Impacts of Atlantic Meridional Overturning Circulation Weakening on Arctic Amplification

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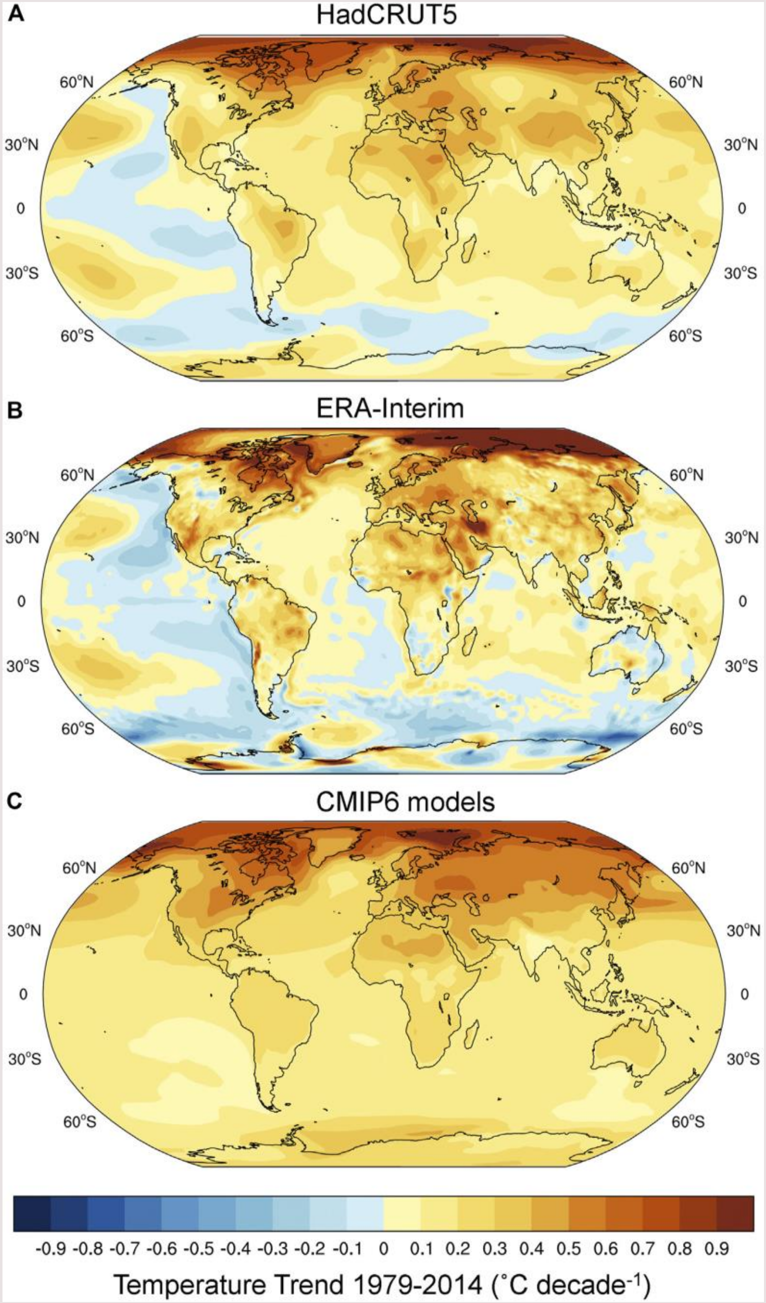
Background

Arctic Amplification

The phenomenon whereby the surface air temperature in the Arctic warms at an enhanced rate relative to the rest of the globe.

First identified in Manabe and Wetherald (1975)

It is believed to be one of the most robust features of the climate system‘s response to external forcings.

