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The origin of the Younger Dryas cold period

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20 **The Younger Dryas (YD) is a prominent climate cooling phase that disrupted the overall**
21 **warming trend in the North Atlantic region during the last deglaciation¹⁻⁶. The YD**
22 **provides unprecedented evidence for abrupt climate change⁷⁻⁹, making it a crucial**
23 **period for our understanding of the climate system sensitivity to perturbations. The**
24 **classical explanation for this sudden cooling is a shut-down of the Atlantic Meridional**
25 **Overturning Circulation (AMOC) due to meltwater discharges¹⁰⁻¹³. However, recently**
26 **this classical mechanism has been challenged by alternative explanations, including**
27 **strong negative radiative forcing¹⁴ and a shift in the atmospheric circulation¹⁵. Here we**
28 **evaluate these different forcings in coupled climate model experiments constrained by**
29 **data assimilation and find that the YD climate signal as registered in proxy evidence is**
30 **best explained by a combination of processes: weakened AMOC, moderate negative**
31 **radiative forcing and altered atmospheric circulation. We conclude that an AMOC shut**
32 **down or any of the other individual mechanisms does not provide a plausible**
33 **explanation for the YD cold period. This indicates that the triggers for abrupt climate**
34 **change are more complex than suggested so far. Studies on the climate system response**
35 **to perturbations should account for this complexity.**

36

37 Proxy data from the North Atlantic region indicate that the YD started 12.9 thousand years
38 ago (ka) with a strong cooling that abruptly terminated the Allerød warm phase^{3-4,16}. Summer
39 temperatures in Europe dropped sharply by several degrees^{4,16}, during a time when the
40 orbitally-induced summer insolation at 60°N was close to its 11 ka maximum (i.e. 47 Wm⁻²
41 above the modern level¹⁷). Concurrently, the North Atlantic Ocean also experienced a cooling
42 of several degrees⁴. However, the YD cooling was not global, as the Southern Hemisphere
43 extratropics were not cooler or even slightly warmer than during Allerød time^{4,18}. Thus, a
44 mechanism is required that explains all these specific features of the YD cold period.

45

46 The main hypothesis for the YD cause is a catastrophic drainage of Lake Agassiz, leading to
47 freshwater-induced AMOC collapse and abrupt reduction of the associated northward heat
48 transport¹⁰. Indeed, model simulations¹⁹ suggest that this mechanism fits very well with
49 several characteristics of the YD, including the abruptness of the YD start, and its specific
50 spatial pattern with strongest cooling in the North Atlantic region and relatively warm
51 conditions in Antarctica. However, reconstructions of the AMOC strength do not support a
52 full collapse during YD time²⁰⁻²¹, thus questioning the validity of this hypothesis. In addition,
53 several alternative mechanisms have been proposed for the trigger of the YD. A prominent,

54 but highly debated, hypothesis suggests that the YD was triggered by an extraterrestrial
55 impact¹⁴, leading to enhanced atmospheric dust levels and reduced radiative forcing, possibly
56 in combination with increased ice-sheet melt. Other suggestions include a large solar
57 minimum²² triggering strong cooling and a wind shift associated with changes in ice sheet
58 configuration¹⁵. Hence, despite decades of intense research, the forcing mechanism of the YD
59 is still debated.

60

61 In this study, we analyse different forcing mechanisms for the YD by combining climate
62 model simulations with proxy-based reconstructions, mainly consisting of European July
63 temperatures and annual sea surface temperatures (SSTs) in the North Atlantic Ocean (see
64 Methods and Supplementary Information). These proxy-based reconstructions indicate that
65 European summers were on average 1.7°C cooler than in the preceding Allerød period at 13ka
66 (Fig. 1, Extended Data Fig. 1), with the strongest reduction (up to 4.0°C) in NW Europe,
67 diminishing towards the southeast (0.5°C cooling). The annual SST reconstructions suggest
68 that the North Atlantic was on average 2.4°C cooler at mid latitudes (Fig. 1, Extended Data
69 Fig.1), while further north the cooling was even stronger (-5°C).

70

71 To analyze the possible mechanism for the YD, we performed a set of experiments in which a
72 13 ka Allerød reference state was perturbed (Table 1). This reference state was obtained by
73 running the model with persistent appropriate 13 ka background forcings, consisting of orbital
74 parameters, ice sheets, land-sea distribution, and atmospheric trace gas levels. To represent
75 the background melting of the Laurentide and Scandinavian Ice Sheets, we also applied
76 freshwater fluxes of 0.05 Sv (1 Sv equals $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$) in both the NW Atlantic and the
77 Norwegian Sea during 500 yrs (see Supplementary Information). This freshwater forcing
78 resulted in local shut-down of Labrador Sea deep convection in agreement with
79 palaeoceanographic evidence²³ and reduced AMOC strength (from 24 to 16 Sv, Extended
80 Data Fig. 4). All these forcings were maintained in our perturbation experiments.

