Examining the AMO: A paleoclimate AMOC approach to abrupt climate change

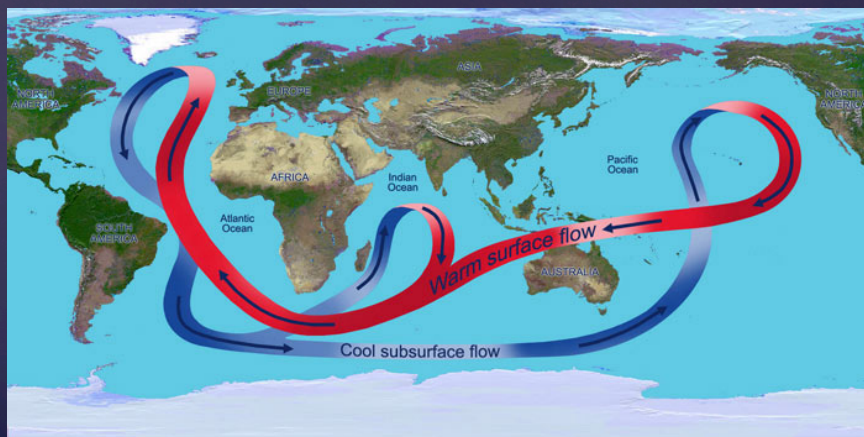
Celeste Gambino

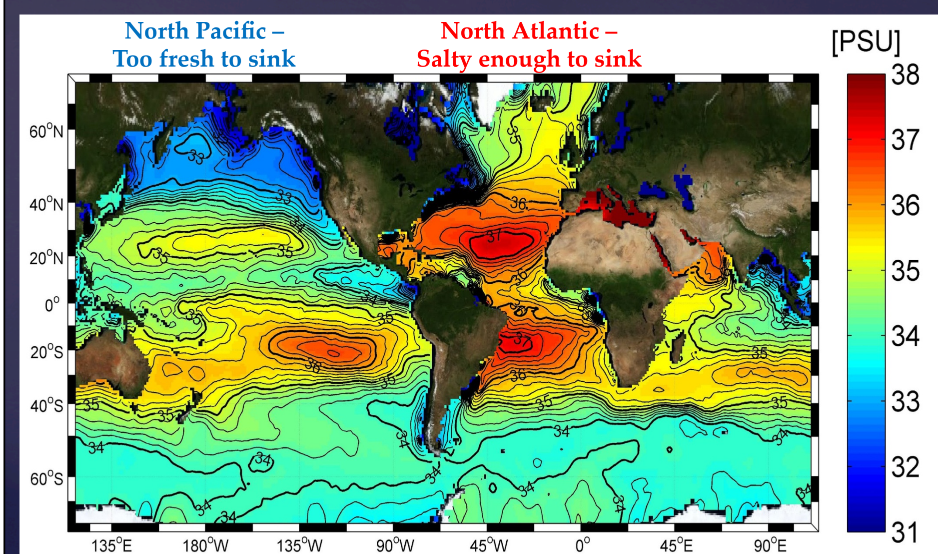
AMO

vs.

AMOC

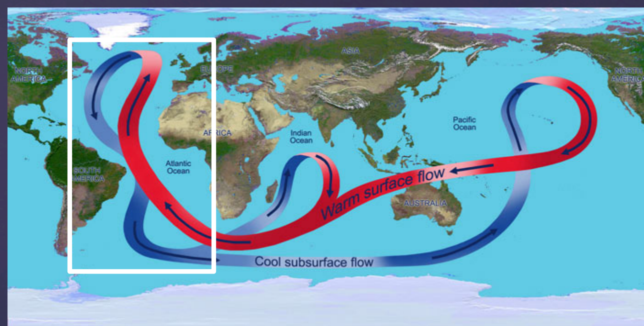
Thermohaline Circulation, Atlantic Meridional Overturning Circulation





Northward heat transport

Warm water flows northward at surface



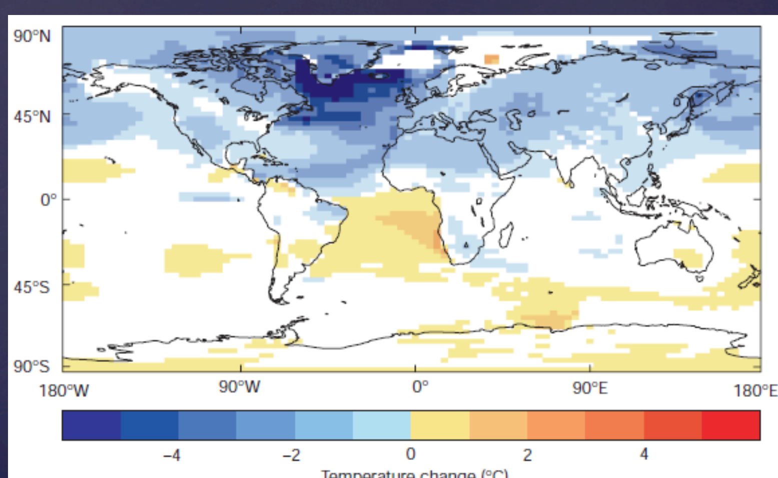
2°C

18° C

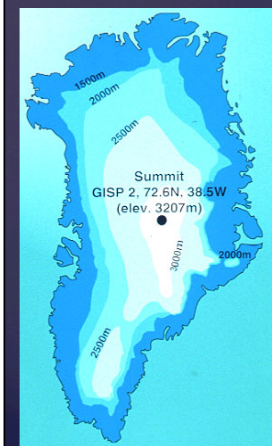
Cold water returns southward at depth

The net result is that the Northern Hemisphere steals heat from the Southern Hemisphere

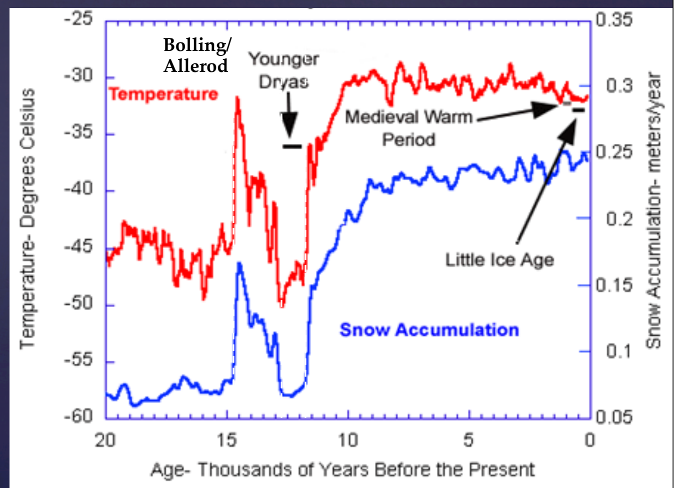
"Bipolar seesaw" response in models when the AMOC shuts off



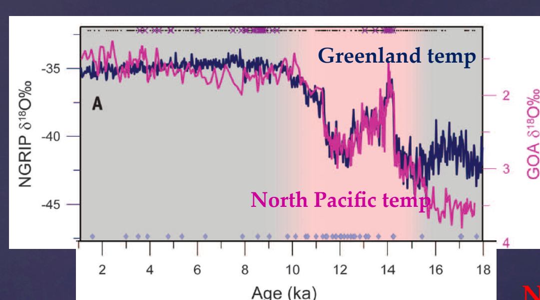
Greenland ice core record

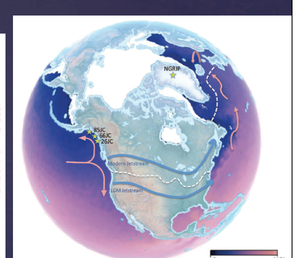


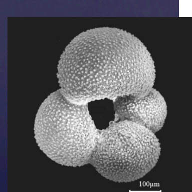
Abrupt changes in temp and precip (years to decades)



