapycnal diffusivity due to use of monthly-mean data (e.g., Reynolds averaging effects)
- Reported diapycnal diffusivity alone could be sufficient to substantially change the AMOC depth