Deciphering the climate impacts of a weakened Atlantic Meridional Overturning Circulation during the 21st century

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AMOC observation and projection

Scientific question: What is the role of the AMOC in future climate change?

Problems: Under anthropogenic warming, this AMOC slow-down occurs along with variations in other parts of the climate system. Therefore, within a fully coupled climate system, it is difficult to separate the effect of AMOC slowdown on climate from the effects of other varying and interacting climate components.
CCSM4 sensitivity experiment

- Freshwater removal from the subpolar North Atlantic covering deep water formation regions.

- CCSM4 is a fully coupled, broadly used IPCC AR5 climate model.
- We use CCSM4 historical + RCP 8.5 simulation, 5 ensemble members (< 1980, purple; > 1980, green).
- Sensitivity experiment (since 1981, hist+RCP8.5 forcing but with fixed AMOC, 1981-2100, purple), 5 ensemble members.
The vanishing North Atlantic warming hole (NAWH)

A-C The impact of the weakened AMOC

For future projections, the emergence of the NAWH is largely attributed to the weakening of the AMOC, especially considering the relatively weak AMOC slowdown so far.

Specifically, fresh water is removed from the broad deep-water formation region in the subpolar North Atlantic (fig. S1), causing an increase in upper-ocean salinity and hence density, which compensates the density reduction due to surface warming and other factors that contribute to the weakening of the AMOC. This so-called North Atlantic warming hole (NAWH) has been found in both historical observations and IPCC AR5 projections, significant at the 95% confidence level of Student’s t-test. AMOC impacts on surface temperature and precipitation are revealed in (E) and (F).

CCSM4 experiments show that the weakened AMOC primarily accounts for the NAWH in the 21st century.
The physical mechanism

Heat budget analysis on the full-depth water column in 48-60°N in the North Atlantic

\[ \iint_{V} \left( \rho C_p \frac{\partial \theta}{\partial t} \right) dv' = \iint_{S} (shf) ds' - \iint_{V} \left\{ \rho C_p \left[ \nabla \cdot (v\theta) \right] \right\} dv' + \iint_{V} (diff) dv' \]

<table>
<thead>
<tr>
<th>Heat budget term</th>
<th>Difference (PW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEN</td>
<td>-0.031</td>
</tr>
<tr>
<td>SHF</td>
<td>0.074</td>
</tr>
<tr>
<td>D</td>
<td>-0.002</td>
</tr>
<tr>
<td>-ΔOHT</td>
<td>-0.103</td>
</tr>
<tr>
<td>OHT(S)</td>
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</tr>
<tr>
<td>OHT(N)</td>
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<tr>
<td>OHT_{Eul}(S)</td>
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<tr>
<td>OHT_{ed+sub}(S)</td>
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<tr>
<td>OHT_{ev}</td>
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<tr>
<td>OHT_{az}</td>
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<tr>
<td>OHT_{Eul}(N)</td>
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<tr>
<td>OHT_{ed+sub}(N)</td>
<td>0.017</td>
</tr>
</tbody>
</table>

The cooling is primarily caused by the reduced net meridional ocean heat transport, which is mainly due to the weakening of the AMOC.
AMOC impacts on rainfall projection

- The weakened AMOC causes **reduced** precipitation over the NAWH region
- It also induces a **southward** shift of ITCZ, but not the leading mode of tropical precipitation projection.

**Weakened AMOC**

**B-D**

The impact of the weakened AMOC

**Fixed AMOC**

**F**
- Enhanced ocean heat uptake, primarily via turbulent heat fluxes, in the North Atlantic drives a northward cross-equatorial atmospheric energy transport, which explains the southward ITCZ shift.

- This enhanced ocean heat uptake acts to damp the anomalous SST cooling in the North Atlantic, i.e., a negative feedback.
Delayed Arctic summer ice-free time

Weakened AMOC

Fixed AMOC

Summer Arctic ice-free time is delayed by 6 years due to the weakened AMOC.
The zonally averaged zonal wind response to the AMOC slowdown displaces the Northern Hemisphere westerly jets poleward during boreal winter.
AMOC impacts on global marine heatwaves (MHWs)

1981-2020

- AMOC impacts on MHWs are insignificant during 1981-2020 except the NAWH but become significant in the North Atlantic and North Pacific by 2100.
- The NAWH region would reach a near-permanent MHW state over 2061-2100 without a slowdown of the AMOC.
Conclusion

• The projected AMOC slowdown causes the NAWH to the south of Greenland, along with local reduced precipitation and enhanced ocean heat uptake.

• The weakened AMOC explains a reduction in Arctic sea ice loss in all seasons and, in particular, a delay by about 6 years of the emergence of an ice-free Arctic in boreal summer.

• In the troposphere, a weakened AMOC causes an anomalous cooling band stretching from the lower levels in high latitudes to the upper levels in the tropics and displaces the Northern Hemisphere midlatitude jets poleward.

• The AMOC slowdown will have significant impacts on MHWs in the North Atlantic and North Pacific by 2100. The NAWH region would reach a near-permanent MHW state over 2061-2100 without a slowdown of the AMOC.
Thank you!
