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# 1 **AMOC as the key driver of the spread in Mid-Holocene** 2 **winter temperature patterns over Europe in PMIP3** 3 **models**

4  
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## 18 **Abstract**

19 The mid-Holocene (6,000 years before present) was a warmer period than today in summer in  
20 most places of the Northern Hemisphere. In winter, over Europe, reconstructions of temperature  
21 based on pollen data show a dipole of temperature anomalies as compared to present-day, with  
22 warmer conditions in the north and colder in the south. It has been proposed that this pattern of  
23 temperature anomaly could be explained by a persisting positive phase of the North Atlantic

24 Oscillation during this period, which was, however, not reproduced in general by climate  
25 models. Indeed, PMIP3 models show a large spread in their response to the mid-Holocene  
26 insolation changes, the physical origins of which are not understood. To improve the  
27 understanding of the reconstructed temperature changes and of the PMIP3 model spread, we  
28 analyze the dynamical response of these model simulations in the North Atlantic for mid-  
29 Holocene conditions as compared to pre-industrial. We focus on the European pattern of  
30 temperature in winter, which allows comparing the simulations with a pollen-based  
31 reconstruction. We find that some of the model simulations yield a similar pattern to the  
32 reconstructed one, with lower amplitude, but which remains within the reconstruction  
33 uncertainty. We attribute the northern warm part of the latitudinal dipole of temperature  
34 anomaly in winter to a lower sea-ice cover in the Nordic Seas. The decrease of sea ice in winter  
35 indeed reduces the sea-ice insulation effect there, allowing the ocean heat released in winter to  
36 reach the continental northern Europe. This decrease in winter sea-ice cover is related to an  
37 increase in the Atlantic meridional overturning circulation (AMOC) and its associated ocean  
38 heat transport, as well as the effect of insolation changes on sea ice in summer, which persists  
39 until winter. Concerning the cooling of southern Europe, we only find a slight cooling signal  
40 mainly related to the insolation-induced cooling in winter over Africa. We show that the models  
41 that failed to reproduce any AMOC increase under mid-Holocene conditions are also the ones  
42 that do not reproduce the temperature pattern over Europe. The change in sea level pressure is  
43 not sufficient to explain the spread among the models. The ocean-sea ice mechanisms that we  
44 proposed constitute an alternative explanation to the pattern of changes in winter temperatures  
45 over Europe in the mid-Holocene, which is in better agreement with available model  
46 simulations of this period. Finally, we argue that this period can provide interesting emerging  
47 constraints on key changes in European climate, and indirectly of AMOC response to radiative  
48 changes.

49 *Keywords: PMIP3, Mid-Holocene, NAO, AMOC, inter-model spread*

## 51 **Introduction**

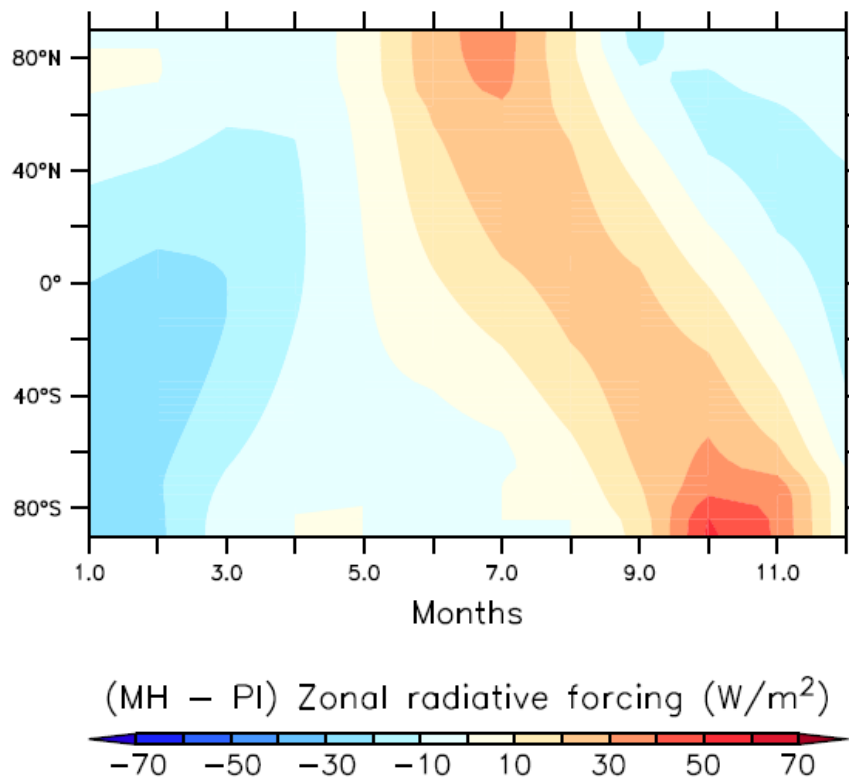
52 Projections of the climate of Europe show a large spread for the ongoing century (IPCC  
53 Working Group 1 et al. 2013). For a given emission scenario, uncertainties are related to the  
54 internal variability, that can be large at the regional scale (Deser et al. 2012), and to the model-  
55 dependent sensitivity of the climate system to external forcings (Hawkins and Sutton 2009). In  
56 particular, changes of the atmospheric or oceanic circulation tend to vary a lot between models.  
57 Future projections of the North Atlantic Oscillation (NAO), that plays a crucial role in the  
58 climate variability of Europe in winter (Hurrell 1995), do not even agree on its sign (Cattiaux  
59 and Cassou 2013). At multi-decadal timescales, the Atlantic Meridional Overturning  
60 Circulation (AMOC) also plays a key role for the climate of Europe through its massive  
61 northward transport of heat all along the Atlantic Ocean (Swingedouw et al. 2009, Haarsma et  
62 al. 2015, Jackson et al. 2015). Its long-term projections are, similarly, very uncertain (Weaver  
63 et al. 2012), even though all the models agree that it should decrease in the coming century,  
64 especially when the Greenland ice sheet melting is accounted for (Bakker et al. 2016;  
65 Swingedouw et al. 2015b). To improve our estimate of the response of the NAO or the AMOC  
66 to external forcing, paleoclimate data could provide key observational constraints (Schmidt et  
67 al. 2014; Harrison et al. 2015).

68 Paleoclimate reconstructions are based on proxy records that have been collected for decades  
69 around the world. The main issue with proxies is that they are indirect records of climate  
70 variables, so that they could be subject to large uncertainties and biases. Nevertheless, except  
71 for the short instrumental era, they are the only observational estimates of the climate response  
72 to different external forcings. Even though there is no exact analogue of the future in the past,  
73 information on the climate response to changes in external forcings has a high relevance to

74 better evaluate the sensitivity of climate models and possibly reduce the uncertainty concerning  
75 the on-going climate change (Schmidt et al. 2014), especially at the regional scale.

76 The mid-Holocene (MH: 6000 years Before Present) is a recent period where the climate of the  
77 northern high latitudes was considerably warmer than today in summer (Fischer et al. 2018),  
78 due to a different insolation forcing (Figure 1). This is an interesting climate period, when the  
79 Sahara is suspected to have been greener than today (Claussen and Gayler 1997). This is notably  
80 why the Paleoclimate Model Intercomparison Project, phase 3 (PMIP3) initiative (Braconnot  
81 et al. 2012) proposed this period as a key snapshot to be simulated by the same climate models  
82 that produce climate projections (Schmidt et al. 2014; Harrison et al. 2015).

83



84

85 **Figure 1:** Zonally-averaged climatological monthly differences in the incoming shortwave radiation at the top of  
86 the atmosphere between mid-Holocene and pre-industrial simulations.

87 A recent study proposed an improved reconstruction of climate over Europe for the MH based  
88 on a broad compilation of pollen data (Mauri et al. 2014). The results showed a dipole of winter

89 near-surface temperature anomalies, with warm anomalies in the north of Europe and cold  
90 anomalies in the south. The authors suggested this pattern could be caused by an atmospheric  
91 circulation anomaly similar to a positive phase of the North Atlantic Oscillation (NAO<sup>+</sup>). Other  
92 studies also proposed such a change for mid-Holocene European climate in winter (Guyard et  
93 al. 2013; Chabaud et al. 2014). This hypothesis therefore provides an interesting testbed for  
94 climate models. Mauri et al. (2014) argued that PMIP3 simulations in general did not  
95 reproduced very well the reconstructed dipole in temperature in winter because they not show  
96 any NAO<sup>+</sup>-like changes in atmospheric circulation for the MH. This was also the case for the  
97 older PMIP2 dataset (Gladstone et al. 2005). Nevertheless, It have been proposed that PMIP2  
98 dataset still showed some skill in capturing the pattern of climate change over Europe for the  
99 MH (Brewer et al. 2007). While the new generation of PMIP3 models show larger changes in  
100 sea ice for MH conditions than PMIP2 models over the Arctic (Berger et al. 2013), which may  
101 impact the response over Europe, a quantitative comparison of the PMIP3 models with winter  
102 reconstruction of temperature over Europe has not been made yet. Furthermore, a detailed  
103 analysis of the mechanism explaining the wintertime response in PMIP3 simulations for MH is  
104 also missing for the North Atlantic.

105 The large increase in summer insolation for MH conditions may have strongly affected the sea  
106 ice in polar regions, even in winter through inertia. This could then influence the continental  
107 climate, notably in winter where the heat flux release by the ocean is largest, as well as the  
108 insulation effect of sea ice (Goosse et al. 2002). Such an impact was illustrated by Fischer and  
109 Jungclaus (2011) in a transient simulation over part of the Holocene using the MPI climate  
110 model. Otto et al. (2009), using different simulations for the MH including a coupling to the  
111 ocean and vegetation or not, also showed that the ocean plays a key role for the amplitude of  
112 the temperature response of the northern high latitudes to the radiative forcing. The insolation  
113 during the MH was indeed very different from the pre-industrial period. The latitudinal gradient

114 was strongly reduced during the summer season, which could have impacted the oceanic and  
115 atmospheric meridional heat transport (Davis and Brewer 2009).

116 In the present study, we propose to analyze the response of climate models participating to  
117 PMIP3 under MH wintertime conditions, with a specific focus on the North Atlantic region.  
118 We will assess the potential causes for the model spread in temperature response over Europe  
119 in winter and analyze the role played by changes in atmospheric circulation, oceanic circulation  
120 and radiative changes amplified by sea ice response. We will also compare these simulations,  
121 using classical skill scores, with the reconstruction of Mauri et al. (2014). This will allow us to  
122 determine the models that best reproduce the temperature dipole pattern over Europe. Our main  
123 result is that atmospheric circulation changes are not the main driver of the simulated patterns  
124 of temperature anomalies. These are instead linked to sea-ice anomalies, forced either by  
125 AMOC slowdown or summer sea-ice melt.