Abrupt changes elsewhere

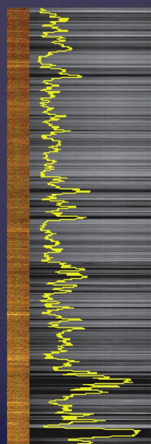


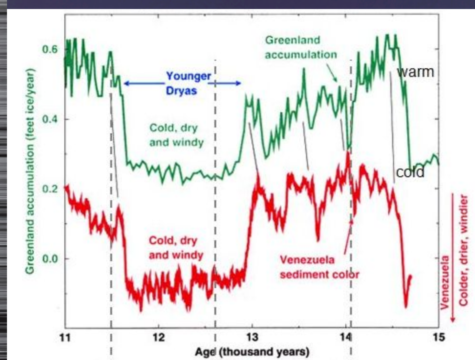


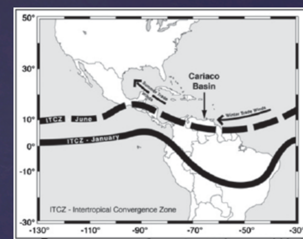


North Pacific:
Foram d18O records sea surface temperature.
Correlated with Greenland.

Abrupt changes elsewhere

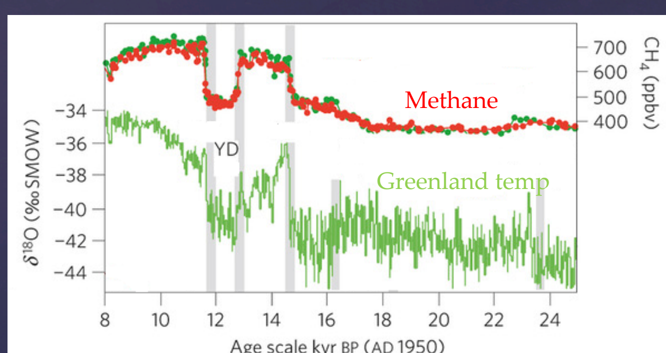






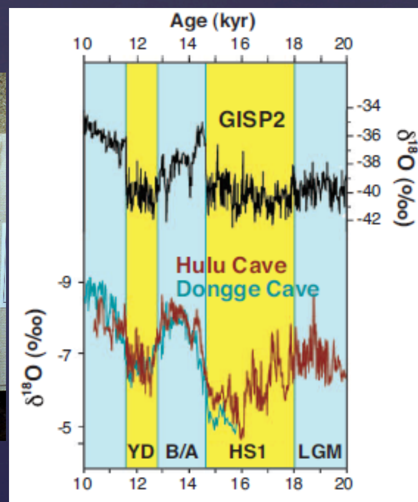
Cariaco Basin, Venezuela:
Stronger trade winds cause more upwelling and productivity, leading to more deposition of white seashells and lighter colored sediment.
Correlated with Greenland.

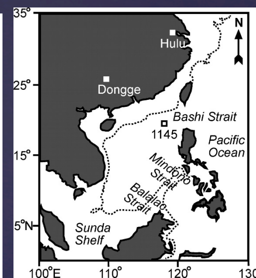
Abrupt changes elsewhere



Atmospheric methane:
Likely driven by amount of tropical wetlands.
Correlated with Greenland.

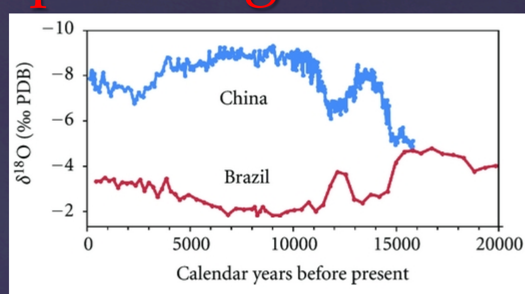
Abrupt changes elsewhere

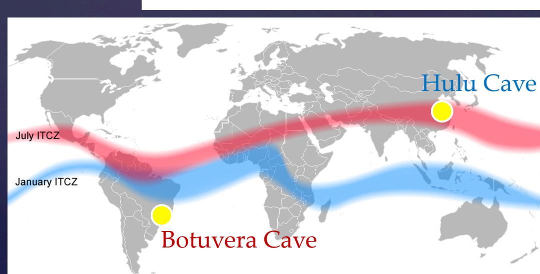




Hulu Cave, China:
Stalagmite d18O tracks strength of Asian monsoon.
Correlated with Greenland.

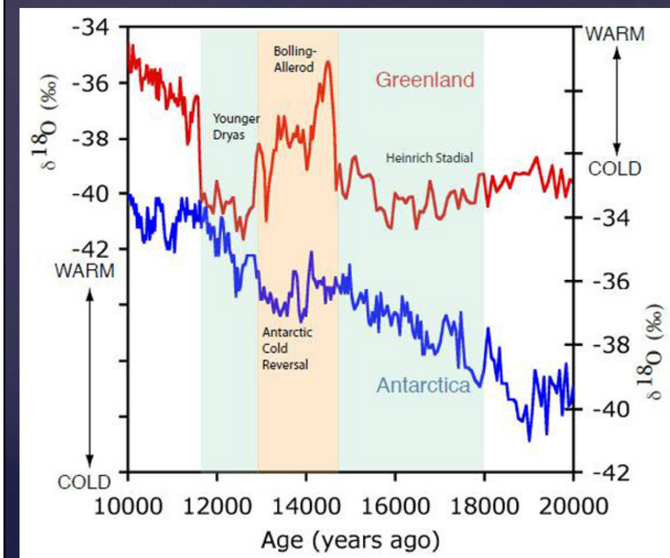
Abrupt changes elsewhere





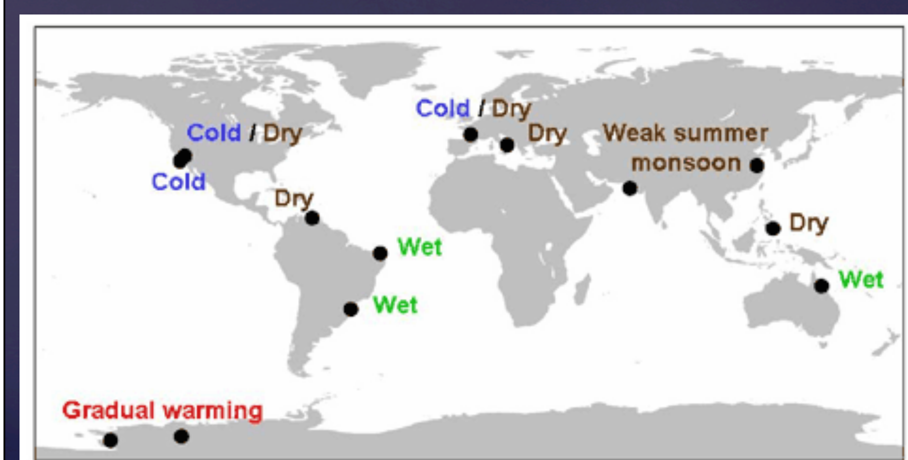
Botuvera Cave, Brazil:
Stalagmite d18O tracks strength of South American monsoon.
<u>Anti-correlated</u> with Greenland.

