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Original Article

On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models

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CMIP5 models have been shown to exhibit rapid cooling events in their projections of the North Atlantic subpolar gyre. Here, we analyze the CMIP6 archive, searching for such rapid cooling events in the new generation of models. Four models out of 35 exhibit such instabilities. The climatic impacts of these events are large on decadal timescales, with a substantial effect on surface temperature over Europe, precipitation pattern in the tropics—most notably the Sahel and Amazon regions—and a possible impact on the mean atmospheric circulation. The mechanisms leading to these events are related to the collapse of deep convection in the subpolar gyre, modifying profoundly the oceanic circulation. Analysis of stratification in the subpolar gyre as compared with observations highlights that the biases of the models explain relatively well the spread in their projections of surface temperature trends: models showing the smallest stratification biases over the recent period also show the weakest warming trends. The models exhibiting abrupt cooling rank among the 11 best models for this stratification indicator, leading to a risk of encountering an abrupt cooling event of up to 36.4%, slightly lower than the 45.5% estimated in CMIP5 models.

Keywords: abrupt climate changes; North Atlantic circulation; subpolar gyre; climatic projections; CMIP6 climate models

Introduction

Paleo records, notably from Greenland ice cores, suggest that the North Atlantic is a region susceptible to large and rapid climatic instabilities on a decadal timescale,[1,2] which might be related to changes in ocean circulation.[3] The subpolar gyre (SPG), located south of Greenland, is a key feature of the large-scale North Atlantic oceanic circulation.[4] It comprises two convection sites, where deep water is formed, in the Labrador and Irminger Seas. In this respect, the SPG is a crucial component of the Atlantic Meridional Overturning Circulation (AMOC), the large-scale oceanic circulation that brings warm water from the tropics toward the high latitudes, transporting a large amount of heat and, therefore, influencing the climate of the North Atlantic.[5] The SPG region has exhibited a cooling trend over the last century,[6] not significant, but opposed to the significant warming seen over the vast majority of the planet. The associated spatial pattern is typically called the *warming hole* in the literature (e.g., Ref. 7), and it raises questions about the processes at play in that region. Recently, Caesar *et al.*[8] proposed that the absence of warming in this region might be related to an ongoing weakening of the AMOC over the last 6–7 decades, also consistent with long-term climatic records.[9–11] Although such a weakening over the historical era has been estimated in the IPCC SROCC report[12] to have "medium confidence," and is still disputed in the observations over the last three decades,[13] it is

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consistent with what climate models suggest in response to increases in greenhouse gas emissions in the 5th Coupled Model Intercomparison Project (CMIP5) over the last century.[12] However, the new generation of models from the 6th phase (CMIP6) do not exhibit in their ensemble mean a significant AMOC weakening trend over the same period.[14–16]

While the risk of an abrupt collapse of the AMOC has been estimated in the SROCC report[12] as "very unlikely" over this century, some CMIP5 models have shown that part of the AMOC system, namely the SPG, could experience a large change in less than a decade.[17] Indeed, the SPG has been recently recognized as a tipping element of the climate system[18–20] that can shift from the current steady state to another one on a far shorter timescale than the AMOC. In this second state, the heat transport toward the SPG might strongly decrease leading to large changes in sea surface temperature (SST) in this region. The climatic impacts of a rapid change in SPG temperature are similar, but far weaker, than that of an AMOC collapse.[17] Rapid changes in the SPG are still suspected of having played a crucial role in rapid climatic change in the North Atlantic of the last glacial period through its coupling with sea ice.[21] In the projections, these impacts might substantially affect temperature trends over, for example, Europe on multidecadal timescales.[22] The risk of encountering such an event has been evaluated as 17.5% when considering all the models from CMIP5 and up to 45.5% when selecting the models that best represent the observed oceanic stratification in the SPG, a key element of ocean circulation and stability in this region. While the models showing such abrupt changes can potentially be considered as outliers of the ensemble, we argue here that accounting for potential rapid changes, even if their probability remains low, is of paramount importance to correctly assess risks related to climatic changes at the regional scale.[23]

The present work provides an analysis of the CMIP6 database to evaluate if, and with what likelihood, the new generation of climate models continues to manifest such a risk.

Materials and methods

We use the CMIP6 database. Because of data accessibility constraints at the time of analysis, we examine the following subset of 35 not fully independent CMIP6 models: ACCESS-ESM1-5, **AWI-CM-1-1-MR**, **BCC-CSM2-MR**, **CAMS-CSM1-0**, **CanESM5**, **CanESM5-Can0E**, **CESM2**, **CESM2-WACM**, **CIESM**, **CNRM-CM6-1**, CNRM-CM6-1-HR, CNRM-ESM2-1, EC-Earth3-Veg, FGOALS-f3-L, FGOALS-g3, FIO-ESM-2-0, GFDL-CM4, **GFDL-ESM4**, GISS-E2-1-G, HadGEM3-GC31-LL, HadGEM3-GC31-MM, **INM-CM4-8**, **INM-CM5-0**, **IPSL-CM6A-LR**, **MCM-UA-1-0**, **MIROC6**, MIROC-ES2L, **MPI-ESM1-2-LR**, MPI-ESM-1-2-HAM, **MRI-ESM2-0**, **NESM3**, **NorESM2-LM**, NorESM2-MM, **UKESM1-0-LL**, TAI-ESM1.

Bold font marks those models for which data availability enabled the whole analysis proposed here, while the lack of three-dimensional data for the ocean prevented the analysis of vertical oceanic stratification in the other models. We thus analyze here 35 CMIP6 models in total, of which 20 are examined for their stratification and SST trends. In order to keep consistency in our results and since for a number of models, only one member was available, we focus in this study on the first member (named *r1i1p1f1* in the database) of each ensemble of simulations.

Following the approach of Sgubin *et al.*,[17] we propose an algorithm to diagnose abrupt cooling events in the SPG. We define SPG as the box 70°W–20°W, 45°N–60°N and focus on the surface atmospheric temperature (SAT) owing to its superior availability compared with SST. The two variables are highly correlated on annual timescale (not shown), so that we assume that the abrupt events found in SAT are also seen in SST.

As in Sgubin *et al.*,[17] our search criterion is based on the difference of two individual years separated by 10 years. For each model configuration, we compute the distribution of these 10-year differences in the 500-year preindustrial control simulation as well as the historical and all available Shared Socio-economic Pathways (SSPs) simulations. We search in the forced simulations for 10-year cooling jumps that exceed three standard deviations of the preindustrial simulation of a given model. Under a Gaussian assumption—which is disputable given the potential nonlinearities of the SPG[4]—this would mean that such events have a chance of less than one in 500 to occur in the associated preindustrial climate. To avoid selecting interannual extreme events that might be due to a volcanic eruption for instance, we then visually inspect the events found, and only select those that show a decadal-scale change in SAT over the SPG. This approach is, therefore, very conservative and avoids false positives, that is, models showing an abrupt, but transient, change due to external forcing or very extreme atmospheric conditions over 1 year only, which are not the target here. Instead, we aim to focus on decadal-scale shifts of the SPG, searching for potential instabilities of the ocean circulation that might affect the climate on a long timescale.

To investigate the climatic impact of the detected events, we analyze surface temperature as well as the CMIP6 variables of precipitation (*pr*) and sea level pressure (*slp*). We also use the CMIP6 oceanic variables of mixed layer depth (*mlotst*), AMOC (*msftmyz*), barotropic streamfunction (*msftbarot*), and three-dimensional temperature (*thetao*) and salinity (*so*), to evaluate the oceanic processes that might explain the abrupt changes found.