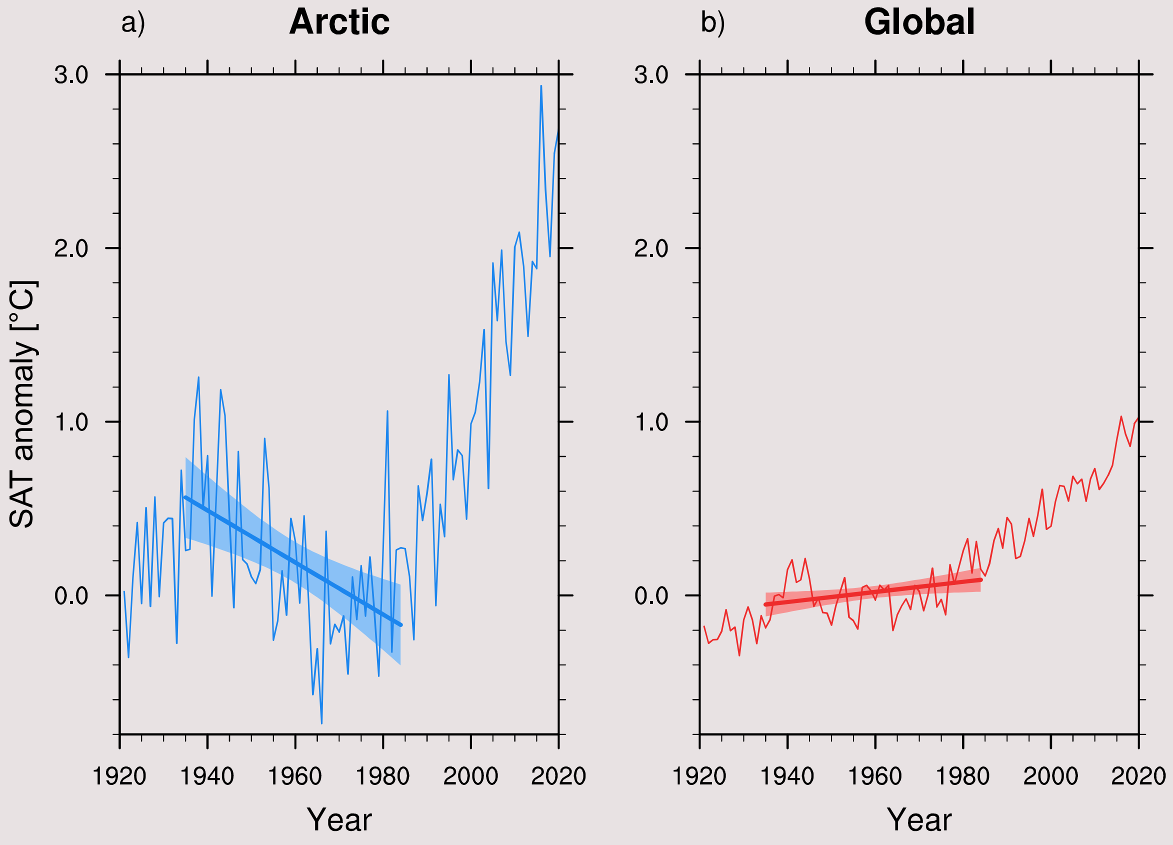


A: station-based observation
B: reanalysis
C: model simulation

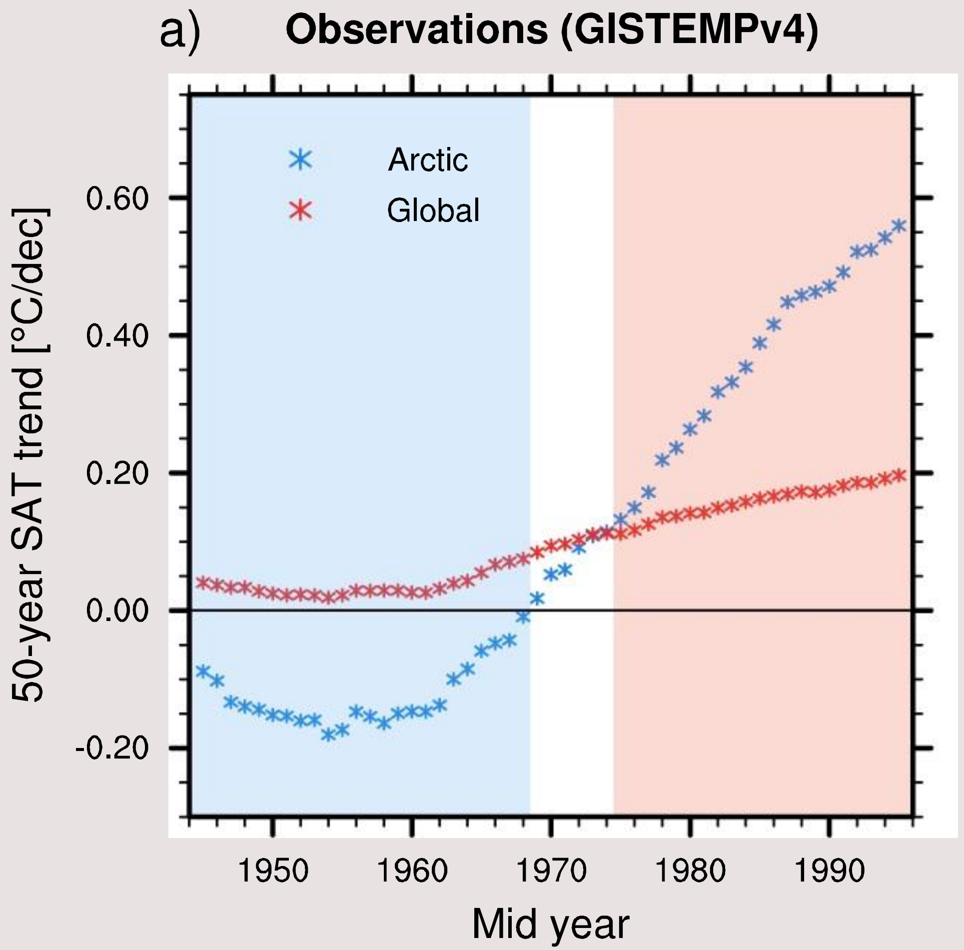
Hahn et al., 2021, Frontiers in Earth Science

Background

Actually, the Arctic Amplification is only a recent phenomenon…



The switch from Arctic cooling to Arctic amplified warming was rapid, transitioning in less than five years.



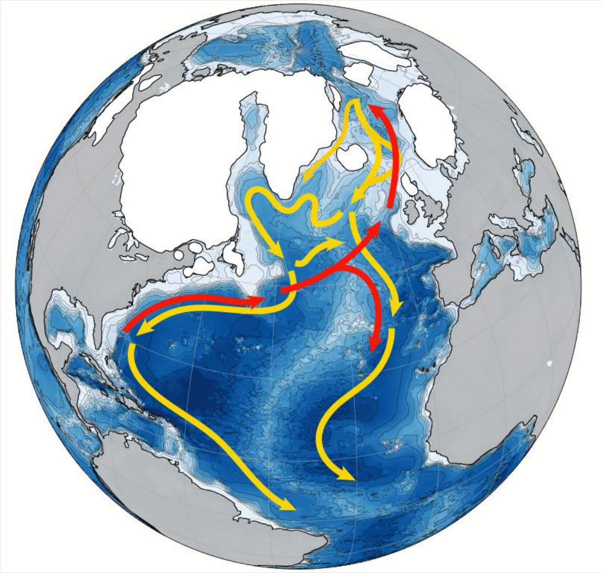
GISTEMPv4: observations

Anomalies relative to the mean temperature during the period 1951-1980

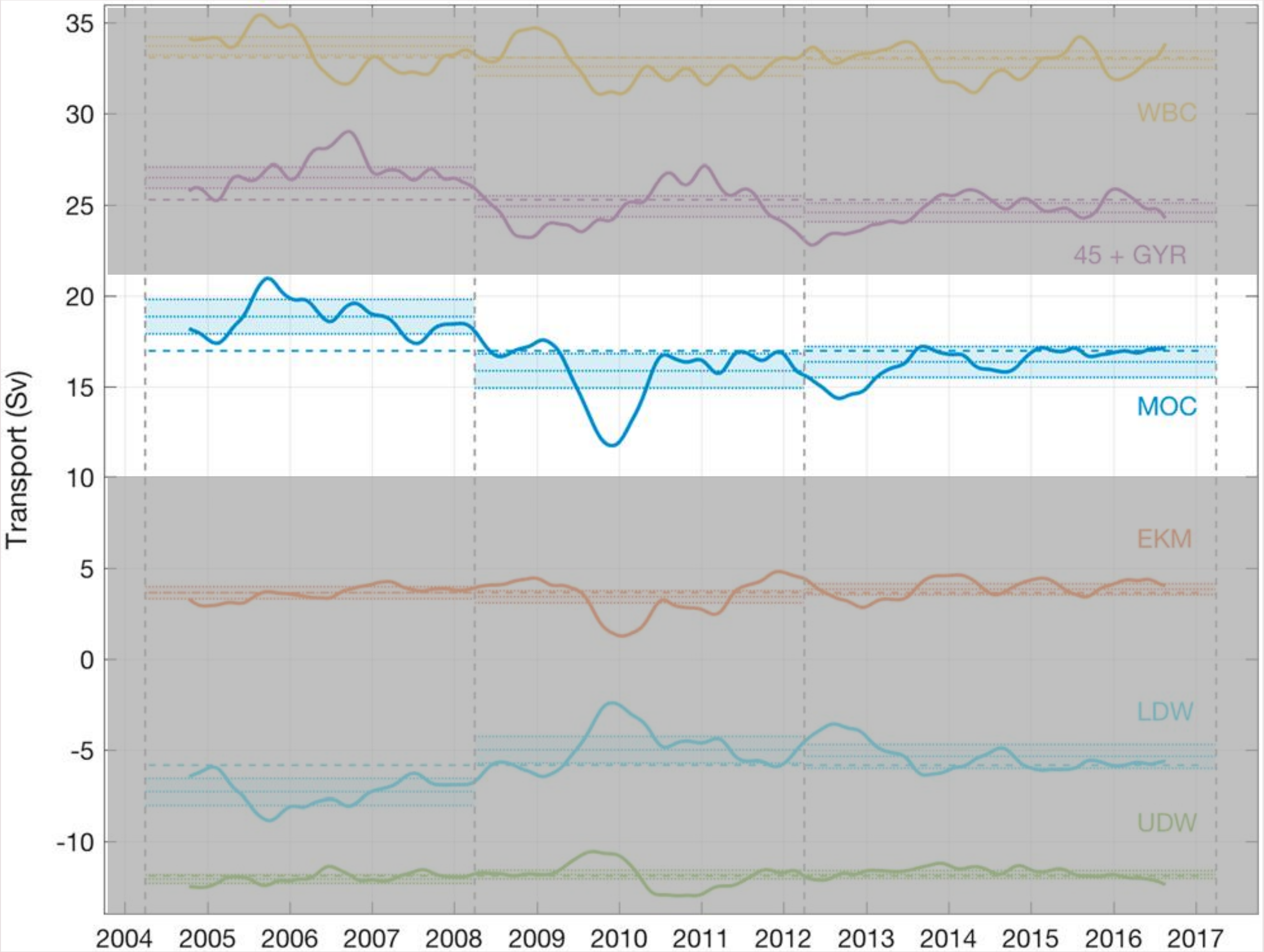
England et al., 2021, GRL

Background

With the observed weakening in the Atlantic Meridional Overturning Circulation (AMOC), we would like to understand the role of AMOC weakening in Arctic Amplification.