## 126 **Experimental design**

127 We analyze pairs of mid-Holocene and pre-industrial (PI) simulations performed with PMIP3  
128 climate models. Only 12 models (Table 1) are retained, as we require at least 100 years of both  
129 PI and MH simulations to perform robust statistical analyses. When more than 200 model years  
130 are available, we use the last 200 years of the simulation. Throughout the analyses, we use data  
131 on the native grid for each model, except when multi-model statistics are calculated, in which  
132 case the model data is first interpolated on a regular  $1^\circ \times 1^\circ$  grid for the temperature to be  
133 compared with Mauri et al. (2014) and a regular  $2.5^\circ \times 2.5^\circ$  grid for the other variables.

134

135

136

Index	Model	Modeling Center	Reference
A	bcc-csm1-1	Beijing Climate Center (BCC)	Xin et al. (2013)
B	CNRM-CM5	Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancées en Calcul Scientifique (CNRM/CERFACS)	Voldoire et al. (2013)
C	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)	Rotstayn et al. (2012)
D	IPSL-CM5A-LR	Institut Pierre-Simon Laplace (IPSL)	Dufresne et al. (Dufresne et al. 2013)
E	FGOALS-g2	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics/Institute of Atmospheric Physics (LASG/IAP)	Li et al. (2013)
F	FGOALS-s2	LASG/IAP	Bao et al. (2013)
G	MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Watanabe et al. (2011)
H	HadGEM2-ES	Met Office Hadley Center (MOHC)	Collins et al. (2011)
I	MPI-ESM	Max Planck Institute for Meteorology (MPI-M)	Jungclaus et al. (2013)
J	MRI-CGCM3	Meteorological Research Institute (MRI)	Yukimoto et al. (2012)
K	GISS-E2-R	NASA Goddard Institute for Space Studies	Schmidt et al. (2006)
L	CCSM4	National Center for Atmospheric Research (NCAR)	Gent et al. (2011)

137

138 **Table 1: List of PMIP3 models included in this study.**

139 We focus our analysis on Mid-Holocene climatological anomalies with respect to the pre-  
140 industrial period for wintertime (December-February averages – DJF), summertime (June-  
141 August averages – JJA) or annual means (ANM). Wherever suitable, we use a two-sided

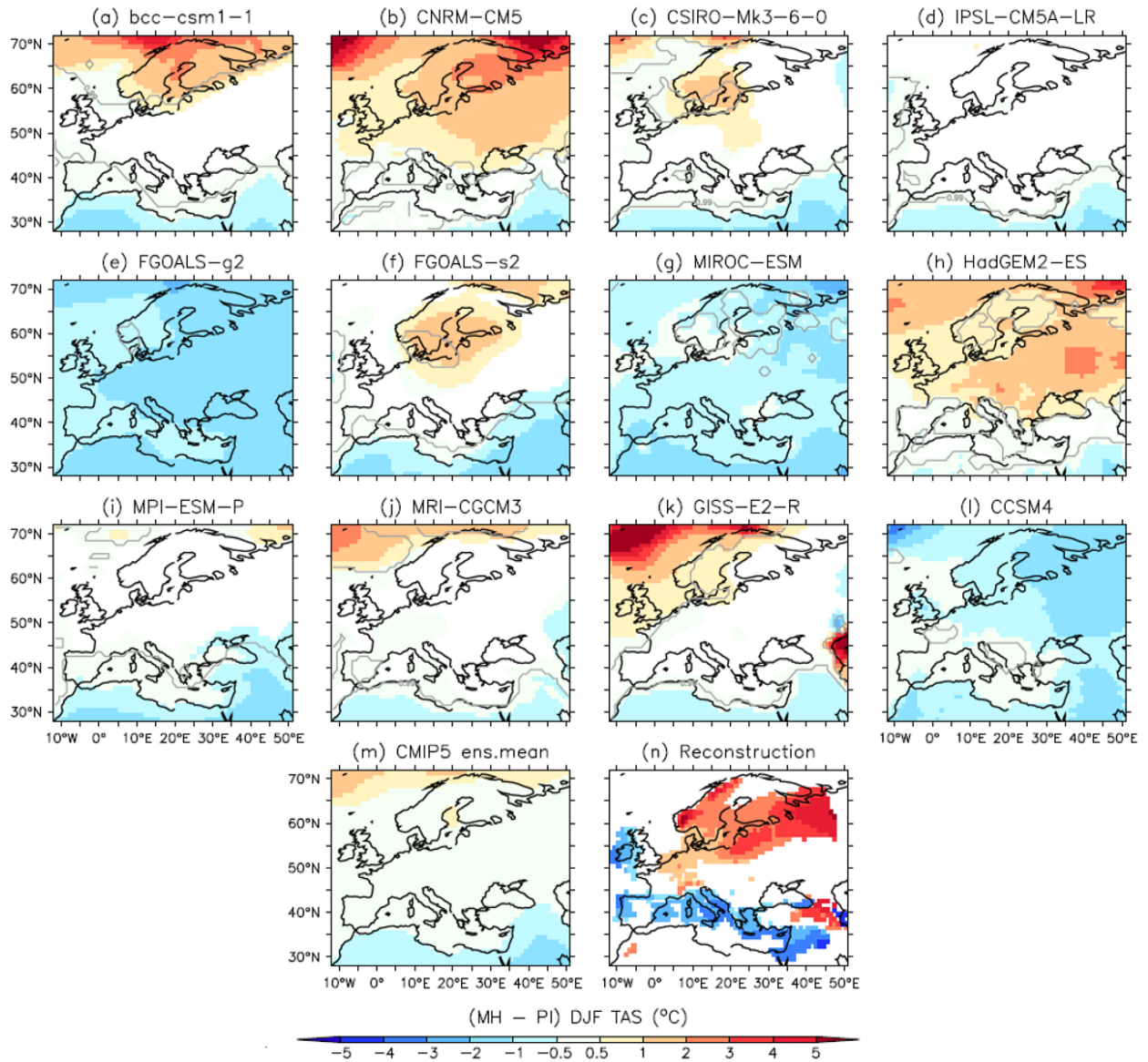


142 independent sample t-test to determine if and to what level these anomalies are statistically  
143 significant, considering the interannual variability in the PI and MH simulations, at each grid  
144 point. Where this is done, we shade in color the regions where the anomalies are significant at  
145 the 90% confidence level. For a more stringent test, we add contours corresponding to  
146 significant anomalies at the 99% confidence interval.

## 147 **Temperature and circulation response**

### 148 **MH winter temperature response in PMIP3 models**

149 While the external forcing (insolation changes) is the same in the different models, their  
150 responses to MH climatic condition in winter over Europe are very different, as shown in Figure  
151 2. This figure shows the significant winter surface atmospheric temperature (SAT) anomalies  
152 over Europe simulated with the 12 different climate models, the multi-model ensemble mean  
153 anomaly and the reconstruction by Mauri et al. (2014). The uncertainties in the pollen-based  
154 reconstruction can be quite large, therefore Figure 2n only shows those  $\Delta\text{SAT}_{\text{DJF,EU}}$  values that  
155 are larger in absolute value than the respective estimated uncertainties. We find a wide range  
156 of simulated SAT anomaly patterns between the 12 models, and some important differences  
157 from the mean reconstructed pattern. We quantify these model-reconstruction differences in  
158 Figure 3, showing the pattern correlation, pattern root-mean-square difference (RMSE; pattern  
159 RMSE obtained by removing the respective spatial average from each field before the RMSE  
160 calculation) and full-field RMSE for each model compared to the Mauri et al. (2014)  
161 reconstruction, as well as for the multi-model ensemble mean.



162

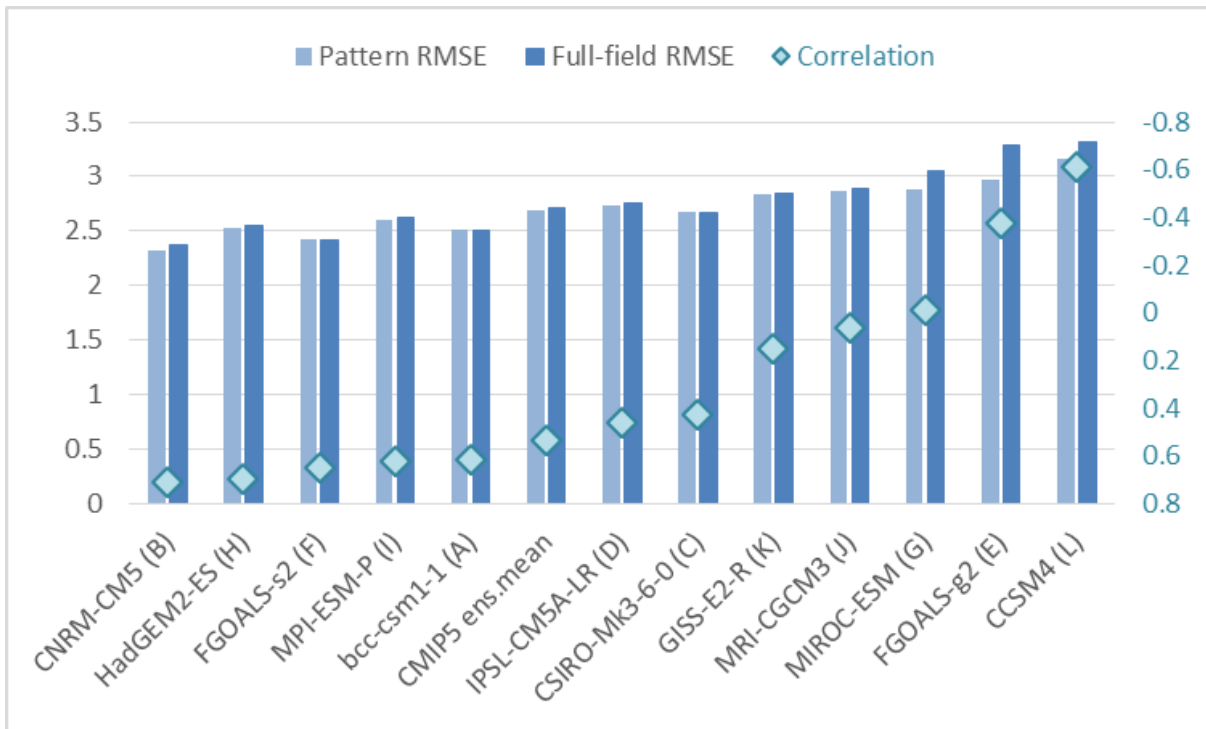
163 **Figure 2:** (a)-(l) Significant differences (color: at 90% confidence level; inside contours: at 99% confidence

164 level) between mean wintertime near-surface air temperature (SAT) in mid-Holocene and pre-industrial

165 simulations run with 12 different climate models; (m) Multi-model ensemble mean difference between MH and