As in Sgubin *et al.*,[17] a stratification index, defined as the oceanic density averaged over the SPG region related to its surface value, and given as a function of depth, is used to analyze the representation of stratification in the models. We then compute the root mean square error (RMSE) of this index, averaged over the period 1984–2014, relative to the reference observational dataset EN4,[24] summed over the upper 2000 meters.

Results

Climatic impacts of the abrupt cooling events

Four models show rapid and large decadal-scale cooling events in SAT in the SPG in their climate projections, based on our search criteria (see Methods). These models are MRI-ESM2-0, CESM2, CESM2-WACM, and NorESM-LM. The characteristics of these events are reported in Table S1 (online only). The abrupt cooling events are found in the ssp126 and ssp245 emission scenarios, while none are found in the most extreme scenario, ssp585. This might be related to the large global warming trends that dominates the response to this strong emissions scenario, which might overwhelm the signal of any abrupt cooling trend caused by internal variability. Our criterion is quite conservative in this respect, since the global warming trend in projections opposes the cooling decadal trend we are searching for, while it does not exist in preindustrial control simulations used as baseline. This likely decreases the probability of encountering such an event in the projections "by chance," based only on extreme events from preindustrial simulations. In addition, events in three models are considered as "false positive," since their 10-year jumps remain moderate (<1.5 °C) and the detected events appear more as extreme annual cooling events, or weak instabilities. The events that we consider here as false positive are from the models CNRM-CM6-A-HR and GFDL-ESM4 in the ssp2.6 scenario and GISS-E2-1-G in the ssp8.5 scenario.

Two of the remaining abrupt events found are from models developed in the same institute (CESM and CESM-WACM) and are thus not entirely independent.[25] We, therefore, choose to consider only CESM-WACM and not CESM, the former exhibiting a larger signal. The three individual models used in the rest of the study are thus, namely, CESM-WACM and NorESM-LM in the ssp126 scenario and MRI-ESM in the ssp245 scenario. It should be noted that NorESM-LM uses an atmospheric model from CESM family and is, therefore, not fully independent from CESM-WACM as well. We consider, nevertheless, that overlapping is less important than among the CESM family itself. The time series of SAT for these different simulations are shown in Figure 1, as well as the preindustrial and historical simulations. The abrupt cooling events are clearly visible in this figure, and show long-term reversal of the warming trend in CESM-WACM and MRI-ESM, while in NorESM-LM, we notice several decadal-scale cooling events that recover after about a decade or two. Most of these abrupt events occur in the 2040s, which means they are relatively close to the present day.

To try to identify the decadal-scale climate impact of those events, Figure 2 shows the differences in SAT averaged 20 years after and 20 years before the approximate transition time. This figure clearly highlights that while most of the world is considerably warming, there is a large cooling of the SPG, which also affects the warming trend in the neighboring regions, and can even reverse it in some locations over Greenland and Western Europe. Associated with this large cooling, we also notice a spatially coherent large warming over the Nordic Seas. This dipole pattern is similar among the three simulations (Fig. 2). We also notice a cooling pattern in west Asia, just east of the Caspian Sea in two of the three models, which might be related to an atmospheric teleconnection.

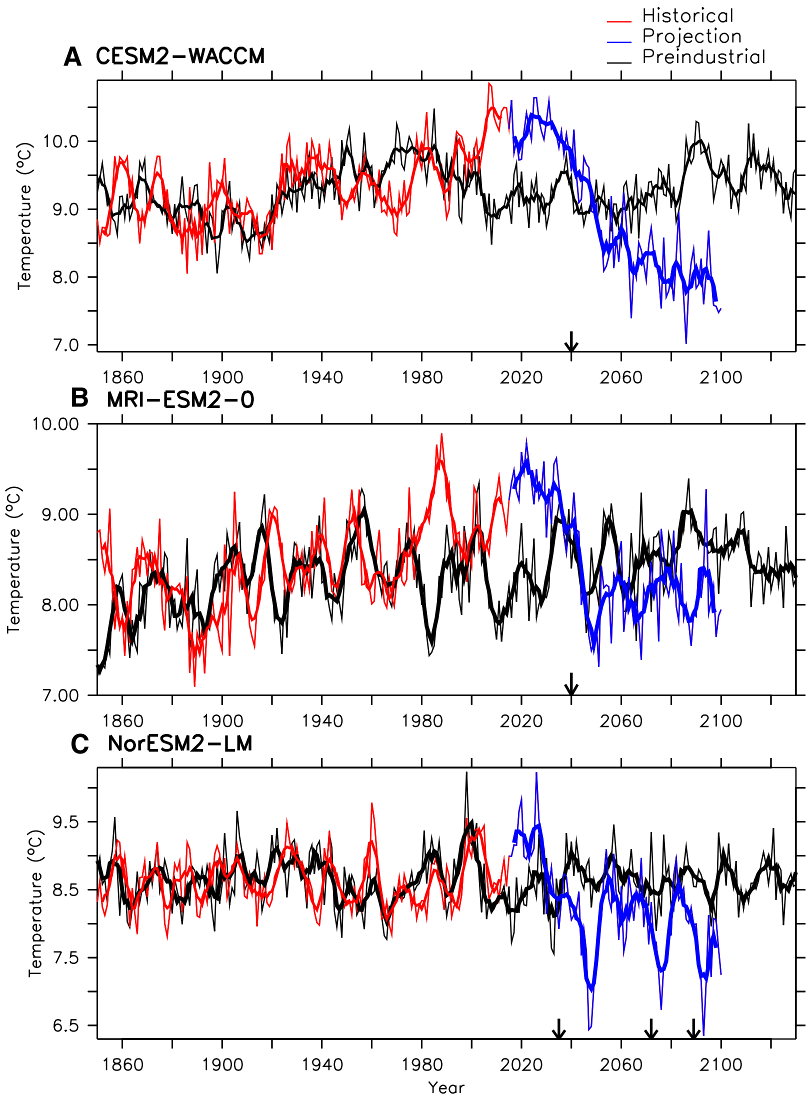

Figure 1. **Examples of abrupt changes found in the subpolar gyre. Time series of surface atmospheric temperature (in °C) averaged over the SPG (70–20°W, 45–60°N) in annual mean (thin line) and 5-year running mean (thick line). In black is the preindustrial simulation, in red the historical simulation, and in blue the projection considered for (A) the CESM2-WACCM model with the ssp126 scenario, (B) the MRI-ESM2-0 model with the ssp245 scenario, and (C) the NorEMS2-LM model with the ssp126 scenario. The black arrows represent the approximate starting of the abrupt events.**

Associated with the changes in SAT, we notice a consistent modification of the sea-level pressure (SLP) in winter in all three simulations with an intensification of the Icelandic Low and of the Azores Anticyclone (Fig. 3B), reminiscent of the positive phase of the North Atlantic Oscillation (NAO). However, compared with the NAO, this SLP pattern is not as meridional and slightly tilted in latitude. Further east, we notice for all three events a coherent high pressure anomaly over Siberia, which could be part of the same wave train. This SLP pressure anomaly, although relatively coherent in the different models, should be considered with caution given the large variability of this field in the models.[26] It corresponds to a northward shift of the jet stream, consistent with the response to a North Atlantic cooling.[27] It might also be related to the large warming found over the Nordic Seas in all