81

82 We constrained part of the simulations by applying a data-assimilation (DA) method (particle
83 filter, see Supplementary Information), enabling us to find the estimate of both the system
84 state and the forcing that is most consistent with the proxy-based YD signal and the model
85 physics. In our evaluation of the model results, we focus on differences between the last 100-
86 year mean of each experiment and the 13ka reference state (Fig. 1), based on the same

87 variables as provided by the utilized proxy-based reconstructions, i.e. North Atlantic annual
88 SSTs, European July air temperatures, and Greenland annual air temperatures.

89

90 We first evaluate the impact of short 1-year long freshwater pulses injected into the Arctic
91 Ocean at the Mackenzie River mouth, in agreement with recent geological evidence²⁴ and
92 supported by model studies²⁵⁻²⁶ (See Supplementary Discussion). To account for uncertainty,
93 we tested fluxes of 0.5 Sv and 5 Sv, and pulse durations of 1 and 3 year (Table 1). Without
94 DA, the 1-year pulses produce no discernible long-term cooling in Europe and the North
95 Atlantic (Fig.1, experiments **1yrS** and **1yrL**), and no long-term AMOC weakening. We
96 repeated these simulations with DA using a particle filter applied annually. This generates
97 much stronger cooling in both these areas of interest, ranging from -0.6 to -0.9°C (Fig. 1,
98 **1yrS_DA** and **1yrL_DA**). Over Europe, the summer cooling is mainly due to an anomalous
99 northerly atmospheric flow, transporting cold polar air southward. This atmospheric shift is
100 associated with reduced surface pressure over Europe and relatively high pressure over the
101 cold North Atlantic, that acts as a blocking for westerly flow (Extended Data Fig. 2b,d). A
102 similar pattern is also generated in a simulation with DA, but without any other change in
103 forcings, but is strengthened by the Atlantic Ocean cooling due to freshwater pulses.
104 Nevertheless, the simulated cooling over Europe is still strongly underestimated compared to
105 the proxies (Fig. 1).

106

107 We compare this result with two simulations that evaluate alternative mechanisms without
108 data assimilation: AMOC shutdown and negative radiative forcing. In a first experiment
109 (**SHUTD**), we forced the AMOC to collapse (Extended Data Figs. 3 and 4) by quadrupling
110 the background melt fluxes during 500 years. As expected, this generates intense cooling over
111 both the North Atlantic and Europe, on average by more than 3.5°C (Fig. 1, Extended Data
112 Fig. 3). However, these temperature reductions clearly exceed the reconstructed cooling over
113 both areas. In the second experiment (**RAD10**), we prescribed only a strong negative radiative
114 forcing, obtained by reducing the solar constant by 10 Wm⁻². As anticipated, this causes more
115 widespread cooling than the freshwater-induced AMOC perturbations (Extended Data Fig. 3),
116 but in Europe and the North Atlantic the temperature reduction is comparable to **1yrS_DA**
117 and **1yrL_DA** (Fig.1). So, compared to these DA runs with a 1-year freshwater pulse,
118 **SHUTD** and **RAD10** do not produce an improvement of the model-data temperature match.
119 A larger negative radiative forcing would generate stronger cooling that could be closer to the
120 proxy based estimates in Europe and the North Atlantic, but would not match with the

121 relatively mild YD conditions reconstructed in the Southern Hemisphere. Our interpretation is
122 that none of these two mechanisms could be the sole origin of the YD, which is supported by
123 additional experiments performed with different scenarios for freshwater perturbations and
124 radiative forcing and also with different models (see Supplementary Information).