Credit: Francesco Muschitiello/Lamont-Doherty Earth Observatory

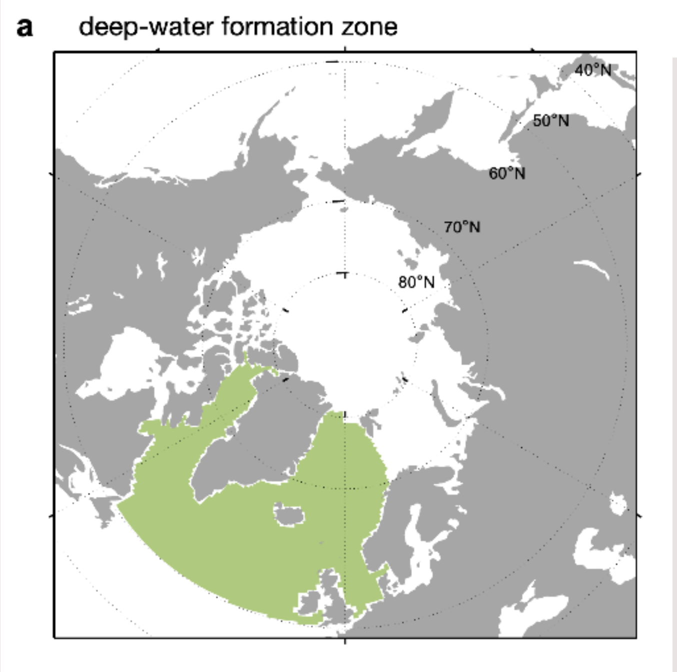


Smeed et al., 2018, GRL

Model Simulations

The Community Climate System Model version 4 (CCSM4)

- Fully coupled: CAM4 (atm), CLM4 (land), CICE4 (ice), and POP2 (ocean)
- Temporal resolution: monthly
- Spatial resolution:
  atm: 288*192 (Lon: 1.25°; Lat: 0.9375°)
  ocean/ice: 320*384

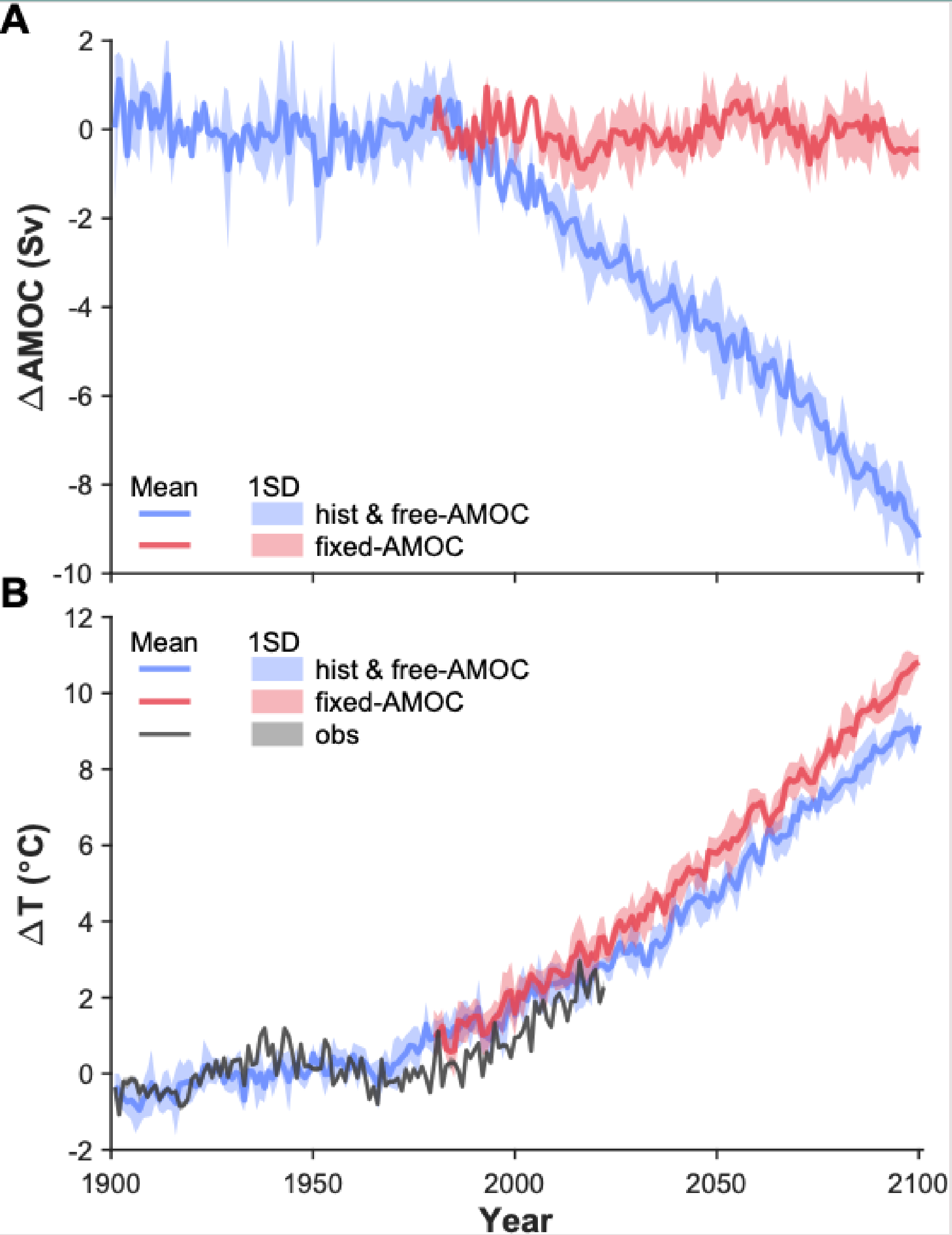


Experiments

RCP8.5 & freshwater removed from north of 50°N in the North Atlantic and the Labrador and Greenland, Iceland, and Norwegian Seas. (**Liu et al., 2020**)

The difference between free- and fixed-AMOC simulations indicates the impact of AMOC weakening.

Model Simulations



A: AMOC strength changes
B: Arctic surface air temperature changes

Anomalies compared to 1901-1980 average

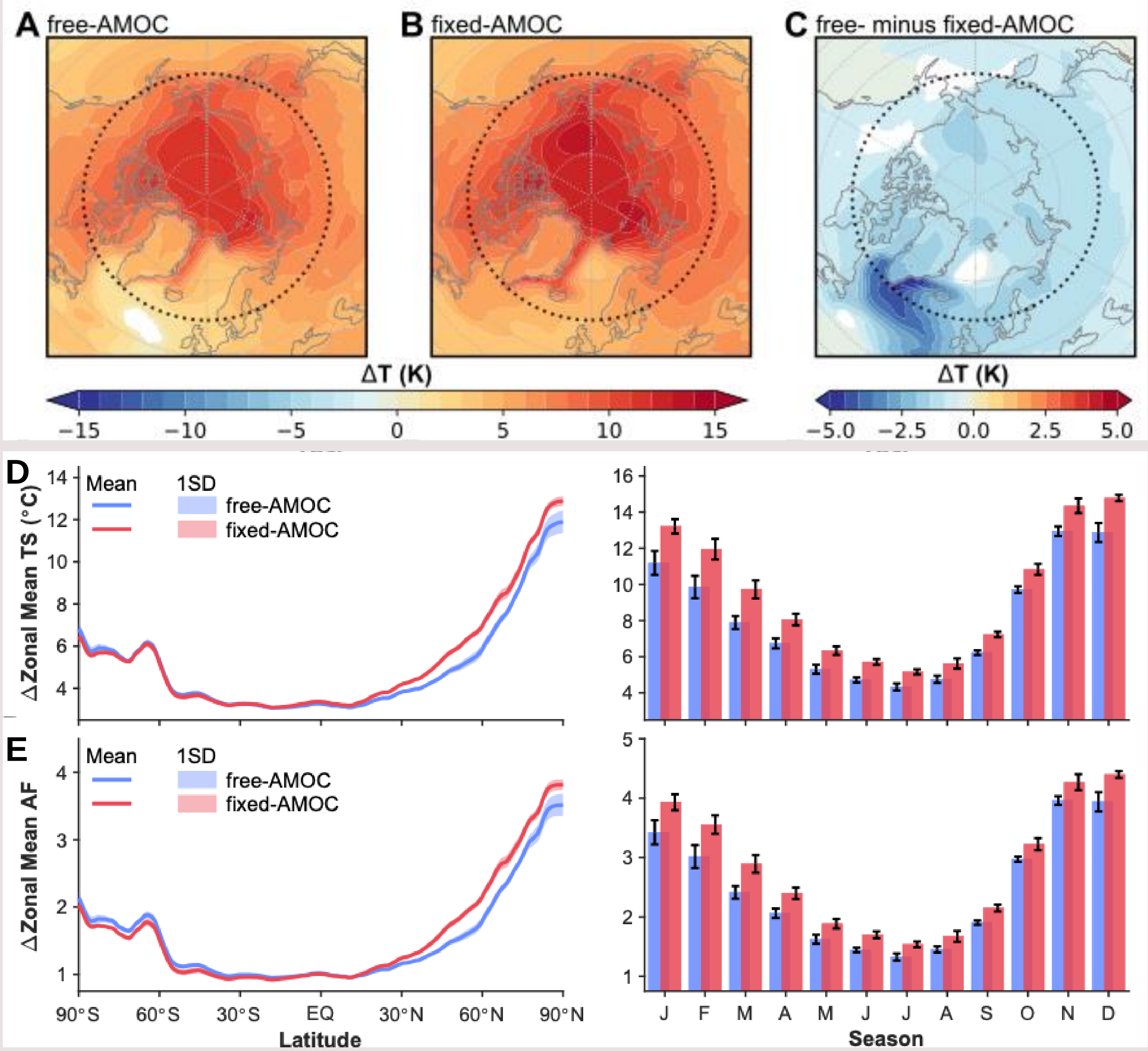
free-AMOC: weakened AMOC
fixed-AMOC: stable AMOC