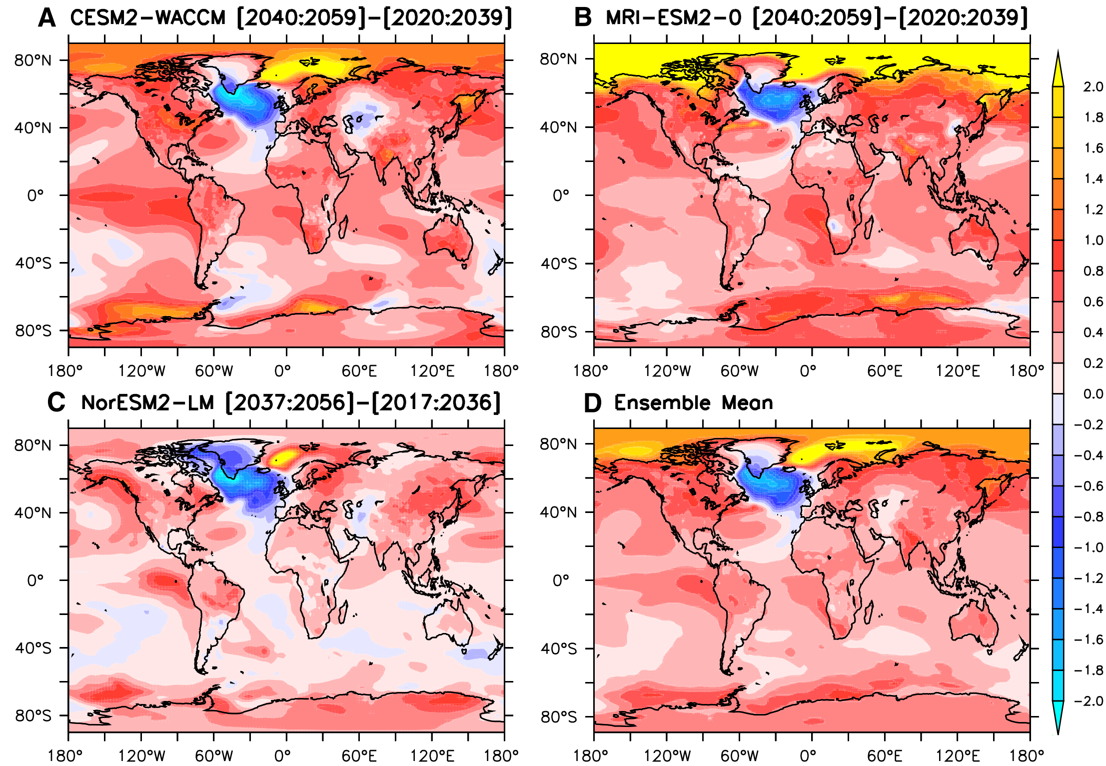

Figure 2. Large-scale impact of the abrupt shift on a 40-year timescale. Differences of atmospheric surface temperature (in °C) for the 20 years following the shift and the 20 years before the shift in the SPG for (A) the CESM2-WACCM model, difference between years 2040–2059 and 2020–2039, (B) the MRI-ESM2-0 model, difference between years 2040–2059 and 2020–2039, (C) the NorESM2-LM model, difference between years 2037–2056 and 2017–2036, and (D) the ensemble mean of panels A to C.

simulations, associated with large retreat in sea ice cover there (not shown), which might have led, in association with the cooling in the SPG, to a strong anomalous temperature gradient. In summer, we notice coherent high pressure over Northern Europe in all three events (Fig. 3A), which might influence heat wave occurrence over Europe, as suggested recently for the 2015 cooling event in the SPG,[28,29] although this remains under debate.[30]

Figure 4 depicts the three-model ensemble mean response to cooling events in terms of precipitation. It shows a relatively clear southward shift of the Intertropical Convergence Zone (ITCZ) over the Atlantic sector for both summer and winter seasons. Such a shift is in line with other studies,[31] and can be explained by a modification of latitudinal temperature gradients in the Atlantic Ocean (Fig. 2), which can modify the Hadley Cell.[31] Over land, the associated climate is dryer in Boreal summer over the Sahel region, and drier over the Amazon region in Austral summer, the respective monsoon seasons. These precipitation changes remain, however, modest (of the order of 1–2 mm/day). Over the other basins, the signal is more noisy and not consistent among the models (not shown).

Oceanic processes at play

Rapid SPG cooling is associated with large changes of the mixed layer depth in that region as illustrated in Figure 5. There is, indeed, a very large decrease of mixed layer depth in the Labrador and Irminger Seas in all three models, which were active convection sites before the shift in those models, as shown by the mean state estimate represented in contours. After the shift, the annual mean mixed layer depth is about halved in amplitude in the western SPG. In the Nordic Seas, on the contrary, we notice a slight deepening of the mixed layer, but of far lower absolute magnitude than in the SPG.

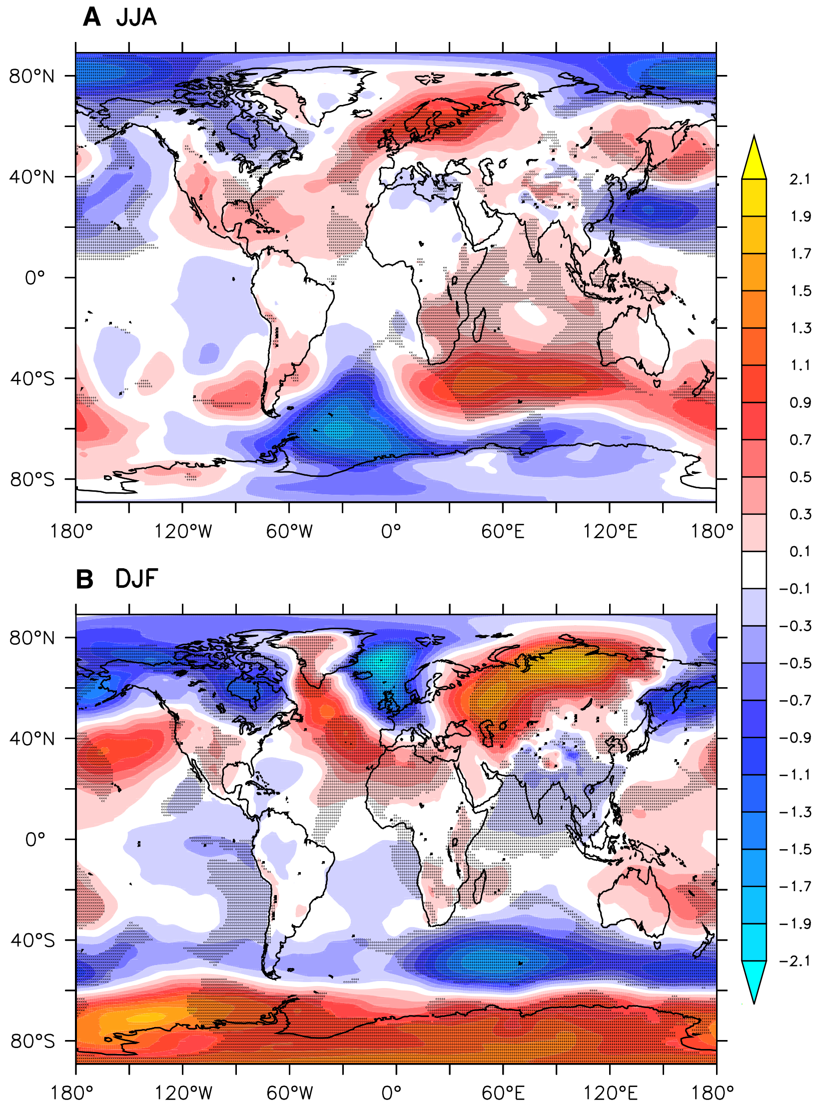

Figure 3. Ensemble means for sea-level pressure (in hPa) similar to Figure 2D showing the differences after and before the abrupt event (A) in JJA and (B) DJF. The stippling indicates the agreement in relation to the three differences averaged.

