Supplement of Clim. Past, 20, 789–815, 2024
https://doi.org/10.5194/cp-20-789-2024-supplement

Climate of the Past
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Supplement of

A multi-model assessment of the early last deglaciation (PMIP4 LDv1): a meltwater perspective

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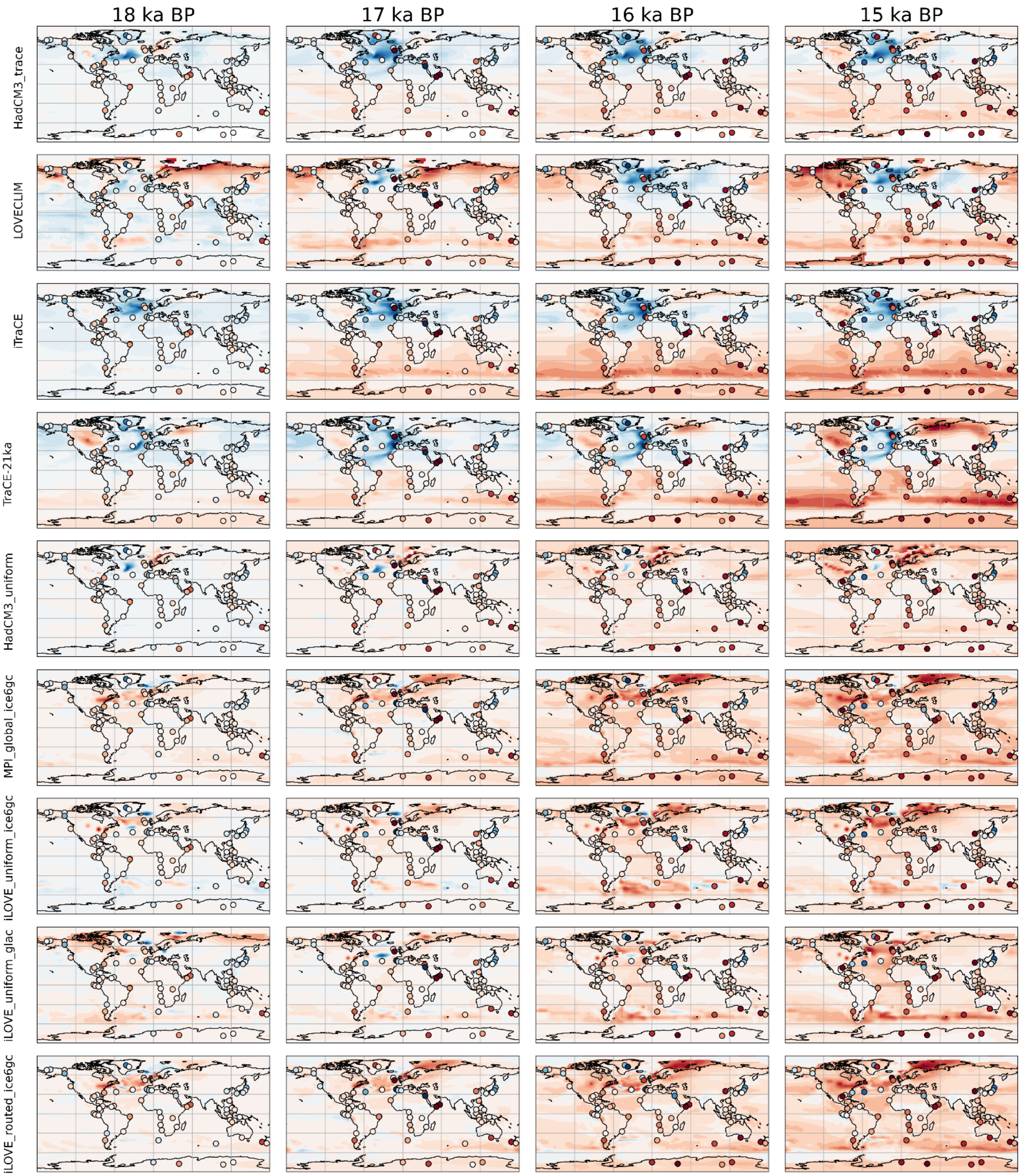
Supplementary Information