166 PI climatological wintertime SAT; (n) Mauri et al. (2014) reconstruction of the MH climatological wintertime

167 SAT anomaly – only data where the signal is larger than the estimated uncertainty is considered.



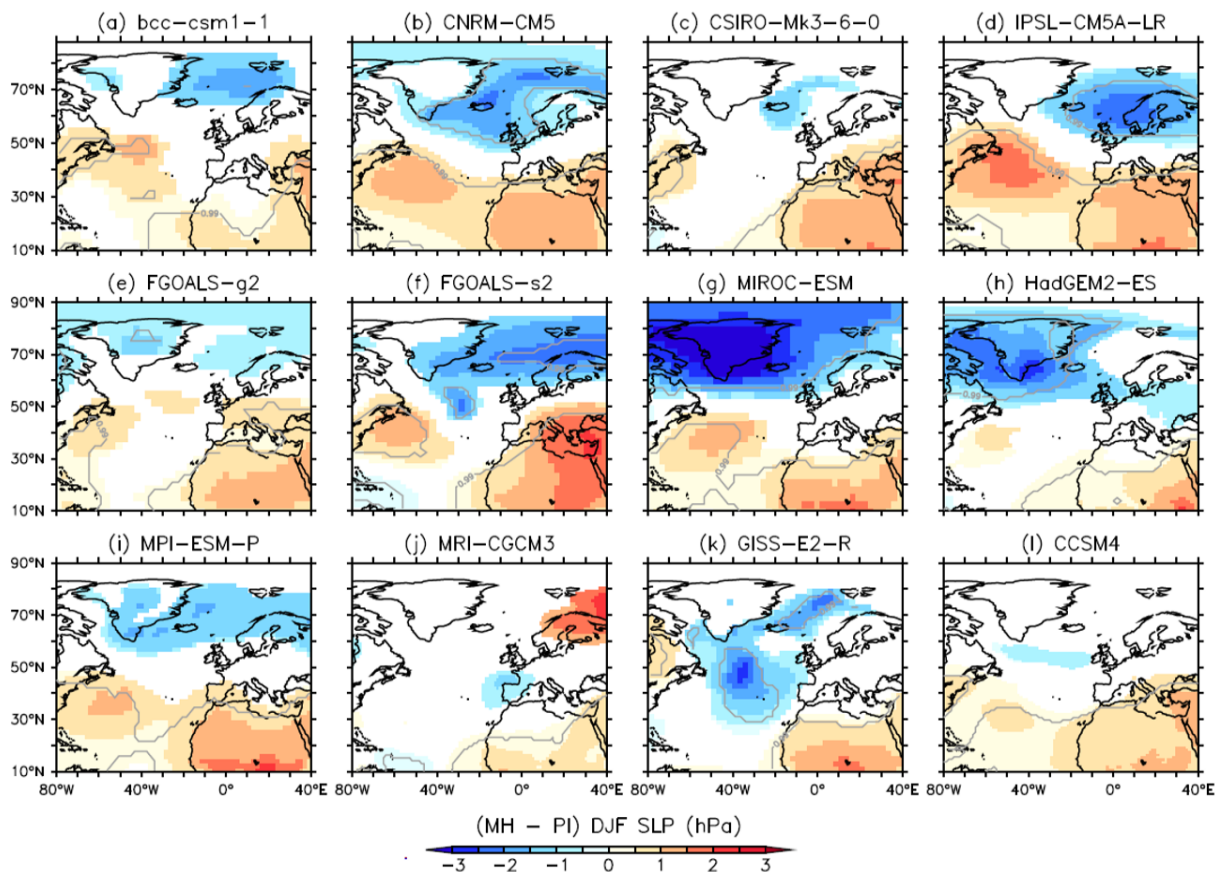
169

170 **Figure 3:** Statistics comparing the simulated and reconstructed (Mauri et al. 2014) mid-Holocene wintertime SAT  
 171 anomalies over Europe. Correlation (values shown on the right-side vertical axis): spatial correlation coefficient  
 172 between the two fields compared; Pattern RMSE: root-mean-square error when the respective spatial average has  
 173 been removed from each of the two fields compared; Full-field RMSE: total root-mean-square-difference between  
 174 the two fields. The model data, including the multi-model ensemble mean, are sorted from the highest to the lowest  
 175 spatial correlation with the reconstructed data. The statistics are only calculated using those grid points where the  
 176 reconstructed signal is stronger than the estimated uncertainty (see Figure 4n).

177 Some models fail to represent the reconstructed  $\Delta\text{SAT}_{\text{DJF, EU}}$  pattern, like CCSM4, FGOALS-  
 178 g2 and MIROC-ESM, which show near-zero or negative spatial correlation coefficients with  
 179 the reconstructed field and RMSEs larger than  $3^\circ\text{C}$ . Other models like CNRM-CM5 and  
 180 HadGEM2-ES have some success in simulating a similar pattern, *i.e.*, a positive north-south  
 181 temperature anomaly gradient (spatial correlation coefficient  $\sim 0.7$ ) but still fail at simulating  
 182 the reconstructed amplitude (pattern RMSE  $\geq 2.3^\circ\text{C}$ ), and the temperature anomalies  
 183 themselves (full-field RMSE  $\geq 2.4^\circ\text{C}$ ).

184 **MH winter atmospheric circulation anomalies in the PMIP3 models**

185 Mauri et al. (2014) proposed that the MH temperature anomaly pattern over Europe could be  
186 caused by a NAO-like atmospheric circulation anomaly. To explore this possibility in the  
187 PMIP3 database, Figure 4 shows the statistically significant sea-level pressure differences  
188 ( $\Delta$ SLP) between the climatological wintertime (DJF) MH and PI simulations over the North  
189 Atlantic (NA) sector for the 12 analyzed models. All models show significant MH winter SLP  
190 anomalies, of the order of 0.5-1.5 hPa, with corresponding 1000-hPa wind speed anomalies  
191 ( $\Delta U_{\text{horiz,DJF,1000}}$ , not shown) of the order of 0.2-0.7 m/s.

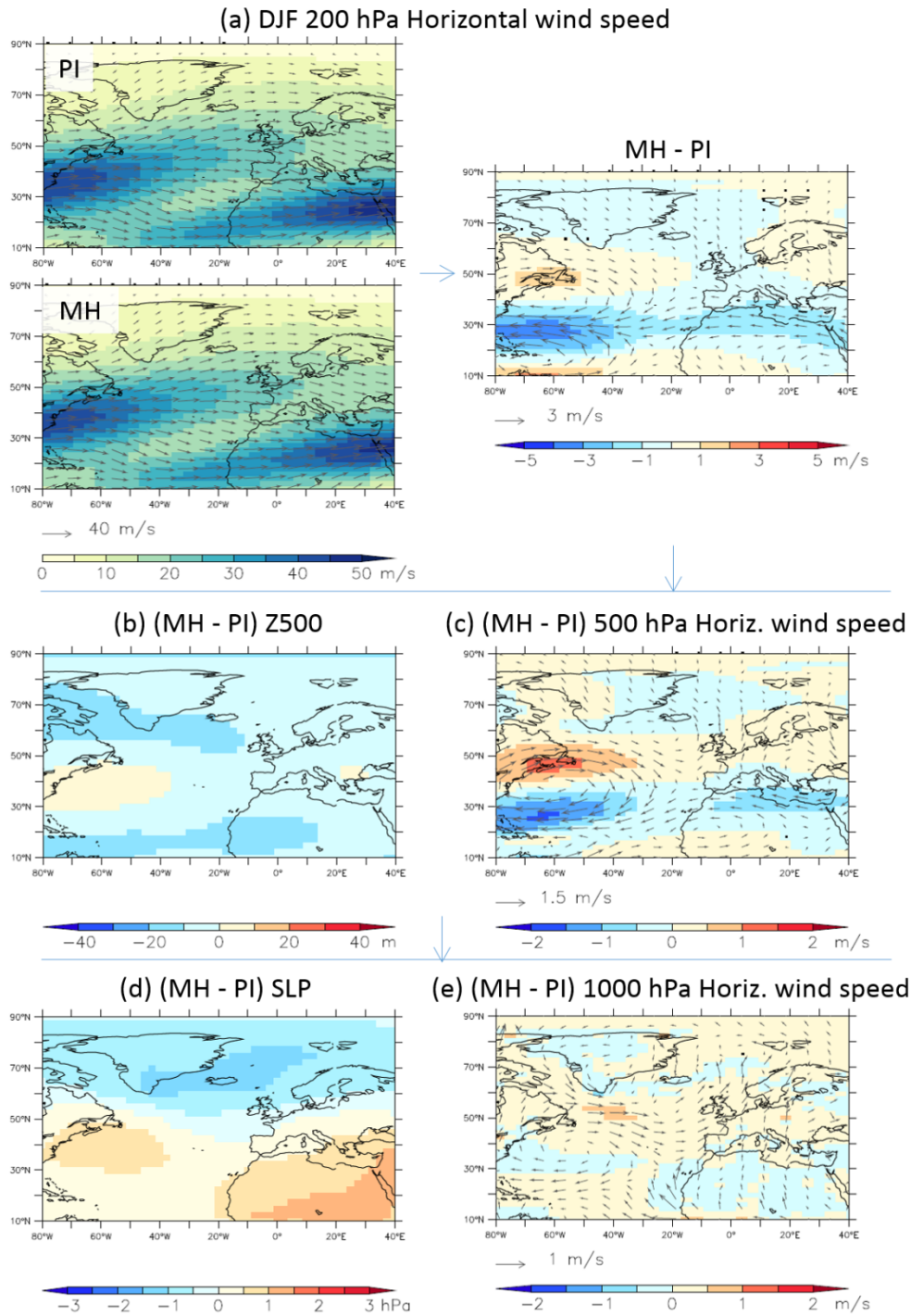


192

193 **Figure 4:** Significant differences (color: at 90% confidence level; inside contours: at 99% confidence  
194 level) between mean wintertime sea-level pressure in mid-Holocene and pre-industrial simulations run  
195 with 12 different climate models.

196 Figure 5 shows the multi-model mean circulation anomalies at different levels in the  
197 troposphere. Significant anomalies are found at all atmospheric levels. The most notable feature  
198 is a negative zonal wind speed anomaly in the subtropics (around 30°N), maximum at upper  
199 levels ( $\Delta u_{200}$ ) and over the western half of the North Atlantic. This feature is present in all  
200 models, but with structures varying in strength, extent and zonal orientation. We can trace it to  
201 a local weakening of the jet streams (in some models, accompanied by a slight northward shift  
202 of the eddy-driven jet) and, for most models, a more marked separation between the eddy-  
203 driven and subtropical jet streams over the North Atlantic (illustrated in Figure 5a for the multi-  
204 model ensemble mean). This results in an anticyclonic horizontal wind speed anomaly and local  
205 high pressure in the West Atlantic northward of the negative  $\Delta u_{200}$  region. For most models,  
206 this anticyclonic anomaly dominates the pattern of mean atmospheric circulation change over  
207 the North Atlantic. In those cases, this anomaly structure is found throughout the atmospheric  
208 column (as illustrated in Figure 5c for the 500 hPa level), down to the surface (Figure 5e),  
209 explaining the positive SLP anomalies found in most models over the southwestern North  
210 Atlantic (Figure 4, Figure 5d). Even the MRI model, which has no significant anomalies in the  
211 lower atmosphere, shows a similar significant anomaly in the jet stream.

