

Supplementary Information for

Glacial mode shift of the Atlantic deep circulation by warming over the Southern Ocean

Authors: Akira Oka⁽¹⁾, Ayako Abe-Ouchi⁽¹⁾, Sam Sheriff-Tadano⁽¹⁾, Yusuke Yokoyama⁽¹⁾, Kenji Kawamura⁽²⁾, and Hiroyasu Hasumi⁽¹⁾

⁽¹⁾ *Atmosphere and Ocean Research Institute, University of Tokyo,*

5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan

⁽²⁾ *National Institute of Polar Research*

10-3 Midorichou, Tachikawa, Tokyo 190-8518, Japan

Correspondence to: akira@aori.u-tokyo.ac.jp

Note on Supplementary Information

The following materials are included:

Supplementary Text

Multiple equilibria of the AMOC around the thermal threshold

Supplementary Figures

Supplementary Figure 1

Supplementary Figure 2

Supplementary Figure 3

Supplementary Figure 4

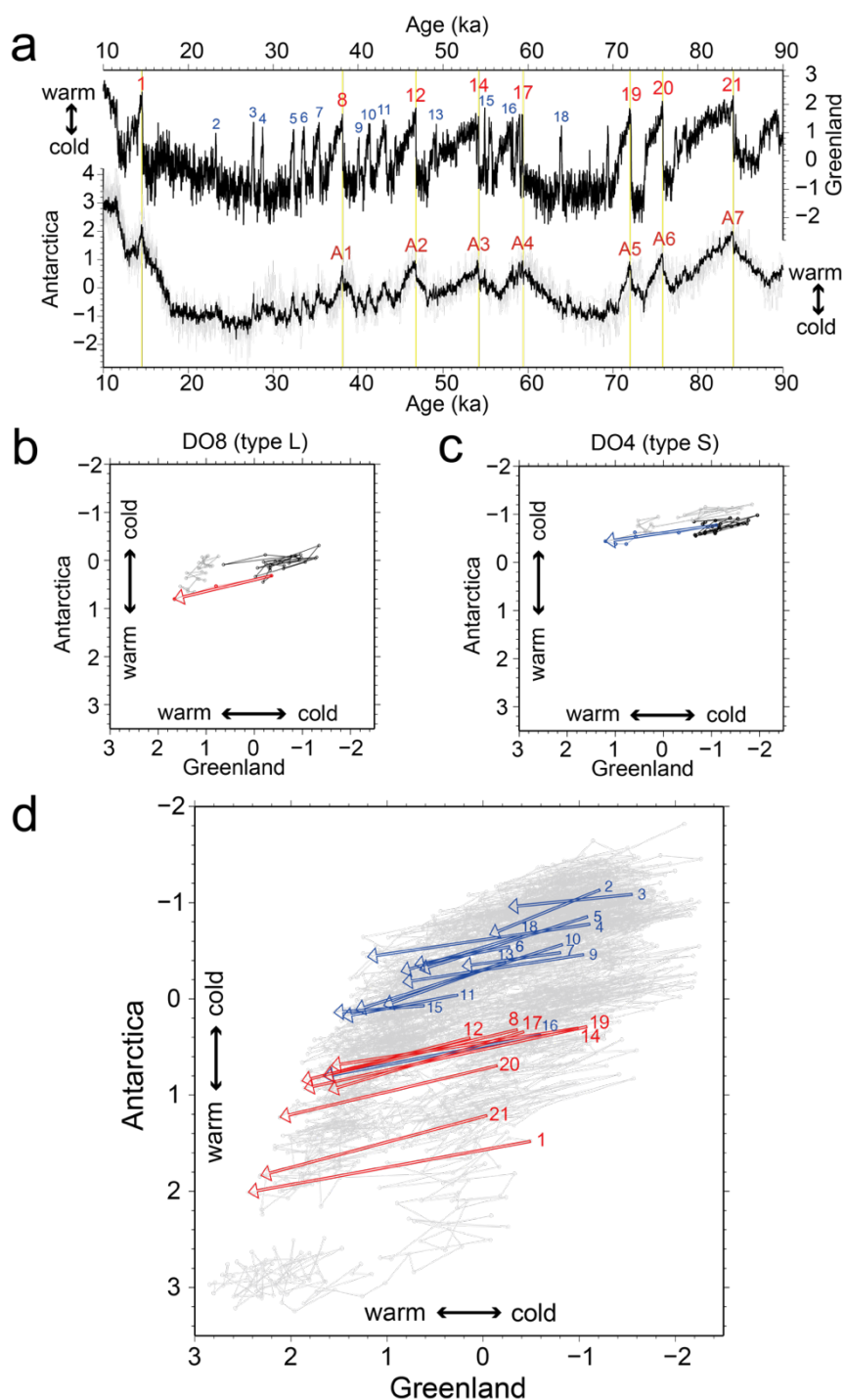
Supplementary Text

Multiple equilibria of the AMOC around the thermal threshold

We showed that multiple equilibria of the AMOC are obtained under certain thermal conditions (Fig. 3a). When the system is close to the thermal threshold of the AMOC, two solutions (stadial and interstadial modes) become possible. This is because there is positive feedback associated with the strength of the AMOC and the extent of the sea ice¹. A stronger AMOC leads to more heat transport northward toward the North Atlantic and more vertical mixing there, which helps to cause less sea ice around the North Atlantic. At