In both scenarios, we see the Arctic's surface getting warmer under anthropogenic forcing.

The gap in warming between the free- and fixed- AMOC simulations starts to widen after the 2030s and hits its maximum by the end of the 21st century.

For this study, we will focus on the last two decades of the 21st century (2081-2100) to show the impact of AMOC weakening on Arctic Amplification.

Results



A-C: Annual mean surface air temperature changes
D-E: Annual zonal and Arctic (60-90°N) averaged surface temperature and amplification factor (ratio of Arctic to Tropics)

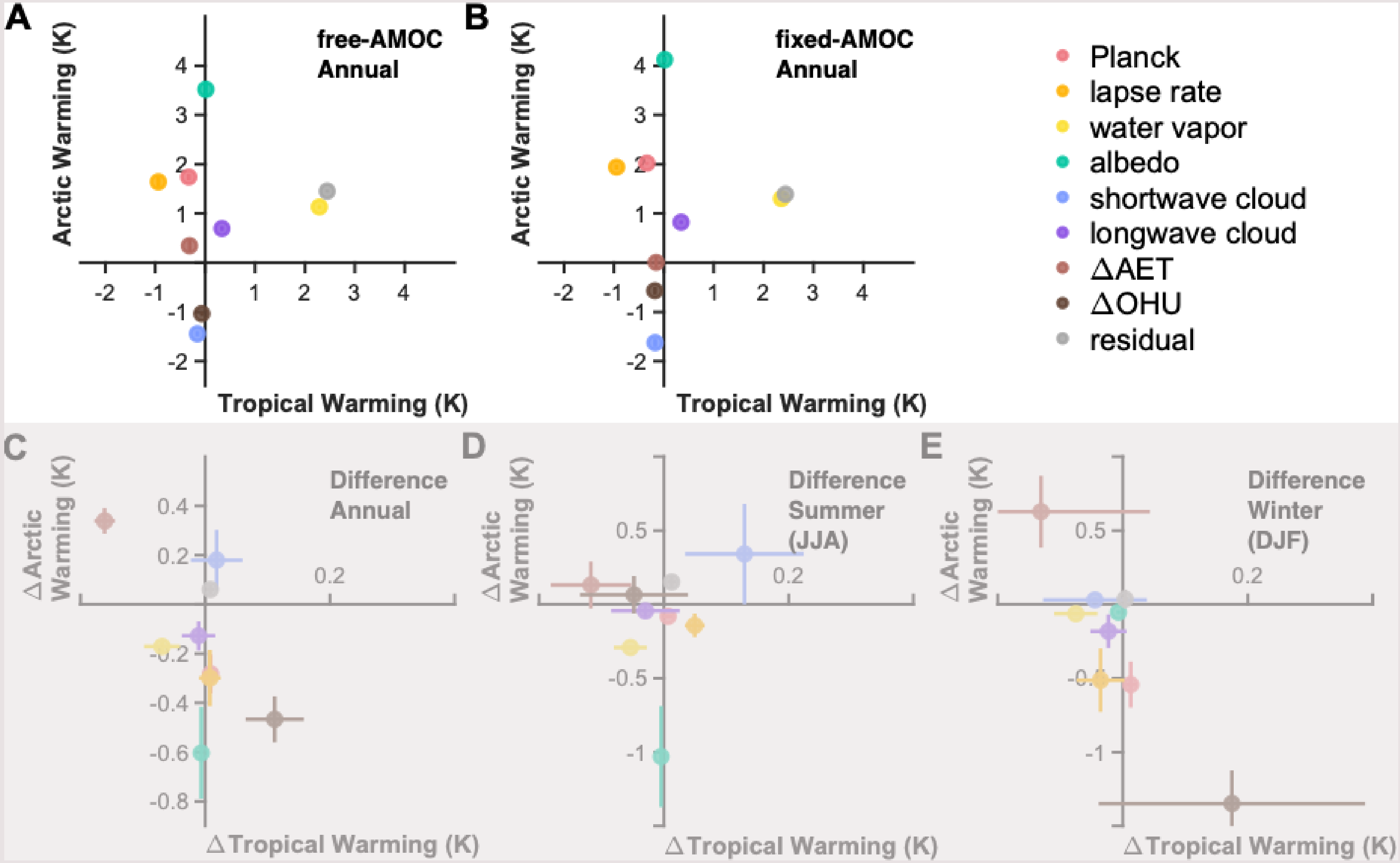
Period: 2081-2100 compared to 1961-1980

When the AMOC is weakened, the Arctic tends to stay cooler compared to conditions where the AMOC remains stable.

Between 2081 and 2100, a weakened AMOC is projected to reduce Arctic warming by **1.37℃**, which corresponds to a **0.36** decrease in the amplification factor.

Seasonally, the AMOC-induced cooling is most prominent during the cold season (Dec to Mar).

Results



Partial temperature contribution

$$\Delta T_s = -\frac{\lambda'_{plk}[\Delta T_s]}{\overline{\lambda_{plk}}} - \frac{\sum_i \lambda_i[\Delta T_s]}{\overline{\lambda_{plk}}} - \frac{\Delta AET}{\overline{\lambda_{plk}}} - \frac{\Delta OHU}{\overline{\lambda_{plk}}} - \frac{\Delta R_{rd}}{\overline{\lambda_{plk}}}$$