1. Supplement to timing of the deglaciation



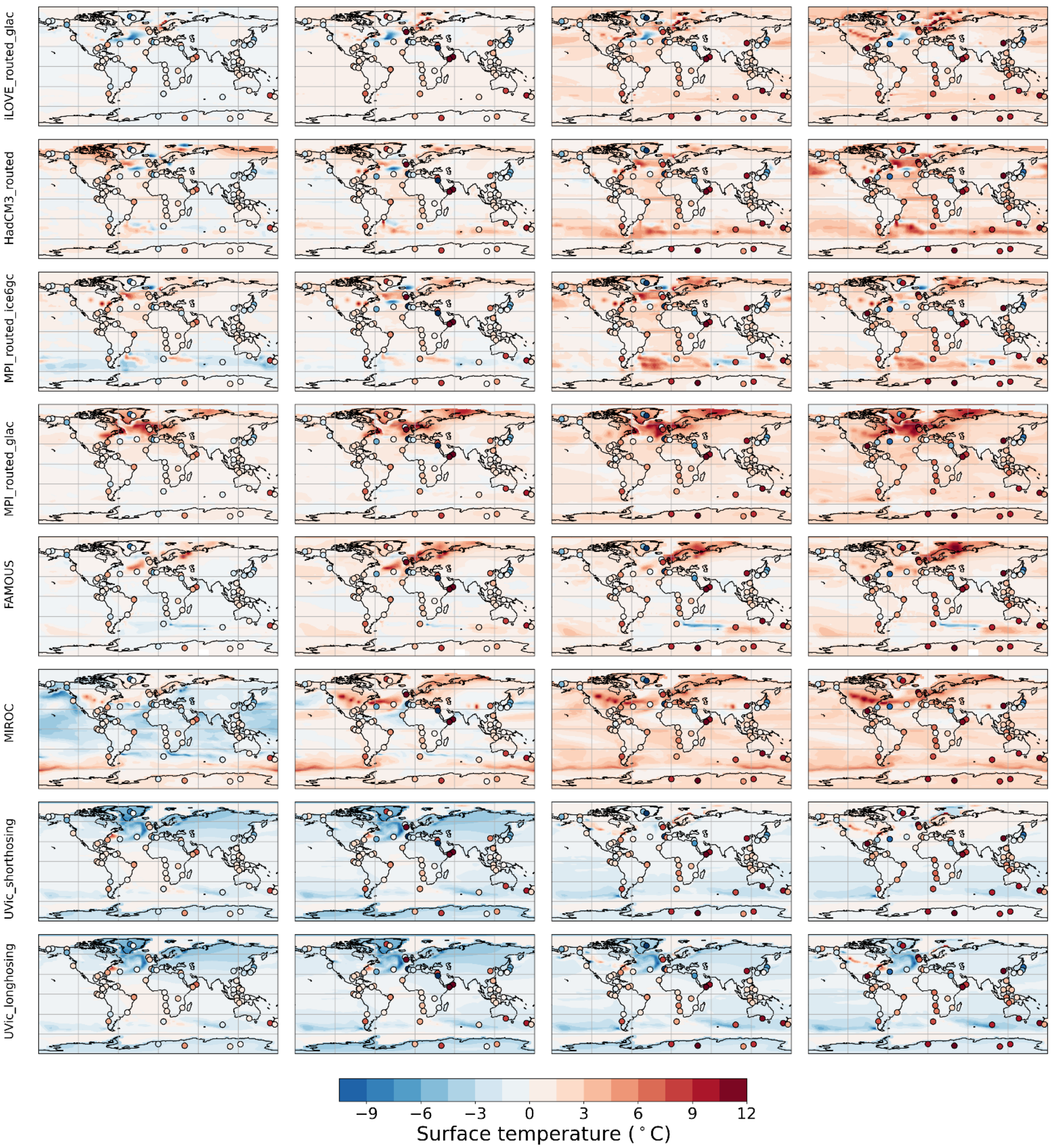


Fig. S1: Global decadal surface temperature as anomalies from the LGM (average between 20 and 19.5 ka BP). 18, 17, 16, and 15 ka BP are calculated as 60-year decadal means centred around the respective time period (e.g., from 17.97 to 18.03 ka BP for 18 ka BP). The surface temperature stack by Shakun et al., (2012) as anomalies from the LGM is overlayed.