212 While this positive pressure anomaly in the Western Atlantic has an equivalent barotropic  
213 structure that extends throughout the troposphere, the positive SLP anomaly seen over North  
214 Africa in the multi-model mean (Figure 5d) is on the contrary very shallow, disappearing or  
215 even changing sign at 500 hPa. This baroclinic structure is linked to a cold temperature anomaly  
216 in the atmospheric column, which can be explained by the negative DJF radiative forcing. The  
217 reduction of the radiative forcing is strongest at low latitudes (Figure 1), and has a larger impact  
218 over continental regions like North Africa.



219

220 Figure 5: Multi-model ensemble mean wintertime: (a) 200 hPa horizontal wind speed in pre-  
 221 industrial (PI), mid-Holocene (MH) simulations and the corresponding MH-PI difference; (b)  
 222 500 hPa geopotential height MH anomaly; (c) 500 hPa horizontal wind speed anomaly; (d)  
 223 sea-level pressure anomaly; (e) 1000 hPa horizontal wind speed anomaly.

## 224 **Atmospheric circulation vs. European temperature anomaly patterns**

225 Figure 4 shows that several PMIP3 models simulate a positive SLP anomaly over the southern  
226 part of the North Atlantic and a negative SLP anomaly over the northern part of the basin during  
227 MH winters. This pattern could be roughly construed to be NAO<sup>+</sup>-like, as Mauri et al. (2014)  
228 argued could cause their reconstructed DJF  $\Delta\text{SAT}_{\text{EU}}$  pattern. This section examines whether  
229 such a relationship between a NAO<sup>+</sup>-like circulation anomaly and a  $\Delta\text{SAT}_{\text{EU}}$  pattern can be  
230 found within our multi-model ensemble.

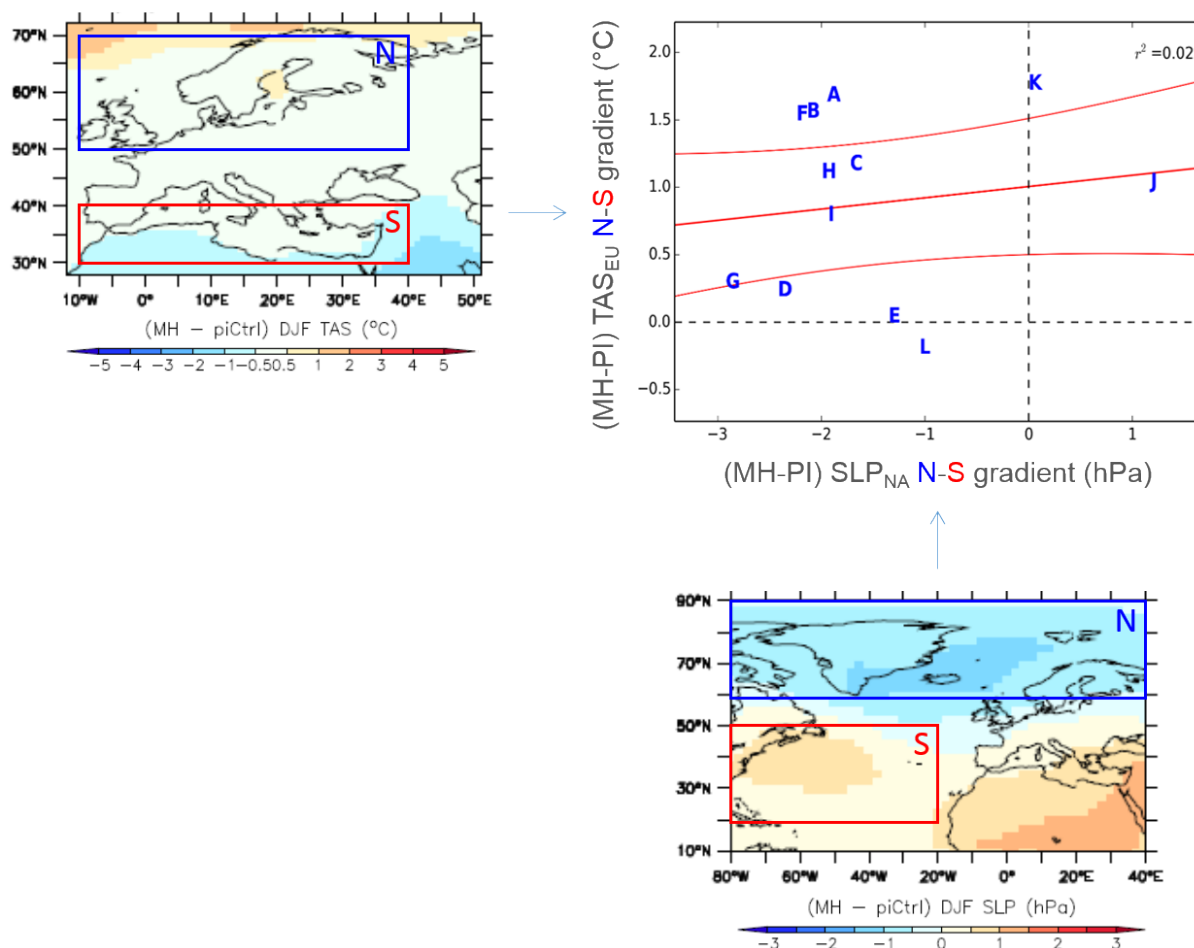
231 A key question is whether the differences between the simulated temperature anomaly patterns  
232 between models can be attributed to the differences in their simulated atmospheric circulation  
233 anomalies over the North Atlantic. More specifically, we want to assess whether the models  
234 that simulate a positive north-south temperature gradient over Europe are only the models that  
235 also simulate a NAO<sup>+</sup>-like circulation anomaly over the North Atlantic.

236 A qualitative comparison of Figure 2 and Figure 4 indicates that this is not the case. While the  
237 hypothesis of a NAO<sup>+</sup>-like cause of marked north-south gradients in  $\Delta\text{SAT}_{\text{DJF, EU}}$  could hold  
238 for a few models (*e.g.*, CNRM-CM5), the ensemble of models does not support it. Some models  
239 exhibit a NAO<sup>+</sup>-like circulation without a strong north-south  $\Delta\text{SAT}_{\text{DJF, EU}}$  gradient (*e.g.*, IPSL-  
240 CM5A-LR, MIROC-ESM), while other models show a marked  $\Delta\text{SAT}_{\text{DJF, EU}}$  gradient without  
241 simulating a NAO<sup>+</sup>-like circulation anomaly (*e.g.*, GISS-E2-R). For some model simulations  
242 showing a negative SLP anomaly around Iceland, which can look like part of a NAO<sup>+</sup> pattern,  
243 just like over Africa the pressure anomaly disappears with height (not shown), and is most likely  
244 a thermal structure caused by the local warming at the surface.

245 For a quantitative assessment, Figure 6 evaluates the relationship between first-order indices of  
246 the large-scale temperature and circulation changes, namely the north-south  $\Delta\text{SAT}_{\text{DJF, EU}}$   
247 gradient and the NAO<sup>+</sup>-like  $\Delta\text{SLP}_{\text{NA}}$ . The north-south  $\Delta\text{SAT}_{\text{DJF, EU}}$  gradient is defined as the



248 mean temperature difference between a northern and a southern region over Europe chosen to  
 249 approximately reflect the Arctic Oscillation signature on  $SAT_{EU}$ , as shown in Mauri et al. (2014  
 250 - top left panel in Figure 6). The NAO<sup>+</sup>-like  $\Delta SLP_{NA}$  is defined as the mean sea-level pressure  
 251 difference between regions chosen to approximately reflect the centers of action of the North  
 252 Atlantic Oscillation index (*cf.* Hurrell & Deser 2010 – bottom right panel in Figure 6). The  
 253 scatterplot between the two indices in the top right panel of Figure 6 shows a lack of significant  
 254 correlation that confirms that the PMIP3 models do not support a straightforward link between  
 255 MH temperature anomaly patterns over Europe and a NAO<sup>+</sup>-like circulation anomaly over the  
 256 North Atlantic.



257  
 258 **Figure 6:** Top left: PMIP3 ensemble mean anomalies of SAT (in °C) in DJF for MH minus PI. The blue box  
 259 defines the northern region and the red box, the southern region used for calculating the north-south SAT gradient.  
 260 Bottom right: PMIP3 ensemble mean anomalies of SLP (in hPa) in DJF for MH minus PI. The blue box defines



261 the northern region and the red box, the southern region used to define the SLP north-south gradient. Top right:  
262 Multi-model relationship of the land temperature anomaly gradient (defined in top left panel) - on the y-axis - and  
263 the SLP anomaly gradient (defined in bottom right panel) - on the x-axis. The squared correlation coefficient is  
264 shown in the top-left corner of the figure. The red lines indicate the linear regression and the 95% confidence  
265 interval for this regression.

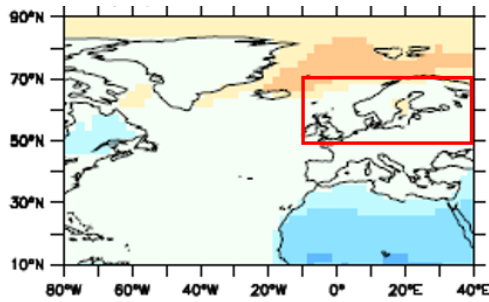
## 266 **Factors determining the simulated $\Delta\text{SAT}_{\text{DJF,EU}}$ meridional gradients**

267 Figure 2 shows that the strongest  $\Delta\text{SAT}_{\text{DJF,EU}}$  signals are found, for most models, close to the  
268 latitude boundaries of the region considered. Enlarging the domain of our analysis places the  
269 European temperature anomalies patterns in the larger-scale context (Figure 7a). We find that  
270 the modeled north-south  $\Delta\text{SAT}_{\text{DJF,EU}}$  contrasts are dominated, to the north, by warm  
271 temperature anomalies over the Nordic Seas and, to the south, by cold temperature anomalies  
272 over northern Africa.

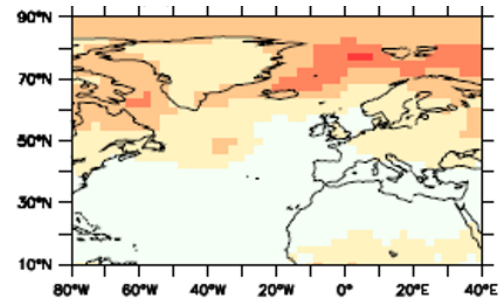
273 To a large extent, the negative SAT anomalies over northern Africa (and the positive SLP  
274 anomalies) are related to the negative radiative forcing in winter at these latitudes (Figure 1).  
275 This anomaly is strongest at low latitudes and has an amplified effect on SAT over continents  
276 vs. oceanic regions, possibly due to the lower heat capacity of land than water.