Antarctic ice core record



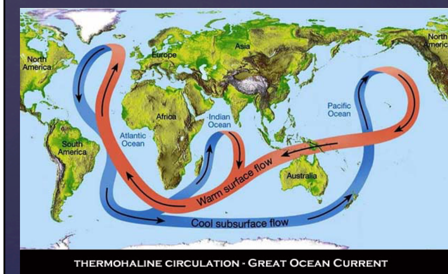
Antarctic temp is anti-correlated with Greenland temp over abrupt climate changes
→ The "bipolar seesaw"

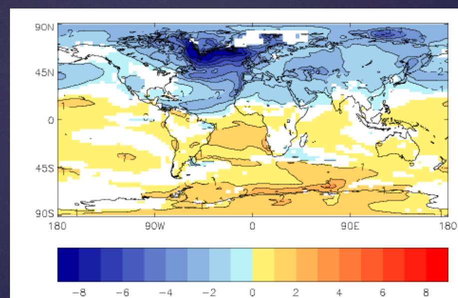
Younger Dryas bipolar seesaw pattern



Bipolar seesaw due to AMOC?

Atlantic Meridional Overturning Circulation (AMOC) is a key agent of *heat redistribution between* the hemispheres…



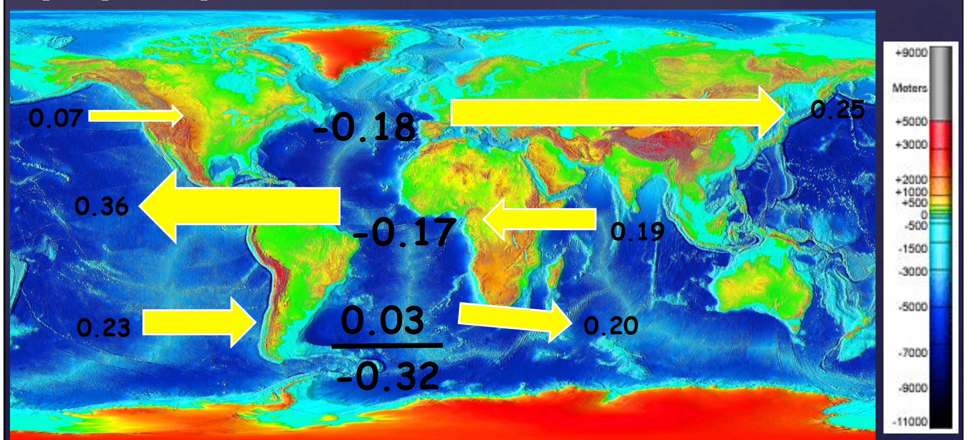


Why did the AMOC flip flop?

Re-routing of continental drainage by fluctuating ice sheet margin…

Why did the AMOC flip flop?

Perhaps AMOC can only stay "off" for so long. E.g., it has to export continual build-up of salt in the Atlantic due to uneven evaporation/precipitation patterns back to rest of oceans.



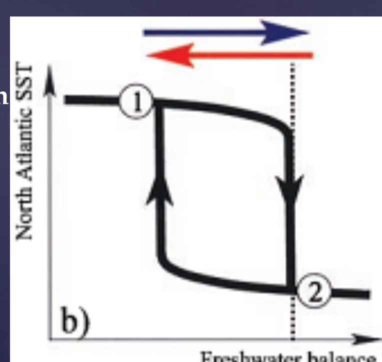
Sverdrups; 1 Sv = 10^6 m^3/s (global river flow is about 1 Sv)

Why did the AMOC flip flop?

Flip-flopping might also reflect *hysteresis* of AMOC – tendency to tip between "on"/"off" states across a threshold.

Strong circulation

Weak circulation

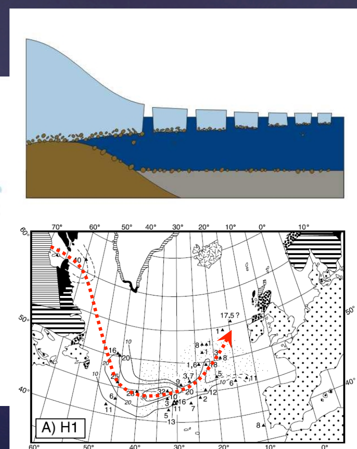


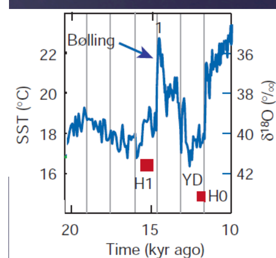
Salty North Atlantic **Fresh North Atlantic**

AMOC conceptual hysteresis loop

Why did the AMOC flip flop?

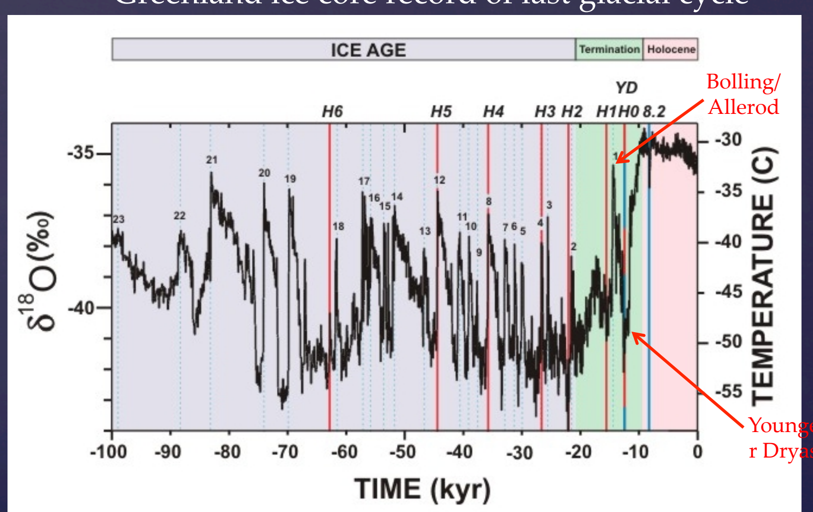
"Heinrich Events" - partial collapse of Laurentide Ice Sheet delivered armada of icebergs to North Atlantic – recorded by coarse layers of ice-rafted debris on sea floor. Big injection of freshwater to North Atlantic…

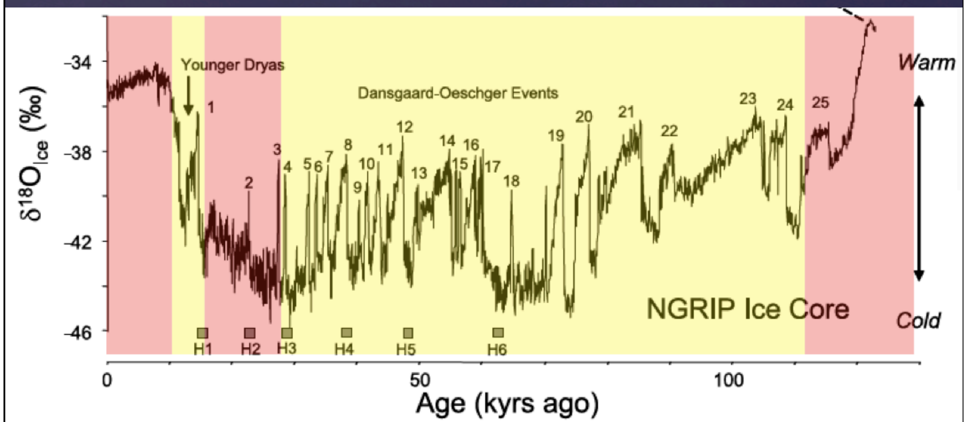




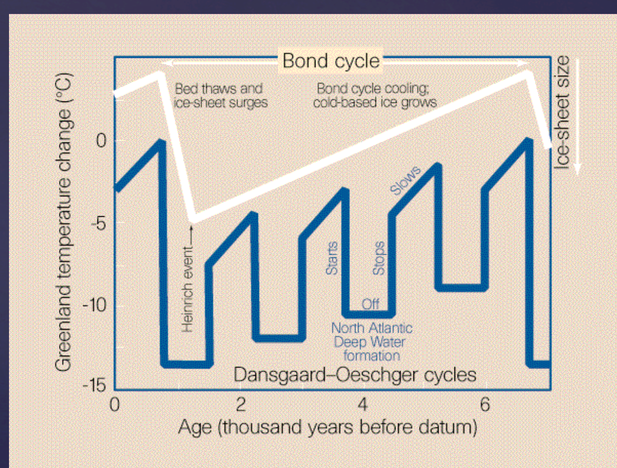
Heinrich layers are thickest near Hudson Strait (source), up to 0.5 meters. Then transported east with North Atlantic Current

Greenland ice core record of last glacial cycle





Long-term cooling with bundles of progressively smaller D/O events, culminating in a Heinrich event. Roughly every 7,000 years.



