Abrupt Bolling-Allerod Warming Simulated under Gradual Forcing of the Last Deglaciation

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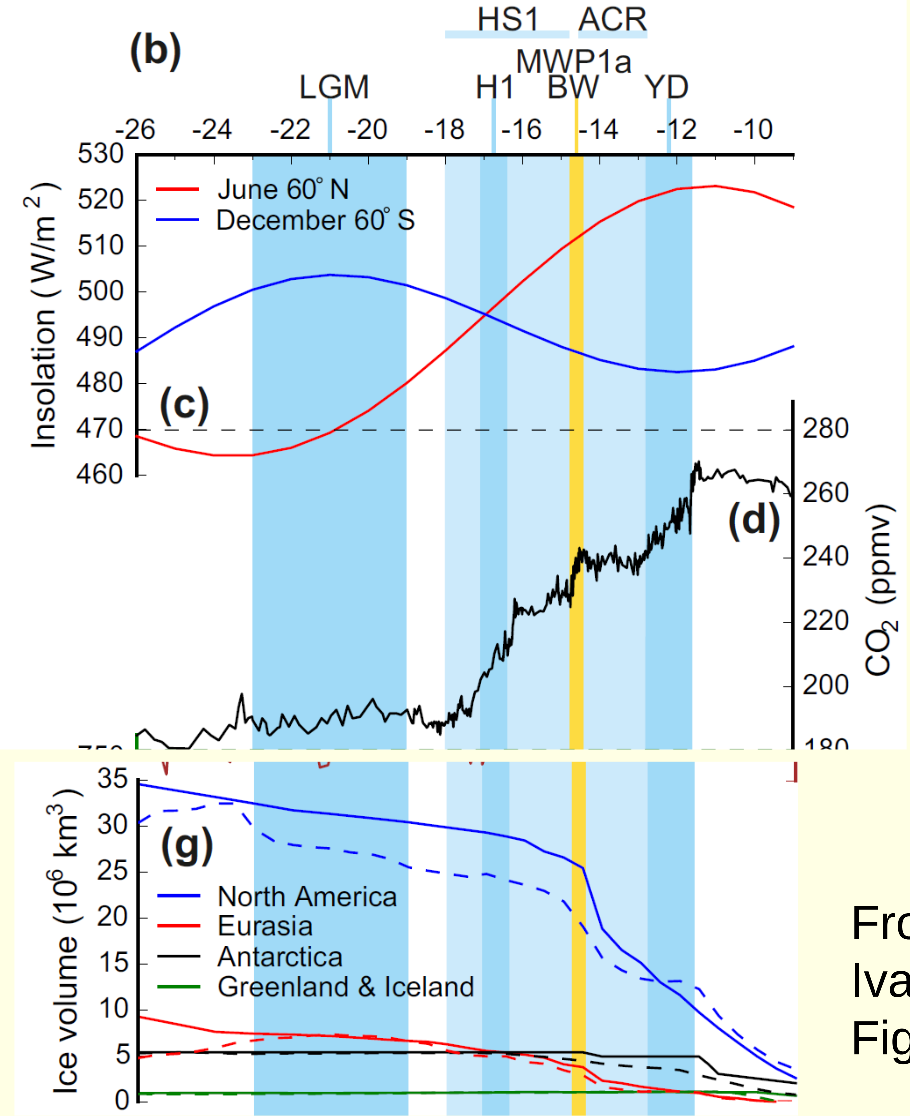
Paleoclimate Modelling Intercomparison Project

Introduction: last deglaciation and abrupt climate changes

Insolation

Atmospheric CO2

Ice sheets volume



From Ivanovic et al. (2016) Fig. 1

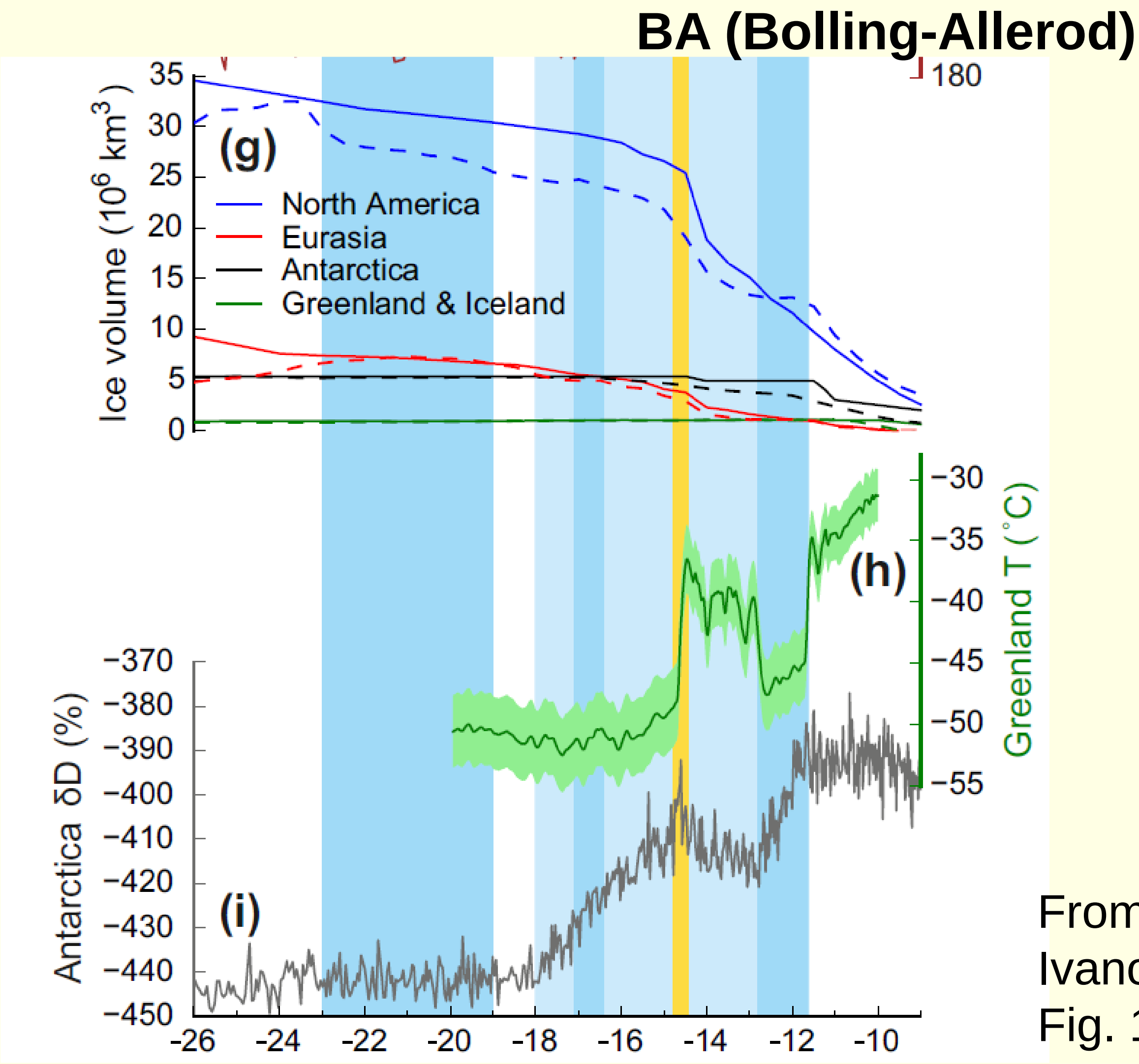
- Last deglaciation: disintegration of continental ice sheets, <u>driven by insolation and climate system dynamics</u> (Denton et al. 2010; Clark et al. 2012)

Introduction: last deglaciation and abrupt climate changes

Ice sheets Volume

Greenland SAT

Antarctic SAT



From Ivanovic et al. (2016) Fig. 1

- **Abrupt Greenland warming** occurred at BA transition (~14.7ka BP), and the Antarctic region turned into a cooling trend.