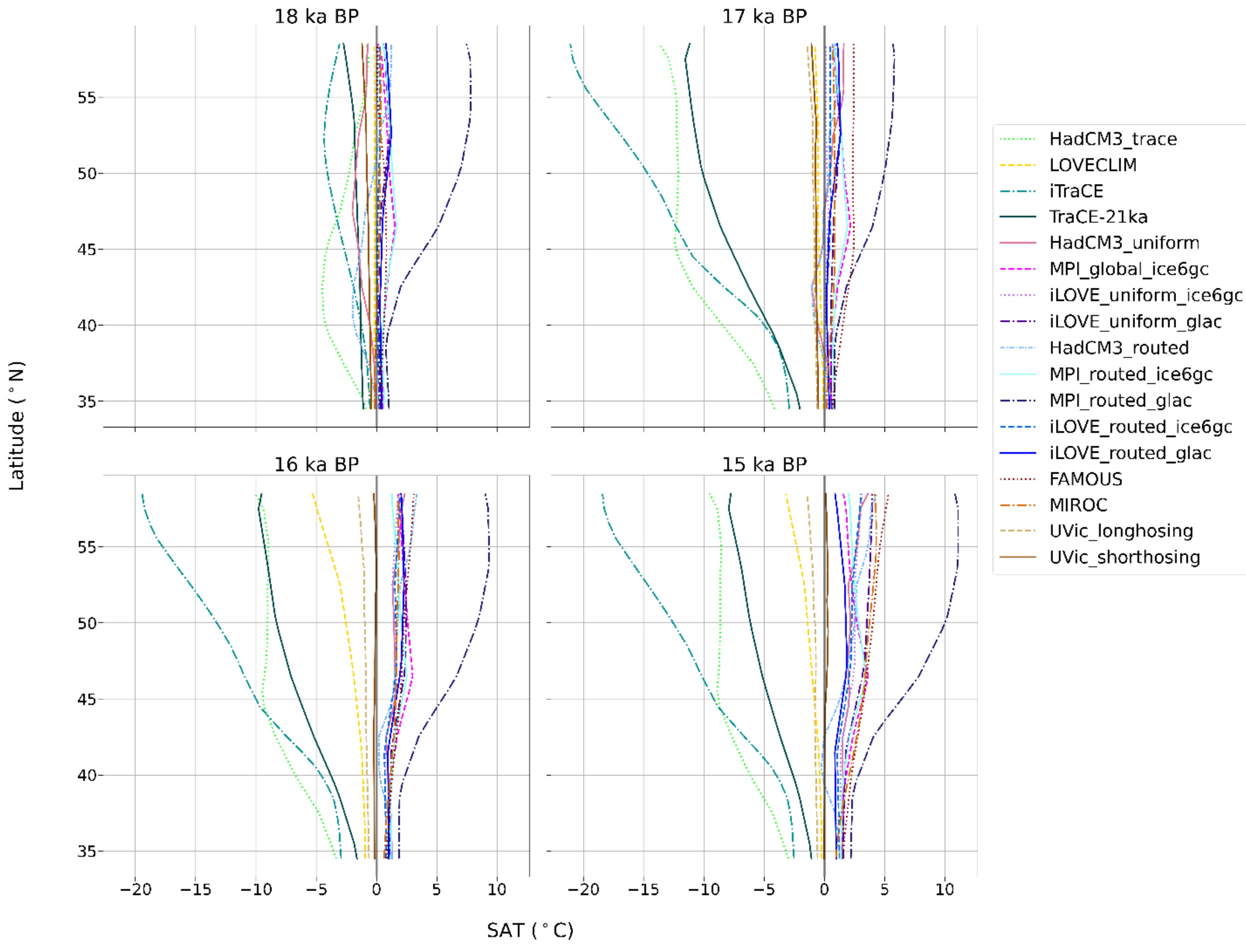


Fig. S2: Zonal average of decadal surface air temperature across the ensemble for the North Atlantic (between 35 and 60° N and -60 and 0° E) as anomalies from the LGM (20 – 19.5 ka BP) for each simulation. 18, 17, 16, and 15 ka BP are calculated as 60-year decadal means centred around the respective time period (e.g., from 17.97 to 18.03 ka BP for 18 ka BP).

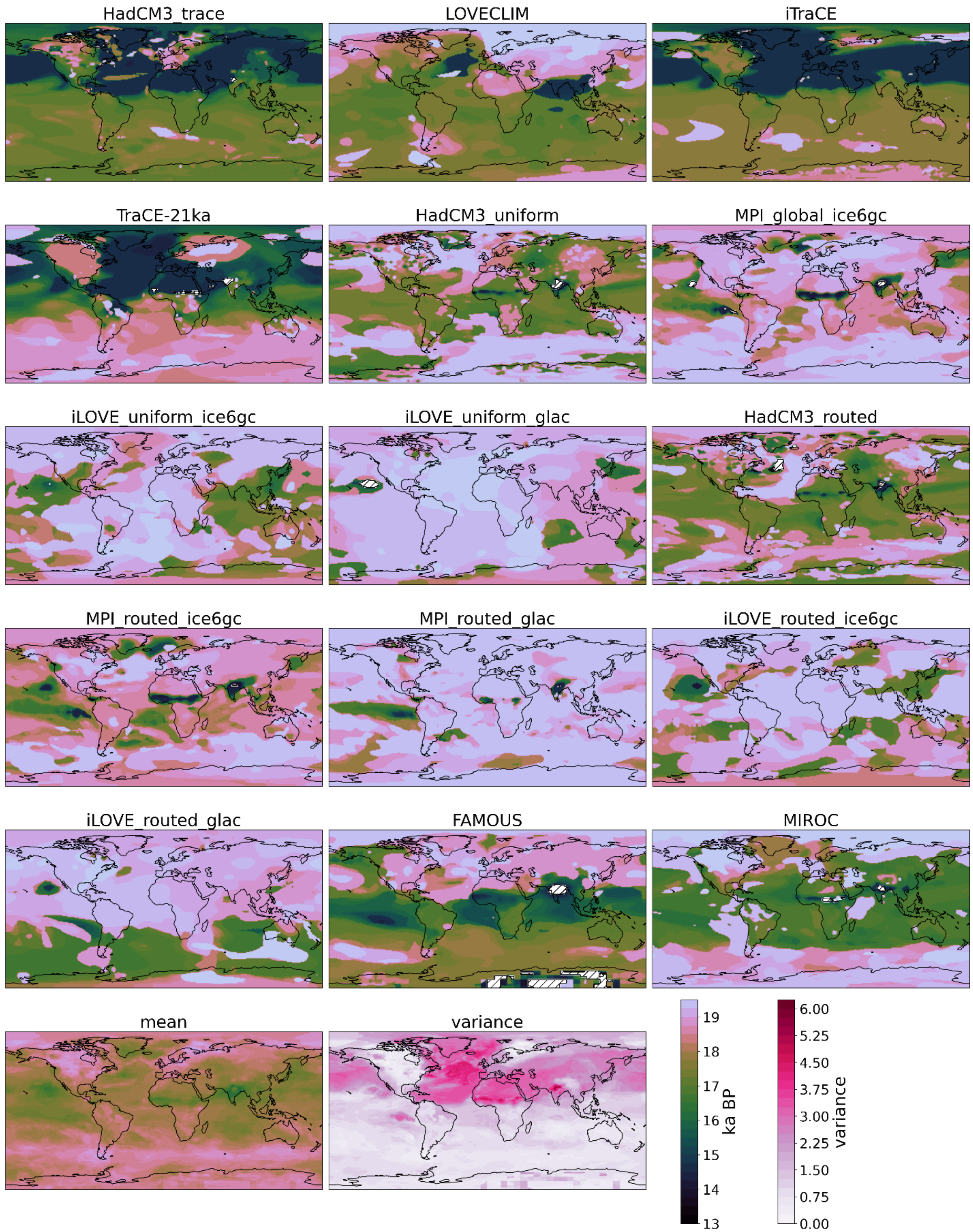


Fig. S3: Year of first significant warming from 20 ka BP, where 'significant warming' is determined as discussed in section 3 but the reference period is between 20 and 19.5 ka BP instead of between 21 and 20.5 ka BP. Hatching denotes where significant warming did not occur before 13 ka BP.