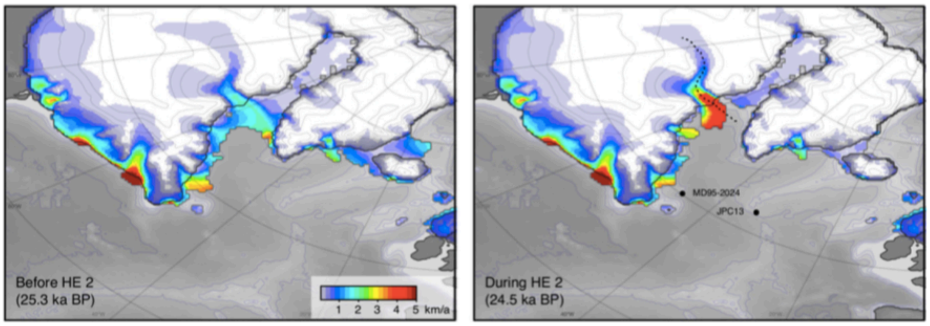


Fig. 3. Laurentide ice stream velocities (in kilometers per year) before (*Left*) and during (*Right*) H event 2, along with locations of the cores of the IRD proxies shown in Fig. 2. The dashed line in the right panel indicates the location of the profiles shown in Fig. 4.

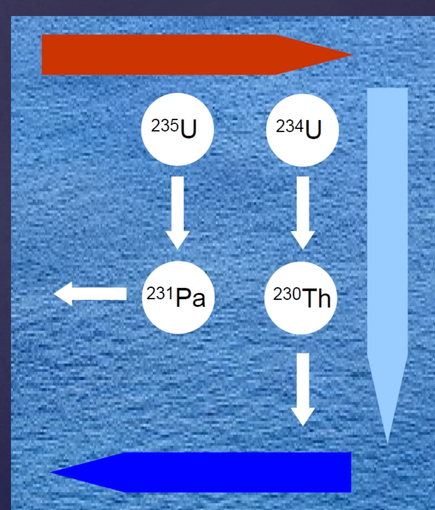
North Atlantic ocean circulation and abrupt climate change during the last glaciation

{ Henry et al., 2016

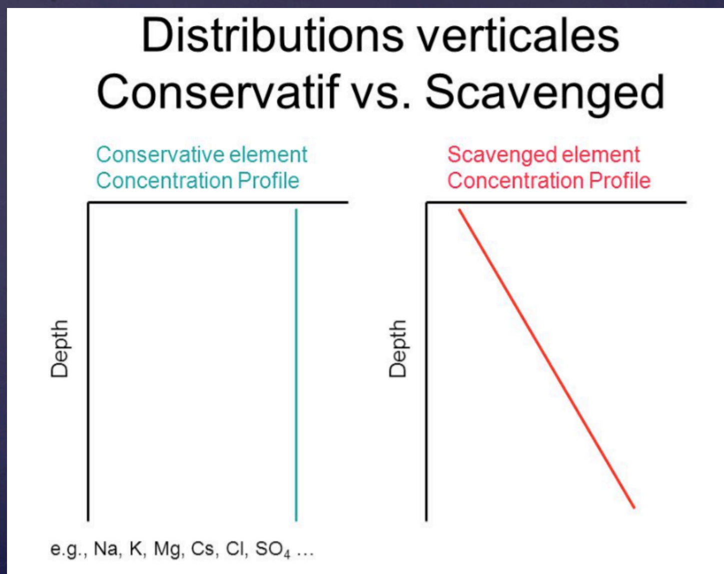
Key Proxies!

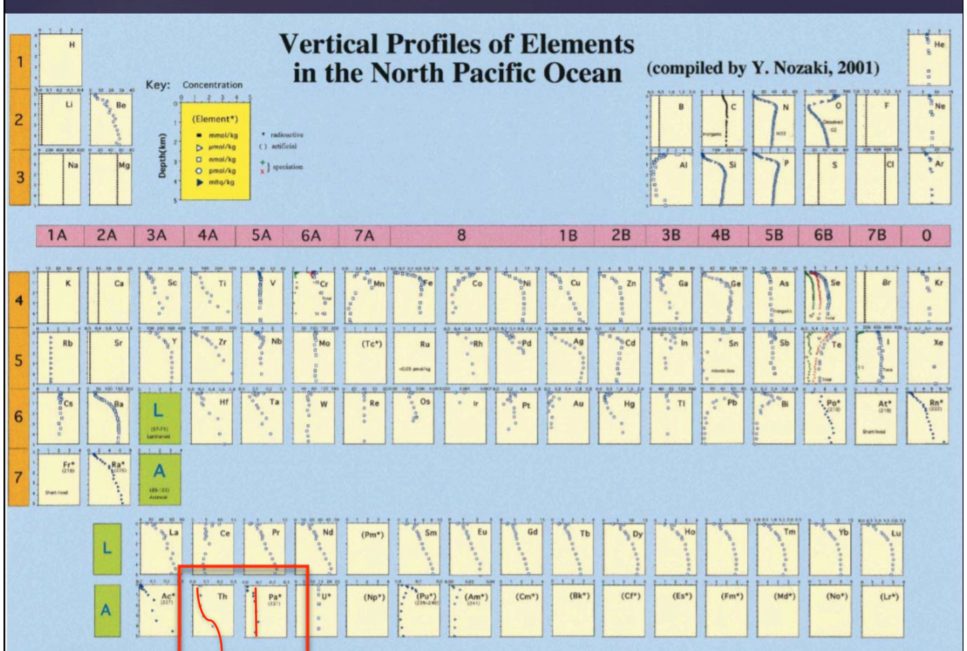
- $\delta^{18}O$
- SST
- Pa/Th
- $\delta^{13}C$
- $CaCO_3$
- IRD

Pa/Th

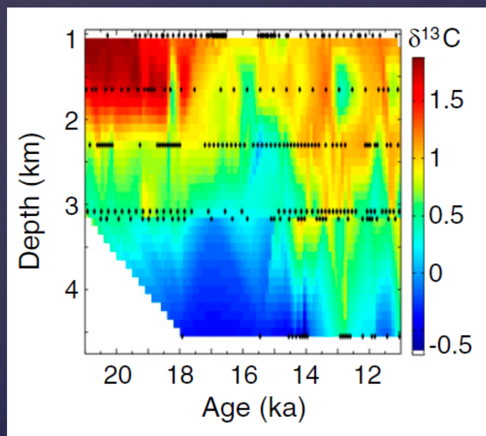


Pa/Th


Distributions verticales
Conservatif vs. Scavenged
Conservative element
Concentration Profile
Scavenged element
Concentration Profile
Depth
Depth
e.g., Na, K, Mg, Cs, Cl, SO4 …


Vertical Profiles of Elements
in the North Pacific Ocean
(compiled by Y. Nozaki, 2001)
Key: Concentration
Depth(km)
1A
2A
3A
4A
5A
6A
7A
8
1B
2B
3B
4B
5B
6B
7B
0

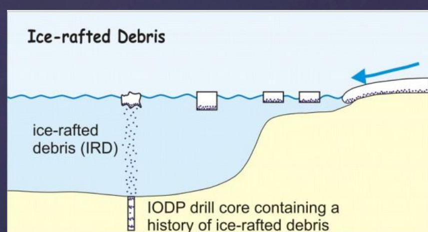
$\delta^{13}C$

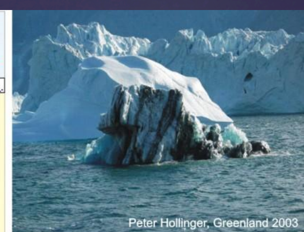


$$\delta = \left[\frac{\frac{^{13}C}{^{12}C}\,sample}{\frac{^{13}C}{^{12}C}\,standard} - 1\right] * 1000$$

$CaCO_3$

Ice Rafted Debris (IRD)





What are any assumptions made for each of these proxies?