Introduction: Transient simulation of the last deglaciation

- Transient simulation of the last deglaciation have been conducted using climate models, and the **abrupt increase in the AMOC** reproduce the reconstructed climate responses across BA. (Liu et al. 2009; Menviel et al. 2011; Shakun et al. 2012)

- One of remained question is, why there was BA during the middle stage of the deglaciation, in spite of continuous melting of Northern ice sheets, which may have tend to weaken the AMOC.

- Several studies indicate abrupt AMOC increase can occur due to gradual changes in thermal condition or atmospheric CO_2. (Knorr and Lohmann 2003; Ganopolski and Roche 2009; Zhang et al. 2017)

Introduction: PMIP4 deglaciation protocol

Geosci. Model Dev., 9, 2563–2587, 2016
www.geosci-model-dev.net/9/2563/2016/
doi:10.5194/gmd-9-2563-2016

Geoscientific Model Development
Open Access
EGU

Transient climate simulations of the deglaciation 21–9 thousand years before present (version 1) – PMIP4 Core experiment design and boundary conditions

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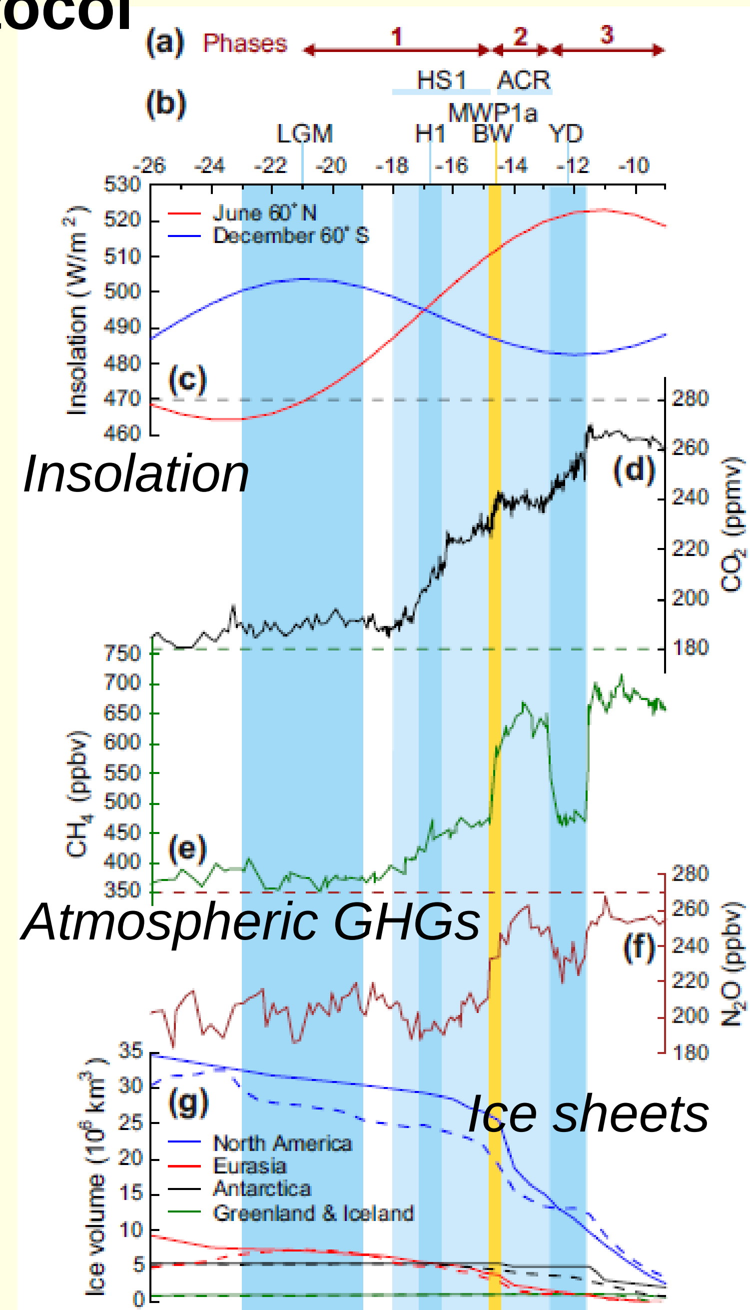
PMIP4 deglaciation working group (Ivanovic et al. 2016 GMD) :

- Collected boundary conditions and proposed protocols of deglaciation experiments for climate models.

- insolation, atmospheric GHGs, ice sheets, meltwater flux to the ocean



From Ivanovic et al. (2016) Fig. 1

Methods: Model and climate forcing

We conducted transient simulation from LGM to the middle of the last deglaciation (21 to 13 ka BP) using transient forcings:

★ Model: MIROC 4m, Atmosphere-Ocean coupled GCM

Atmospheric resolution: T42 (2.8 x 2.8 degrees) with 20 levels,

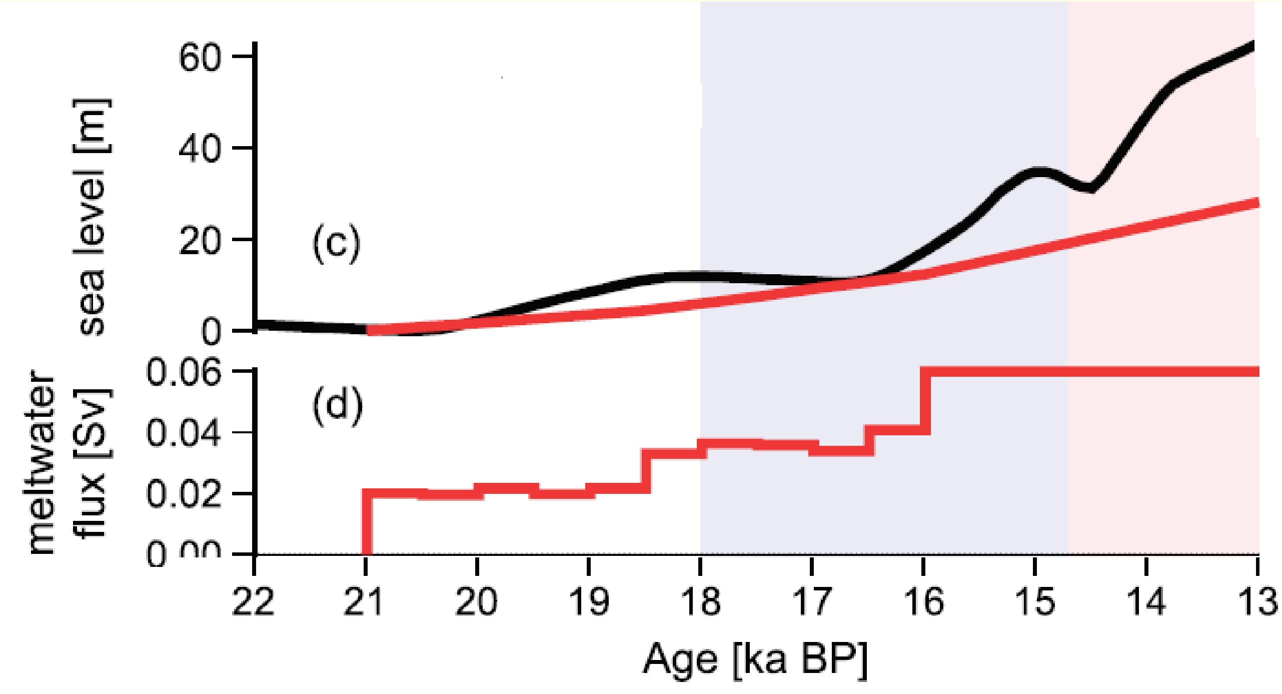
Oceanic resolution: 1.4 x 1 degrees with 43 levels.

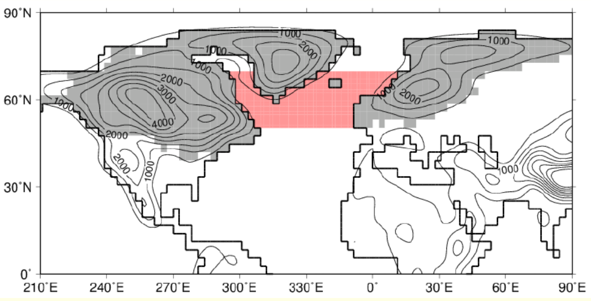
(Model is same as Kawamura et al. 2017)

★ Climate forcing: (＊ indicates different from PMIP4 protocol)

- Astronomical parameters which determines insolation
- Atmospheric GHGs of CO_2, CH_4, N_2O
- Meltwater flux to the North Atlantic based on volume of ice sheets
- ＊ Ice sheet topography, coastline, sea level is fixed to that of LGM

Methods: North Atlantic Freshwater Forcing





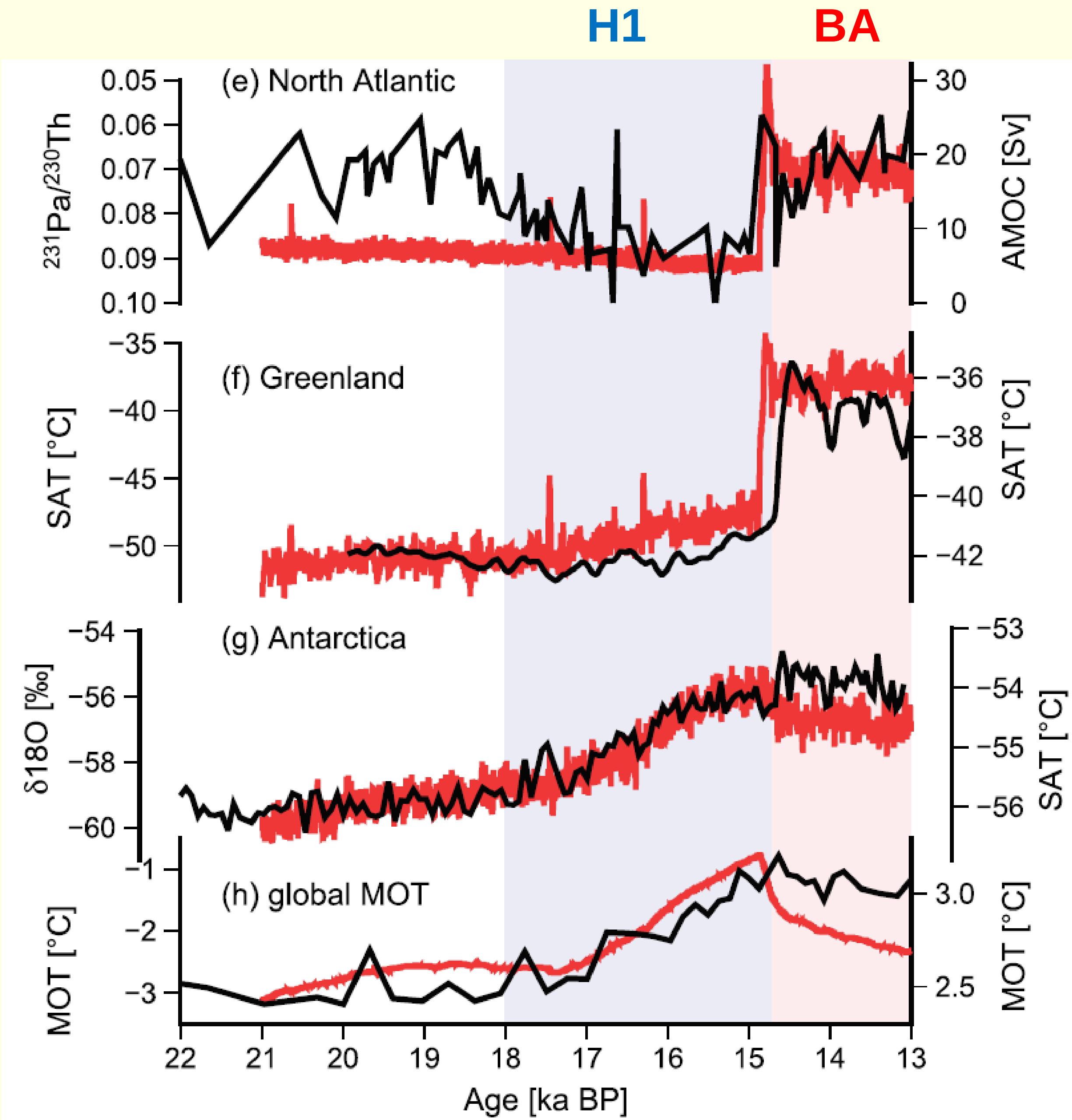
Area of hosing (50-70N)

Black: reconstructed sea level (Lambeck et al. 2014)

Red: meltwater used in this study (from Fig. 1 of OA19)

- Meltwater is uniformly applied to 50-70N fixed area of the North Atlantic.
- We mainly analyze one experiment (Red lines), which shows abrupt increase in the AMOC near the actual BA (~15 ka BP). In this exp, <u>meltwater flux is from Ice6G (21-16ka BP) and kept to 0.06Sv</u> thereafter.