The main text shows the year of first significant warming from the LGM defined as 21 – 20.5 ka BP. For three of the simulations, *LOVECLIM, HadCM3_TraCE*, and *iTraCE*, we did not have the data to do this analysis. We have repeated the analysis here but with a later reference period (20 – 19.7 ka BP). The year of first significant warming from the reference perspective of 19.7 ka BP opposed to 21 ka BP (as Fig. S3 shows) demonstrates the impact of the large freshwater forcing the *TraCE-like* simulations use on the speed of warming during the deglaciation. Immediately coming out of the LGM, *TraCE-21ka* does warm in the north and south high latitudes (Fig. 5). However, in the North Atlantic, the meltwater flux induces a cooling that pauses significant warming until ~15 ka BP when temperatures would have increased towards the Bølling Warming. This same pattern is also evident in *HadCM3_TraCE, LOVECLIM*, and *iTraCE* except *LOVECLIM* warms earlier in Fennoscandia and Russia than the other *TraCE-like* simulations.

By 16 ka BP, the non-*TraCE-like* simulations show significant warming throughout the globe with respect to 20 – 19.5 ka BP, whereas the *TraCE-like* simulations still have the strong cooling in the North Atlantic associated with the freshwater input (Fig. S3 and S1). *FAMOUS* also has more delayed warming in the tropics which could correspond with the later increase in CO_2 concentration. In the *TraCE-like* simulations (most evident in *HadCM3_TraCE* and *TraCE-21ka*), the earlier deglacial warming in the Southern Hemisphere and the delayed warming in the Northern Hemisphere are due to the bipolar seesaw (Broecker 1998; Stocker 1998) associated with the simulated slowdown of AMOC within Heinrich Stadial 1 (He et al. 2013). This is less evident in *LOVECLIM*, potentially because the cooling from the freshwater flux occurs later, at 17 ka BP, and therefore, significant warming has already occurred beforehand (as also evident by the zonal surface air temperature means; Fig. 3).

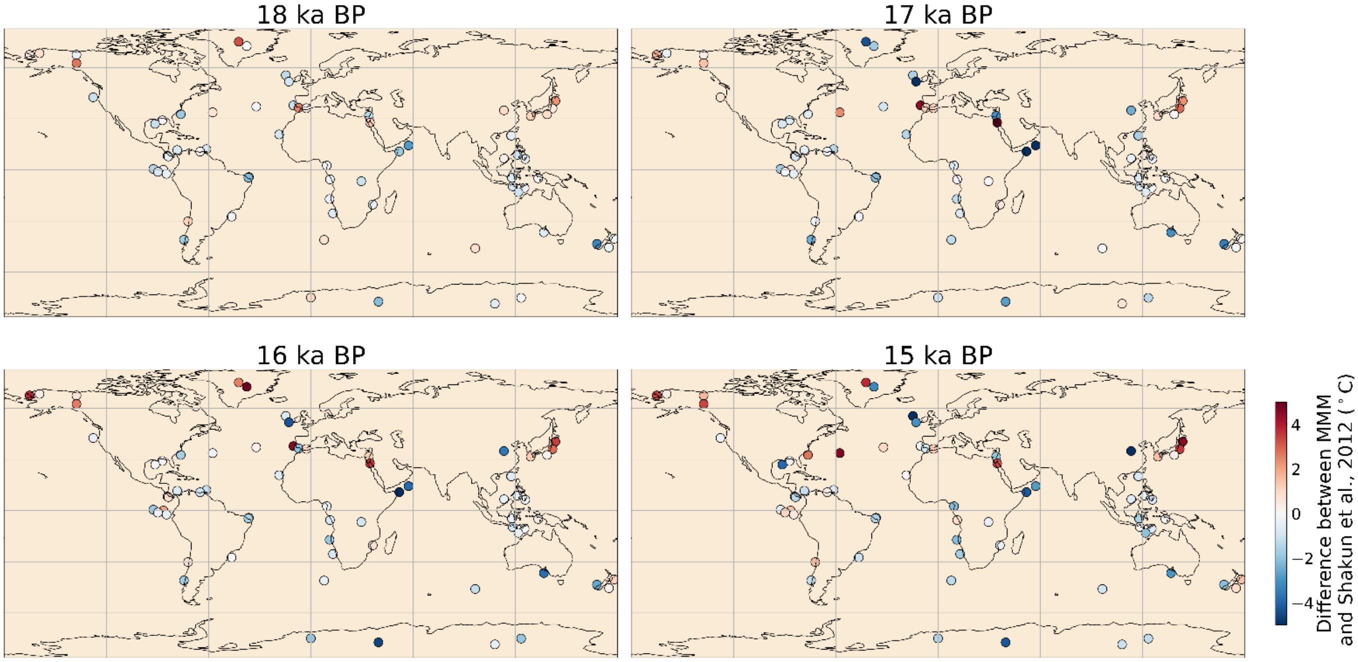


Fig. S4: Point-by-point difference between multi-model ensemble mean surface temperature (Figure 4) and the surface temperature stack by Shakun et al., (2012).