277 Inter-model differences of  $\Delta\text{SAT}$  over the southern region in Figure 5 are indeed small ( $0.3^{\circ}\text{C}$   
278 inter-model standard deviation) relative to the ones over the northern region ( $0.8^{\circ}\text{C}$ ), consistent  
279 with a lower  $\Delta\text{SAT}$  inter-model standard deviations over northern Africa than over the Nordic  
280 Seas (Figure 7b). Thus, for the rest of the paper we will focus mainly on what determines the  
281 inter-model spread in  $\Delta\text{SAT}_{\text{DJF}}$  over the Nordic Seas, that dominates the north-south contrast.

(a)  $\Delta$ TAS ens. mean



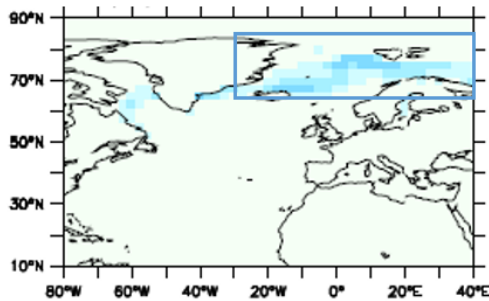
(b)  $\Delta$ TAS ens.  $\sigma$



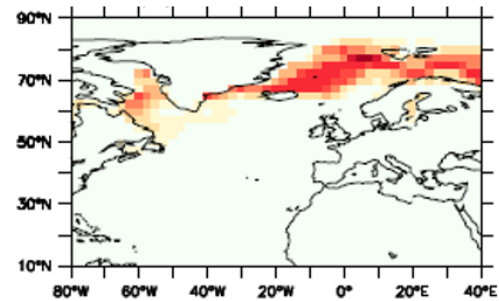
(MH - piCtrl) DJF TAS ( $^{\circ}$ C)

-5 -4 -3 -2 -1 -0.5 0.5 1 2 3 4 5

(c)  $\Delta$ SIC ens. mean



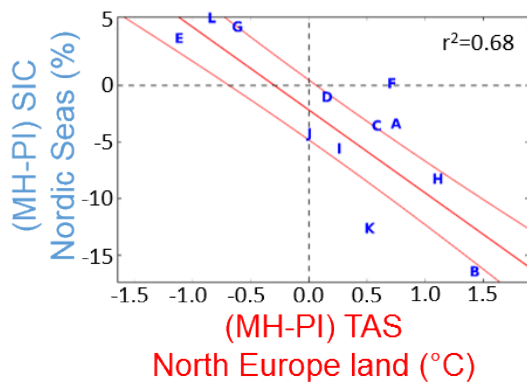
(d)  $\Delta$ SIC ens.  $\sigma$



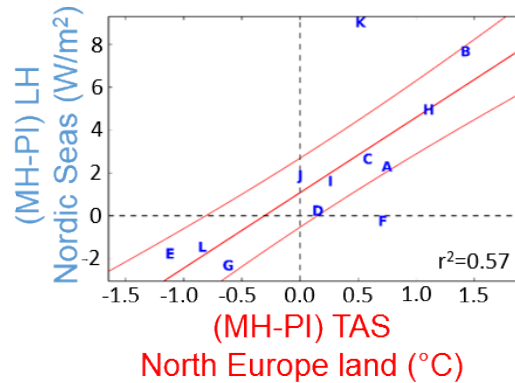
(MH - piCtrl) DJF SIC (%)

-20 -12.5 -5 5 12.5 20

(e)  $\Delta$ SIC<sub>NS</sub> vs.  $\Delta$ TAS<sub>NEU</sub>



(f)  $\Delta$ LH<sub>NS</sub> vs.  $\Delta$ TAS<sub>NEU</sub>



282

283 **Figure 7:** MH winter anomalies of (a, b) near-surface air temperature and (c- d) sea ice cover over the North  
 284 Atlantic sector. (a) and (c) show the multi-model ensemble mean anomalies and (b) and (d) show the ensemble  
 285 standard deviation. (e) Relationship between simulated near-surface air temperature over land in northern Europe  
 286 and sea ice cover anomalies averaged over the region highlighted in (a) and (c) for the 12 models analyzed. (f)  
 287 Same as (e) but with sea ice cover anomalies replaced by latent heat flux anomalies from the ocean to the

288 atmosphere. The squared correlation coefficient is shown in the top- and, respectively, bottom-left corner of the  
289 plots. In both plots, the red lines indicate the linear regression and the 95% confidence interval for the regression.  
290 The spatial patterns of both the  $\Delta\text{SAT}_{\text{DJF}}$  signal in the Nordic Seas and its inter-model spread  
291 (Figure 7a, b) are strongly reminiscent of those of the DJF sea-ice cover anomalies (Figure 7c,  
292 d). Sea-ice cover changes have a strong impact on near-surface temperatures *via* air-sea fluxes  
293 and albedo feedbacks (Swingedouw et al. 2006, Årthun et al. 2017). This influence extends to  
294 neighbouring land regions: the inter-model differences in  $\Delta\text{SAT}_{\text{DJF}}$  in land areas of northern  
295 Europe (Figure 7e) are well correlated ( $r^2=0.68$ ,  $p<0.01$ ) with the differences in  $\Delta\text{SIC}_{\text{DJF}}$  over  
296 the Nordic Seas. Furthermore, these differences in  $\Delta\text{SAT}_{\text{DJF}}$  are also well correlated with the  
297 changes in latent heat flux from the ocean to the atmosphere over the Nordic Seas. Thus, we  
298 argue that it is the difference in latent heat flux released in winter by the ocean to the atmosphere  
299 and associated with the insulation effect of the presence (or not) of sea ice that explains the  
300 response of  $\Delta\text{SAT}_{\text{DJF}}$  over northern Europe land. A similar mechanism was indeed highlighted  
301 by Årthun et al. (2017) to explain the impact of Nordic Seas SST variability on the temperature  
302 of Scandinavia.

303 Thus, to understand the differences between the wintertime MH European temperature  
304 anomalies between the models, we mainly need to understand the origins of the differences  
305 between the simulated sea ice cover anomalies in the Nordic Seas region.

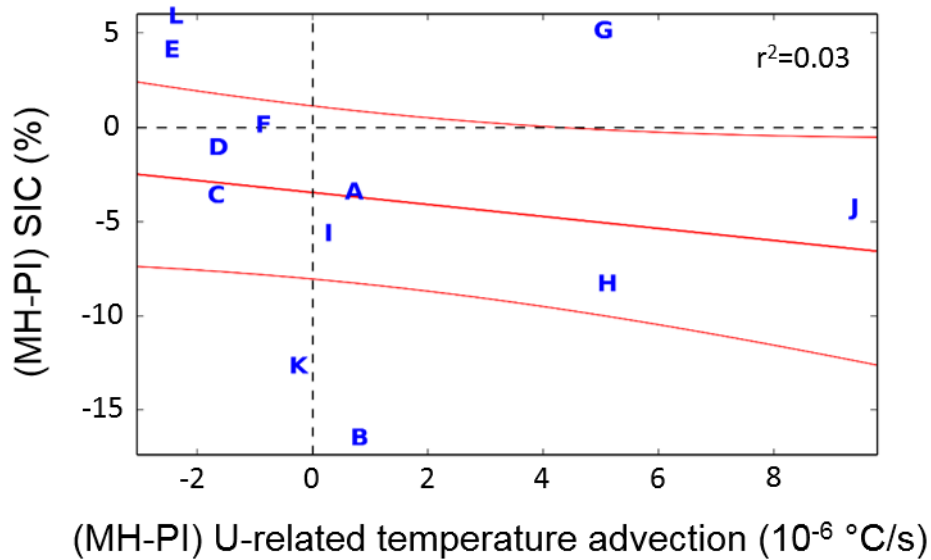
## 306 **Origins of winter sea-ice decline**

### 307 **Atmospheric circulation anomalies**

308 While NAO-like anomalies do not directly determine the inter-model differences in winter  
309 temperature anomalies over Europe in PMIP3 ensemble, atmospheric circulation changes  
310 between MH and PI winters could potentially control the sea ice anomalies in the Nordic Seas,  
311 through anomalous atmospheric heat transport.

312 To test this hypothesis, we tried to calculate the total atmospheric heat transport into the Nordic  
313 Seas region. This computation should be based on changes of both the mean and transient  
314 circulation. Unfortunately, the PMIP3 database does not routinely include data at sufficiently  
315 high frequencies to allow for the calculation of the latter term, nor does it provide estimates of  
316 atmospheric heat transport computed at the model time step. We can thus only offer a partial  
317 answer, related to the mean wind anomalies only.

318 Whether we consider the near-surface horizontal temperature advection due solely to the change  
319 in the mean winter near-surface horizontal wind velocities between PI and MH (estimated as  
320  $-\Delta\vec{U} \cdot \nabla T_{PI}$ , where  $\Delta$  stands for MH-PI differences,  $\vec{U}$  for the horizontal wind velocity and  $T_{PI}$   
321 for the temperature for pre-industrial simulation; Figure 8) or the change between the mean  
322 circulation-induced horizontal temperature advection in PI vs. MH winters (estimated as  $-\Delta$   
323  $(\vec{U} \cdot \nabla T)$ ; not shown), we find no correlation of these respective anomalies with the winter sea  
324 ice cover anomaly over the Nordic Seas region (Figure 8). More generally, two other elements  
325 of the energy budget argue against an increased poleward atmospheric transport in MH winter:  
326 at the top of the atmosphere, the latitudinal gradient of insolation decreases (with more cooling  
327 at lower latitudes), and the ocean heat transport tends to increase (due to AMOC strengthening  
328 as shown below). Both would typically lead to a compensating equatorward energy transport  
329 by the atmosphere, away from the sea ice region. Such a response has actually been  
330 demonstrated in MH simulations run with the IPSL-CM5A-LR model (Saint-Lu et al. 2016).  
331 We thus find no evidence that the changes in the atmospheric heat transport may be responsible  
332 for  $\Delta\text{SIC}_{\text{DJF}}$  in the models.



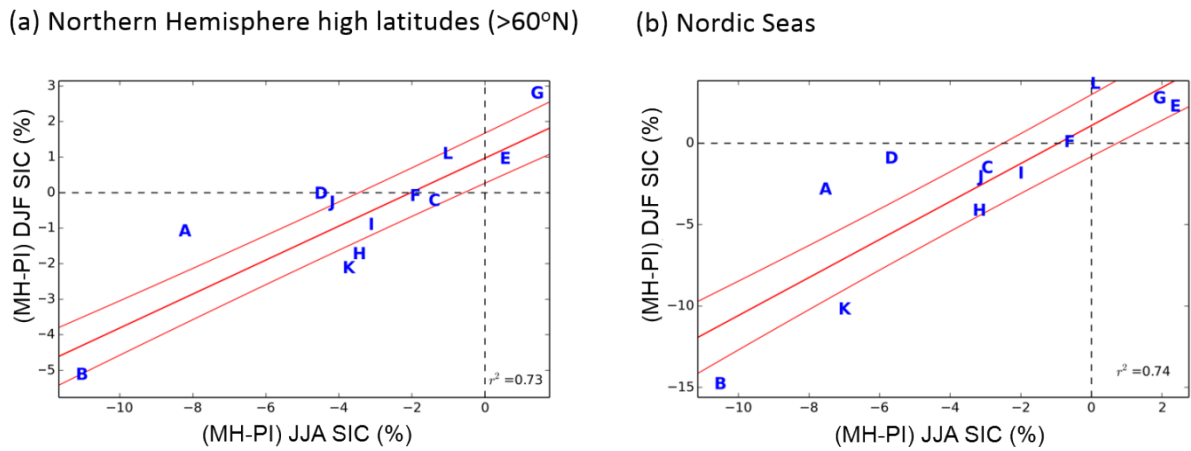
333

334 **Figure 8:** Multi-model relationship between wintertime sea ice cover anomalies and mean 1000hPa horizontal  
 335 circulation anomaly-related temperature advection in the NS region. The red lines indicate the linear regression  
 336 and the 95% confidence interval for this regression.