Setting the scene

- Why did this study choose MIS 3 to focus on?
- Why is the Bermuda Rise such an interesting region for this type of study?

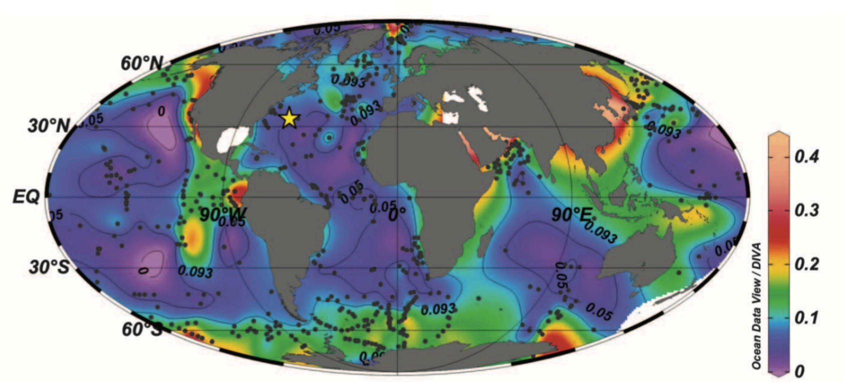
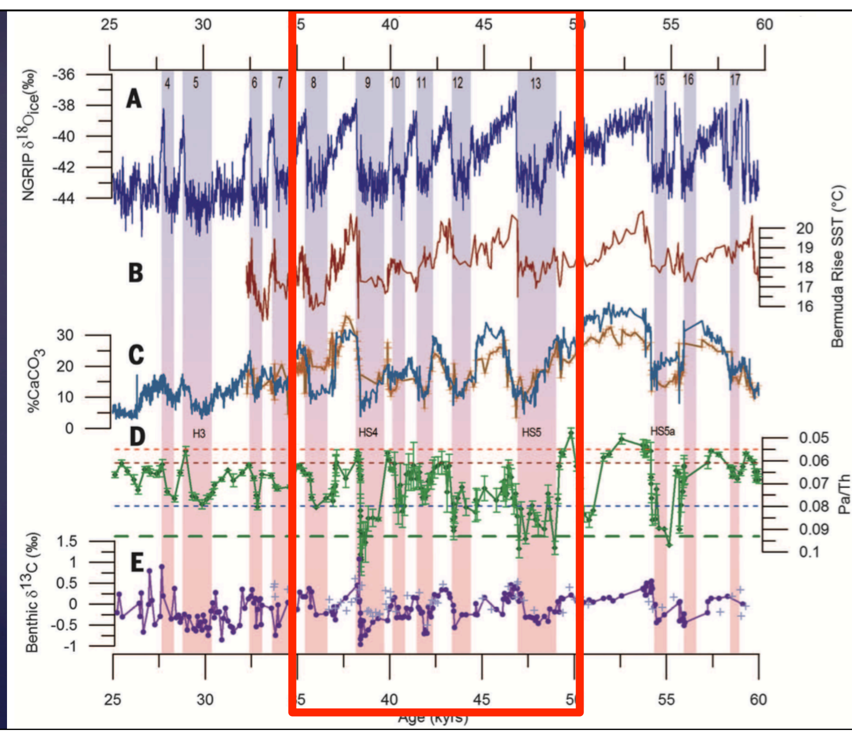
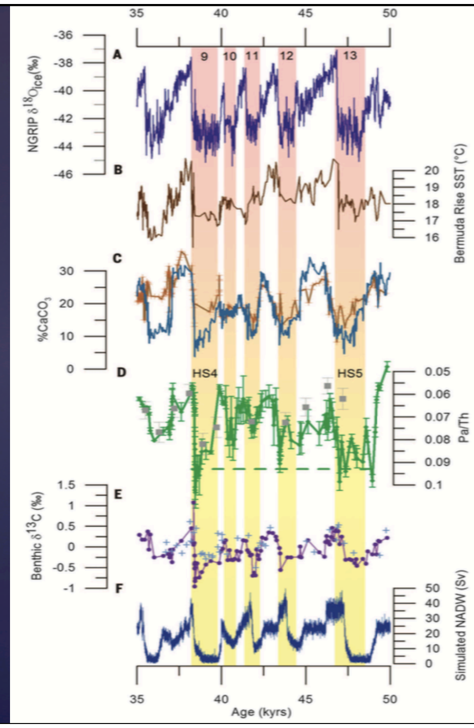


Fig. 1. Study core location and coretop distribution of Pa/Th. Location sediment core CDH19 indicated with a star (33° 41.443' N; 57° 34.559' W, 4541-m water depth), with Pa/Th ratios (black dots) in core top sediments used with Ocean Data View Data-Interpolating Variational Analysis gridding to produce the color contours. White areas contain no data.

What was the AMOC doing for each stadial and interstadial interval? What is the key evidence for this?





Antarctic Lag

- Based on any ocean/atmosphere processes we've discussed so far this semester, why does northern hemispheric climate leading Antarctic climate make sense?
- Does this paper suggest that northern hemispheric climate is *forced* or *reinforced* by AMOC variations?

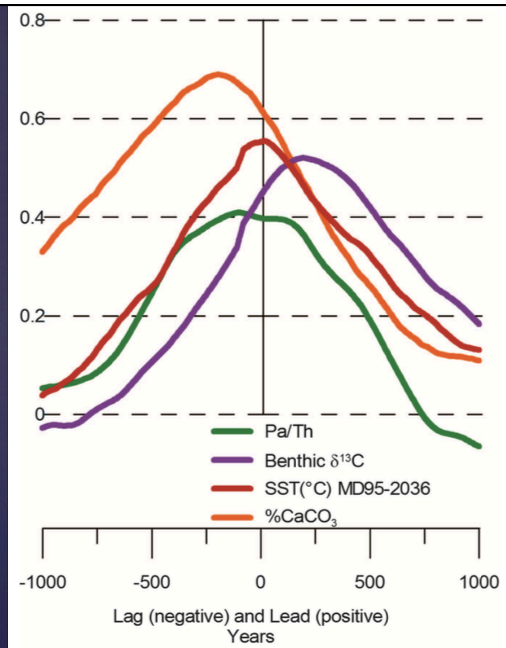


Fig. 4 Phasing lag correlations. Correlation of NGRIP ice core $\delta^{18}O$ with CDH19 %$CaCO_3$ (orange), Pa/Th of bulk sediment from CDH19 (green), $\delta^{13}C_{BF}$ from CDH19 (purple), and SST °C from MD95-2036 (*31*) (red).

Thoughts?

Hosed vs. unhosed: interruptions of the Atlantic Meridional Overturning Circulation in a global coupled model, with and without freshwater forcing

Brown and Galbraith, 2016

Assumptions?