the same time, the system prefers the interstadial mode of the AMOC when there is less sea ice around the North Atlantic (i.e., less sea ice leads to a stronger AMOC). This means that the strengthening (weakening) of the AMOC and the reduction (increase) in sea ice tend to operate in the same direction and amplify each other; this positive feedback process (which is the origin of the multiple solutions) is responsible for the existence of the thermal threshold of the AMOC.

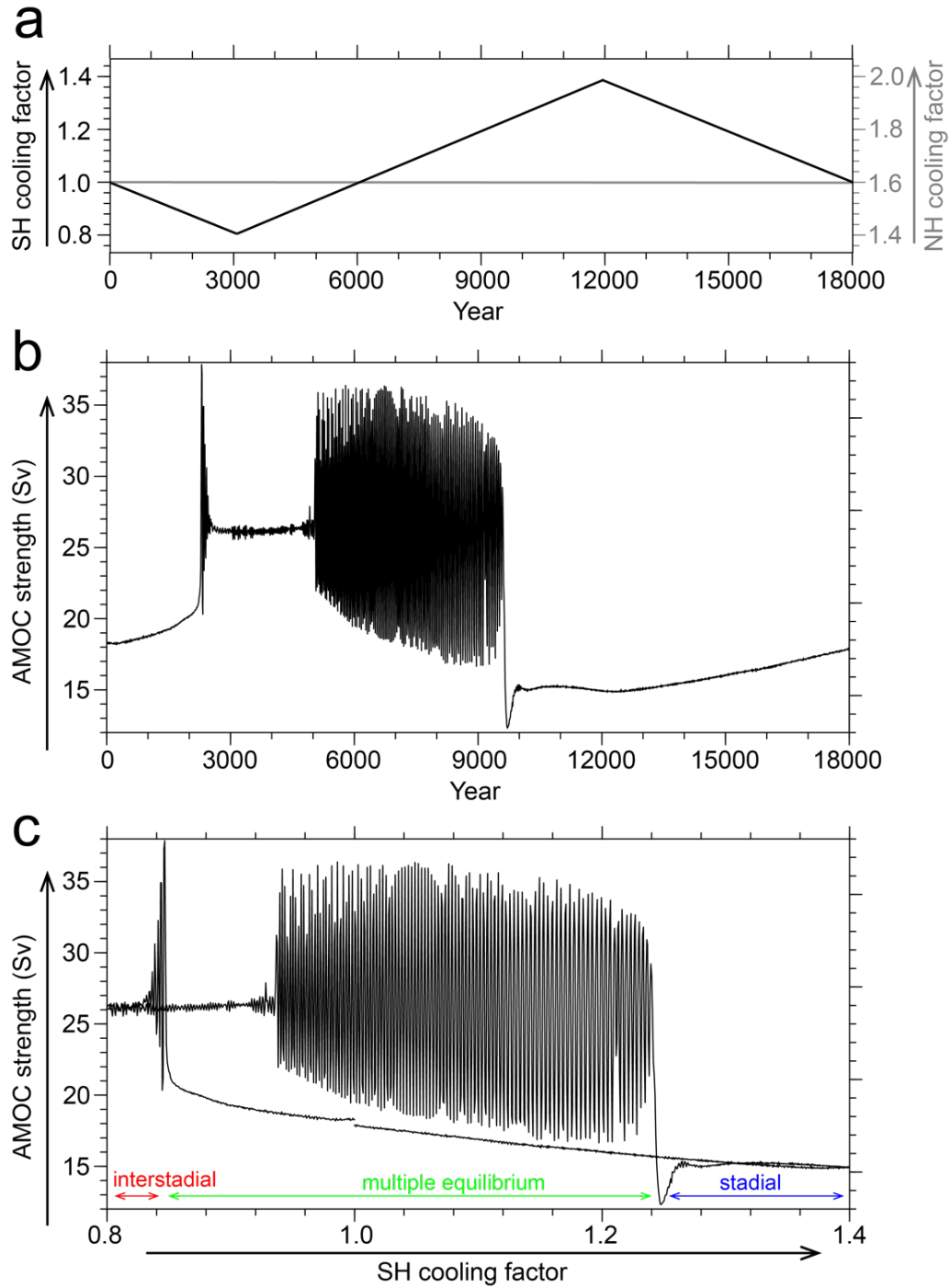
To demonstrate the structure of this multiple equilibrium in more detail, we investigated the hysteresis of the AMOC, shown in Supplementary Figure 2, by extending the transient simulation (Figs 3b and 3c). Unlike previous studies that modified the amount of the freshwater flux, here the thermal condition in the Southern Hemisphere is changed very slowly (Supplementary Fig. 2a) and the simulated strength of the AMOC (Supplementary Fig. 2b) is plotted against the value of the parameter fc_s in Supplementary Fig. 2c. Although only an interstadial (stadial) mode of the AMOC appears for small (large) fc_s in Supplementary Fig. 2c, the multiple equilibria are actually found for intermediate values of fc_s (between approximately 0.85 and 1.25). When the system is in the lower branch of this multiple equilibrium, the figure presents that a mode shift of the AMOC can be triggered by warming of the Southern Ocean