125

126 Therefore, as a final step, we applied a combined forcing setup to simulate a climate that is
127 more consistent with proxy-based evidence (Figs. 1 and 2). In this experiment
128 (**COMBINED**), we employed DA and prescribed both a 3-year, 5Sv freshwater pulse and a
129 moderate 2 Wm^{-2} reduction of the solar constant. In addition, this radiative forcing was
130 randomly perturbed after each DA step, for which a 5-year period was selected in this case.
131 The total radiative perturbation in **COMBINED** could represent the impacts of the enhanced
132 atmospheric dust load, and reduced atmospheric greenhouse gas concentrations (see
133 Supplementary Information). In **COMBINED**, we observe considerable changes in the
134 Atlantic Ocean (Fig. 2b), with a southward shift of deep convection, extended Nordic Seas ice
135 cover, and a further AMOC reduction to 7 Sv (Fig. 3c). Over this extended sea-ice cover, air
136 temperatures are 5 to 10°C lower than in the reference state. In the North Atlantic, the
137 associated SST anomalies closely match reconstructions, as both indicate 2.4°C cooling
138 (Fig.1). The simulated atmospheric circulation is similar to the other DA experiments, with
139 anomalous northerly flow over Europe (Fig. 2c). The simulated European cooling of 2.4°C
140 matches reasonably well with the proxy-based average of -1.7°C (Figs. 1 and 2a). We
141 continued **COMBINED** in the same setup for 1000 years, resulting in a state strongly
142 resembling the YD (Fig. 3ab). In **COMBINED**, the particle filter selects and maintains a
143 weakened oceanic state that is most consistent with proxy evidence (Figs. 1 and 3), even when
144 the 3-yr freshwater pulse has finished. Importantly, this state could only be obtained in
145 experiments with DA that combine the three mechanisms (freshwater pulse, radiative forcing
146 and shift in atmospheric circulation), as other combinations either produced a non-stationary
147 state (Extended Data Fig. 5), or a considerable mismatch with the proxy-based reconstructions
148 (see Supplementary Information). After 1000 years we removed the background freshwater
149 forcing, resulting in rapid resumption of the Nordic Seas deep convection, and abrupt
150 warming in the North Atlantic region that closely matches the reconstructed YD termination¹⁶
151 (Fig. 3).

152

153 The **COMBINED** results fit excellently to proxy-based YD evidence in Europe and the North
154 Atlantic region with respect to the magnitude, distribution, duration, and the abruptness of the

155 changes at the start and termination. The simulated temperature anomalies agree also with
156 proxy-based reconstructions from other regions (Extended Data Figs. 6 and 7) and the
157 simulated global cooling of 0.6°C is fully consistent with independent estimates⁴. Based on
158 this excellent model-data match, we conclude that the YD was most likely caused by a
159 combination of 1) sustained severe AMOC weakening due to an initial, short-lived Arctic
160 freshwater pulse and background ice sheet melt, 2) anomalous atmospheric northerly flow
161 over Europe, and 3) moderate radiative cooling related to an enhanced atmospheric dust load
162 and/or reduced atmospheric methane and nitrous oxide levels. The exact magnitude of the
163 forcings at the origin of these three processes or potential interactions between them may
164 depend on our experimental design and requires further investigation. Nevertheless, the need
165 for this particular combination of different processes to explain the observed YD cooling
166 pattern is a robust feature of our analysis (see Supplementary discussion). We regard other
167 mechanisms highly implausible, particularly a full AMOC collapse or a very strong negative
168 radiative perturbation due to an extraterrestrial impact. The origins of abrupt climate change
169 may thus be more complex than previously suggested. Our results may indicate that the YD
170 only occurred due to an unusual combination of events, potentially explaining why the YD
171 was different from preceding stadials. This complexity should be accounted for in studies of
172 past abrupt changes and in analyses of the probability of future climate shifts under influence
173 of anthropogenic forcings.

174

175 Methods Summary

176 We performed our climate simulations with the LOVECLIM1.2 global climate model²⁷. This
177 model has been successfully applied in various palaeoclimatic studies, simulating climates
178 that are consistent with proxy-based climate reconstructions, for example for the last glacial
179 maximum, the Holocene, the 8.2 ka event and the last millennium²⁷, showing that
180 LOVECLIM is a valuable tool in palaeoclimate research. Still, it should be noted that this
181 model has an intermediate complexity. We have performed this study with an intermediate
182 complexity model to be able to make large ensemble experiments with up to 96 members.
183 Compared to comprehensive general circulation models, particularly the atmospheric module
184 has simplified dynamics and low spatial resolution, which limits a detailed representation of
185 the atmospheric circulation. Yet, in the extratropics our model has similar responses to
186 radiative and freshwater forcings as general circulation models (see Supplementary
187 information) . In several of our simulations we applied a particle filter, which is a data-
188 assimilation method to constrain the model results with proxy-based estimates²⁸⁻³⁰. The

189 proxy-based temperatures employed in this study are based on selected quantitative
190 reconstructions from different sources. Details on the model, the experimental design, the
191 particle filter and the proxy-based temperature reconstructions are provided in the
192 Supplementary Information.