Results: AMOC, SAT over Greenland and Antarctica



Black: Proxies

Red: Model results

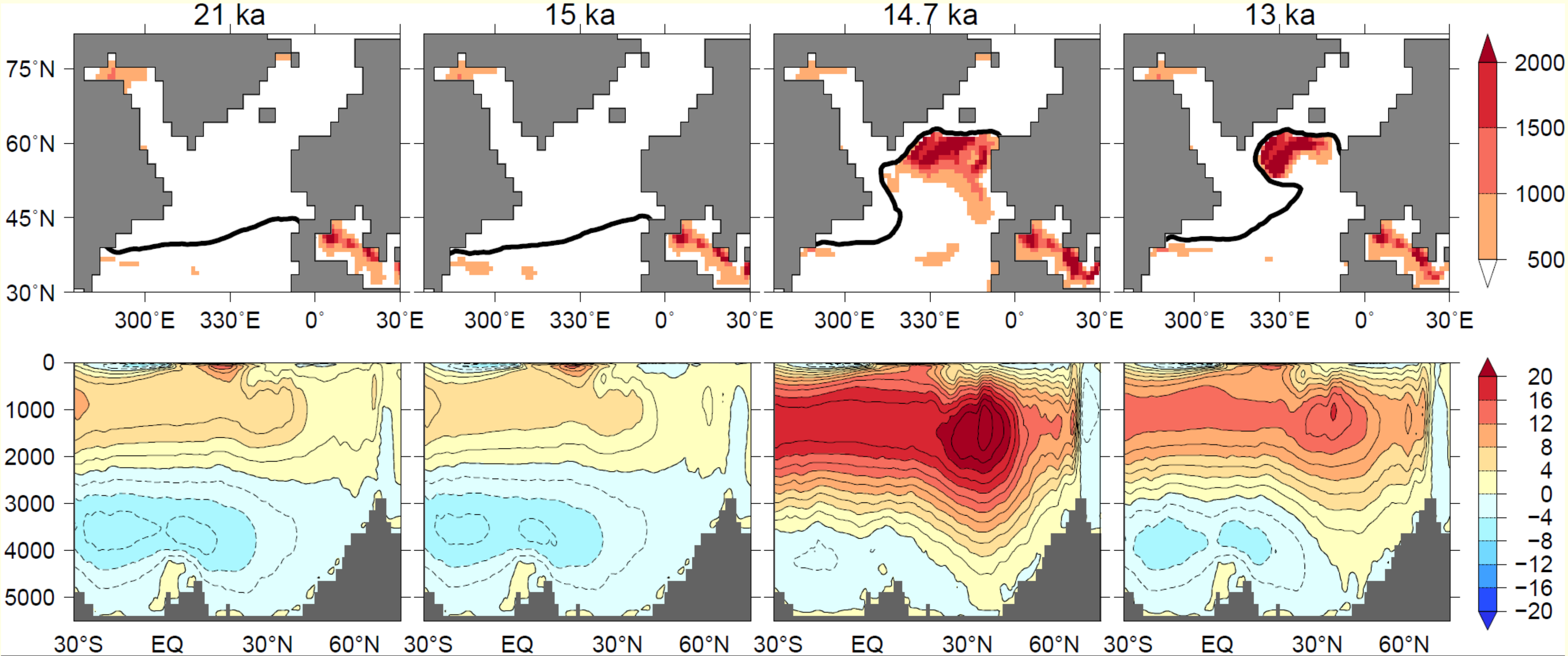
(Fig. 1 of OA19)

The left axises -> proxies
The right axises -> model

At the H1/BA transition, model simulates

- Abrupt AMOC increase
- Abrupt (~100yr) warming in Greenland
- Standstill of Antarctic temp., global mean ocean temp., and turn to a cooling trend.