(e.g., when the value of f_{cs} is decreased from 1.0 to 0.8, shown in Fig. 3). The existence of multiple equilibria suggests that a mode shift of the AMOC itself can be triggered even if the value of f_{cs} is not changed; a mode shift from the lower to the upper branch can be triggered by any perturbation (e.g., freshwater forcing) when the system is in the multiple-equilibrium regime. It is also interesting that oscillations of the AMOC take place (around $f_{cs} = 1.0 \sim 1.2$) for the upper branch of the multiple-equilibrium solution. Recently, several atmosphere and ocean coupled models (AOGCMs) have succeeded in simulating millennium-scale oscillations of the AMOC without any external forcing²⁻⁴. This supports the idea that the cycle of DO events is an unforced spontaneous oscillation of the coupled atmosphere-ice-ocean system⁵. Although the timescale of the oscillation in our OGCM simulations is too short compared with those reported from the AOGCMs and with the actual cycle of DO events, the oscillation found in our OGCM simulations may also imply that mode shifts of the AMOC can take place internally in the atmosphere and ocean system. Our idealized ocean model simulations are insufficient for discussing the role of such atmosphere-ocean feedbacks in actual DO-like oscillations, and further studies using a coupled climate model are required for this purpose. In any case, our result suggests that the thermal threshold and its control by the temperature of the Southern Ocean are key processes for understanding the mechanism responsible for the glacial mode shifts of the AMOC.