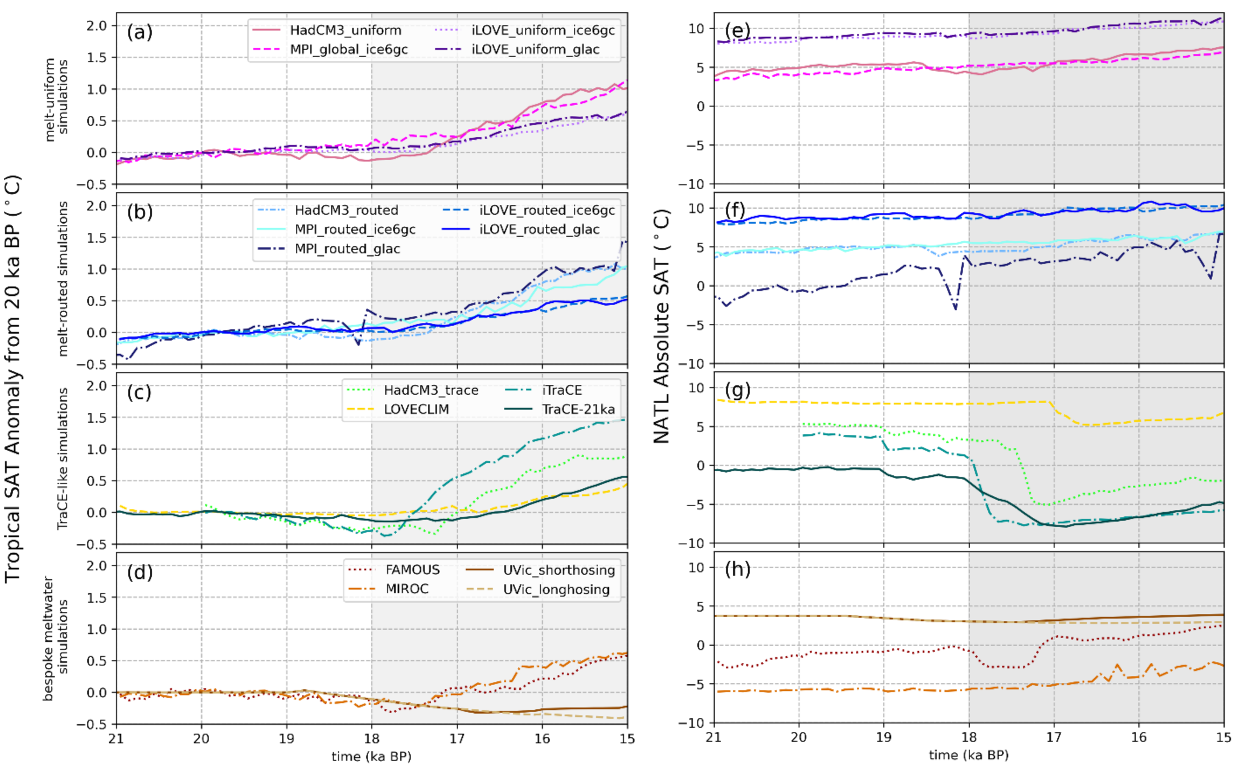


Fig. S5: (a) – (d) Surface air temperature of the tropics (30° N to 30° S) anomaly from the LGM (20 to 19 ka BP) (e) – (h) Absolute surface air temperature of the North Atlantic region (between 35 and 60° N and -60 and 0° E) for each simulation grouped by meltwater scenario.