The changes in mixed layer depth in the SPG are due to a large decrease of the surface density related to salinity (not shown), as also found in CMIP5 models.[17] On the other hand, the surface temperature cooling increases the surface density, forming a negative feedback, but not sufficient to overcome the effect of the salinity decrease. This cooling also weakens the mean evaporation, which, on the other hand, decreases SSS and acts as a positive feedback.[32] Also, the changes in seasonality, with warmer and fresher summers in the SPG due to global warming, might also favor the accumulation of freshwater in the SPG.[33] The temperature decrease is mainly located in the first hundred meters of the SPG (Fig. S1, online only). Below, there is a clear anomalous warming in CESM2-WACM (maximum at 1000 m), which is less pronounced in MRI-ESM and absent in NorESM-LM, where cooling is present throughout the first 2000 meters. In the first two models, the vertical changes in temperature can be interpreted as a decrease in vertical heat mixing, due

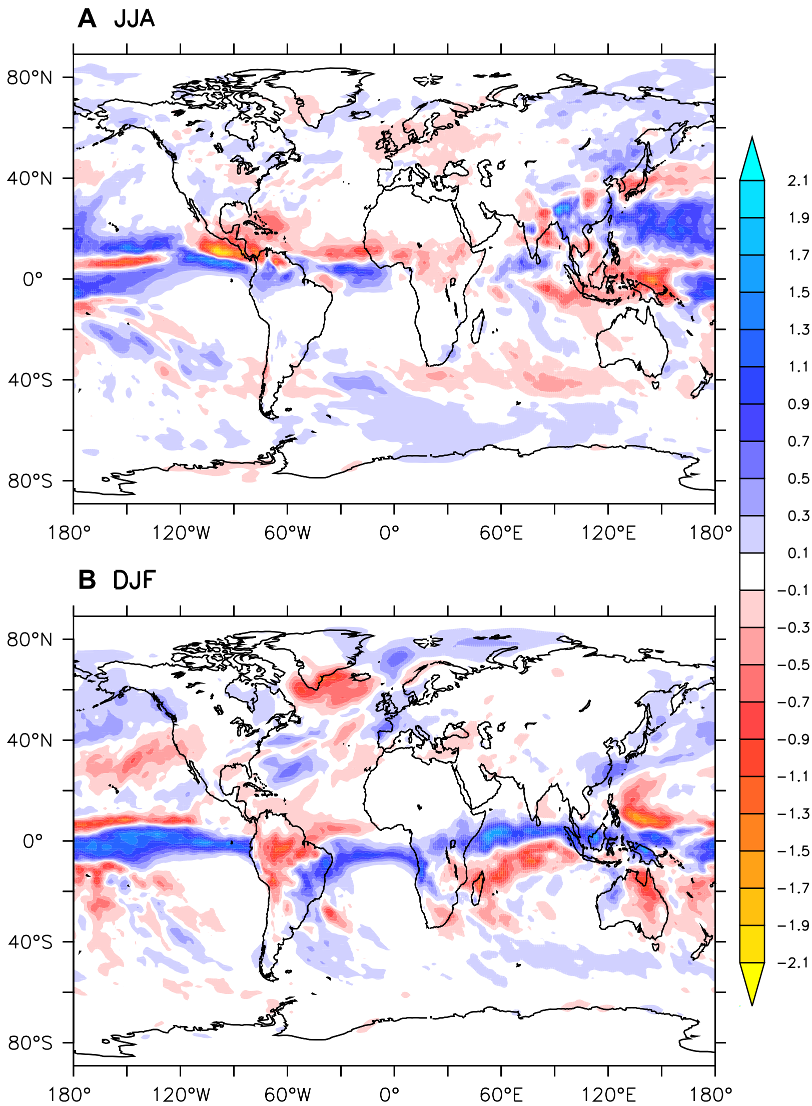

Figure 4. Ensemble means for precipitation changes (in mm/day), following the methodology of Figure 2D, (A) for June–July–August (JJA) and (B) December–January–February (DJF). Note the reversed color bar.

to the collapse of convective activity, and might, in turn, contribute to the cooling of the surface as highlighted for CMIP5 models.[17]

Figure 6 depicts the time evolution of the winter mixed layer depth in the western SPG (60–30°W, 50–60°N), where most of the deep convection occurs in control conditions in all three models. We notice in all the models that just after the cooling, the mixed layer is twice as shallow as the mean state, estimated over 1985–2014. The AMOC is also weakening, but only by about 20% and the decrease seems less abrupt than that of mixed layer depth. This might be due either to the large inertia of this large-scale oceanic circulation, or the increase of mixed layer depth in the Nordic Seas (cf. Fig. 5), which might act to feed the AMOC, through deep water formation, and limit its weakening due to the collapse of convection in the SPG, as suggested in Sgubin *et al.*[17] In the CMIP6 models analyzed, we do not find any model showing an AMOC collapse within 2100, contrary to CMIP5 where two models were exhibiting a larger weakening than 70% of

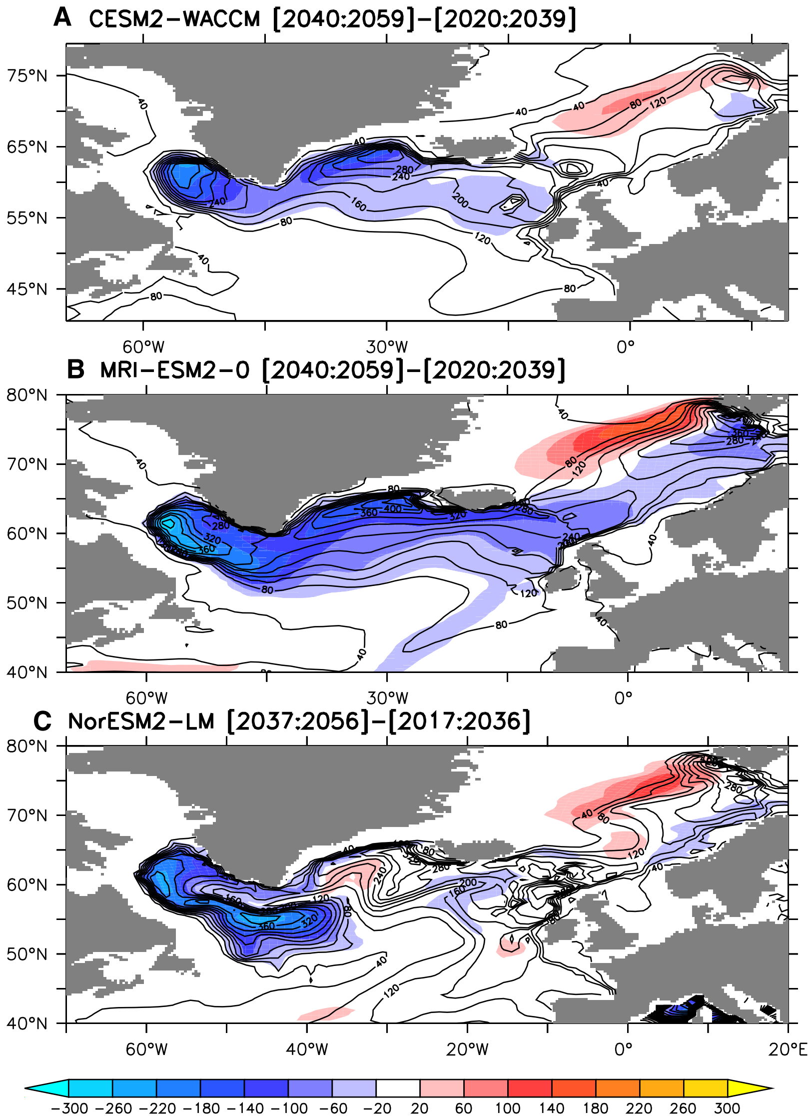

Figure 5. Changes in mixed layer depth in the ocean. The contour represents the mean state of mixed layer depth (MLD, in m) for the period 1985–2014, while the colors indicate the difference after and before the shift (cf. Fig. 2) for (A) the CESM2-WACM model, difference between years 2040–2059 and 2020–2039, (B) the MRI-ESM2-0 model, difference between years 2040–2059 and 2020–2039, and (C) the NorESM2-LM model, difference between years 2037–2056 and 2017–2036.

preindustrial AMOC value. Therefore, unlike what was done in Sgubin *et al.*,[17] we do not distinguish here between models showing only an abrupt SPG collapse, or a whole AMOC collapse, where the Nordic Seas convection is also strongly decreasing in the projections.