Results: North Atlantic sea ice and ocean circulations

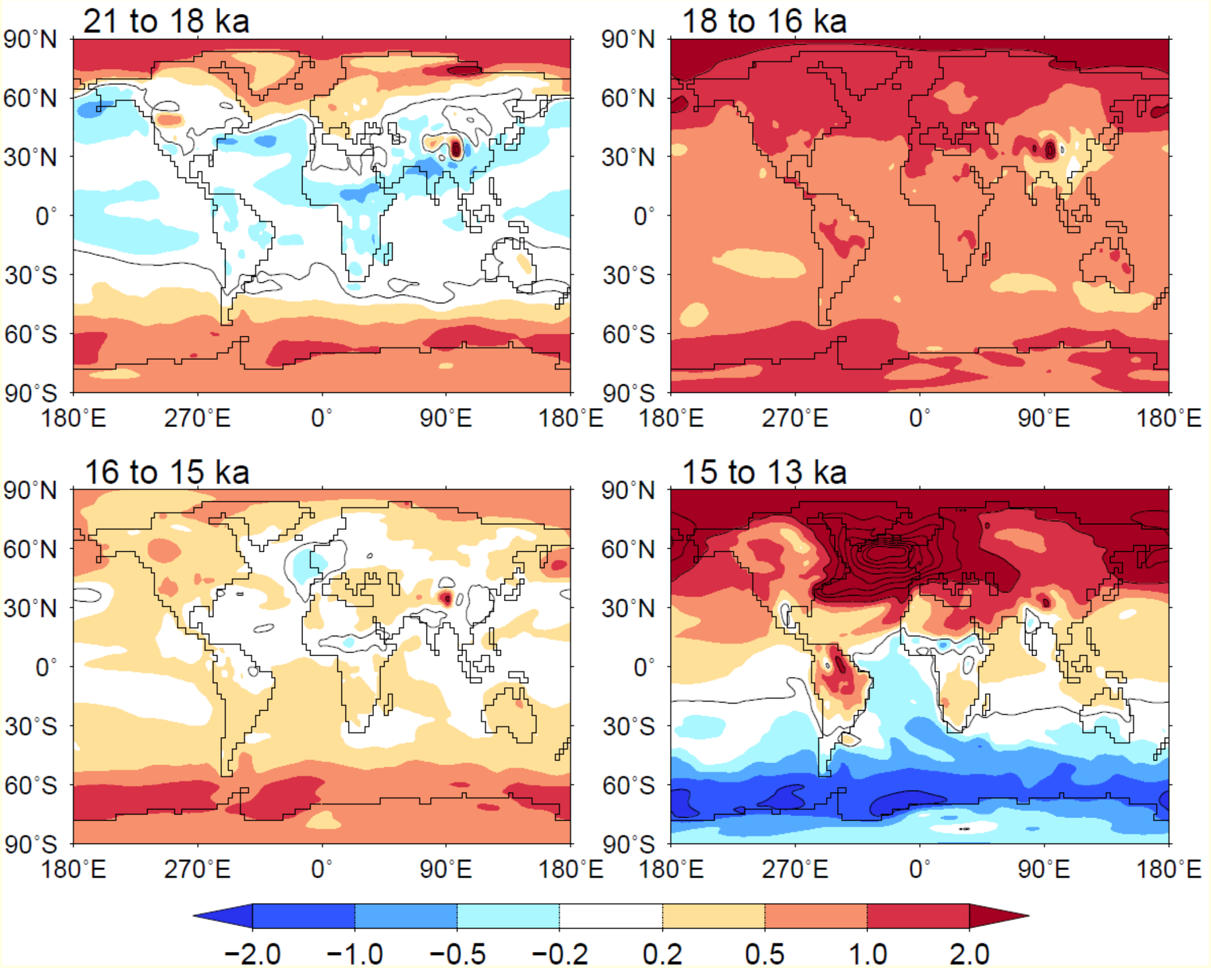


Top: Winter sea ice edge (lines), winter mixed layer depth [m] North Atlantic
Bottom: Atlantic meridional streamfunctions [Sv] Fig. 2 of OA19

- <u>Atlantic winter sea ice extent</u> did not retreat during 21 to 15 ka BP.
- Drastic retreat of sea ice, increase in meridional ocean circulation occurred between 15 to 14.7 ka BP, which continued to 13 ka BP.

Results: SAT changes during different stage of deglaciation

Surface air temperature changes during four periods (Fig. 3 of OA19)



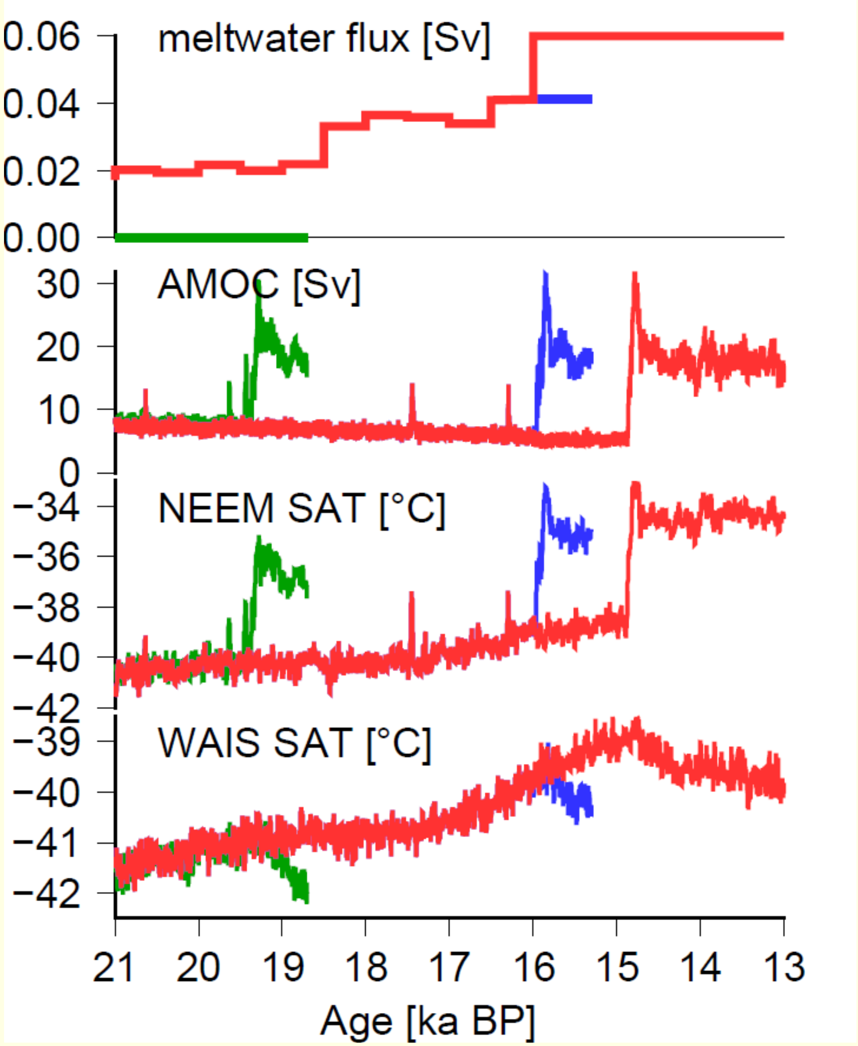
Primary factors in SAT changes are different between stages:

- 21 to 18 ka: warming in polars & cooling in tropics, mainly by <u>obliquity</u>
- 18 to 15 ka: global warming, mainly by <u>CO2</u>
- 15 to 13 ka: bipolar temperature change in response to the <u>AMOC</u>

Results: Different meltwater flux

Experimental Design:
same as previous
0.04 Sv after 16ka
no meltwater

Results:



We conducted two additional exps which use different meltwater flux.

- If the meltwater were less (blue, green), the recovery in the AMOC occurred earlier than the reference experiments.

Discussion

- **Results Summary:** BA-like climate change due to abrupt increase in the AMOC could be caused without stopping meltwater in the North Atlantic. Consistent with previous studies in that gradual climate change can cause it.

- strength: abrupt BA-like climate change can be simulated by an coupled AOGCM under reconstructed forcing of insolation, GHGs, and meltwater of the last deglaciation.