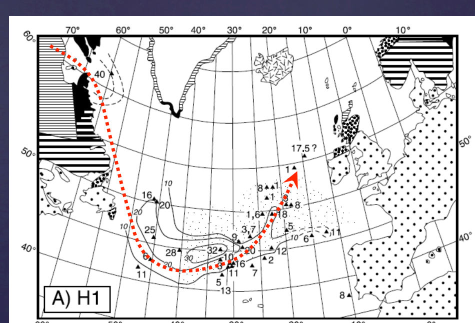
- What is a key assumption this study (and pretty much all "hosing" experiment studies) is based on?

Definitions

- “hosing” experiment?
- Heinrich (H) Event
- Dansgaard-Oeschger (D/O) event

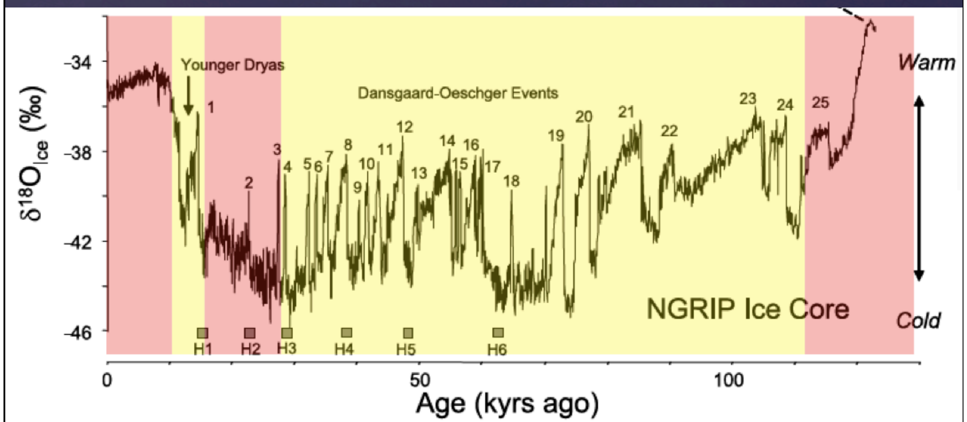
H Events

“Heinrich Events” - partial collapse of Laurentide Ice Sheet delivered armada of icebergs to North Atlantic – recorded by coarse layers of ice-rafted debris on sea floor. Big injection of freshwater to North Atlantic



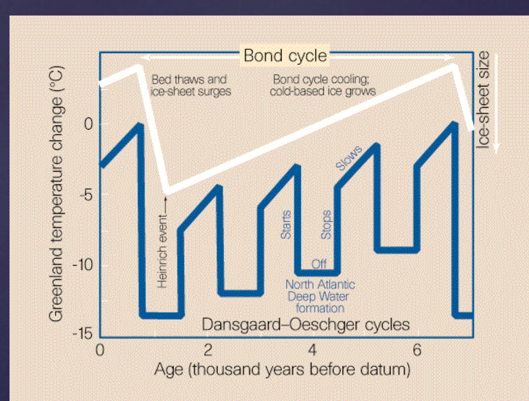
Heinrich layers are thickest near Hudson Strait (source), up to 0.5 meters. Then transported east with North Atlantic Current

D/O Events



D/O Events

Long-term cooling with bundles of progressively smaller D/O events, culminating in a Heinrich event. Roughly every 7,000 years.



The model

- What are the pros and cons of using a "moderately low resolution, but full-complexity" model?

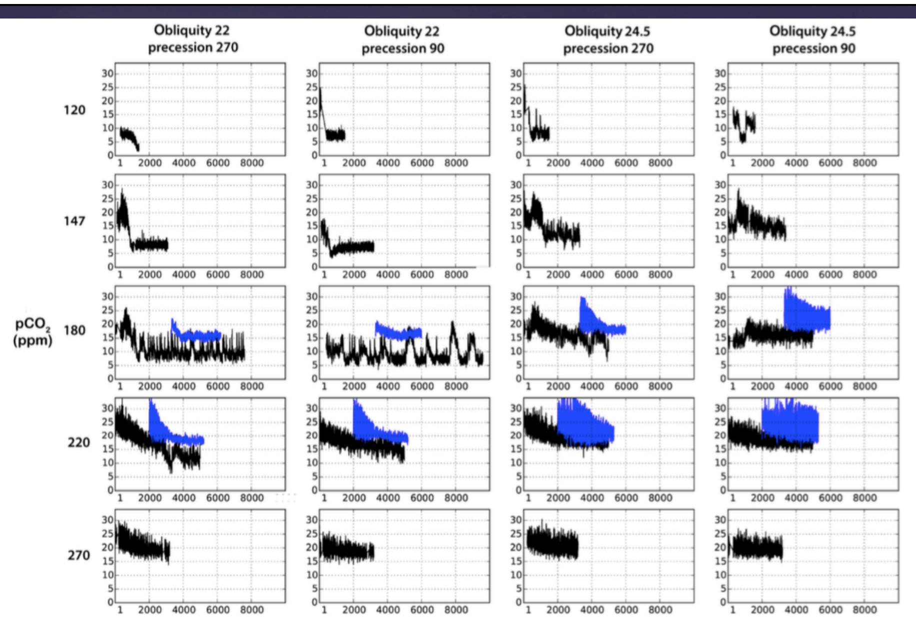


Figure 1. Time series of AMOC for the matrix of simulations with prescribed atmospheric pCO_2 (rows) and orbital configurations (columns). Black lines have preindustrial ice sheets and blue lines, when applicable, have full LGM ice sheets. The AMOC, shown on the vertical axes in sverdrups, is defined as maximum of Atlantic meridional stream function between 30 and 50° N and water depths of 500 and 5000 m. Precessional phases of 270 and 90° are equivalent to strong and weak boreal seasonalities, respectively.

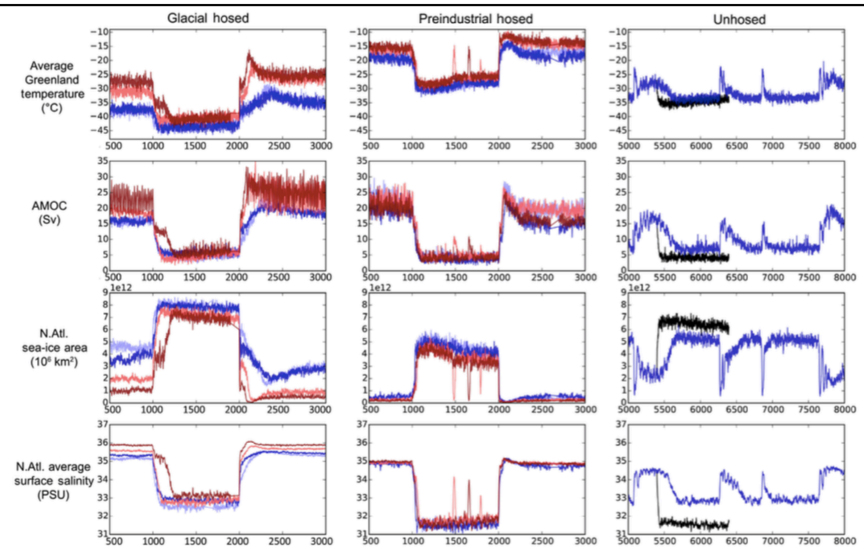


Figure 2. North Atlantic climate metrics for all simulations. The left column shows four simulations under the glacial boundary conditions (LGM ice sheets and bathymetry with closed Bering Strait; 180 ppm CO_2), the central column shows four simulations run under the preindustrial boundary conditions (preindustrial ice sheets and bathymetry; 270 ppm CO_2), and the right column shows the unhosed simulation in which spontaneous AMOC variations occur under constant boundary conditions. For the left and centre columns, freshwater hosing was applied between years 1001 and 2000. Orbital configurations are indicated as follows: red, high obliquity; blue, low obliquity; dark, weak boreal seasonality; pale, strong boreal seasonality. The black lines in the right column show the "hosed–unhosed" simulation, in which 0.2 Sv of freshwater was added in the North Atlantic during an unforced AMOC "interstadial". AMOC is defined as the maximum Atlantic stream function between 500 and 5500 m and 30 and 50° N.