193

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253 between proxy-based reconstructions and climate models using data assimilation: a mid-Holocene
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255

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257

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265 **Author Contributions:** All authors contributed substantially to this work. HR and HG
266 conceived the project. HR, AM, HG and PM designed and performed the LOVECLIM
267 experiments. HR, AM and HG analysed the model results. OH provided proxy-based
268 reconstructions. DMR provided unpublished initial conditions and forcings for the
269 experiments. PJV and KHN performed additional experiments with the HadCM3 and IGSM2
270 models, respectively. The manuscript was written by HR, with input from all other authors.
271

272 **Author Information:** The authors declare no competing financial interests. Correspondence
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275

Experiments	Duration (yr)	Additional FW forcing (Sv)	Radiative forcing	Ensemble members	Data assimilation
noFW	500	0	0	10	No
1yrS	500	0.5 Sv (1 yr)	0	10	No
1yrL	500	5 Sv (1 yr)	0	10	No
noFW_DA	100	0	0	32	every 1yr
1yrS_DA	100	0.5 Sv (1 yr)	0	32	every 1yr
1yrL_DA	100	5 Sv (1 yr)	0	96	every 1yr
SHUTD	500	4x Backgr FWF	0	10	No
3yrL	100	5 Sv (3 yr)	0	10	No
RAD10	100	0	-10Wm ⁻²	10	No
3yrLRAD2	100	5 Sv (3 yr)	-2Wm ⁻²	10	No
COMBINED	1500	5 Sv (3 yr)	-2Wm ⁻²	96	every 5yr

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Table 1. Overview of the experimental design of all perturbation experiments. All experiments were started from a 13 ka **reference state** (See Supplementary Methods) and have been run in ensemble mode, with the number of ensemble members indicated in the fifth column. The freshwater (FW) pulses were added to the Mackenzie River outlet. In all experiments we included a representation of the background melt of the Scandinavian and Laurentide Ice Sheets (Backgr FWF, both amounting 0.05 Sv, see Supplementary Methods). In experiment **SHUTD** this background ice-sheet melt was multiplied by 4. The radiative forcing is included as a reduction of the solar constant by 10 Wm⁻² (**RAD10**) or 2 Wm⁻² (**3yrLRAD2** and **COMBINED**), equivalent to a radiative perturbation at the top of the troposphere of respectively -1.75 or -0.35 Wm⁻². In **COMBINED**, an additional random radiative perturbation is applied (see Supplementary Methods), resulting because of the DA in a supplementary negative forcing of around -0.17 Wm⁻². In **COMBINED** the background melt was removed after 1000 years. Further details on boundary conditions are provided in the Supplementary Information.

293 **Figure legends**

294

295 Figure 1. Simulated anomalies for European July surface temperatures (in °C, green bars) and
296 annual mean North Atlantic SSTs (in °C, blue bars) from various experiments relative to the
297 13ka reference experiment, compared with proxy-based reconstructions of 12ka minus 13ka
298 anomalies (far right hatched bars). For details on the experiments, see Table 1 and
299 Supplementary Information.

300

301 Figure 2. Simulated anomalies for the **COMBINED** experiment relative to the 13ka reference
302 run: a) upper left, July surface temperatures (in °C), b) upper right, annual mean SSTs (in °C),
303 and c) lower left, July 800 hPa height (in m^2s^{-2}). In our low resolution atmospheric model, the
304 800 hPa geopotential height (GPH) is considered a better diagnostic for the atmospheric
305 circulation near the surface than sea level pressure (SLP), since GPH is directly calculated by
306 the model whereas SLP is derived from other variables. Positive and negative 800 hPa GPH
307 anomalies directly reflect positive and negative SLP anomalies. These results are 100-year
308 mean values averaged over years 401-500.

309

310 Figure 3. Simulated evolution of a) European July Surface temperatures (°C), b) North
311 Atlantic Annual Mean SSTs (°C) , and c) maximum strength of the Atlantic Ocean meridional
312 overturning circulation (in Sv) as a measure for the AMOC strength. The results of the first
313 100 years are derived from our 13 ka reference simulation. The perturbation experiment
314 **COMBINED** starts in year 101. At year 1101, the background meltwater forcing is removed
315 (see Supplementary Information), leading to a rapid recovery of the AMOC, which is
316 accompanied by warming of the Atlantic Ocean surface and Europe. All results are ensemble
317 means (96 members).