2. Supplement to linking surface climate, ocean circulation, and greenhouse gas forcing

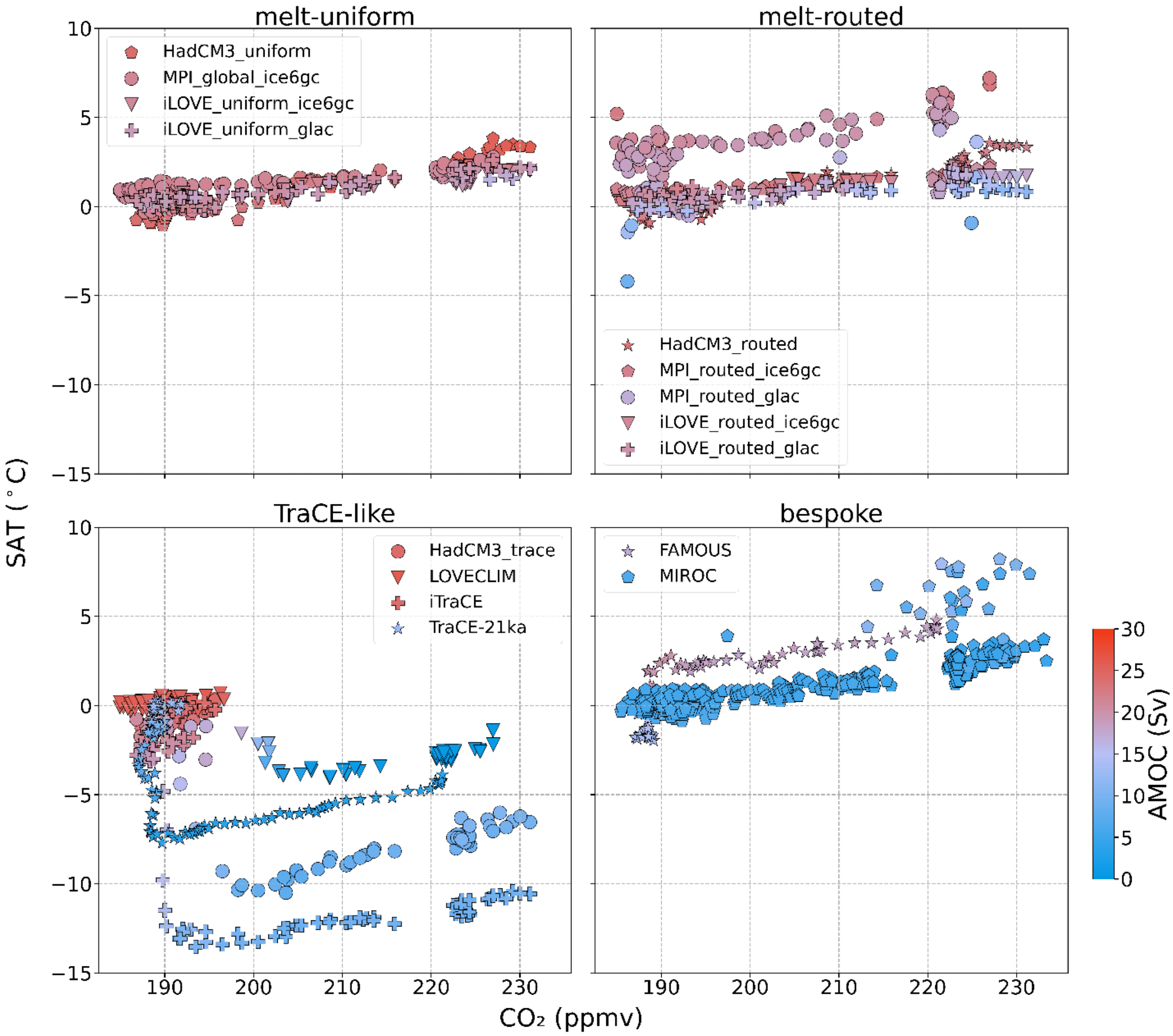


Fig. S6: Anomalous surface air temperature from the LGM (20 – 19.5 ka BP) over the North Atlantic (between 35 and 60° N and -60 and 0° E) as a function of CO_2 concentration with symbols' shading representing the strength of the AMOC (Sv) split into groups defined by meltwater scenario. Each simulation is represented as 50 year means except for MIROC which is shown as decadal means to capture the smaller-scale variability.

3. Supplement to impact of different climate and ice sheet forcings and boundary conditions on model output

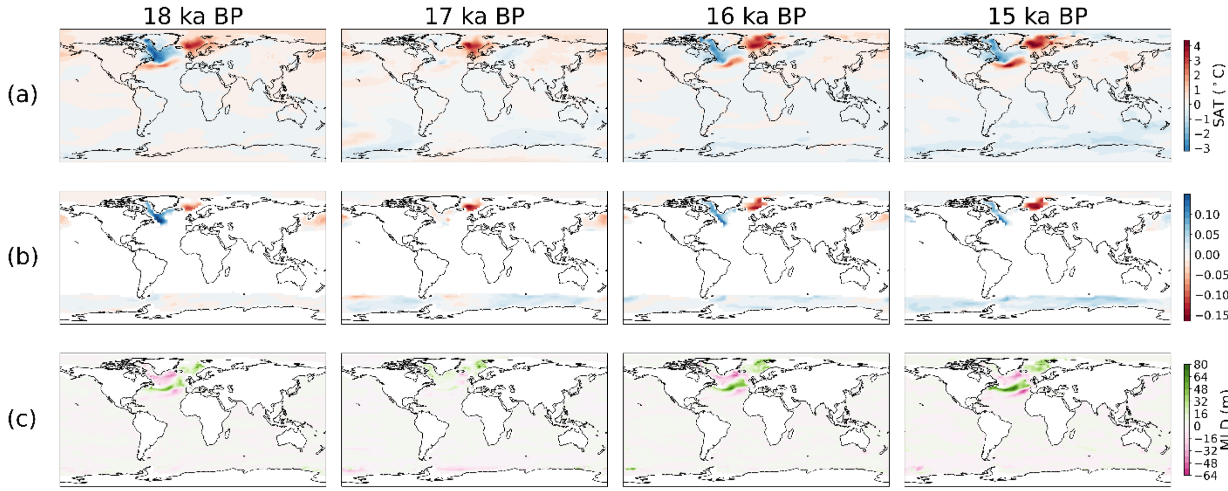


Fig. S7: Anomaly of HadCM3_uniform and HadCM3_routed for (a) surface air temperature, (b) sea ice concentration, and (c) Mixed-layer depth (MLD). 18, 17, 16, and 15 ka BP are calculated as 60-year decadal means centred around the respective time period (e.g., from 17.97 to 18.03 ka BP for 18 ka BP).