The model

- Do you think the model's unhosed situations are realistic or unrealistic?

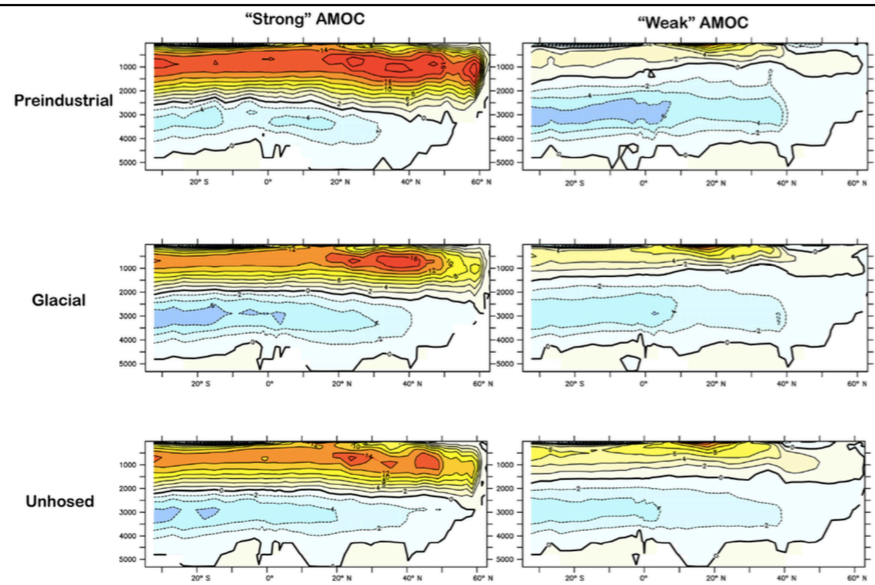


Figure 3. Atlantic meridional overturning stream functions in strong and weak states. All plots show 100-year averages. In glacial and preindustrial hosing simulations, weak AMOC state is defined by averaging the last century of hosing (model years 1901–2000) and strong AMOC state is defined by averaging the same years from the corresponding control simulation (to correct for potential drift). In the unhosed simulation, the weak AMOC state is defined by averaging model years 7501–7600 and the strong AMOC state is defined by averaging model years 7901–8000. For the top two rows, the stream functions are averaged over the corresponding four sets of orbital configurations. The bottom row shows the stream functions for the unhosed simulation. Contours in sverdrups.

If it's not due to hosing, what might be causing an AMOC shift?

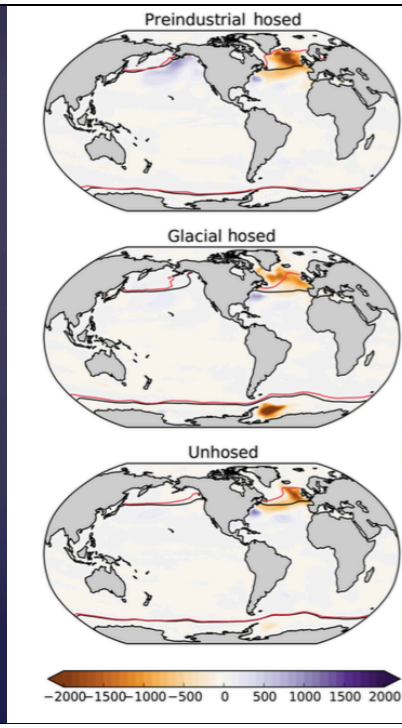


Figure 4. Stadial winter mixed-layer depth anomaly. The top two panels show the difference in winter mixed-layer depth between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S6 to view all eight hosing simulations individually). The bottom panel shows the winter mixed-layer depth between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Black and red contours show the sea-ice edge for the weak AMOC and strong AMOC states, respectively. Sea-ice edge is defined as > 30 % of annually averaged ice concentration. Shading in m.

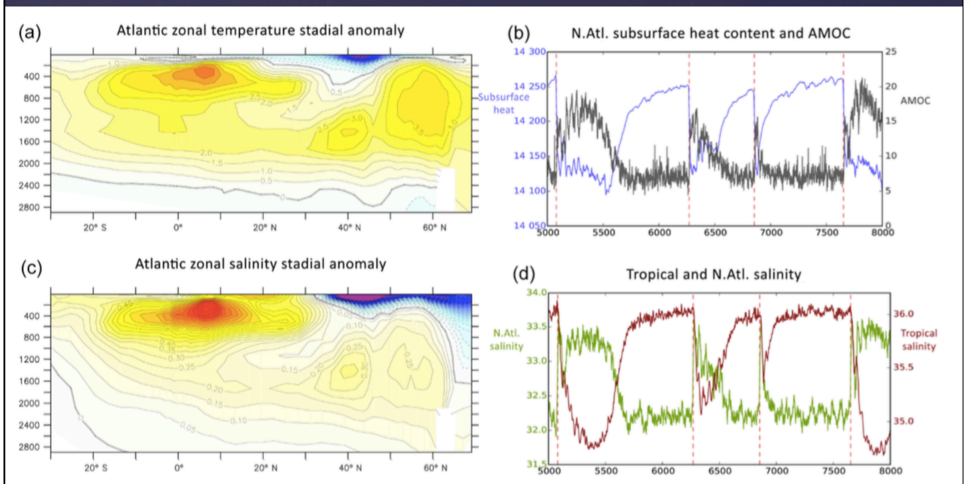


Figure 5. Thermohaline oscillations in the unhosed simulation. **(a, c)** Atlantic zonally averaged temperature and salinity anomalies between weak AMOC state (years 7501–7600) and strong AMOC state (years 7901–8000). Units in °C and PSU, respectively. **(b)** Subsurface (500–2500 m) heat content in the North Atlantic > 45° N in zettajoules (blue) and AMOC transport in sverdrups (black). **(d)** Sea surface salinity in the North Atlantic (> 45° N) (green) and tropical Atlantic (0:10° N, 70:30° W) (red), in PSU. Red vertical dashed lines indicate onset of deep convection in the North Atlantic.

Under both hosed and unhosed scenarios, what is the general trend for surface air temperatures, precipitation, and ocean biogeochemistry?

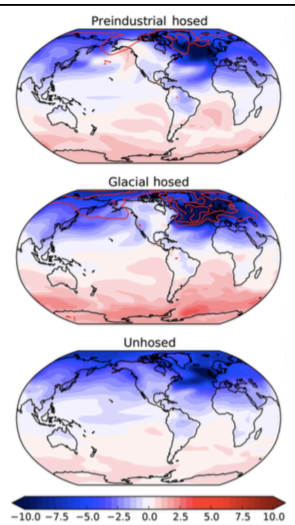


Figure 6. Stadial surface air temperature anomaly. The top two panels show the surface air temperature difference between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S2 to view all eight hosing simulations individually). Red contours show the standard deviation between the four sets of orbital configurations at 1 °C intervals. The bottom panel shows the surface air temperature difference between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in °C.

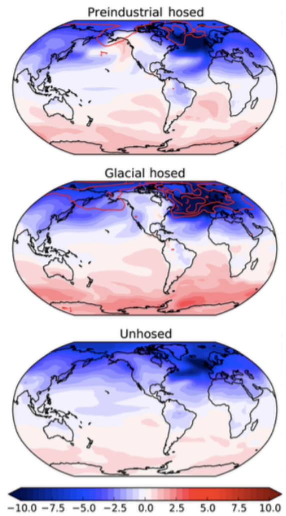


Figure 6. Stadial surface air temperature anomaly. The top two panels show the surface air temperature difference between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S2 to view all eight hosing simulations individually). Red contours show the standard deviation between the four sets of orbital configurations at 1 °C intervals. The bottom panel shows the surface air temperature difference between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in °C.