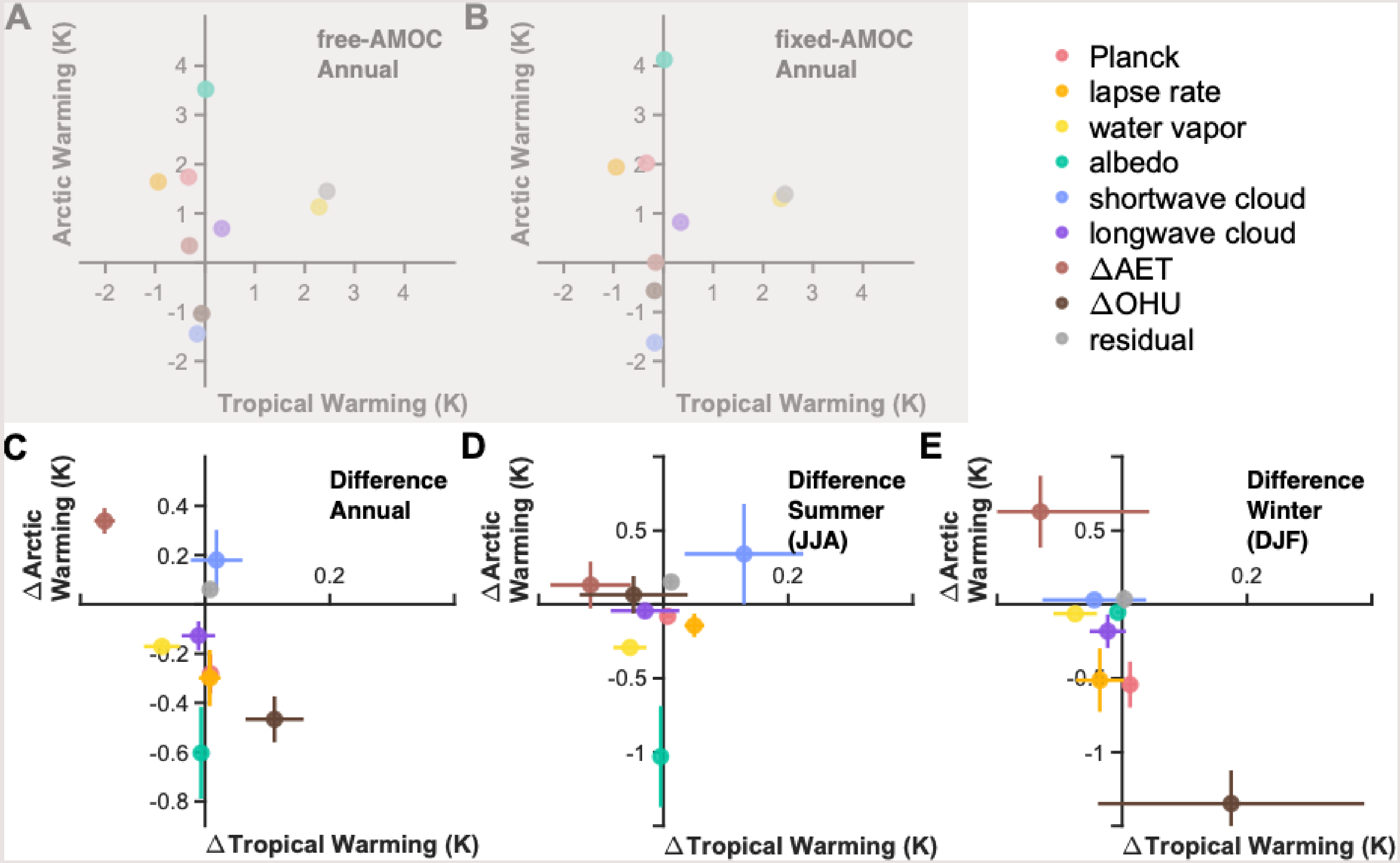
For both free-AMOC and fixed-AMOC simulations, the effects of individual feedback mechanisms are similar, differing only in magnitude.

Period: 2081-2100 compared to 1961-1980

Radiative Kernel: CAM5 from Pendergrass et al. (2018)

Tropic: 30°S-30°N
Arctic: 60°N-90°N

Results



Partial temperature contribution

$$\Delta T_s = -\frac{\lambda'_{plk}[\Delta T_s]}{\overline{\lambda_{plk}}} - \frac{\sum_i \lambda_i[\Delta T_s]}{\overline{\lambda_{plk}}} - \frac{\Delta AET}{\overline{\lambda_{plk}}} - \frac{\Delta OHU}{\overline{\lambda_{plk}}} - \frac{\Delta R_{rd}}{\overline{\lambda_{plk}}}$$

The AMOC weakening reduces the Arctic warming via:

1) Surface albedo feedback (JJA)
2) Ocean heat uptake (DJF)
3) Temperature feedback

And this reduction in warming would be slightly offset by:

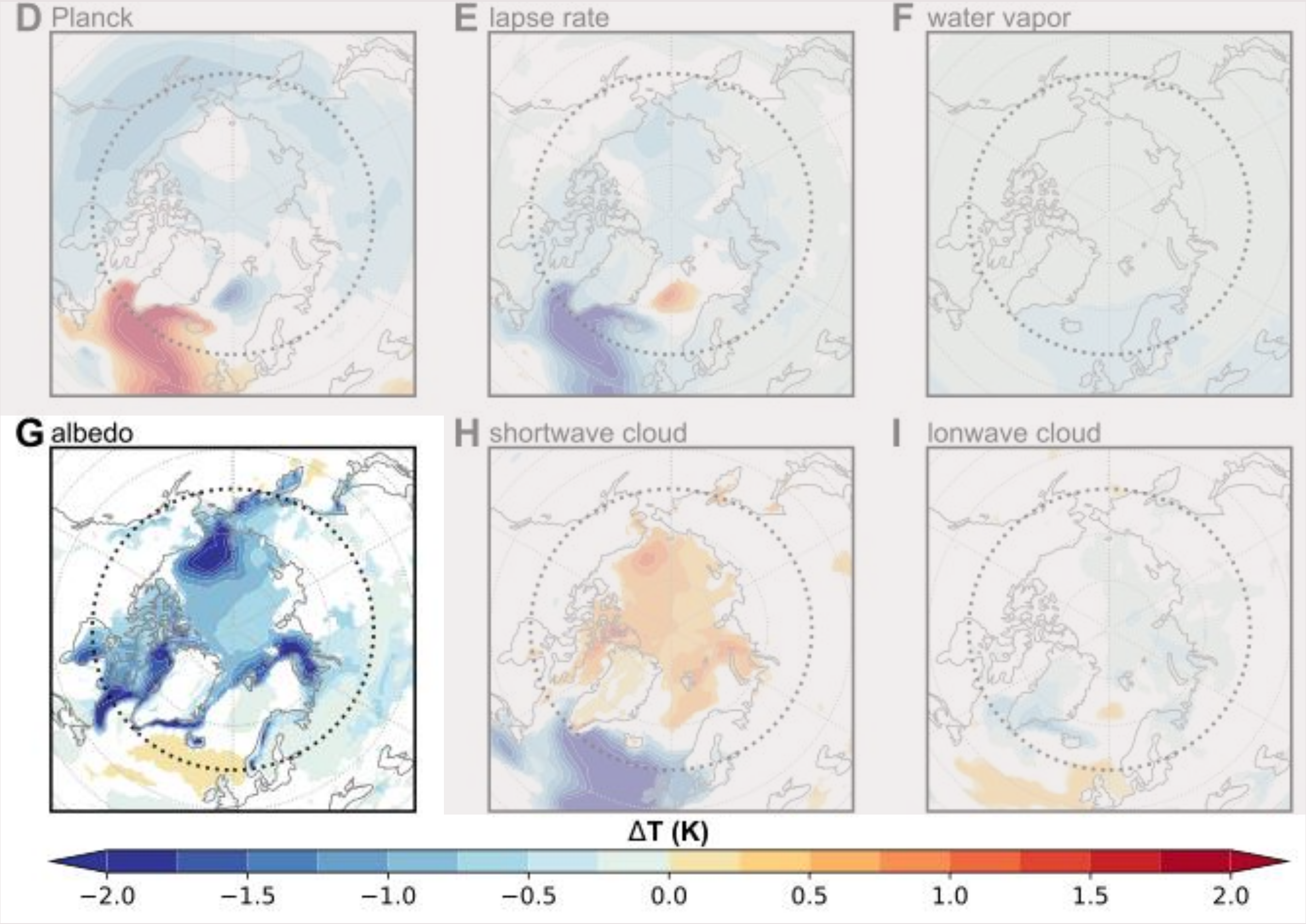
1) Atmospheric energy transport
2) Shortwave cloud feedback