The changes in barotropic circulation associated with SPG cooling also exhibit relatively coherent behavior in the three events (Fig. S2, online only), with a weakening of both the Atlantic subtropical gyre and SPG, and a slight increase of the gyre in the Nordic Seas. The subtropical gyre tends to extend a bit further northeastward in the three models, which might feed the Nordic Seas with more tropical waters, and could explain the increase of convection there.[34–37] On the other hand, the weakening of the SPG might decrease the input of tropical water toward the Labrador and Irminger Seas, which can

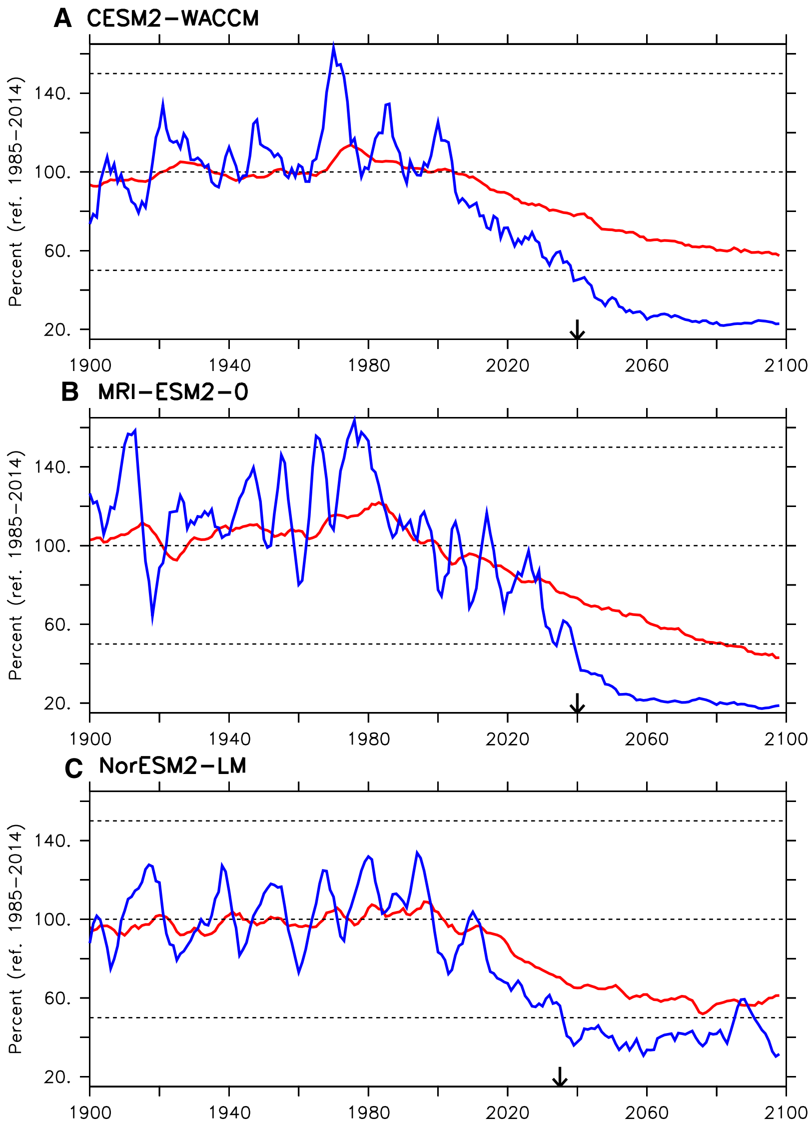

Figure 6. **Variations of the AMOC and MLD. Both variables are expressed as a percentage of the reference period 1985–2014 and are, therefore, expressed as a percentage. The blue line represents the MLD for the months January–February–March, and the red line stands for the maximum of Atlantic Meridional Overturning Circulation taken below 500 m and over all latitudes from 30°S to 80°N. (A) CESM2-WACM model, (B) MRI-ESM2-0 model, and (C) NorESM2-LM model. The black arrows represent the approximate starting of the abrupt events.**

be seen as a positive feedback to the decrease of convection there.[17,18]

To conclude, we find similar oceanic processes in CMIP6 as in CMIP5, which suggest an explanation for the abrupt changes in the subpolar temperature summed up by the following suite of processes, similar to those proposed in Born and Stocker:[19] (1) Salinity gradually decreases in the SPG in projections, through increased precipitation and runoff due to enhanced global hydrological cycle. (2) After reaching a threshold in surface density, convection strongly decreases in the west SPG, which diminishes the import of salty water from the tropics there, through weakening of the SPG, further enhancing the salinity decrease in the SPG convection sites. This constitutes a positive feedback

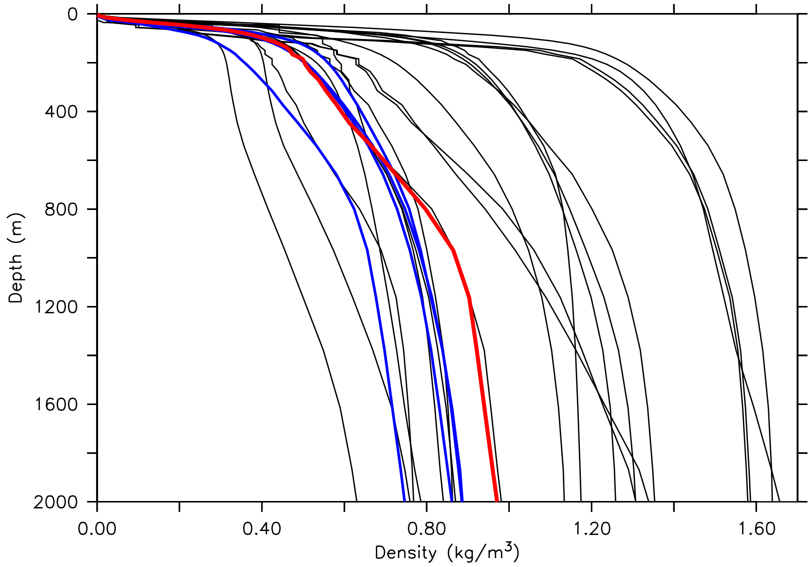

Figure 7. **Stratification in the SPG. Density (with reference to surface level, in kg/m^3) averaged over the SPG in the different models showing abrupt changes (blue lines) or not (black lines). The red lines represent the observations from EN4. All the densities have been averaged over the period 1985–2014 from historical simulations and observations.**

loop. (3) This leads to a collapse of convection in the SPG, a sudden change in vertical heat transport, and a weakening of the SPG as well as of the AMOC. The sum of these different processes leads to the rapid surface cooling observed in those models. The relative strengths of the various processes depicted above are likely model dependent. Differences in the feedback's amplitude among models might explain why only four models exhibit such rapid cooling, while other models only experience slower and smaller amplitude warming hole.