318

319 **Extended Data Figure legends**

320

321 Extended Data Figure 1. Proxy-based reconstructions of July surface temperatures (circles),
322 annual surface temperatures (diamonds) annual SSTs (squares) that were used in the data-
323 assimilation. The temperatures are expressed as anomalies at 12 ka relative to the values for
324 13 ka from the same records. Details on the reconstructions can be found in Supplementary
325 Table 1.

326

327 Extended Data Figure 2. Simulated anomalies in July surface temperatures ($^{\circ}\text{C}$, left column)
328 and July 800 hPa Geopotential heights (m^2s^{-2} , right column), relative to the 13ka reference
329 experiment: **noFW_DA** (a,b), **1yrL_DA** (c,d).

330

331 Extended Data Figure 3. Simulated anomalies in July surface temperatures ($^{\circ}\text{C}$, left column)
332 and July 800 hPa Geopotential heights (m^2s^{-2} , right column), relative to the 13ka reference
333 experiment: **SHUTD** (a,b), and **RAD10** (c,d).

334

335 Extended Data Figure 4. Simulated Meridional overturning streamfunction (Sv) for different
336 experiments: a) **spin-up**, b) **13ka reference**, c) **3yrL**, d) **SHUTD**, e) **COMBINED**. Positive
337 values represent clockwise flow. The averages over the last 100 years of each experiment are
338 shown, except for **COMBINED**, for which the years 401 to 500 are averaged.

339

340 Extended Data Figure 5. Simulated evolution of the ensemble mean, maximum AMOC
341 strength (Sv). The results for the first 100 years (black) are identical and represent the **13ka**
342 **reference** climate. At year 101, this state is perturbed. Shown are the results of **1yrL_DA**
343 (yellow), **3yrL** (blue), **3yrLRAD2** (green), d) **COMBINED** (red). The **COMBINED**
344 experiment has been continued (see main Figure 3). Including the -2 Wm^{-2} perturbation of the
345 solar constant (compare blue and green curves), does not have a discernible impact.
346 Employing data-assimilation (i.e. the difference between green and red curves) results in a
347 continued weakening of the AMOC after the initial perturbation.

348

349 Extended Data Figure 6. Simulated global temperature fields ($^{\circ}\text{C}$). a) July temperature in
350 **13ka reference**, b) annual-mean temperature in **13ka reference**, c) annual-mean temperature
351 anomaly ($^{\circ}\text{C}$) in **COMBINED** (averaged over years 401-500) relative to the 13ka reference
352 state, with contours at -6, -5, -4, -3, -2, -1, -0.5, -0.25, 0, 0.25, and 0.5°C .