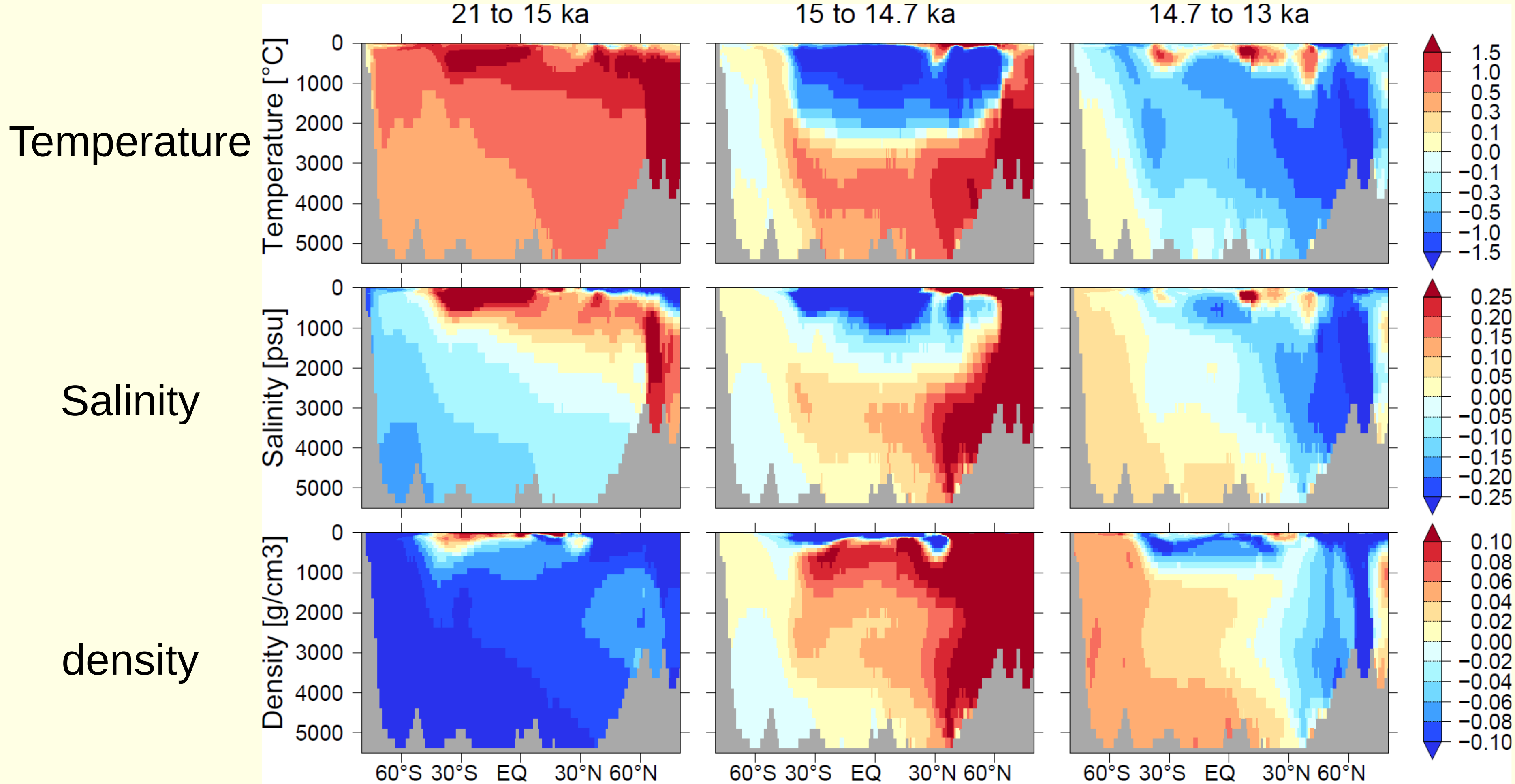
- We speculate that gradual warming affected the North Atlantic and the AMOC, through the sea ice & AABW in the Southern Ocean (Liu et al. 2005; Kawamura et al. 2017). Relative contributions of the processes should be clarified in future.

- BA-like climate change occurred in a very early stage (19ka) of the last deglaciation if meltwater flux was not applied. Suggesting continuous meltwater contributed to preventing BA-like climate changes for about several thousand years.

- Suggested climate system dynamics during the last deglaciation: Summer insolation melted Northern continental ice sheets, and produced meltwater and weakened the AMOC. The reduced AMOC warmed the Southern Ocean through the bipolar warming and raised atmospheric GHG, and in turn contributes to abrupt AMOC increase at BA

- From comparison of the last four deglaciations, not all deglaciations accompanied BA-like climate changes as in the last deglaciation (Cheng et al., 2009). We expect further investigations on the critical processes, and model-data comparisons will improve understanding of the climate system dynamics during deglaciations.

Results: Atlantic zonal mean ocean structures

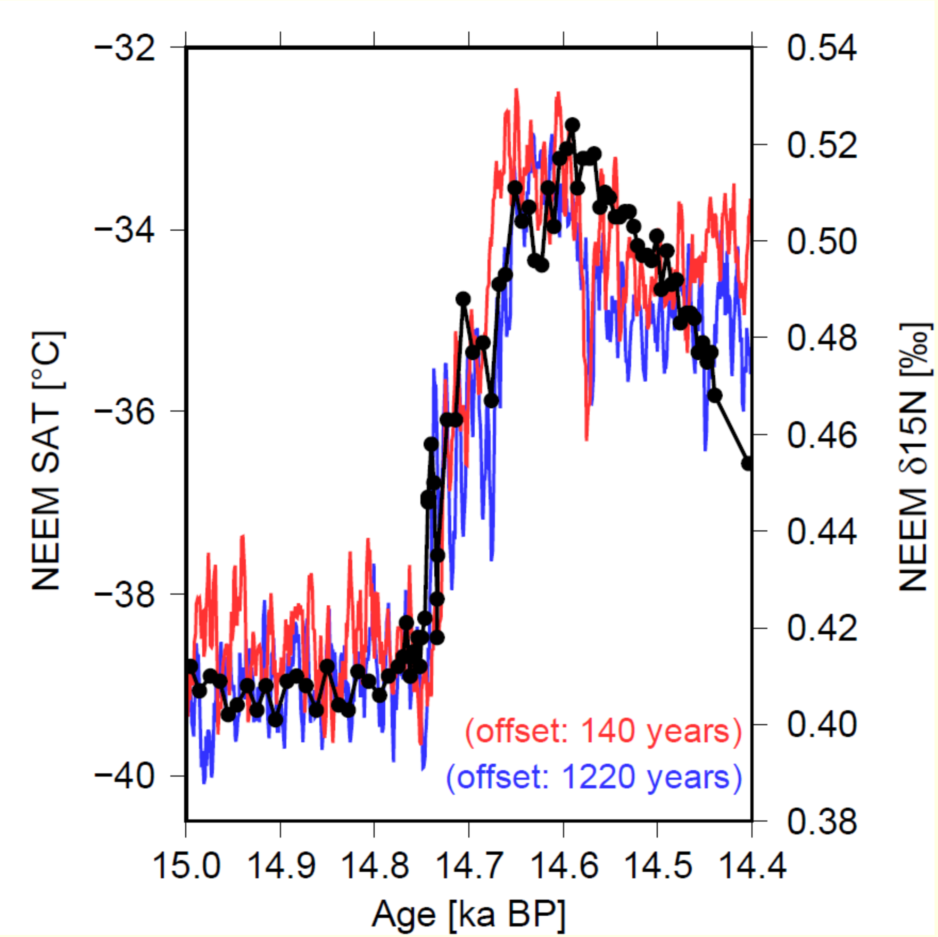


Zonal mean ocean properties changes during 3 periods (Fig. 3 of OA19)

21-15 ka: Warming in the subsurface of the North Atlantic, freshening in the Antarctic-Atlantic bottom water contributed to less stratification in the North Atlantic.

15-14.7ka: increase in the AMOC caused drastic changes in ocean properties.