Evaluation of the models in terms of stratification

Following the approach of Sgubin *et al.*,[17] we now evaluate the representation of oceanic vertical stratification in the different models. The idea is to estimate how realistically the few models exhibiting an abrupt event represent this oceanic characteristic notably related to convection and water mass transformation.[38] We also evaluate whether this variable can help explain the difference in SAT trends over the SPG in the various CMIP6 models analyzed (cf. Methods). Stratification is a key variable for the dynamics of oceanic currents since it controls the occurrence of convective events, but also the depth of the mean upper flow, the vertical exchange of heat with the deeper ocean, the baroclinicity, and therefore, the strength and shape of the gyre through the Joint Effect of Baroclinicity and Relief (JEBAR).[39]

The mean density profile averaged over the SPG area for the period 1985–2014 is shown in Figure 7 for the models that provided enough data at the time of the analysis. Twenty models allowed this, highlighting the wide range of mean stratification in the SPG within CMIP6 models. Most of the models show a stronger stratification than observed, while the four abrupt models show a slightly lower stratification. This is intuitively consistent with the fact that the latter may be more unstable, while most of the other models might be already in a weakened, stratified, state, highlighted by such a strong stratification bias. The RMSE between modeled and observed stratification averaged over the SPG region from 0 to 2000 m represents the capacity of a given model to accurately represent observed stratification. Following Sgubin *et al.*,[17] we plot this metric as a function of the trend of the SPG in terms of SAT for the whole period of the considered projections (2015–2100) (Fig. 8). We are thus also considering here the long-term fate of the SPG, and not only the occurrence of abrupt events. Nonetheless, this diagnostic allows us to evaluate the quality

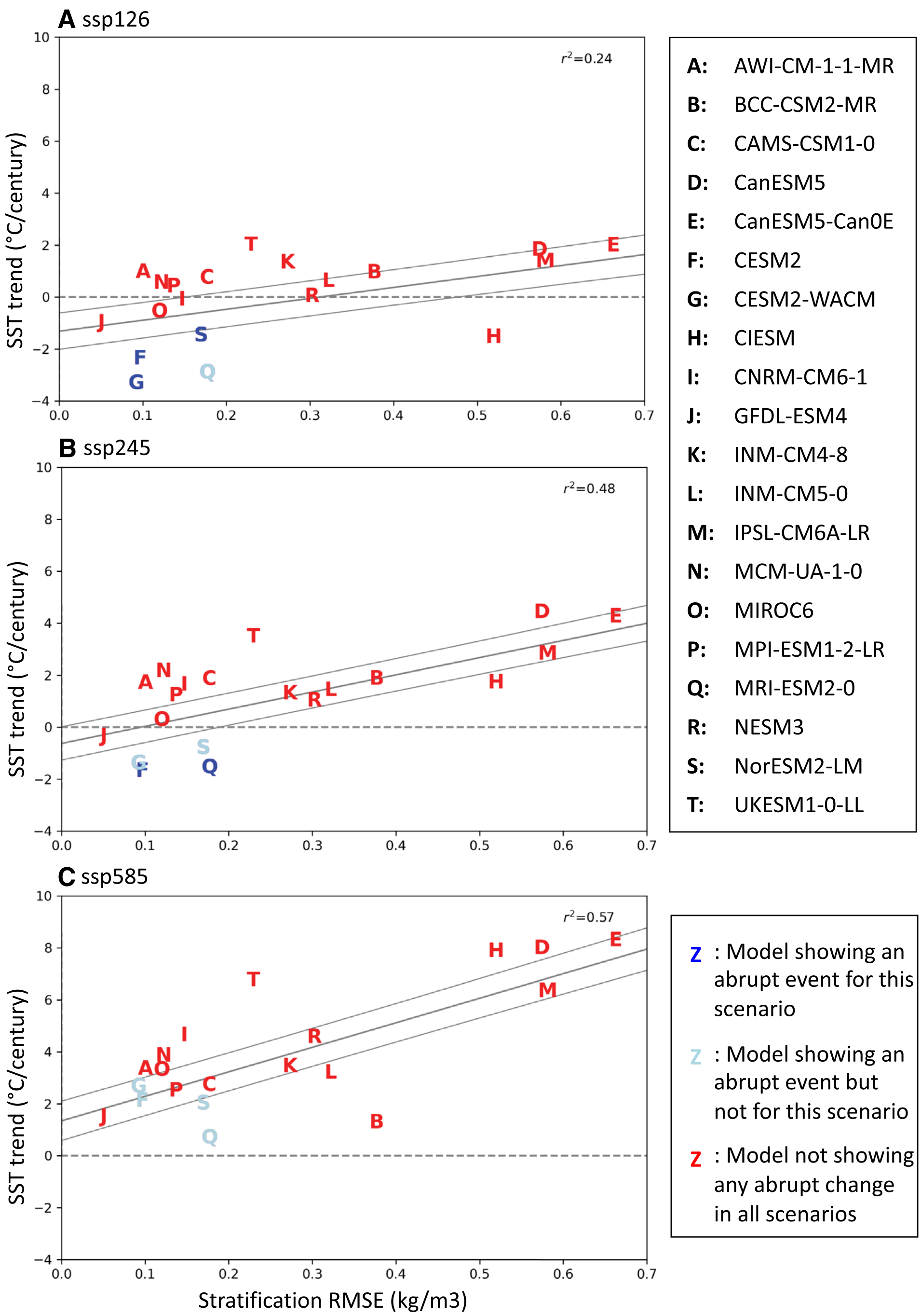

Figure 8. Link between stratification and centennial temperature trend over the SPG. Scatterplot of the root mean square error of the density in the SPG as compared with the observation depicted in Figure 7, for the period 1985–2014, averaged over the first 2000 m of the ocean versus the linear trend of surface atmosphereic air temperature (in °C/century) computed in different emission scenarios: (A) ssp126, (B) ssp245, and (C) ssp585. The letters correspond to the models enumerated in the Method section in their alphabetical order. The red letters corresponds to a model showing no abrupt changes, while the blue letters indicate a model showing an abrupt event for the considered scenario; it is in light blue letters when it is not occurring in this particular scenario, but still corresponds to a model that does show abrupt changes for other emission scenarios.

of the models showing an abrupt change in terms of stratification.

Figure 8 shows that the stratification RMSE commonly explains a large amount of the spread in SPG temperature trends among the models, with a maximum of 57% of variance explained for the ssp585 emission scenario. All correlations computed between the two variables defining the scatterplots are significantly different from zero at the 95% level. Thus, the stratification RMSE appears to be a significant explaining factor for the spread of SPG temperature trends within the 20 models considered and can, therefore, be considered an emergent constraint,[40] useful to reduce the uncertainty in the projections in this region. We notice that the four models exhibiting an abrupt cooling events are among the 11 best models. We, therefore, estimate that the risk of encountering an abrupt event is up to 36.4% among these 11 models. Nevertheless, for a given emission scenario, this risk is estimated with a lower likelihood, because all the models do not exhibit such an abrupt change in all scenarios. For instance, it is of 27% in ssp126, and abrupt changes in the SPG are not found in ssp585 (cf. Fig. 8). Thus, the 36.4% estimate is an upper end for the risk assessed from available models for this particular emergent observational constraint.