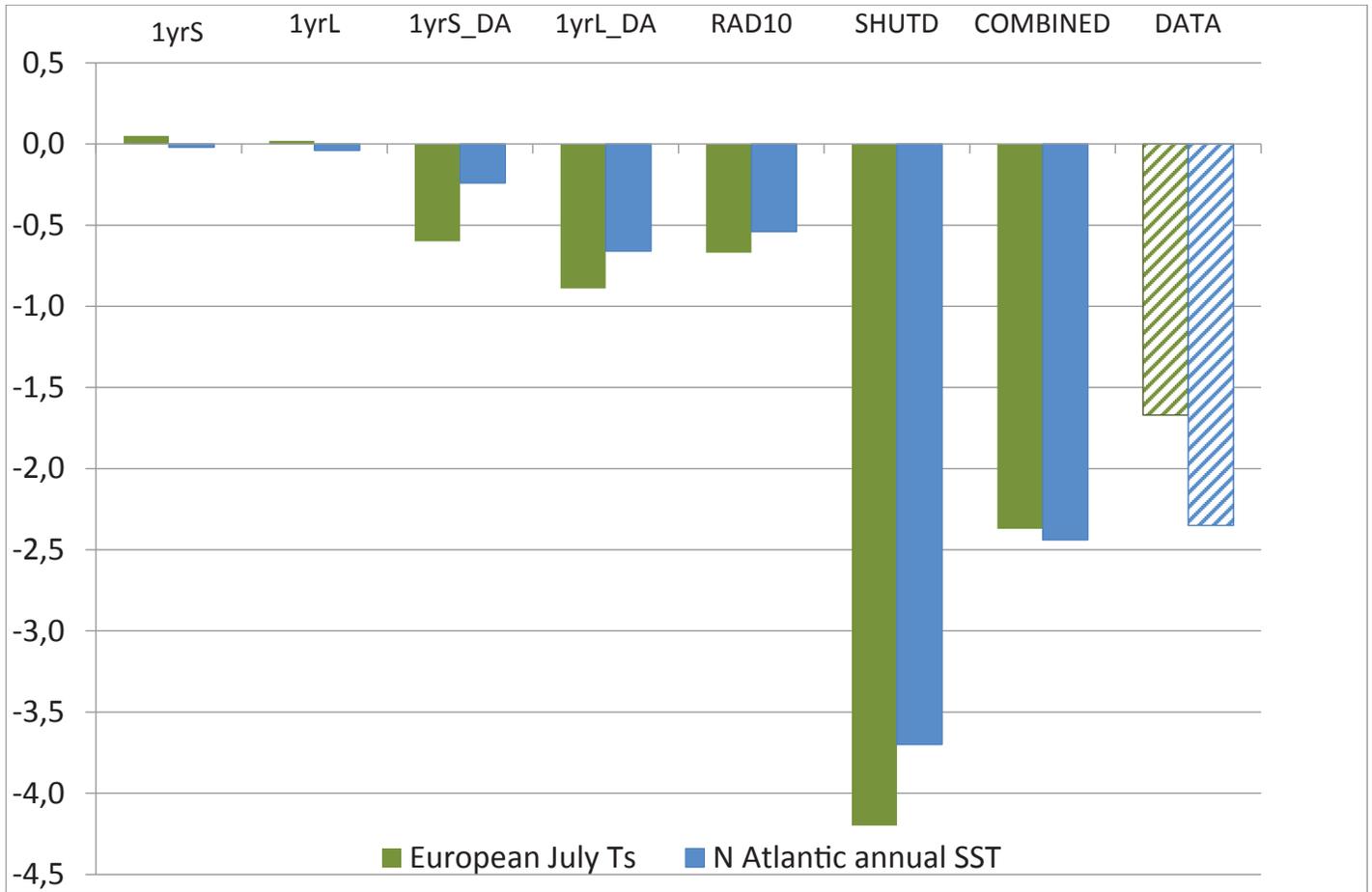
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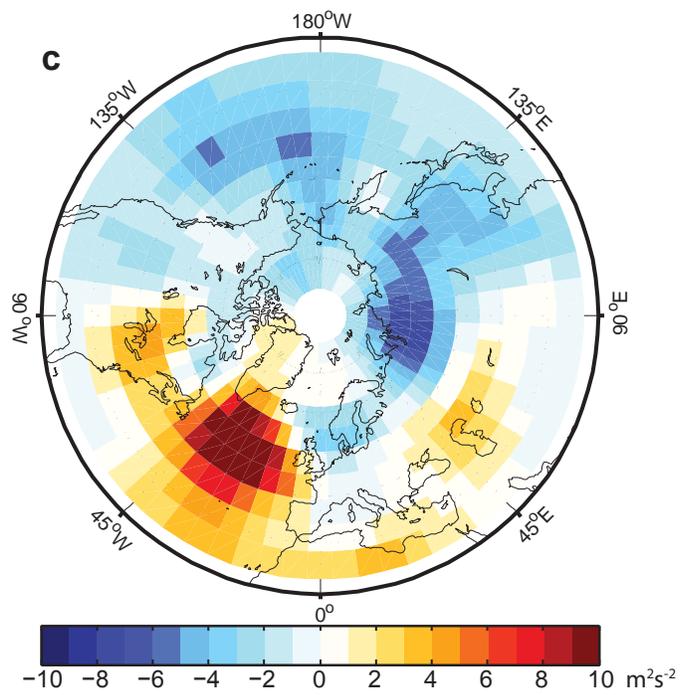
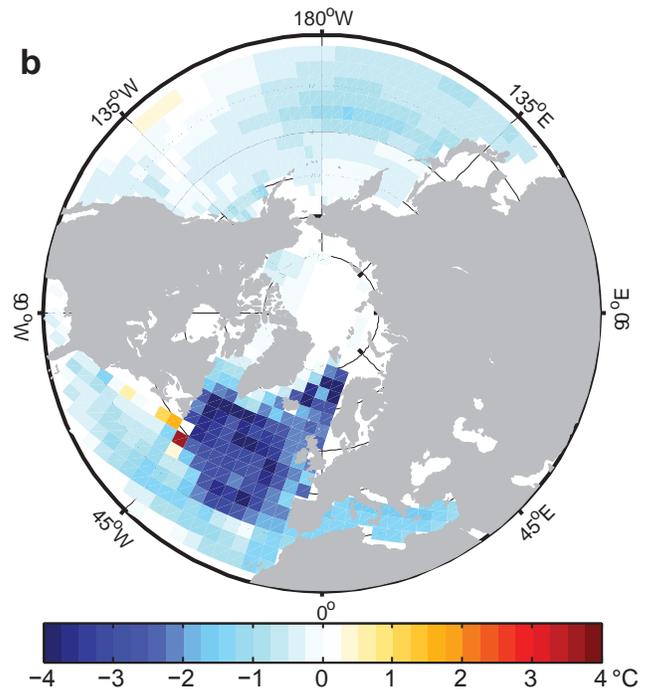
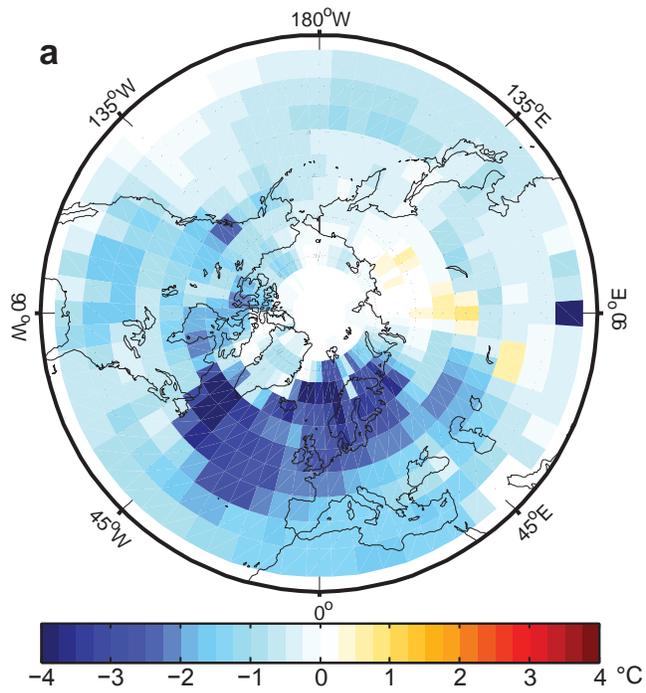
354 Extended Data Figure 7. Model-data comparison for the annual mean temperature change
355 from the Allerød to the YD plotted against latitude. Four different longitudinal zones are
356 shown: a) 60°W - 30°E , b) 30°E - 120°E , c) 120°E - 150°W , d) 150°W - 60°W . The dots represent
357 proxy-based estimates published by Shakun and Carlson (ref. 4, their Figure 12b), with the
358 bars providing a conservative $\pm 1^{\circ}\text{C}$ uncertainty estimate. The lines are the simulated zonal
359 mean temperature differences between the **COMBINED** experiment (years 401-500) and the
360 13 ka reference, while the grey shading shows the range of temperatures within the sector.