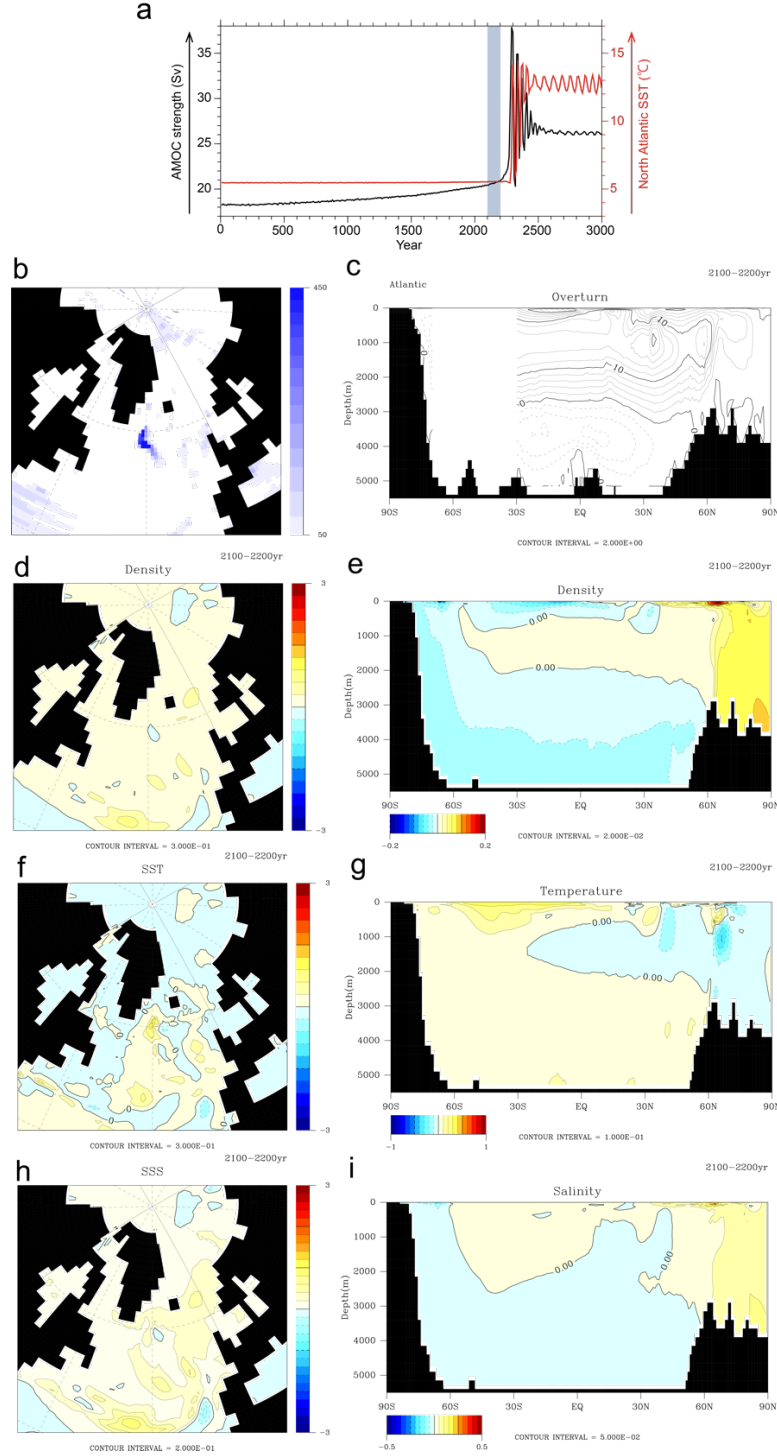
Supplementary Figure 1.

The same as Fig.1 except from the Greenland NGRIP⁶ (top) and stack (Vostok, EDML, EDC and Taldice) of Antarctic ice core data⁷ (bottom). The time scales are synchronised using AICC2012. As for Antarctic, the average stack value is shown with the bold black line, and the individual ice core records are depicted in light grey lines. All ice core values are normalized so that the standard deviation becomes unity.