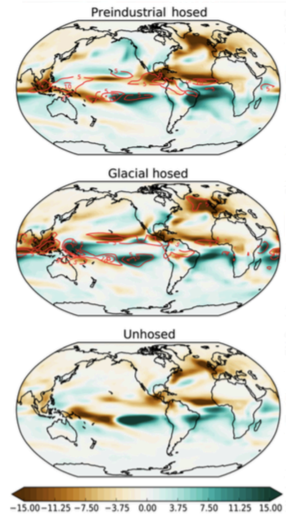


Figure 7. Stadial precipitation anomaly. The top two panels show the precipitation difference between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S4 to view all eight hosing simulations individually). Red contours show the standard deviation between the four sets of orbital configurations at $5 \times 10^{-6}\,\mathrm{kg\,m^{-2}\,s^{-1}}$ intervals. The bottom panel shows the precipitation difference between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in $10^{-6}\,\mathrm{kg\,m^{-2}\,s^{-1}}$.

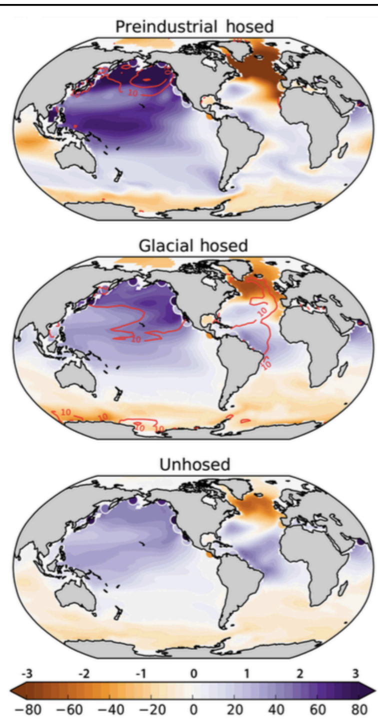


Figure 8. Stadial intermediate-depth (400–1100 m) oxygen concentration anomaly. The top two panels show the oxygen concentration difference between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S7 to view all eight hosing simulations individually). Red contours show the standard deviation between the four sets of orbital configurations at $1\,\mu\mathrm{mol\,kg^{-1}}$ intervals. The bottom panel shows the oxygen concentration difference between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Markers represent the first principal component of the detrended time series for benthic oxygenation proxies compiled by Galbraith and Jaccard (2015). Shading and contours in $\mu\mathrm{mol\,kg^{-1}}$.

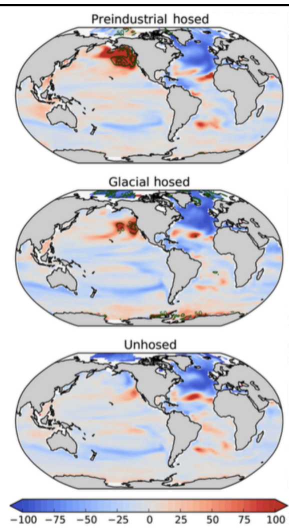


Figure 9. Stadial export production anomaly. The top two panels show the ratio of organic matter export at 100 m between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S8 to view all eight hosing simulations individually). Green contours show the standard deviation between the four sets of orbital configurations at 50 % intervals. The bottom panel shows the ratio of export between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in %.

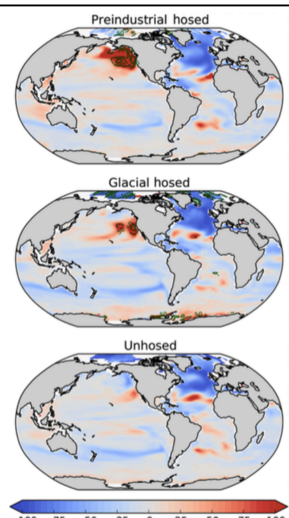


Figure 9. Stadial export production anomaly. The top two panels show the ratio of organic matter export at 100 m between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S8 to view all eight hosing simulations individually). Green contours show the standard deviation between the four sets of orbital configurations at 50 % intervals. The bottom panel shows the ratio of export between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in %.

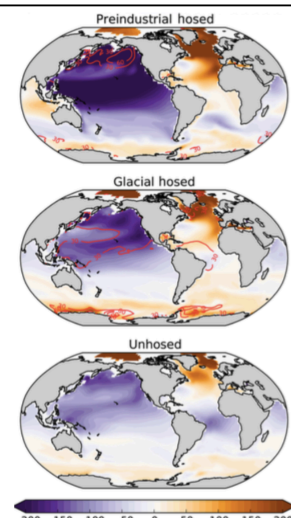


Figure 10. Stadial intermediate-depth (400–1100 m) ideal age anomaly. The top two panels show the age difference between weak and strong AMOC states (as defined in Fig. 3) under preindustrial and glacial boundary conditions, averaged between the four sets of orbital configurations (see Fig. S9 to view all eight hosing simulations individually). Red contours show the standard deviation between the four sets of orbital configurations at 30-year intervals. The bottom panel shows the age difference between weak and strong AMOC states (as defined in Fig. 3) in the unhosed simulation. Shading and contours in years.

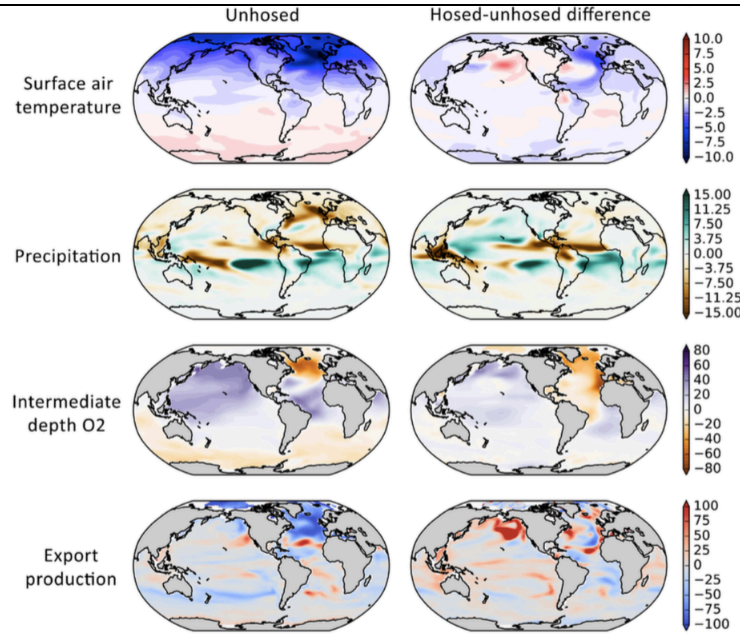


Figure 11. Impacts of hosing the unhosed. Left column: differences between weak and strong AMOC states for the unhosed simulation as shown in Figs. 6, 7, 8, and 9. Right column: differences between the last century (model years 6151–6250) of the 800-year hosed–unhosed stadial and the corresponding unhosed stadial. Scale and units are the same as in Figs. 6, 7, 8, and 9: temperature in °C, precipitation in $10^{-6}\,kg\,m^{-2}\,s^{-1}$, oxygen concentration in $\mu mol\,kg^{-1}$, and export anomaly in %.

Which do you think is more important overall for climate responses to AMOC disruptions: being hosed/unhosed or the background climate state?

Thoughts and Synthesis

"The fact that weakening of the AMOC always occurs in models under sufficient hosing implies that, even in a strong mode, the AMOC is vulnerable to freshwater forcing if it is large enough"