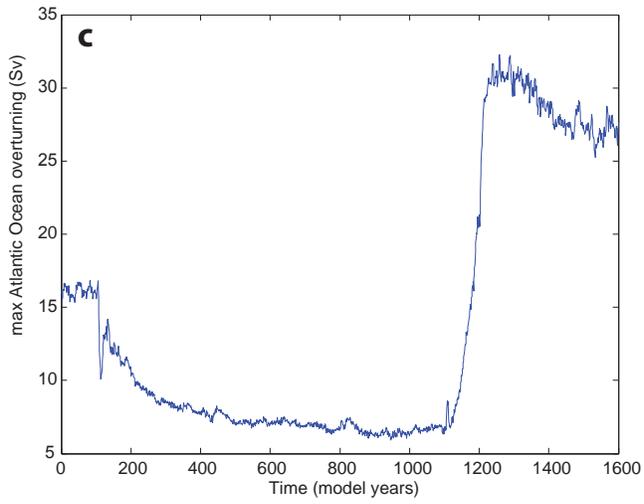
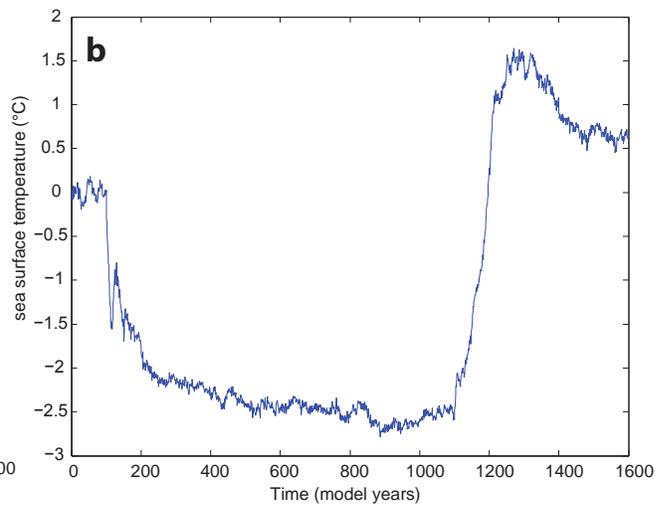
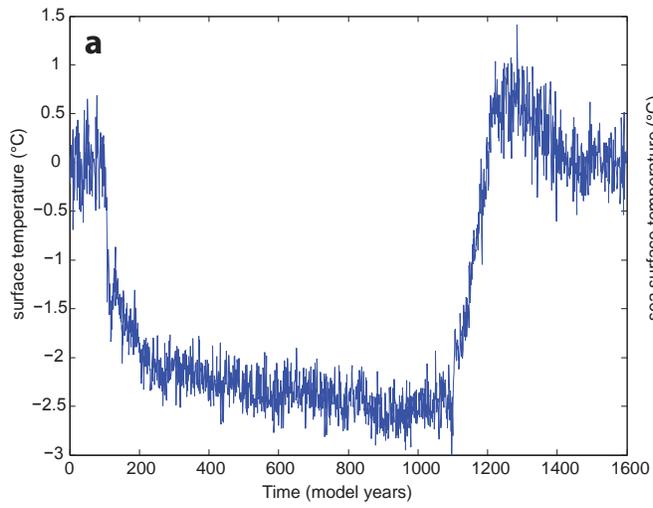
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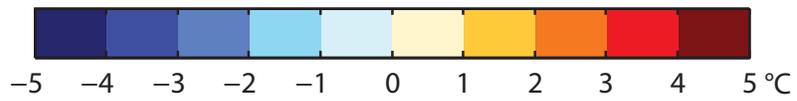
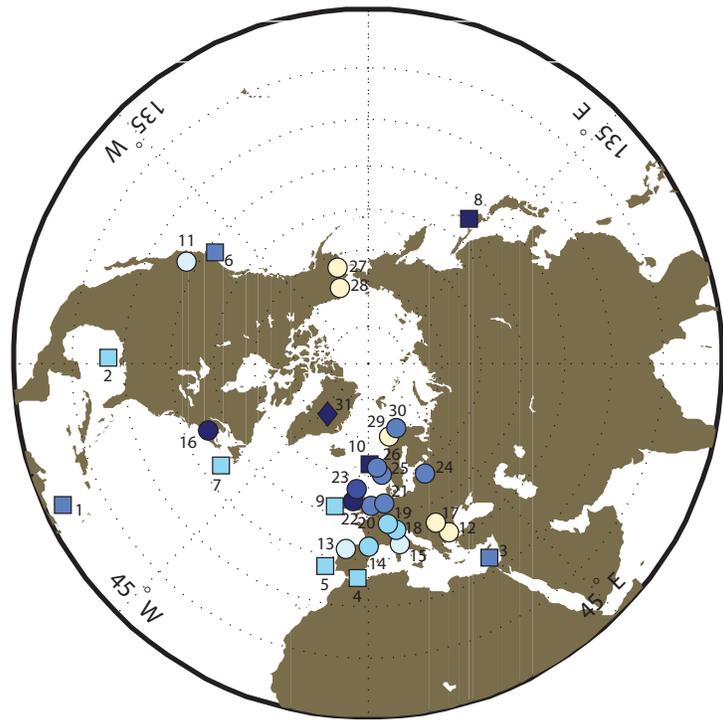
362 Extended Data Figure 8. Inter-model comparison of annual mean temperature response to
363 strong negative radiative forcing and AMOC shutdown, relative to a warm control state
364 without any freshwater forcing (see Supplementary Information section 3.4). Figures a, b, e
365 and f reflect the response to strong negative radiative forcing (**RAD10**, solar constant minus
366 10 Wm^{-2}), while c, d, g and h show the response to an AMOC shutdown (**SHUTD**).
367 LOVECLIM results are shown in the left column (a, c, e, g), HadCM3 results in b and d, and
368 IGSM2 results in f and h. For the comparison with HadCM3, the surface air temperatures are

369 shown, and for IGSM2 the sea surface temperatures, as the latter model includes a zonal
370 statistical-dynamical atmosphere that precludes comparison of atmospheric fields.









○	July Ts	◇	Annual Ts	□	Annual SST
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