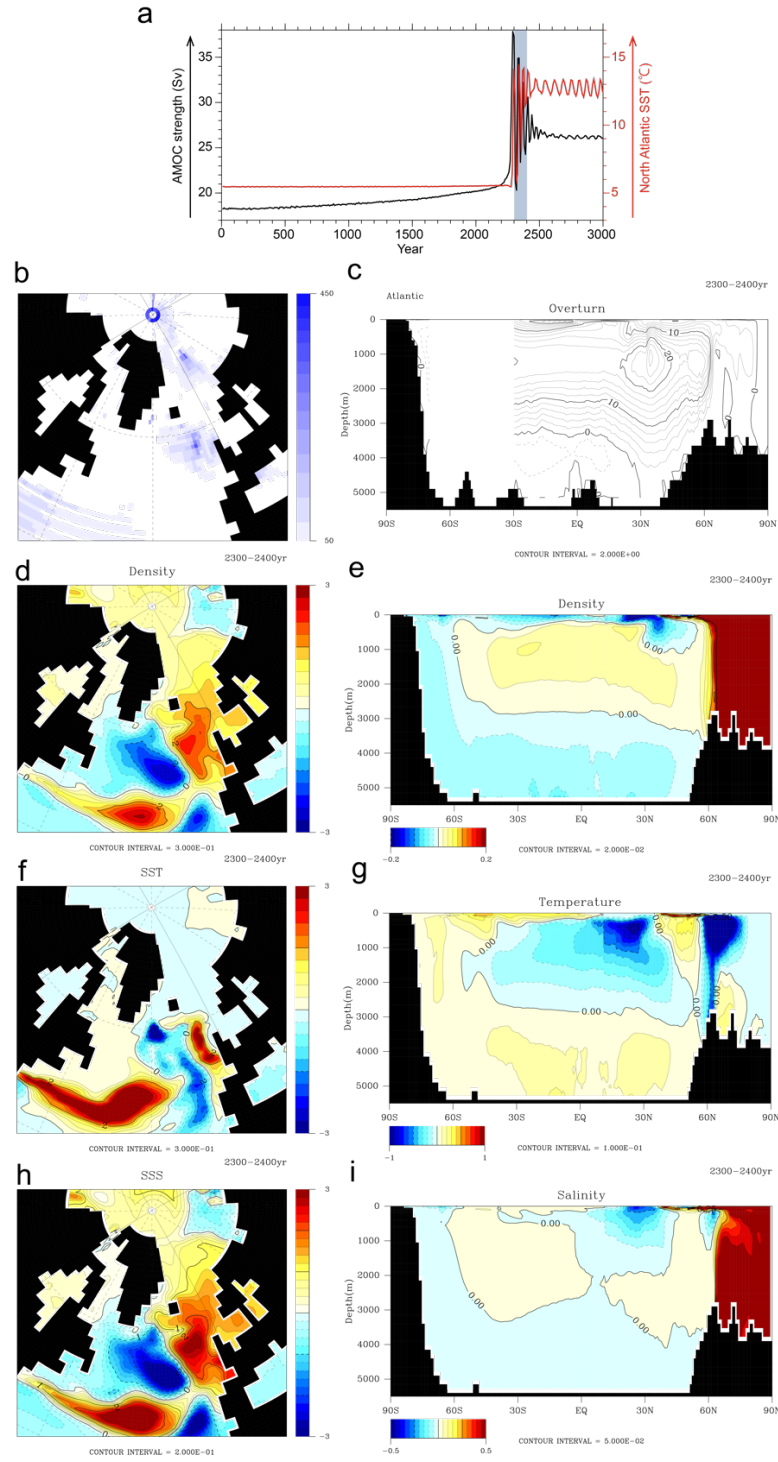
Supplementary Figure 2.

The hysteresis of the AMOC associated with the thermal threshold. (a) Time series of the cooling factor "fc" for investigating the hysteresis. The black line represents the Southern Hemisphere cooling factor and the grey line indicates the Northern Hemisphere cooling factor. (b) The simulated time series of maximum value of AMOC. (c) The hysteresis of the AMOC as a function of the Southern Hemisphere cooling factor.



Supplementary Figure 3.

The ocean state averaged between 2100 and 2200 years (before the strengthening of AMOC) in the transient simulation. (a) The same as Fig. 3c. (b) The penetration depth of convective adjustment (m). (c) AMOC. (d) Surface density anomaly (kg m⁻³). (e) Zonally averaged density anomaly in the Atlantic (kg m⁻³). (f) SST anomaly (°C). (g) Zonally averaged temperature anomaly in the Atlantic (°C). (h) SSS anomaly (‰). (i) Zonally averaged salinity anomaly in the Atlantic (‰). In (b-i), anomaly from the initial state (i.e. 0yr) is shown.



Supplementary Figure 4.

The same as Supplementary Fig.3 but for the ocean state averaged between 2300 and 2400 years (after the strengthening of the AMOC) in the transient simulation.

Supplementary References

1. Sherriff-Tadano, S. & Abe-Ouchi, A. Roles of sea ice–surface wind feedback in maintaining the glacial Atlantic meridional overturning circulation and climate. *J. Clim.* **33**, 3001–3018 (2020).
2. Peltier, W. R. & Vettoretti, G. Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: A “kicked” salt oscillator in the Atlantic. *Geophys. Res. Lett.* **41**, 7306–7313 (2014).
3. Brown, N. & Galbraith, E. D. Hosed vs. unhosed: interruptions of the Atlantic Meridional Overturning Circulation in a global coupled model, with and without freshwater forcing. *Clim. Past* **12**, 1663–1679 (2016).
4. Klockmann, M. *et al.* Two AMOC States in Response to Decreasing Greenhouse Gas Concentrations in the Coupled Climate Model MPI-ESM. *J. Clim.* **31**, 7969–7984 (2018).
5. Li, C. & Born, A. Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events. *Quat. Sci. Rev.* **203**, 1–20 (2019).
6. Andersen, K. K. *et al.* High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* **431**, 147–51 (2004).
7. Veres, D. *et al.* The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years. *Clim. Past* **9**, 1733–1748 (2013).