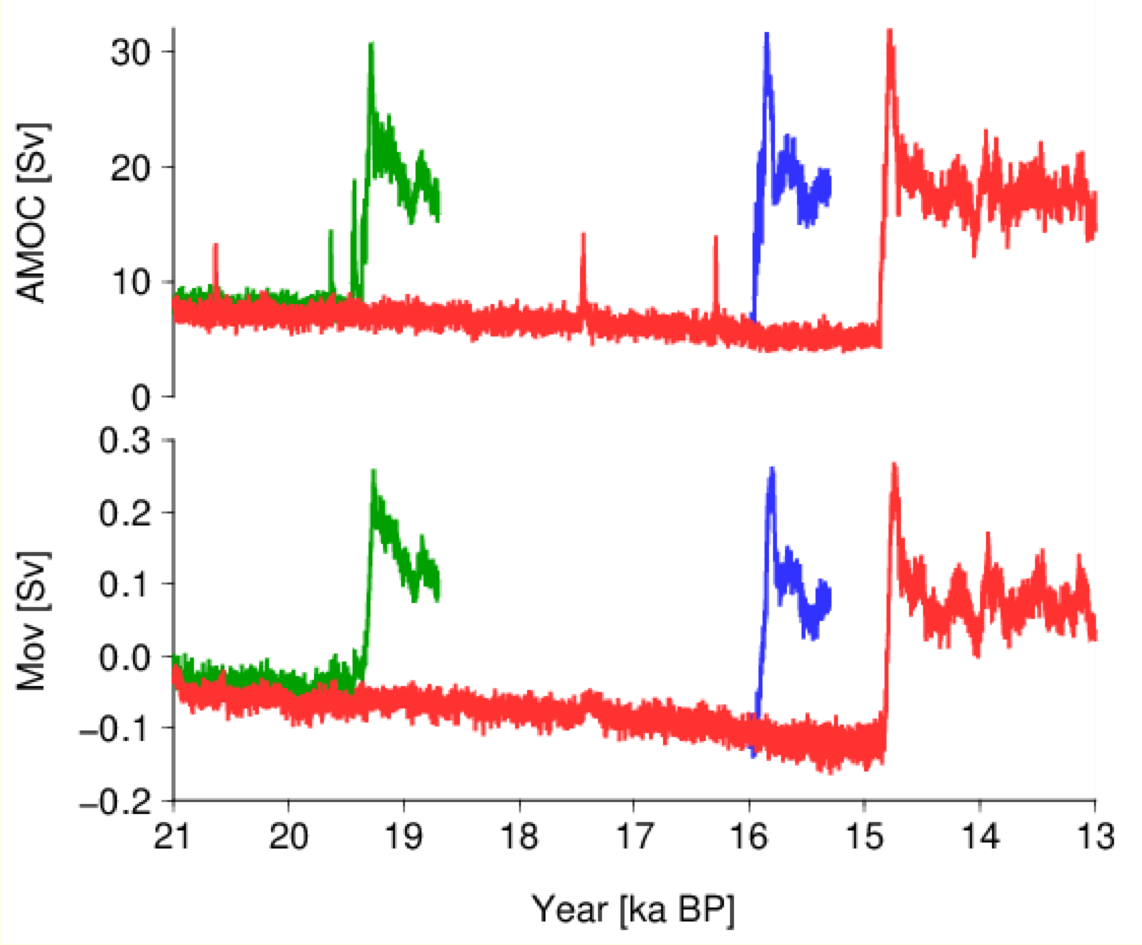
Supporting Information 1: abruptness of Greenland warming

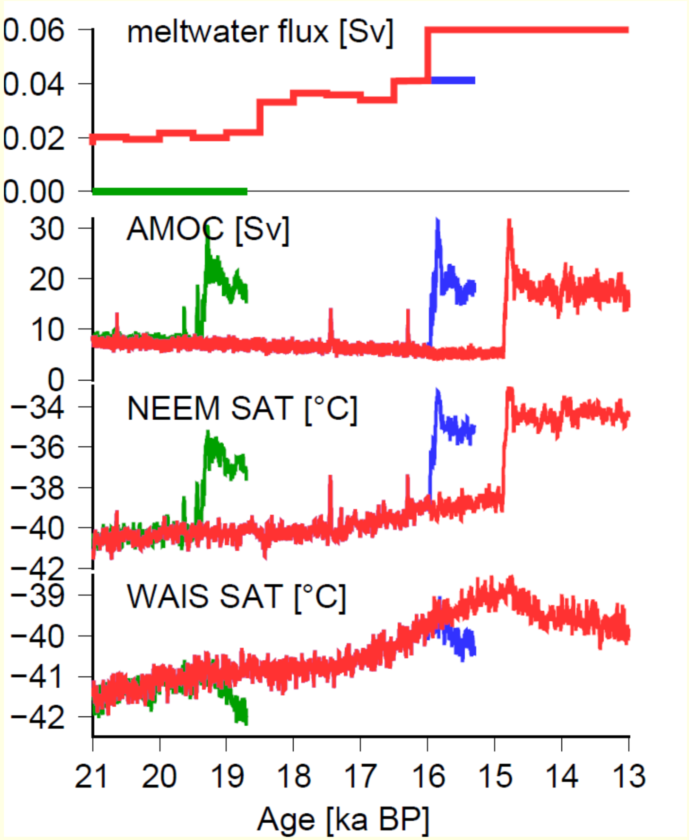


Reconstructions
Model results
Model results

It takes about 100 years to reach the surface air temperature over the Greenland to the maximum, which is close to the reconstruction from the NEEM, Greenland (Rosen et al. 2014)