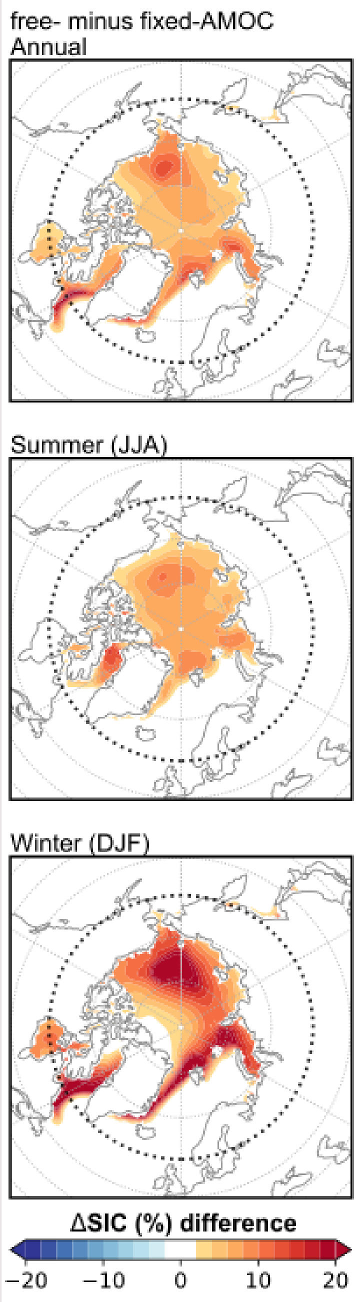
Period: 2081-2100 compared to 1961-1980

Tropic: 30°S-30°N
Arctic: 60°N-90°N

Radiative Kernel: CAM5 from Pendergrass et al. (2018)

Results

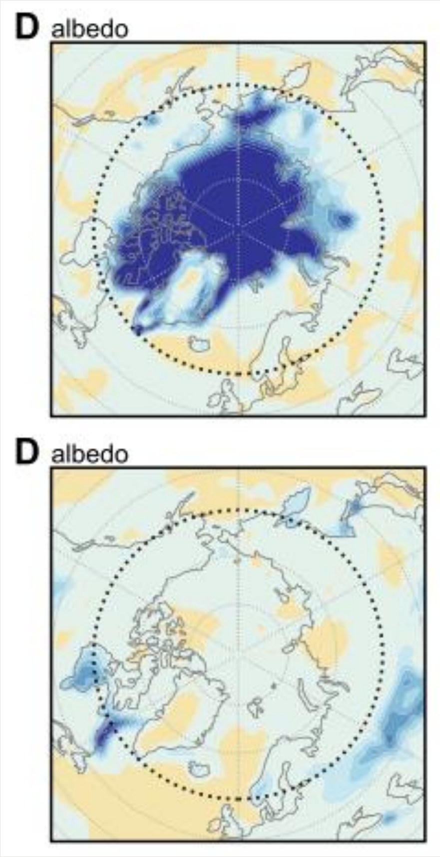




AMOC-induced cooling through albedo feedback is most prominent during boreal summer.

JJA

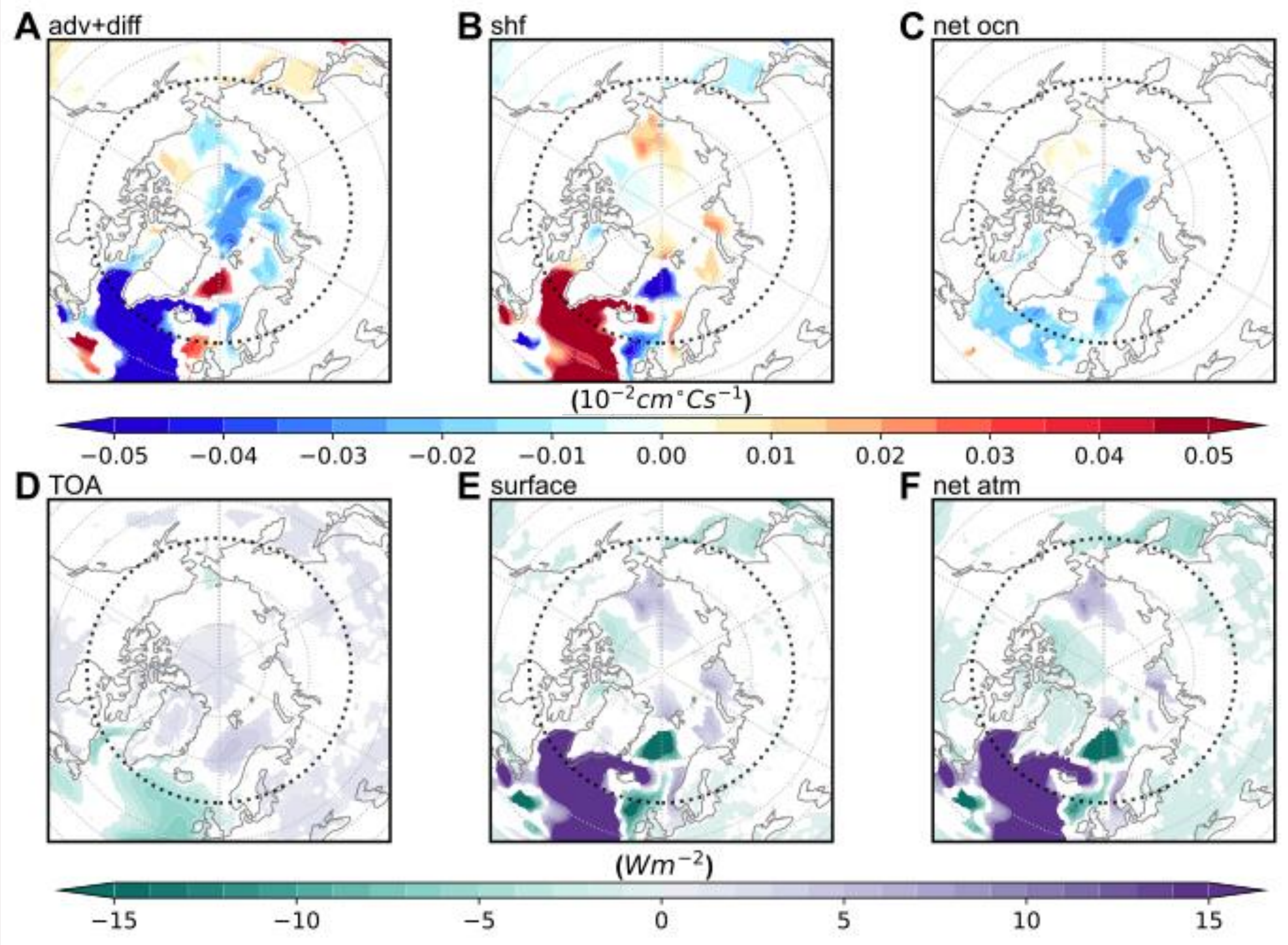
DJF



D-I: Annual mean partial temperature contribution differences.