### 337 **Summer sea ice anomalies**

338 Another potential source of the inter-model differences in winter sea ice anomalies is the  
 339 summer (JJA) sea ice response, with a memory effect between the two seasons. Indeed, the  
 340 insolation is far larger in the Mid-Holocene compared to the pre-industrial period during  
 341 summer (Figure 1), potentially leading to large melting of sea ice and heat storage in the ocean  
 342 in summer, which may then persist into winter due to the large inertia of the ocean. There is a  
 343 fine interplay between winter and summer sea ice: winter sea ice thickness heavily influences  
 344 the ice pack vulnerability to summer melt, and thus has an important effect on summer sea ice  
 345 cover (Berger et al. 2013). Conversely, summer melt allows for ocean surface heat uptake and  
 346 renders new sea ice formation more difficult during autumn and winter. Thus, we can also  
 347 expect a  $\Delta\text{SIC}_{\text{JJA}}$  effect on  $\Delta\text{SIC}_{\text{DJF}}$  (Berger et al. 2013). This latter effect may play an important  
 348 role in determining the inter-model  $\Delta\text{SIC}_{\text{DJF}}$  differences. Indeed, the different models may  
 349 exhibit different sea ice responses to the summer radiative forcing (Figure 1) for example

350 through different strength of feedbacks, like the local cloud response (*cf.* Knudsen et al. 2015;  
 351 Abe et al. 2015). These differences in summer may then project on the winter responses.  
 352 We thus check if the relationship between  $\Delta\text{SIC}_{\text{JJA}}$  and  $\Delta\text{SIC}_{\text{DJF}}$  is consistent between the  
 353 models. Figure 9 indeed shows a strong multi-model relationship between  $\Delta\text{SIC}_{\text{JJA}}$  and  
 354  $\Delta\text{SIC}_{\text{DJF}}$ , both globally over the Northern Hemisphere high latitudes ( $r^2=0.74$ ,  $p<0.01$ ), and  
 355 regionally over the Nordic Seas ( $r^2=0.73$ ,  $p<0.01$ ).



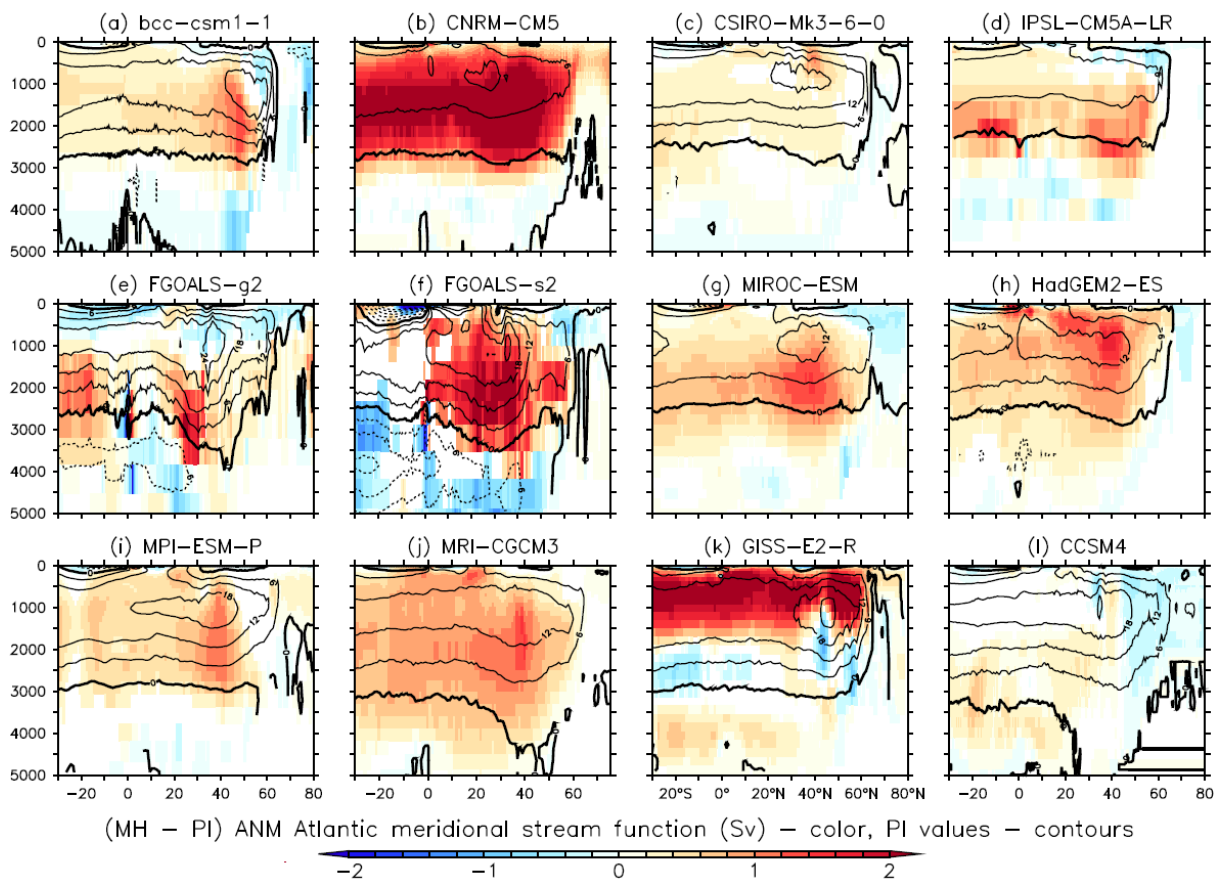
356  
 357  
 358 **Figure 9:** Relationship between MH winter and summer sea ice cover anomalies (a) averaged over the Northern  
 359 Hemisphere high latitudes (above 60°N); (b) averaged over the Nordic Seas (rectangular region contoured in Figure  
 360 7a, c). The text boxes in the bottom-left corner of the figures show the associated squared correlation coefficients.  
 361 The red lines indicate the linear regressions and the 95% confidence interval for the regressions.

362 While it is likely that a memory of the seasonally forced  $\Delta\text{SIC}_{\text{JJA}}$  can influence  $\Delta\text{SIC}_{\text{DJF}}$ , it is  
 363 also possible that both summer and winter sea ice anomalies are influenced by a large-scale,  
 364 common factor such as a change in the Atlantic meridional overturning circulation (AMOC),  
 365 which we investigate in the following section.

366 **Change in AMOC**

367 Figure 10 shows the changes in the AMOC between the simulated MH and PI climates. All 12  
 368 models analyzed show significant anomalies in the mean AMOC, with considerable inter-

369 model variability in terms of both anomalies (Figure 10, colors) and background state (PI  
 370 AMOC – Figure 10, contours). In general, the AMOC is strengthened in MH compared to PI.  
 371 This is consistent with Born et al. (2010), who proposed that for a climate with warmer summer  
 372 (the Eemian in their case), the decrease in sea ice transport through Fram Strait may change the  
 373 salinity in the Labrador Sea and enhance local convective activity, feeding a stronger AMOC.  
 374 AMOC MH anomalies vary between models not just in terms of intensity, but also in terms of  
 375 structure, complicating their quantitative comparison. Nevertheless, maxima of the meridional  
 376 stream function have been shown to be strongly related to the meridional ocean heat transport  
 377 (*e.g.* Boning et al. 1995). Thus, they represent a reasonable parameter to consider in the  
 378 investigation of sea ice changes.



379

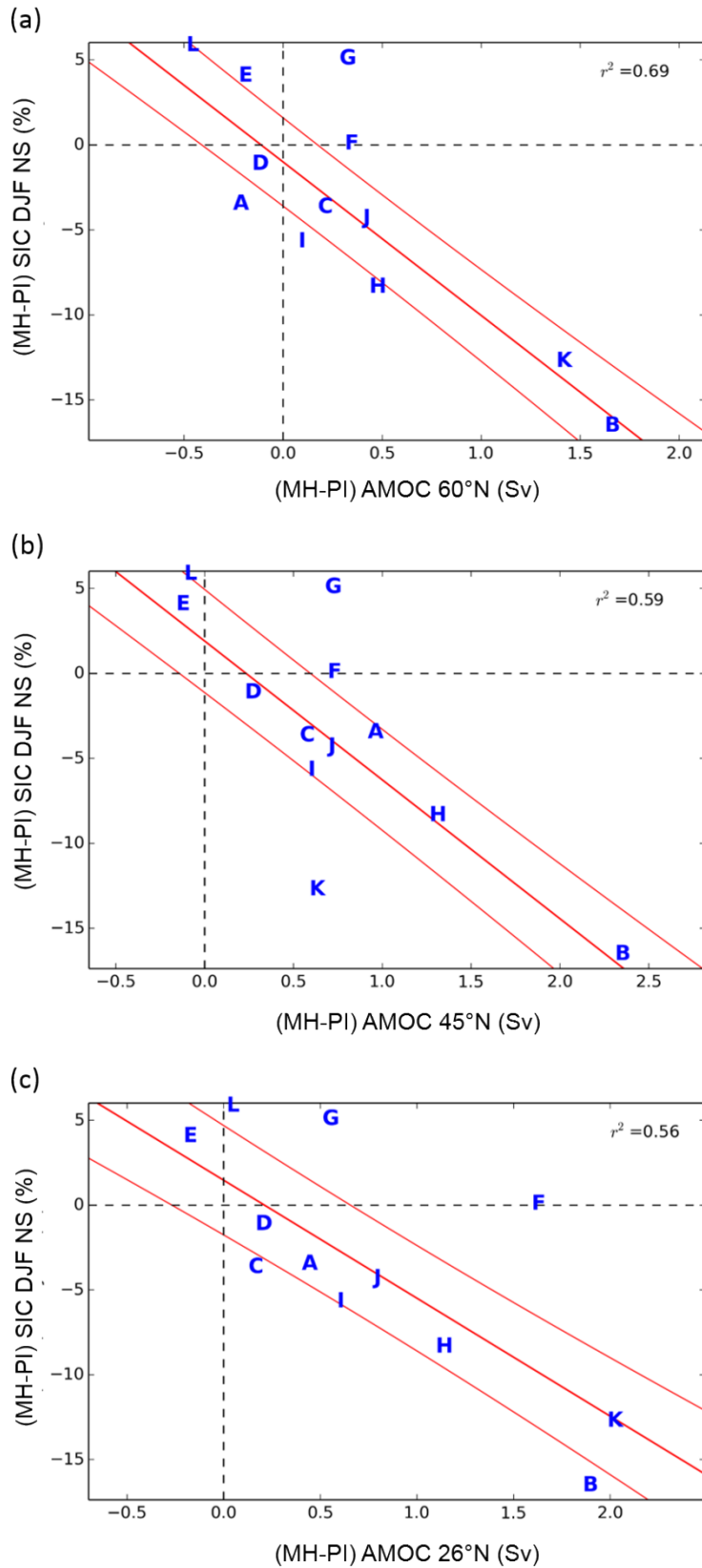
380 **Figure 10:** Color: significant (at 90% level) MH anomalies of the climatological annual mean (ANM) Atlantic  
 381 meridional stream function; contours: PI climatologies (contour spacing: 6 Sv; solid/dashed contours represent  
 382 positive/negative values) for the 12 models analyzed.