Supporting information 2: AMOC stability index

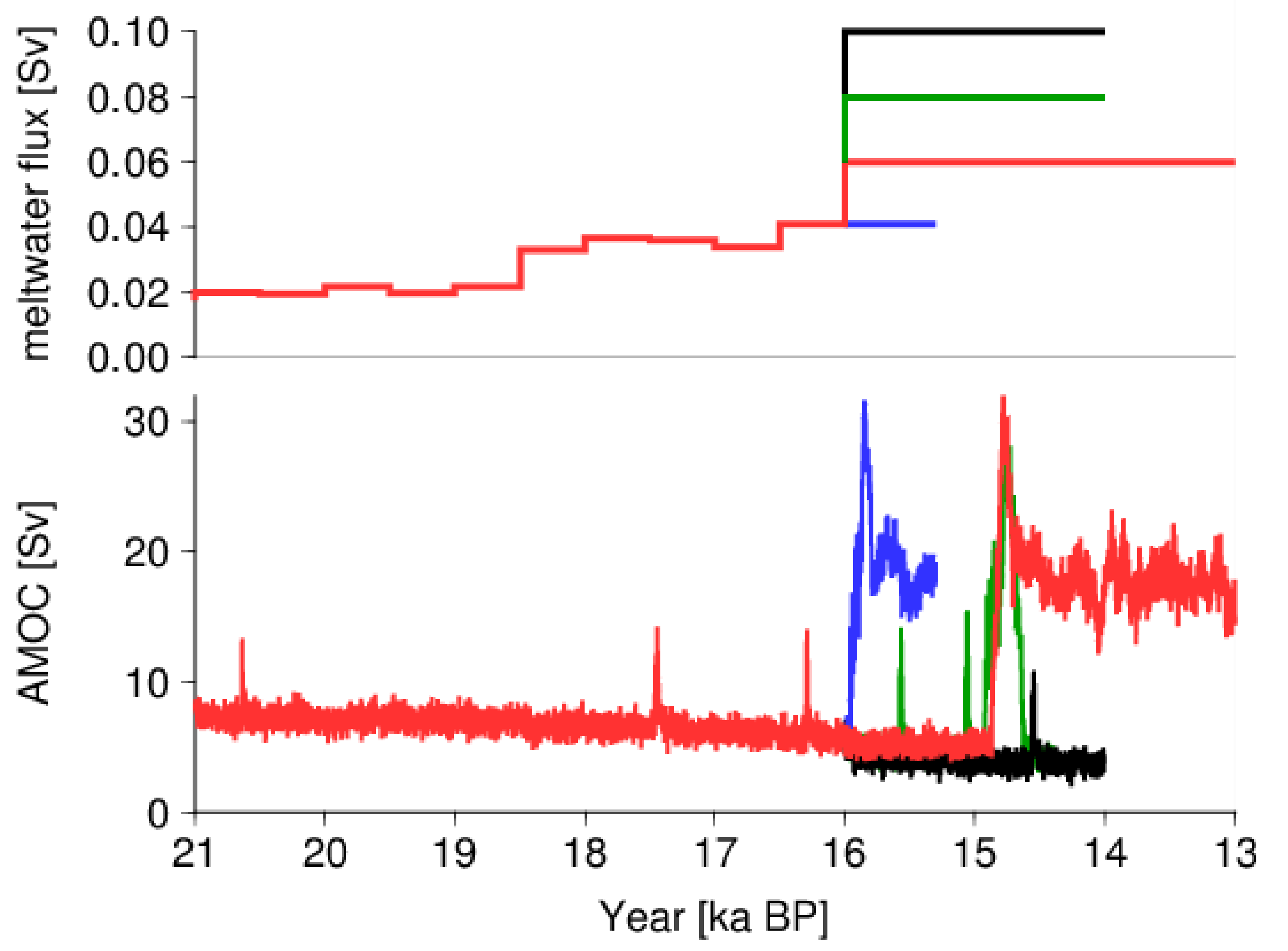




Stability index of Mov (Liu et al. 2015) in three experiments:

Positive (negative) indicates monostable (bistable) AMOC

Supporting information 3: meltwater level



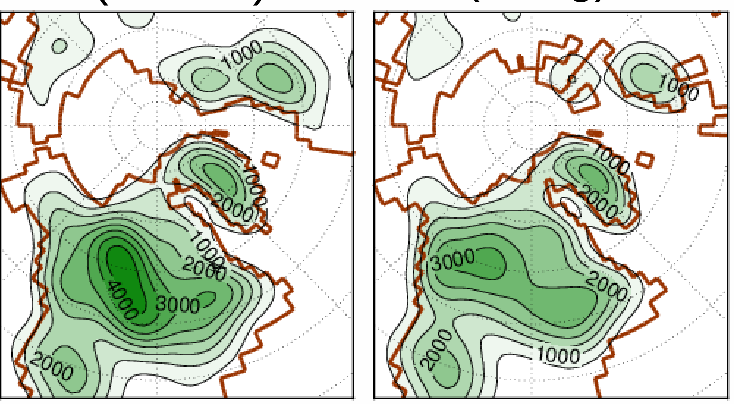
Another set of sensitivity experiments on meltwater flux.

The larger meltwater delays the timing of BA-like AMOC increase.

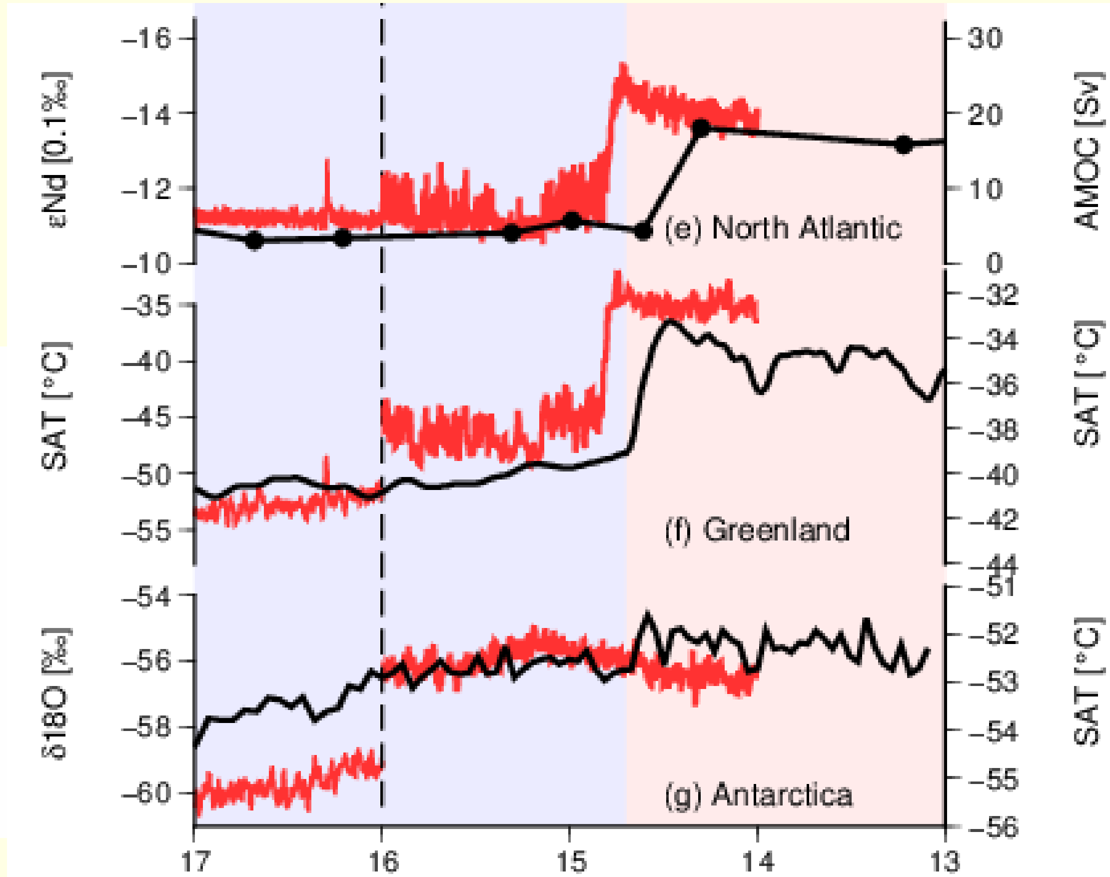
Supporting information 4: impact of LGM ice sheets

Surface topography and coastline

LGM (PMIP2) | 15ka (ice6g)



↓ geometry was switched to 15ka



Results AMOC, SAT Greenland and Antarctica
(Materials are from the poster at INQUA 2019.)

Ice sheets are fixed to that of LGM in the experiments in this study, but abrupt increase in the AMOC can occur under ice sheet topography of 15ka.