Discussion and conclusions

To estimate the risk of abrupt changes in the North Atlantic in the new CMIP6 database, we have analyzed 35 CMIP6 models. We have searched for 10-year cooling events in their projections that are three times larger than the standard deviation in preindustrial control experiments and last for a few years, which can, therefore, be considered as very extreme changes. We have found four models that exhibit such large and abrupt cooling events, reminiscent of a tipping point[41] in this region. The climate impact of such events, diagnosed through a comparison of the 20 years before and after the shift, can temporarily neutralize the warming trend or even reverse it in the neighboring regions of the SPG, for the ssp126 and ssp245 emission scenarios. No event is found in the most extreme scenario ssp585, possibly because it is obscured by the very large global warming trend due to radiative forcing occurring in this emission scenario. The analysis of the processes at play shows that the collapse of convection in the SPG, leading to changes in ocean circulation and associated heat convergence, as well as a rapid decrease in vertical heat exchange in the ocean, might altogether explain these rapid cooling events. We then explored the skill of the CMIP6 models to represent the stratification in the SPG, a key factor in deep convection and, therefore, shaping the large-scale oceanic circulation. Most of the analyzed CMIP6 models show stronger-than-observed stratification over the period 1985–2014. We highlight that the biases in stratification explain a large amount of the spread among the models' long-term temperature trends over the SPG. The four models that show an abrupt cooling event are among the 11 best models in terms of stratification. From this observational constraint, we propose an upper range of the risk of abrupt cooling of the SPG of 36.4%, similar to the 45.5% estimate found in CMIP5 models. In CMIP6, the total number of models showing such an abrupt change is of four compared with nine in CMIP5, but all of them rank among the best models in terms of stratification, which was not the case in CMIP5. We thus conclude that the risk estimated in CMIP6 models seems to be a bit lower than in CMIP5, but is still quite important.

There are a number of caveats in the present study that imply further work on this topic in the near future is warranted. First, precise understanding of the processes at play is still incomplete and might necessitate dedicated sensitivity studies to correctly quantify and attribute the exact impacts of the different processes highlighted here. Such sensitivity studies might notably also help to understand why some CMIP models do not exhibit such rapid cooling events, while others do. Possible hypotheses are that in those other models, one of the processes (e.g., the oceanic vertical heat exchange) is smaller in amplitude or longevity or, alternatively, that the positive salinity advection feedback is smaller than in the models exhibiting abrupt cooling events.

In this study, we have focused on the SPG rather than on the larger-scale AMOC, albeit using climate models that may be suboptimal in representing the important processes, and their linkages, in the SPG.[42,43] However, recent work has highlighted that climate models are *a priori* able to broadly represent the dense water formation occurring in the SPG, and most notably in the Irminger Sea.[44] Nonetheless, our knowledge of the link between the

SPG and AMOC on decadal or longer timescales remains largely indirect.[9]

Concerning the climatic impacts of these abrupt cooling events, we found low statistical robustness, notably with reference to atmospheric circulation changes, given the large noise in CMIP6 models.[26] Idealized simulations, including the abrupt cooling as well as the large warming in the Nordic Seas, could be very useful in deciphering the exact impacts of these changes in North Atlantic surface temperature. Furthermore, such a dipole of temperature trend can be found in most of the analyzed models' projections, even when no abrupt change occurs, and is related with the combination of the warming hole in the SPG and large warming in the Nordic Seas due to sea ice retreat. Such sensitivity simulations would be reminiscent of those proposed in CMIP6-DCPP-C2,[45] although those are only considering the subpolar cooling and not the Nordic Seas warming. Indeed, this dipole of opposite sign can lead to very strong temperature gradient changes in the projections of up to almost 10 °C between the SPG and the Nordic Seas, which might strongly affect jet stream shifts, for instance. It thus deserves further attention.

Only one model family falls in the set of models showing abrupt changes in both CMIP5[17] and CMIP6. That is, the CESM family from NCAR. A former version of the same institute also exhibited similar instabilities.[46] Some models developed by GISS and GFDL were identified in the CMIP5 study but considered as false positives here in CMIP6. This, nevertheless, suggests that these two genealogies of models might be relatively unstable. Finally, NorESM1-M and MRI-GCM3 were not identified as unstable in CMIP5. All of this possibly highlights that the unstable behavior found here remains a very subtle balance of different ingredients, which are not straightforward to identify, necessitating dedicated studies to gain insight into the changes of behavior of different climate models in the SPG from CMIP5 to CMIP6. Also, as highlighted in a number of studies,[46,47] some climate models initiated instabilities without any external forcing, only through internal extreme variability related to ocean–sea ice–atmosphere interaction, as it is also suspected for recorded glacial time instabilities.[21] Stochastic atmospheric forcing can, therefore, play a crucial role in the development of those abrupt changes, which are then nurtured through ocean–sea ice–atmosphere positive feedback. It is, therefore, possible that some instabilities might be found in other members from some of the models analyzed here that do not exhibit instabilities in their member r1i1p1f1.

CMIP6 models are still of relatively coarse resolution and missing a number of crucial processes for the North Atlantic, including the melting of Greenland ice sheet[48] or the impact of eddies on circulation and heat and salinity exchanges, the representation of overflows, mixing processes, and so on.[39] In that respect, there is still considerable uncertainty concerning the reliability of what is simulated in the abrupt models found here, as well as in the others. For instance, it is clear that the gyre dynamics is simplified,[49] notably due to poor representation of the topography, which is crucial for the vorticity budget.[39] Also, the impact of eddies and low viscosity in higher resolution models might strongly modify the stratification structure, and diffusion properties of the ocean as compared with low-resolution models.[50] A recent study,[44] however, showed no impact of medium change in resolution (eddy permitting) on the representation of overturning variability in the SPG. According to another studies,[18] eddies might be a crucial component in the positive salinity transport feedback related to the strength of the SPG. Thus, given the potential importance of this process for the collapse of convection in the western SPG, it is possible that higher resolution models might show stronger instability potential than lower resolution ones and most notably the models with a resolution offering eddy-rich ocean (i.e., resolution lower than 0.1°).[50]

In summary, it is still relatively unclear whether present-day climate models are able to correctly represent the potential instabilities of the SPG. What is clear from this study is that a large spread in behavior can be found among CMIP6 models. Nonetheless, this work sheds light on potential instabilities of the North Atlantic—not only related to AMOC collapse but also simply to SPG changes—which can strongly shape the fate of climate changes in this region, as well as remotely through teleconnections.

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Supporting information

Additional supporting information may be found in the online version of this article.

Table S1. Models exhibiting abrupt changes in the SPG.

Figure S1. Hovmöller diagram of temperature change in the SPG.

Figure S2. Barotropic stream function changes.

Competing interests

The authors declare no competing interests.