383 Figure 11 shows the relationship between winter sea-ice cover anomalies and anomalies in the  
384 maximum of the climatological Atlantic meridional stream function at three different latitudes:  
385 26°N and 45°N, typically used when describing the AMOC strength (*e.g.*, Huck et al. 2008,  
386 McCarthy et al. 2015), and 60°N, closer to the Nordic Seas region. The DJF SIC anomalies are  
387 in all cases negatively correlated with the AMOC strength anomalies. The correlation  
388 coefficient and the slope of the corresponding linear regressions increase with latitude, so that  
389 the strongest link of  $\Delta\text{SIC}_{\text{DJF,NS}}$  with the meridional ocean circulation is found for  $\Delta\text{AMOC}$  at  
390 60°N. The correlation coefficient is 0.89 (p-value < 0.01) and the linear regression line has a  
391 near-zero intercept, indicating that, as would be expected, an intensification of the AMOC at  
392 high latitudes is linearly associated to negative SIC anomalies in the Nordic Seas and *vice-*  
393 *versa*. The correlation remains high even at 26°N ( $r=0.75$ ,  $p<0.01$ ), indicating that this  
394 relationship is not a purely local effect.

395 Changes in the subpolar gyre may also strongly affect the heat transport to the high latitudes  
396 (Born et al. 2015). However, the barotropic stream function was not available for all the models,  
397 limiting the analysis of this effect. Since the strength of the subpolar gyre is closely related to  
398 the strength of the convection in the subpolar gyre (Born et al. 2015), we suggest that the  
399 changes in AMOC would also be reflected in subpolar gyre strength, both leading to an increase  
400 of meridional heat transport.

401 The changes in oceanic heat transport act on longer than seasonal time scales and may thus  
402 affect sea-ice cover in both winter and summer, likely contributing to the correlation between  
403 winter and summer anomalies highlighted in Section 6.2. Nevertheless, direct changes in  
404 summer sea ice in response to changes in insolation are also due to regional sensitivity and  
405 feedbacks that may differ among the models (*e.g.*, Massonnet et al. 2012), and so could remain  
406 a relatively independent factor from AMOC strengthening to explain the inter-model spread.





407

408 **Figure 11:** Relationship between mean winter MH sea ice cover anomalies over the Nordic Seas region and the

409 MH anomaly in the maximum climatological Atlantic meridional stream function at (a) 60°N, (b) 45°N and (c)

410 26°N. The squared correlation coefficients of the associated linear regressions are shown in the respective panels.

411 The correlations are significant above the 99% level. The red lines indicate the linear regression and the 95%  
412 confidence interval for this regression.

### 413 **Combination of multiple factors**

414 In the previous subsections we have analyzed one-to-one relationships between  $\Delta\text{SIC}_{\text{DJF,NS}}$  and  
415 a suite of atmospheric and oceanic variables. However, the inter-model differences in the winter  
416 sea ice anomalies are most likely explained by a combination of different factors which affect  
417 the sea ice cover in different measures depending on the model.

418 We have investigated a wide array of variable combinations to best explain the inter-model  
419 variations in  $\Delta\text{SIC}_{\text{DJF,NS}}$  through multiple linear regressions. We have considered parameters  
420 physically linked with the winter sea ice anomalies, like the temperature advection due to the  
421 mean circulation change in the Nordic Seas region, the surface downward radiative flux  
422 anomalies, the background state (PI) sea ice cover, the summer sea ice cover anomalies and the  
423 change in the AMOC strength.

424 The low number of climate simulations (12), the reductive framework (lack of sensitivity  
425 experiments) and the intrinsic high level of connectivity between climate variables through non-  
426 linear relationships (i.e., variables not independent) limit the potential of such a multivariate  
427 analysis. Nevertheless, some information can be distilled on the basis of this exercise.

428 While in most combinations and for most predictor variables, the high p values associated to  
429 their respective coefficients did not allow for meaningful regressions, the p values associated  
430 to the coefficient for the AMOC strength anomaly at 60°N were always very small (on the order  
431 of  $10^{-4}$ - $10^{-5}$ ) and the coefficients themselves were always found to be negative, indicating a  
432 robust effect of  $\Delta\text{AMOC}$  on  $\Delta\text{SIC}_{\text{DJF,NS}}$  in the direction already described in Section 6.4.

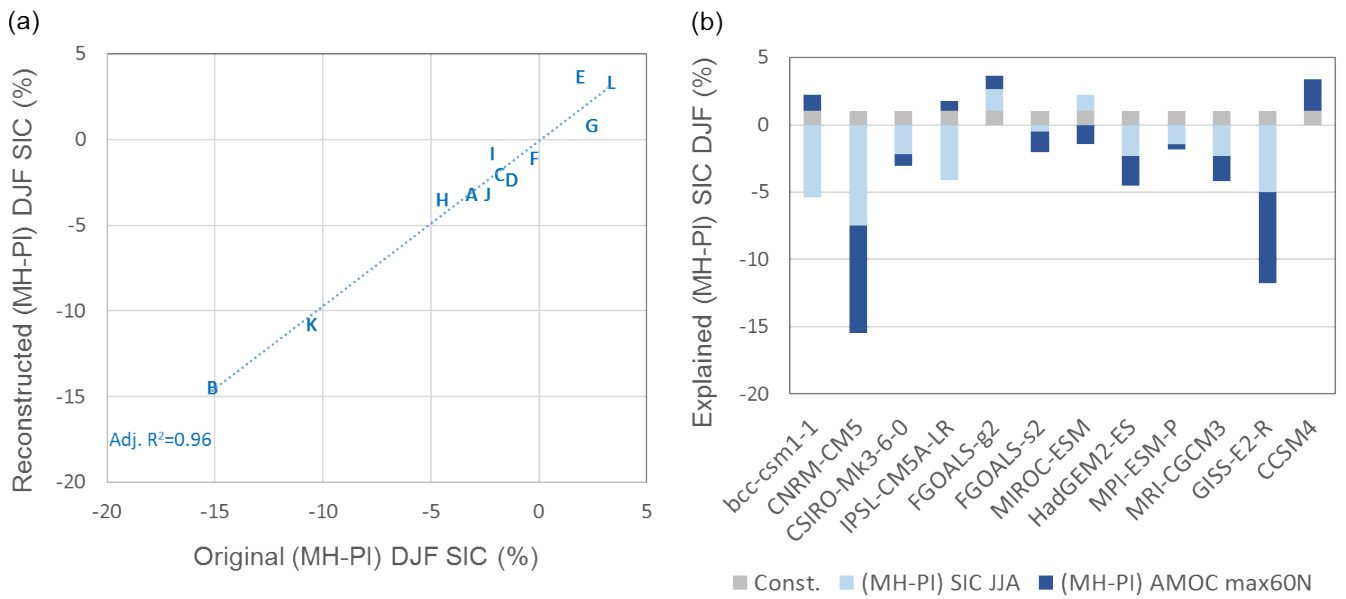
433 One multiple linear regression did yield significant results:

434

$$\Delta SIC_{DJF,NS} = \alpha_0 + \alpha_1 \Delta AMOC_{max.60^{\circ}N} + \alpha_2 \Delta SIC_{JJA,NS} \quad (1)$$

435 with  $p_{\alpha_0} = 0.04$ ,  $p_{\alpha_1} = 10^{-4}$ ,  $p_{\alpha_2} = 4 \cdot 10^{-5}$  and an adjusted  $r^2$  of 0.96.

436 Figure 12 shows the results of the multiple linear regression model in Eq. 1. Figure 12a shows  
 437 the good correspondence between the reconstructed and original  $\Delta SIC_{DJF,NS}$  and Figure 12b  
 438 shows, for each model, the percentage of sea ice cover change associated with each term in the  
 439 regression model. According to the model of Eq. (1), the summer sea ice anomalies and AMOC  
 440 strength anomalies have comparable effects on  $\Delta SIC_{DJF,NS}$ , with the AMOC playing a  
 441 particularly important role in CNRM-CM5 and GISS-E2-R.



442

443 **Figure 12.** Results of the multiple linear regression of  $\Delta SIC_{DJF,NS}$  onto the MH anomaly of the AMOC maximum  
 444 at  $60^{\circ}N$  and  $\Delta SIC_{JJA,NS}$ : (a) correspondence of the reconstructed and original  $\Delta SIC_{DJF,NS}$ ; (b) winter sea ice cover  
 445 anomaly associated to each model predictor, for the 12 models analyzed.

446 The adjusted  $r^2$  can be mildly improved (to a value of 0.97) by adding the pre-industrial sea ice  
 447 cover over the Nordic Seas region,  $SIC_{DJF,PI,NS}$ , as an extra predictor. However, the associated  
 448 p value is 0.015, indicating a 1.5% chance that this predictor has in fact no effect on  $\Delta SIC_{DJF,NS}$ .  
 449 Furthermore, the coefficient for this extra term is positive in this regression model (indicating

450 that climate models where more winter sea ice is present in the Nordic Seas region in pre-  
451 industrial simulations tend to have positive or less negative Mid-Holocene winter sea ice  
452 anomalies) but is negative in all other variable combinations analyzed. The role, if any, of the  
453 background sea ice cover on the  $SIC_{DJF,NS}$  anomalies thus remains uncertain.

454 The main caveat of the model in Eq (1) is that the two predictor variables are not independent.  
455  $\Delta AMOC_{max,60^{\circ}N}$  and  $\Delta SIC_{JJA,NS}$  are correlated with an  $r^2$  of 0.34, significant at the 95% level. It  
456 is indeed very likely that the AMOC anomaly affects winter sea ice both directly, through  
457 oceanic heat transport in winter, and indirectly, by influencing sea ice anomalies during summer  
458 which, in turn, through ocean-sea ice-atmosphere feedbacks, can have a lasting effect on the  
459 winter anomalies. Nevertheless, the AMOC may be affecting the annual sea ice anomalies and,  
460 since sea ice seasonality is model-dependent, adding the summer sea ice as a second predictor  
461 improves the results of the regression analysis. Such a regression could thus allow to explain  
462 some of the spread that can be explained by local sea ice feedback and not only the AMOC  
463 changes.