Period: 2081-2100 compared to 1961-1980

Results



A-C: Annual mean ocean temperature tendency differences.
D-F: Annual mean radiation fluxes

Period: 2081-2100 compared to 1961-1980

Ocean temperature and heat budget

The full-depth integrated ocean temperature tendencies at unit area can be written as

$$tendency_{tot} = tendency_{shf} + tendency_{OHTC}$$

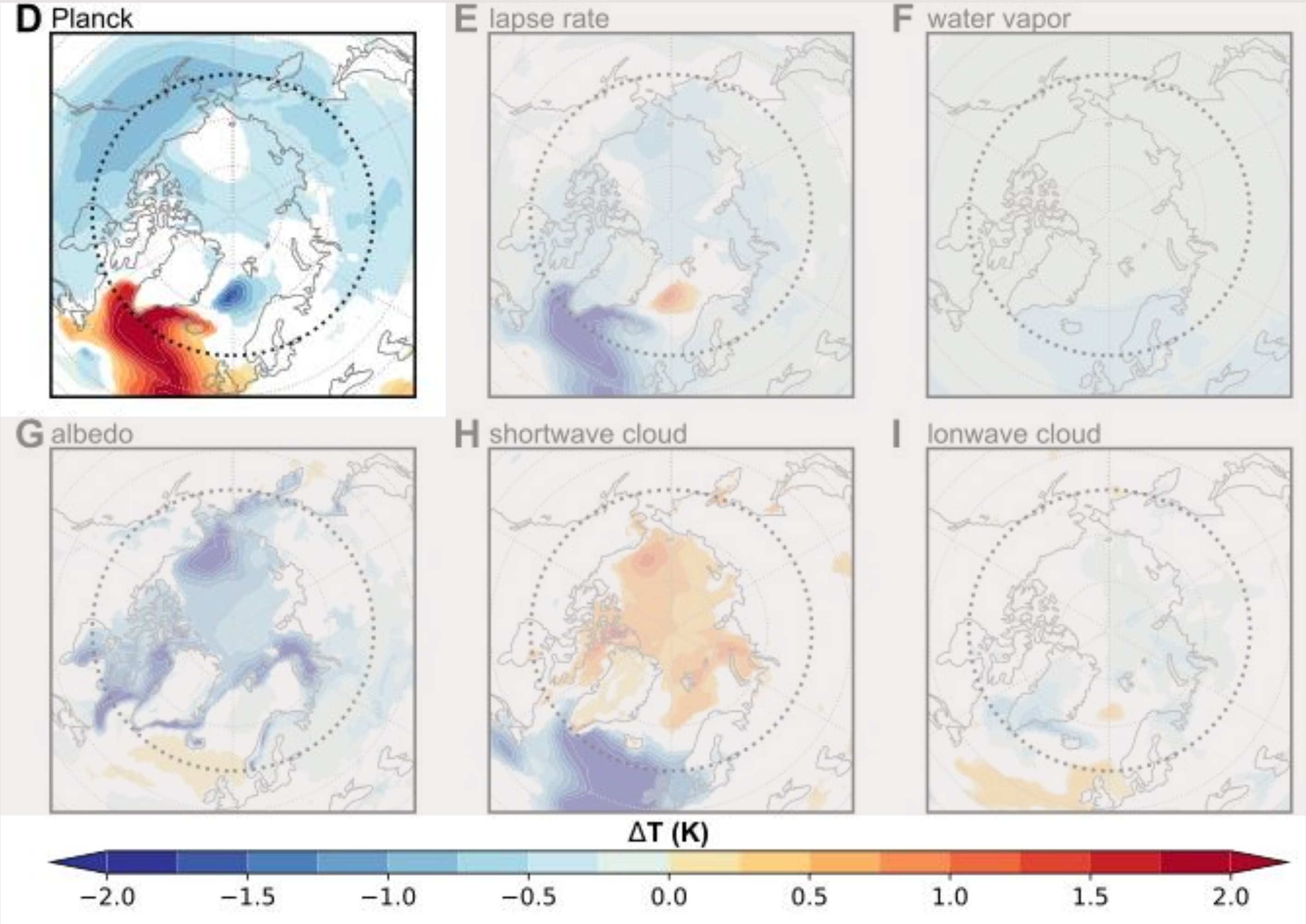
The AMOC weakening lead to

→ Ocean heat transport divergence and whole depth water cooling.

→ Compensated by atmospheric energy convergence, and meanwhile, promote ocean heat uptake.

Result in a net cooling tendency in ocean temperature and lessen the sea ice loss.

Results



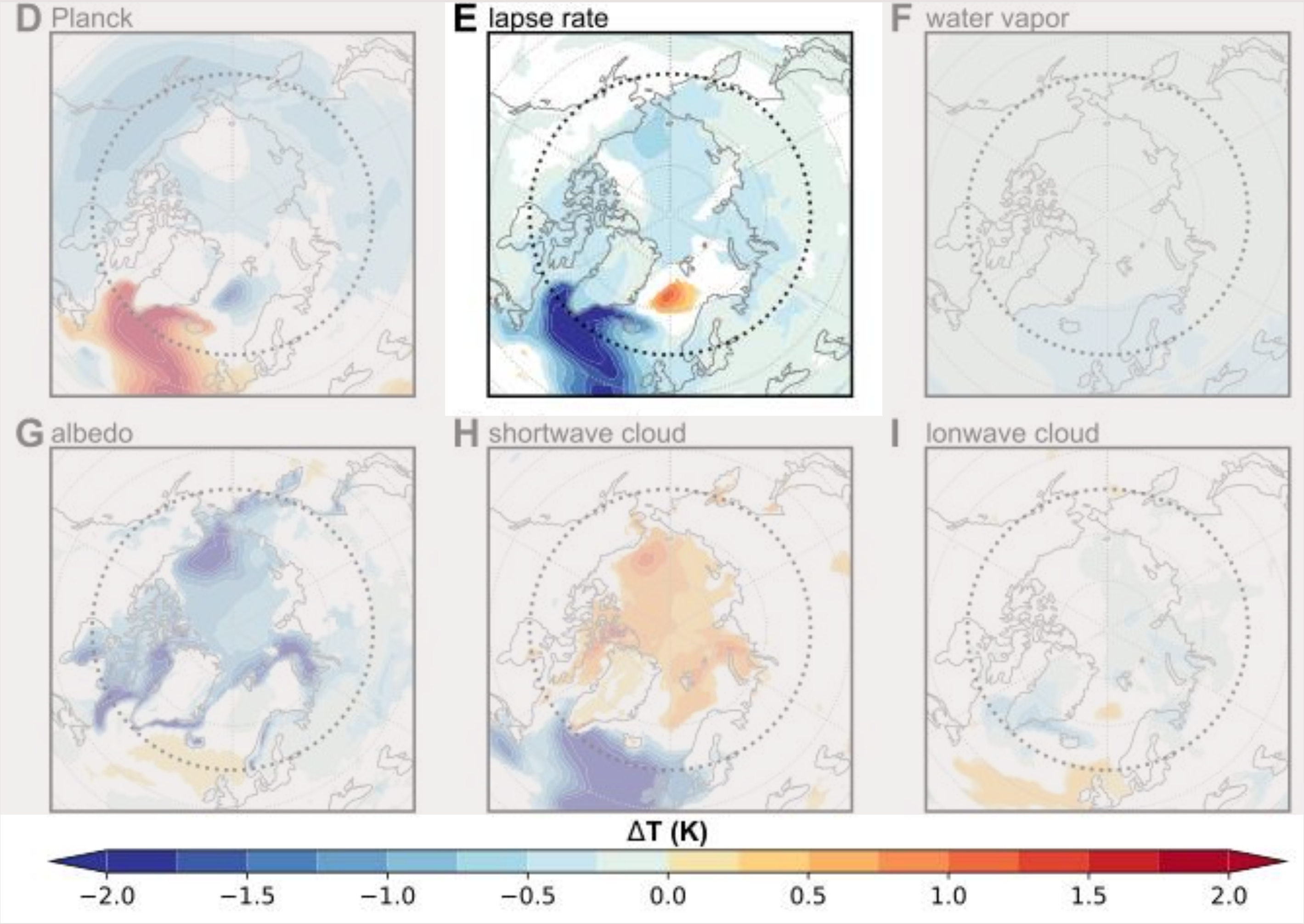
Planck feedback

- ➔ Cooling in the central Arctic and neighboring regions
- ➔ Warming in the North Atlantic warming hole region.

D-I: Annual mean partial temperature contribution differences.