4. Supplement to sensitivity of climate models to similar forcing(s)

Table S1: Corresponding AMOC changes from before the abrupt decrease in Greenland surface air temperature (19 ka BP) and after the abrupt increase in meltwater (16 ka BP) for the TraCE-like simulations. Average depth is calculated as the average vertical reach of the upper cell of the AMOC in the water column between 25° S and 25° N (as Muglia and Schmittner 2021). The level of max AMOC is the depth of the maximum stream function at ~26.6 °N (as Sigmond et al. 2020). Max strength of the Northern Hemisphere (NH) is calculated as the maximum stream function between ~500 and 3500 meters depth above 0 °N. Maximum strength at 26.6° N is calculated at the same depth range, but only at 26.6° N.

[1]Convection site appears to be in Arctic Ocean (Fig. S8) where sea ice is located, however, this is not affecting the global climate or the AMOC (Fig. S9).
[2]Upper cell reaches the seabed (Fig. S9).
[3]At 16.8 ka BP, depth has raised to average of 2650.0 meters before AMOC collapses (see Fig. S9).

Simulation Reference Name	Average depth at 19 ka BP (m)	Average depth at 16 ka BP (m)	Level of max AMOC at 19ka BP at 26.6° N (m)	Level of max AMOC at 16 ka BP at 26.6° N (m)	Max strength in NH 19 ka BP (Sv)	Max strength in NH 16 ka BP (Sv)	Max strength at 26.6° N at 19 ka BP (Sv)	Max strength at 26.6° N at 16 ka BP (Sv)	NADW formation sites at 19 ka BP	NADW formation sites at 16 ka BP
HadCM3_TraCE	2586.5	1995.7	800.0	800.0	24.6	9.8	18.4	7.9	Southeast of Iceland/Norwegian Sea	Weak convection in Irminger Sea
TraCE-21ka	2017.9	1606.6	600.0	600.0	12.6	3.4	12.6	3.4	Irminger Sea/Labrador Sea	Weak convection in Greenland Sea
iTraCE	2500.0	2691.2	800.0	600.0	23.9	9.3	16.8	5.0	Irminger Sea	Weak convection[1]
LOVECLIM	5000.0[2]	AMOC shutdown[3]	1750.0	600.0	26.8	1.0	22.5	0.0	Norwegian Sea	NADW shut down