References

1. Masson-Delmotte, V. *et al.* 2012. Greenland climate change: from the past to the future. *Wiley Interdiscip. Rev.-Clim. Change* **3:** 427–449.
2. Steffensen, J.P. *et al.* 2008. High-resolution Greenland ice core data show abrupt climate change happens in few years. *Science* **321:** 680–684.
3. Rahmstorf, S. 2002. Ocean circulation and climate during the past 120,000 years. *Nature* **419:** 207–214.
4. Born, A., T.F. Stocker, C.C. Raible & A. Levermann. 2013. Is the Atlantic subpolar gyre bistable in comprehensive coupled climate models? *Clim. Dyn.* **40:** 2993–3007.
5. Buckley, M.W. & J. Marshall. 2016. Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: a review. *Rev. Geophys.* **54:** 5–63.
6. IPCC. Summary for policymakers. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker *et al.*, Eds.: 1–30. Cambridge University Press; 2013.
7. Menary, M.B. & R.A. Wood. 2018. An anatomy of the projected North Atlantic warming hole in CMIP5 models. *Clim. Dyn.* **50:** 3063–3080.
8. Caesar, L., S. Rahmstorf, A. Robinson, *et al.* 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556:** 191–196.
9. Caesar, L., G.D. McCarthy, D.J.R. Thornalley, *et al.* 2021. Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nat. Geosci.* **14:** 118–120.
10. Rahmstorf, S. *et al.* 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nat. Clim. Change* **5:** 475–480.
11. Thornalley, D.J.R. *et al.* 2018. Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature* **556:** 227–230.
12. Collins, M. *et al.* 2019. IPCC special report on the ocean and cryosphere in a changing climate. Chapter 6: Extremes, abrupt changes and managing risks.
13. Worthington, E.L. *et al.* 2021. A 30-year reconstruction of the Atlantic Meridional Overturning Circulation shows no decline. *Ocean Sci.* **17:** 285–299.
14. Lobelle, D., C. Beaulieu, V. Livina, *et al.* 2020. Detectability of an AMOC decline in current and projected climate changes. *Geophys. Res. Lett.* **47:** e2020GL089974.
15. Menary, M.B. *et al.* 2020. Aerosol-forced AMOC changes in CMIP6 historical simulations. *Geophys. Res. Lett.* **47:** e2020GL088166.
16. Weijer, W., W. Cheng, O.A. Garuba, *et al.* 2020. CMIP6 models predict significant 21st century decline of the Atlantic Meridional Overturning Circulation. *Geophys. Res. Lett.* **47:** e2019GL086075.
17. Sgubin, G., D. Swingedouw, S. Drijfhout, *et al.* 2017. Abrupt cooling over the North Atlantic in modern climate models. *Nat. Commun.* **8:** 14375.
18. Born, A., T.F. Stocker & A.B. Sando. 2016. Transport of salt and freshwater in the Atlantic subpolar gyre. *Ocean Dyn.* **66:** 1051–1064.
19. Born, A. & T.F. Stocker. 2014. Two stable equilibria of the Atlantic subpolar gyre. *J. Phys. Oceanogr.* **44:** 246–264.
20. Swingedouw, D. *et al.* 2020. Early warning from space for a few key tipping points in physical, biological, and social-ecological systems. *Surv. Geophys.* **41:** 1237–1284.
21. Li, C. & A. Born. 2019. Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events. *Quat. Sci. Rev.* **203:** 1–20.
22. Sgubin, G., D. Swingedouw, I. García de Cortázar-Atauri, *et al.* 2019. The impact of possible decadal-scale cold waves on viticulture over Europe in a context of global warming. *Agronomy* **9:** 397.
23. Sutton, R.T. 2018. ESD ideas: a simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks. *Earth Syst. Dyn.* **9:** 1155–1158.
24. Good, S.A., M.J. Martin & N.A. Rayner. 2013. EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *J. Geophys. Res. Oceans* **118:** 6704–6716.
25. Knutti, R., D. Masson & A. Gettelman. 2013. Climate model genealogy: generation CMIP5 and how we got there. *Geophys. Res. Lett.* **40:** 1194–1199.
26. Smith, D.M. *et al.* 2020. North Atlantic climate far more predictable than models imply. *Nature* **583:** 796–800.
27. Jackson, L.C. *et al.* 2015. Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Clim. Dyn.* **45:** 3299–3316.
28. Duchez, A. *et al.* 2016. Potential for seasonal prediction of Atlantic sea surface temperatures using the RAPID array at 26N. *Clim. Dyn.* **46:** 3351–3370.

29. Mecking, J.V., S.S. Drijfhout, J.J.-M. Hirschi & A.T. Blaker. 2019. Ocean and atmosphere influence on the 2015 European heatwave. *Environ. Res. Lett.* **14:** 114035.
30. Borchert, L.F. *et al.* 2019. Decadal predictions of the probability of occurrence for warm summer temperature extremes. *Geophys. Res. Lett.* **46:** 14,042–14,051.
31. Dunstone, N.J., D.M. Smith & R. Eade. 2011. Multi-year predictability of the tropical Atlantic atmosphere driven by the high latitude North Atlantic Ocean. *Geophys. Res. Lett.* **6:** 38. https://doi.org/10.1029/2011GL047949.
32. Rind, D. *et al.* 2018. Multicentury instability of the Atlantic Meridional Circulation in rapid warming simulations with GISS ModelE2. *J. Geophys. Res. Atmos.* **123:** 6331–6355.
33. Oltmanns, M., Karstensen, J. & J. Fischer. 2018. Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers. *Nat. Clim. Change* **8:** 300–304.
34. Swingedouw, D. *et al.* 2013. Decadal fingerprints of freshwater discharge around Greenland in a multi-model ensemble. *Clim. Dyn.* **41:** 695–720.
35. Wood, R.A., A.B. Keen, J.F.B. Mitchell & J.M. Gregory. 1999. Changing spatial structure of the thermohaline circulation in response to atmospheric CO2 forcing in a climate model. *Nature* **399:** 572–575.
36. Swingedouw, D., P. Braconnot & O. Marti. 2006. Sensitivity of the Atlantic Meridional Overturning Circulation to the melting from northern glaciers in climate change experiments. *Geophys. Res. Lett.* **33:** https://doi.org/10.1029/2006GL025765.
37. Swingedouw, D., P. Braconnot, P. Delecluse, *et al.* 2007. Quantifying the AMOC feedbacks during a 2×CO2 stabilization experiment with land-ice melting. *Clim. Dyn.* **29:** 521–534.
38. Swingedouw, D., P. Braconnot, P. Delecluse, *et al.* 2007. The impact of global freshwater forcing on the thermohaline circulation: adjustment of North Atlantic convection sites in a CGCM. *Clim. Dyn.* **28:** 291–305.
39. Le Corre, M., J. Gula & A.-M. Tréguier. 2020. Barotropic vorticity balance of the North Atlantic subpolar gyre in an eddy-resolving model. *Ocean Sci.* **16:** 451–468.
40. Hall, A., P. Cox, C. Huntingford & S. Klein. 2019. Progressing emergent constraints on future climate change. *Nat. Clim. Change* **9:** 269–278.
41. Lenton, T.M. *et al.* 2008. Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. USA* **105:** 1786–1793.
42. Li, F. *et al.* 2019. Local and downstream relationships between Labrador Sea water volume and North Atlantic Meridional Overturning Circulation variability. *J. Clim.* **32:** 3883–3898.
43. Lozier, M.S. *et al.* 2019. A sea change in our view of overturning in the subpolar North Atlantic. *Science* **363:** 516–521.
44. Menary, M.B., L.C. Jackson & M.S. Lozier. 2020. Reconciling the relationship between the AMOC and Labrador Sea in OSNAP observations and climate models. *Geophys. Res. Lett.* **47:** e2020GL089793.
45. Boer, G.J. *et al.* 2016. The Decadal Climate Prediction Project (DCPP) contribution to CMIP6. *Geosci. Model Dev.* **9:** 3751–3777.
46. Kleppin, H., M. Jochum, B. Otto-Bliesner, *et al.* 2015. Stochastic atmospheric forcing as a cause of Greenland climate transitions. *J. Clim.* **28:** 7741–7763.
47. Drijfhout, S., E. Gleeson, H.A. Dijkstra & V. Livina. 2013. Spontaneous abrupt climate change due to an atmospheric blocking-sea-ice-ocean feedback in an unforced climate model simulation. *Proc. Natl. Acad. Sci. USA* **110:** 19713–19718.
48. Bakker, P. *et al.* 2016. Fate of the Atlantic Meridional Overturning Circulation: strong decline under continued warming and Greenland melting: AMOC projections for warming and GIS melt. *Geophys. Res. Lett.* **43:** 12,252–12,260.
49. Koul, V. *et al.* 2020. Unraveling the choice of the north Atlantic subpolar gyre index. *Sci. Rep.* **10:** 1005.
50. Hirschi, J.J.-M. *et al.* 2020. The Atlantic Meridional Overturning Circulation in high-resolution models. *J. Geophys. Res. Oceans* **125:** e2019JC015522.