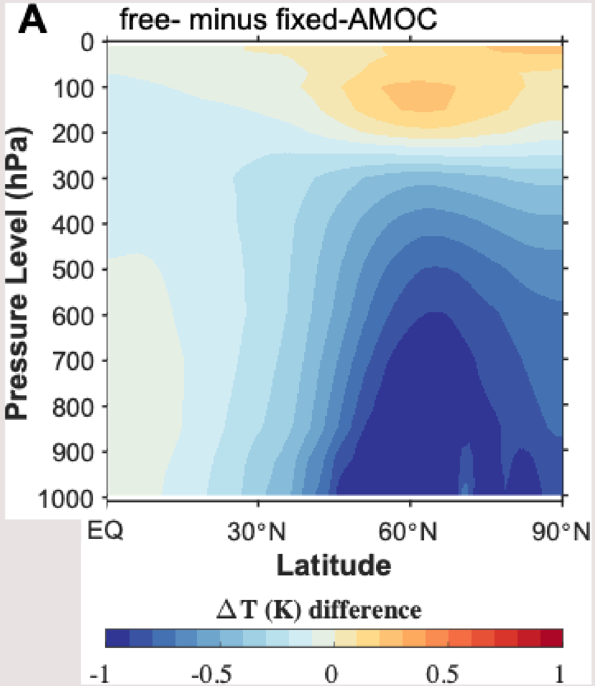
Period: 2081-2100 compared to 1961-1980

Results



D-I: Annual mean partial temperature contribution differences.

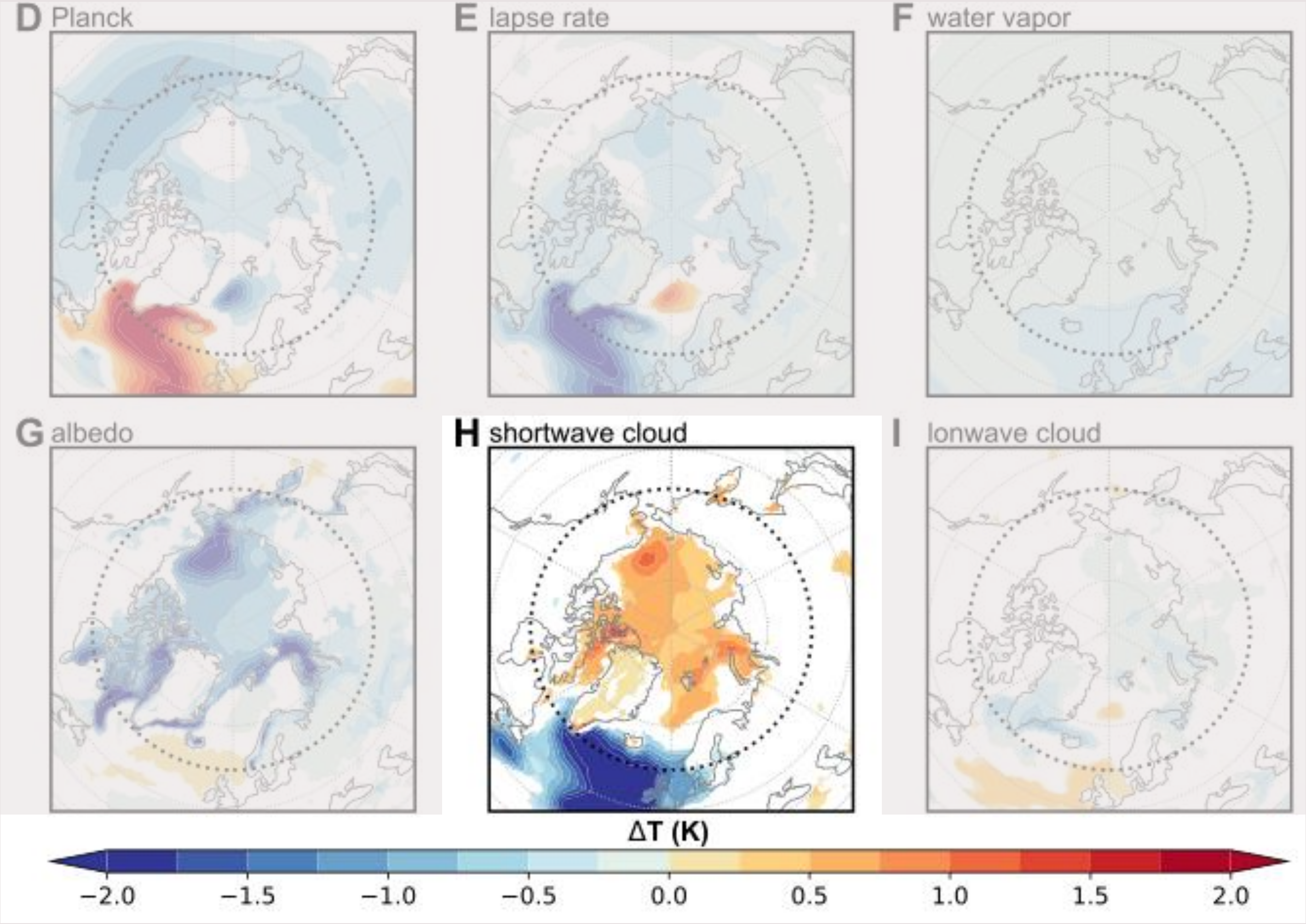
Period: 2081-2100 compared to 1961-1980



Lapse rate feedback

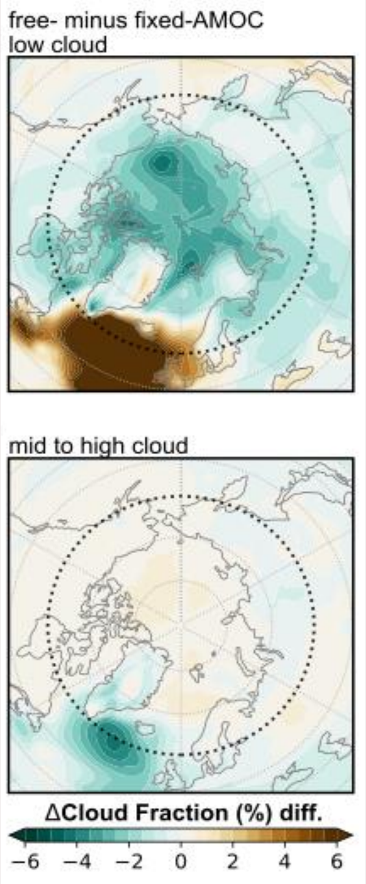
- ➔ Cooling in the central Arctic and neighboring regions
- ➔ Largely offset the warming from Planck feedback in the North Atlantic warming hole region.

Results



Low

Mid-to-high



Shortwave cloud feedback

- ➔ Warming in the central Arctic
- ➔ Cooling in the North Atlantic warming hole region.

D-I: Annual mean partial temperature contribution differences.

Period: 2081-2100 compared to 1961-1980

Y. Lee, W. Liu, A.V. Fedorov, N. Feldl, & P.C. Taylor, Impacts of Atlantic meridional overturning circulation weakening on Arctic amplification, Proc. Natl. Acad. Sci. U.S.A. 121 (39) e2402322121, https://doi.org/10.1073/pnas.2402322121 (2024).

Summary

- AMOC weakening leads to a slower increase in Arctic surface temperature, **reducing projected warming by 1.37°C (0.36 in amplification factor)** by the end of the 21st century.
- The main drivers of reduced warming are **surface albedo feedback** and **ocean heat uptake change**, which are strong during boreal summer and winter, respectively.
- AMOC slowdown induces ocean heat transport divergence at the North Atlantic warming hole, causing the ocean to absorb more heat from the atmosphere and resulting in surface cooling.
- AMOC slowdown leads to strong surface and lower-to-mid troposphere cooling through lapse rate feedback. Its induced changes in shortwave cloud feedback bring about slightly warming over the central Arctic.

Thank you for your attentions.