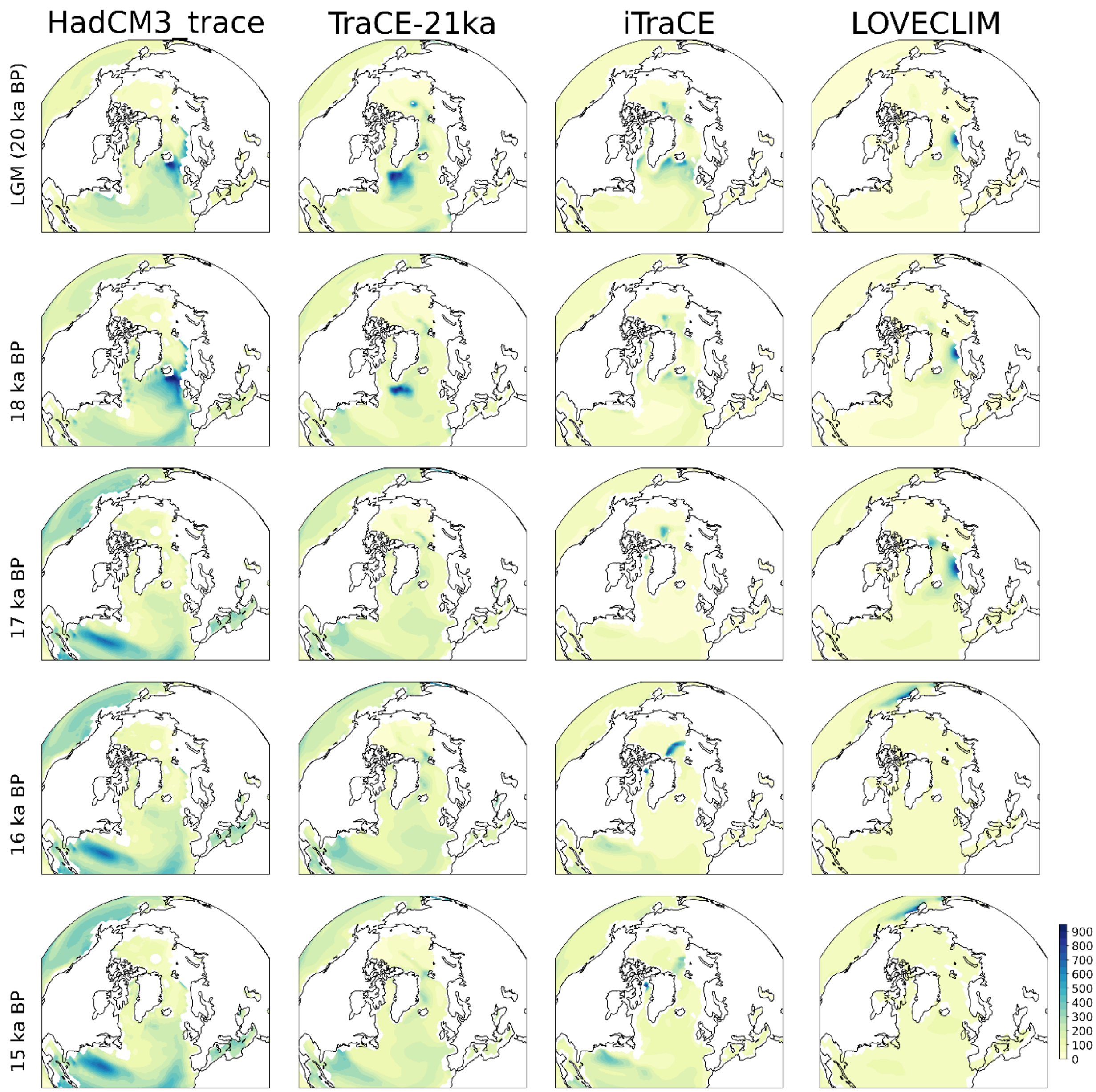


Fig. S8: Evolution of mixed-layer depth for the TraCE-like simulations. 18, 17, 16, and 15 ka BP are calculated as 100-year decadal means centred around the respective time period (e.g., from 17.95 to 18.05 ka BP for 18 ka BP). The LGM is calculated as a 500-year mean between 20 and 19.5 ka BP.

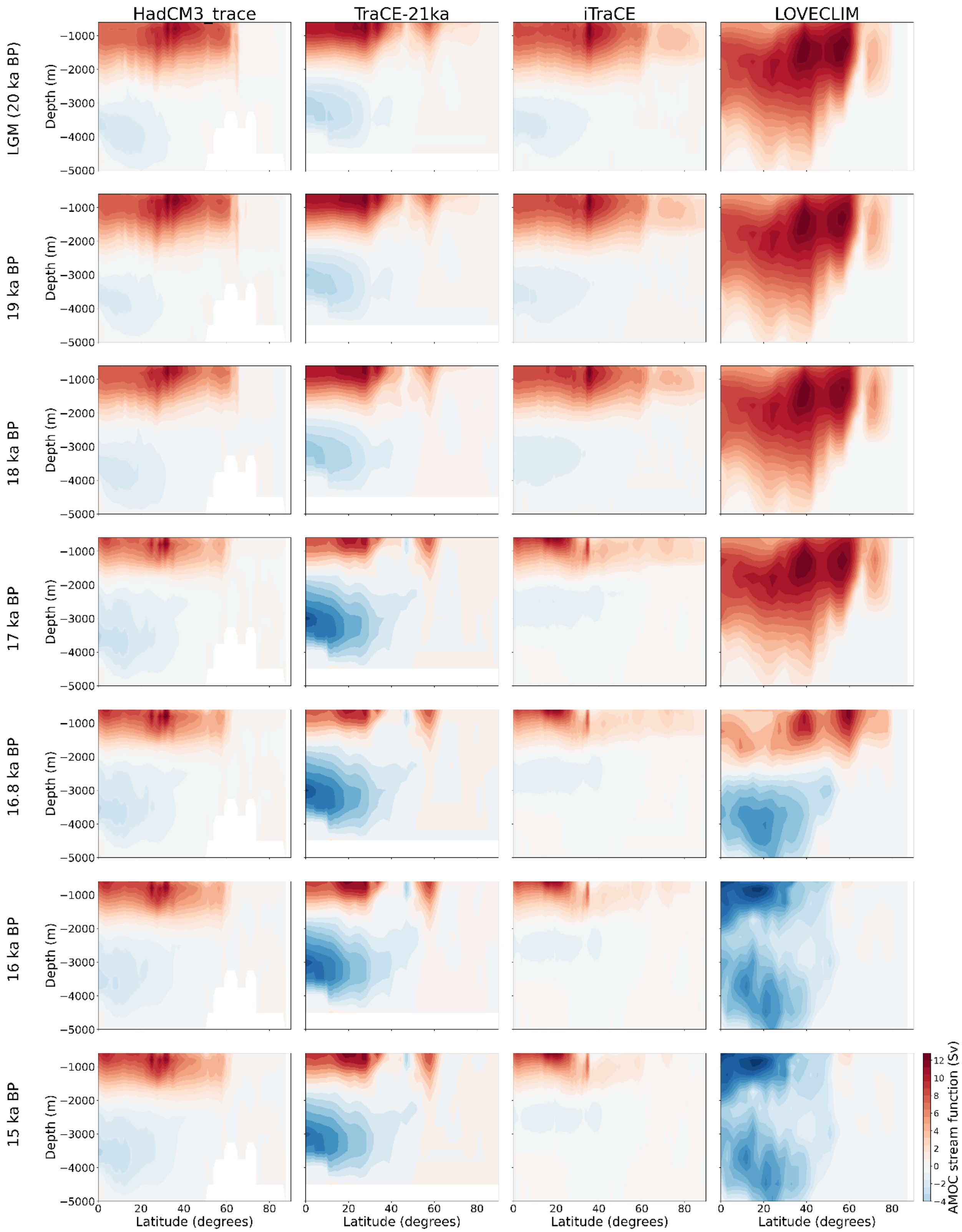


Fig. S9: AMOC stream function evolution for the TraCE-like simulations in the Northern Hemisphere. 19, 18, 17, 16, 16.8, and 15 ka BP are calculated as 100-year decadal means centred around the respective time period (e.g., from 17.95 to 18.05 ka BP for 18 ka BP). The LGM is calculated as a 500-year mean between 20 and 19.5 ka BP.