464 Summer sea ice cover anomalies are actually not entirely determined by the AMOC differences.  
465 As shown in Figure 9, the Mid-Holocene experiences an important positive summer radiative  
466 forcing in the high latitudes and the sensitivity of each model to this forcing is very likely to  
467 have a strong effect on the summer sea ice anomalies. Since Mid-Holocene forcing is seasonal  
468 and unevenly distributed over the globe, classical definitions of climate sensitivity do not apply  
469 and could not be used to directly evaluate the model sensitivity effect on  $\Delta SIC_{JJA,NS}$  and thus  
470 on  $\Delta SIC_{DJF,NS}$ . We have attempted to use different first-order proxies of this effect that would  
471 be less correlated with the AMOC change (such as summer SAT or surface downward  
472 shortwave radiation anomalies over large domains in the Northern Hemisphere) as a  
473 replacement for  $\Delta SIC_{JJA,NS}$  in the regression model above, but with unsatisfactory results in  
474 terms of p values and correlation coefficients.

## 475 **Discussion and conclusions**

476 We have analyzed Mid-Holocene winter anomalies over the North Atlantic sector in 12 PMIP3  
477 models with the purpose of comparing the simulated European winter temperature anomalies  
478 with reconstructed data, and shedding light on their drivers.

479 Comparing the simulated winter near-surface air temperature anomalies with the recent pollen-  
480 based reconstruction of Mauri et al. (2014) for the Mid-Holocene, we found some qualitative  
481 agreement with the paleo-reconstruction for a few models, with pattern correlation coefficients  
482 above 0.6 for 5 out of the 12 models, mostly reflecting a north-south temperature anomaly  
483 gradient over Europe. All models underestimate the amplitude of the winter anomalies,  
484 however, as well as the amplitude of this meridional gradient, compared to the Mauri et al.  
485 (2014) reconstruction. Nevertheless, the uncertainties of this reconstruction do allow for a  
486 weaker gradient as found in the models, so that there is no striking inconsistency between this  
487 reconstruction and the models response to the Mid-Holocene forcing.

488 We have first analyzed the simulated large-scale atmospheric circulation anomalies over the  
489 North Atlantic sector. Our analysis has revealed a consistent climatological winter atmospheric  
490 response in Mid-Holocene consisting of two elements common to all models, though varying  
491 in spatial extent and intensity. The first is a dynamically forced anti-cyclonic anomaly over the  
492 south-western part of the North Atlantic, with a strong barotropic component. This structure is  
493 associated with a local weakening of the jet stream and a more pronounced separation between  
494 the eddy-driven and subtropical jet streams over the North Atlantic sector. The second element  
495 is a positive sea-level pressure anomaly over northern Africa with a shallow baroclinic  
496 structure. This SLP anomaly is a result of the colder atmospheric temperature in response to the  
497 strong negative radiative forcing at low latitudes, the effects of which are amplified over  
498 continental regions. In the same way, a shallow low-pressure anomaly is found in the north of

499 the basin, in thermal balance with positive temperature anomalies. For some models these SLP  
500 anomalies could be interpreted as a NAO<sup>+</sup> signal, although the vertical structure of the NAO is  
501 much more barotropic.

502 While some models exhibit a NAO<sup>+</sup>-like atmospheric circulation anomaly near the surface in  
503 winter, the ensemble of 12 PMIP3 models does not support a link between this type of large-  
504 scale atmospheric response and the MH temperature anomaly patterns over Europe. Instead,  
505 the simulated MH European winter temperature anomaly patterns are, in most models,  
506 determined by the radiatively forced cold anomalies at low latitudes and the more model-  
507 dependent sea ice anomalies over the Nordic Seas, with the latter responsible for approximately  
508 three times more inter-model variability than the former.

509 The analyses carried out to understand the differences in these sea ice anomalies between the  
510 models have revealed multiple footprints of the  $\Delta$ SIC feedbacks onto other fields often  
511 dominating the climatological anomalies in the Nordic Seas region. We have shown here the  
512 signature of these feedbacks on the near-surface air temperature, but similar signatures have  
513 also been found (not shown) on other variables. A very tight collocation between strong  
514 negative (positive) sea ice anomalies and negative (positive) near-surface horizontal wind  
515 divergence anomalies was found in all models for which the latter could be calculated, likely  
516 explained by a response of the near-surface atmospheric circulation to the sea ice anomalies  
517 and to the associated air-sea flux anomalies. A local increase in cloud cover over negative  $\Delta$ SIC  
518 regions (and *vice-versa*) has been found in most models, engendering marked local anomalies  
519 of the downward longwave and shortwave radiative fluxes at the surface (positive and negative  
520 respectively over regions of sea ice loss and *vice-versa*). A strong  $\Delta$ SIC feedback has also been  
521 found on the surface sensible heat flux (SH). In 3 out 12 models this corresponds to a simple  
522 positive response of SH to a positive  $\Delta$ SIC or *vice-versa*. In most models, however, the response  
523 is more complex, taking the form of a strong positive-negative SH dipole over the  $\Delta$ SIC region

524 depending on the background sea ice cover, which shows a subtle interplay of sea surface  
525 temperature and air temperature anomalies in these regions.

526 These ubiquitous sea ice feedback signatures confirm the importance of a correct sea ice  
527 representation in the models for representing the regional climate over Europe. All but three  
528 models show a reduced winter sea ice cover in the Nordic Seas region in Mid-Holocene  
529 compared to the pre-industrial climate. While not allowing for a quantitative model evaluation  
530 of the sea-ice cover anomaly, a recent compilation of multi-proxy reconstructions of Mid-  
531 Holocene  $\Delta$ SIC which expands on the data set used in Klein et al. (2014) (Seidenkrantz, 2015,  
532 personal communication) qualitatively confirms this result. We can thus conclude that the  
533 models simulating an increase in NS winter sea ice cover in the Mid-Holocene, namely  
534 FGOALS-g2, MIROC-ESM and CCSM4, are unrealistic for the Mid-Holocene climate in the  
535 North Atlantic sector.

536 Sea ice feedback signatures dominating the climatological winter anomalies hinder the quest  
537 for the causes of SIC anomalies in the model results. Nevertheless, we were able to highlight a  
538 robust multi-model relationship between the MH winter SIC anomalies in the Nordic Seas  
539 region and the anomalies in the Atlantic meridional overturning circulation, which points to the  
540 AMOC as an important driver of the MH response of European winter temperatures.

541 The MH-PI differences in the atmospheric heat transport due to transient eddies form an  
542 important potential source of information on the drivers of the SIC anomalies. However, these  
543 differences could not be evaluated due to the lack of availability of the corresponding fields in  
544 the PMIP3 data base. This type of drawback will be solved thanks to the inclusion of such fields  
545 in the outputs from future model intercomparison exercises such as the upcoming CMIP6 and  
546 PMIP4.

547 Another potential key player neglected here is the feedback from vegetation changes in the high  
548 latitudes, which could also amplify the pattern found in the MH simulations (Wohlfahrt et al.  
549 2008), potentially bringing the model simulations closer to MH observations.

550 We also know that PMIP3 models systematically underestimate the monsoon anomalies in the  
551 Mid-Holocene (the “Green Sahara” event, Claussen & Gayler 1997). It is plausible that this  
552 event was linked to a northward shift of the Hadley Cell (Claussen and Gayler 1997), which  
553 would therefore not be captured or at best be severely underestimated by the models. We  
554 conjecture that all models underestimate large-scale anomalies in the atmospheric circulation  
555 that may have taken place (Gaetani et al. 2017) and may have affected temperature patterns  
556 over Europe during MH winters. Our study, however, highlights the potential relevance of other  
557 effects, which deserve further study.

558 While previous, paleo-reconstruction-based studies, often attribute Mid-Holocene winter  
559 European temperature anomalies to a NAO<sup>+</sup>-like atmospheric circulation anomaly, our analysis  
560 of PMIP3 models suggests the possibility of an additional or even alternative explanation  
561 coming from a larger geographical context. In this new view, based on the most skillful PMIP3  
562 models, European winter temperature anomaly patterns are determined, to the south, by strong  
563 low-latitude temperature responses to the seasonal negative radiative forcing and to the north  
564 by feedbacks of the negative sea ice anomalies over the Nordic Seas on the atmosphere. Model  
565 simulations also suggest that a major driving force for these sea ice anomalies is an  
566 intensification of the Atlantic meridional overturning circulation in the Mid-Holocene  
567 compared to the modern period, as indirectly suspected in Masson et al. (1999). This is in  
568 agreement with reconstructions based on sortable silt in the North Atlantic, a proxy of deep  
569 water circulation, which indicate a stronger deep current during the MH (Kissel et al. 2013).  
570 The amplitude of the north-south gradient over Europe is weaker in the models than in the  
571 reconstruction. We can suggest that this is related to a general bias of climate models in



572 representing the strong air-sea interaction as recently highlighted by the so-called signal to noise  
573 paradox by Scaife et al. (2018).

574 The cause for the changes in the AMOC has not been analyzed in the present paper since it  
575 necessitates a dedicated study. As noticed before, this could be related to a decrease in sea ice  
576 transport through Fram straight due to a lower sea ice production when insolation is larger in  
577 summer (Born et al. 2010). Another interesting factor could be related to the influence of the  
578 atmospheric circulation on the AMOC. For instance, variability of the AMOC over the last 60  
579 years has been often related to NAO variations (Delworth et al. 2016; Swingedouw et al.  
580 2015a). The mechanism is related to a cooling of the surface Labrador Sea during NAO<sup>+</sup> phases,  
581 which increases the Labrador deep water formation and a few years later the AMOC (Eden and  
582 Willebrand 2001). Thus, if the atmospheric circulation during the MH changed towards a  
583 NAO<sup>+</sup>-like configuration, then it likely amplified the AMOC, as highlighted in Shi and Lohman  
584 (2016) for the ECHAM-FESOM-MPIOM climate model. In our present PMIP3 ensemble, the  
585 NAO changes are not the sole driver, since the relationship between our indices of NAO and  
586 AMOC changes are not significantly correlated (not shown).

587 If this interpretation is correct, it appears that the MH European winter temperatures can be  
588 both a testbed to estimate possible changes of the NAO and the AMOC in the near future. Since,  
589 as we find here, the inter-model differences in MH temperature anomalies are mainly explained  
590 by AMOC changes, we conclude that the MH is indeed an interesting case study to evaluate the  
591 sensitivity of the simulated AMOC to changes in radiative forcing. Nevertheless, to produce a  
592 correct assessment of models, we need to have a finer, quantitative AMOC reconstruction for  
593 this period. The use of a methodology combining climate models and available observational  
594 datasets, as employed for the deglaciation by Ritz et al. (2013) for instance, is an interesting  
595 approach to be developed. This may help to better decipher the sensitivity of the AMOC to

596 different forcings, which may provide new leads to reduce the very large uncertainty (Weaver  
597 et al. 2012) concerning the future of the AMOC.

## 598 **Acknowledgements**

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