Oceanic and climatic impacts of freshwater release over the last few decades

Icebergs at Cape Farewell (Greenland) during the 2010 OVIDE cruise. Credits: Pascale Lherminier (IFREMER/LOPS)

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Summary for publication

The Greenland ice sheet has been melting at an increasing rate for the last few decades. Large rates of melting have also been reported to have occurred in the 1920s, due to a warming of the region during this decade. Recent reconstructions of the ocean circulation in the North Atlantic have suggested that the large-scale overturning circulation might have been reduced over the last century, possibly due to the freshwater released by Greenland ice sheet melting. To evaluate this hypothesis, we have conducted a series of ocean-only and fully-coupled climate simulations where we include or exclude the observed melting of Greenland ice sheet, which is usually neglected in climate simulations of the last century.

Based on a recent estimate of the Greenland ice sheet melting, we have constructed a forcing melting field for the ~100 km resolution IPSL-CM6A-LR climate model (including ocean, atmosphere land and sea ice), and also for a ~2-3 km NEMO regional coupled sea ice-ocean model. The use of two different resolutions for the ocean allows us to evaluate the importance of small-scale oceanic processes for the impact of the Greenland ice sheet melting. We have then integrated these two types of models over two different time periods: 1920-2014 for the climate model, with 10 different members to account for the potential role of intrinsic variability of the climate, and 2004-2017 for the high-resolution ocean-only model, due to its high cost in terms of computing time. We have considered two types of simulations: one where the freshwater release from Greenland ice sheet is computed within the climate model (through a basic freshwater closure) and the other where we apply time-varying observation-based estimates.

The main results highlight several crucial insights. First, the climate model simulations show that the observation-based melting of Greenland ice sheet, even if it has a modest amplitude, does have a significant impact on the state of the North Atlantic, and even induces a slight reduction of the large-scale ocean overturning (by around 0.5 Sv or 2-3%) over the last century. However, such an impact is far lower than the suspected 15% weakening of this circulation by a recent observation-based estimate. It is found in the different members of the ensemble, that intrinsic variability could explain a large part of this observation-based weakening but not the totality. This discrepancy with the observation-based estimate of the weakening may be related to (i) the fact that this estimate of overturning weakening is indirect and therefore subject to a large uncertainty, or, (ii) the fact that the climate models may be missing important processes.

The use of the high-resolution ocean model can help to evaluate the hypothesis (ii). The few years of high-resolution ocean simulation indicate that the spread of fresh water from Greenland towards the center of the Labrador Sea, where oceanic convection occurs, is larger at high than low resolution, due to small-scale processes that increase the lateral exchanges. The larger freshening of the Labrador in the high-resolution model may then limit deep convection, and weaken the oceanic circulation. Thus, the estimate of ~0.5 Sv of weakening in the low-resolution climate model might be a low estimate of the weakening of the Atlantic overturning circulation, which could be larger when the small-scale processes are included. To conclude, based on the climate model simulations analysed here, the observation-based estimate of the weakening of the ocean circulation is more likely due to natural variability than to anthropogenic forcing, but limitations in climate models still preclude high confidence in this result.

Finally, we have estimated the impact that Greenland ice sheet melting may have on the decadal variability of the sea surface temperature in the North Atlantic. Indeed, the melting is also varying in

time, which might have an impact on decadal-scale variation of ocean temperature and therefore the associated potential predictability. We have found that the large warming that was observed in the mid-1990s can be explained to a large extent by the Greenland ice sheet melting. This is a very new result, that will deserve further investigations to have a good understanding of the processes at play, which will be the topic of the last year of the research led within the project.

Work carried out

Adaptation of observed melting for use in ocean models

CNRS-EPOC used the reconstruction of Greenland ice sheet melting from Bamber et al. (2018) who provided observation-based freshwater release in the vicinity of Greenland during the period 1958-2016. It combines high spatial and temporal resolution satellite observations of solid ice discharge and outputs of surface tundra and ice runoff from a regional climate model. The monthly fluxes were redistributed on the ORCA1.2 mesh grid using a conservative nearest neighbour algorithm.

The runoff terms from Bamber et al. (2018) are thus provided with a spatial distribution. The solid ice discharge, related with the icebergs is not. To circumvent this issue, we have adopted a simple approach: we multiplied the time series of the spatially averaged solid ice discharge proposed by Bamber et al. (2018) by the observation-based spatial climatological distribution of icebergs from the Altiberg project (Tournadre, 2017). This parameterisation of the iceberg fluxes is thus not accounting for the actual drifting of the icebergs, which would necessitate the use of an iceberg module as done by Gilles Garric at MERCATOR-Ocean, who also contributes to the design of this freshwater forcing. Nevertheless, such an approach could only be done over the recent period, when remote sensing was tracking the icebergs, and thus not before the 1990s, which is why we have adopted this "climatological mean" approach.

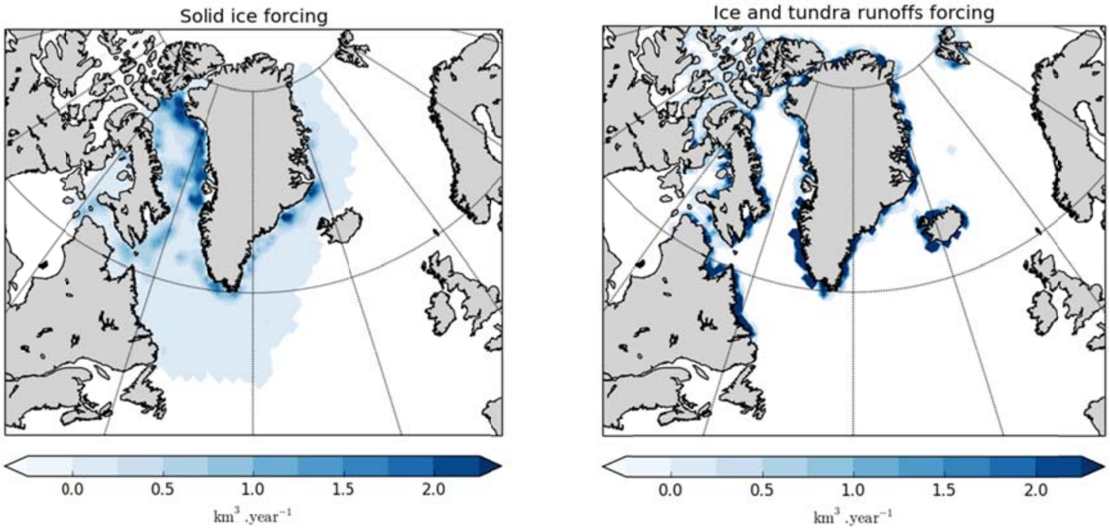

Figure 1: Time averaged (1920-2014) spatial distribution of icebergs (left) and runoff (right freshwater fluxes that are imposed in the melting simulations.

To account for the large melting event in the 1920s, we extrapolated, through linear regression, the fluxes several decades back in the past, using the yearly estimation of Greenland ice loss from (Box and Colgan, 2013) that goes back to 1840. The two reconstructions agree relatively well over their common period, although Box and Colgan (2013) underestimate the amplitude of interannual to decadal variations. We transformed the fluxes into monthly means, using a scaling based on the value of a given year and the seasonal climatology of Bamber et al. (2018). The final spatial distribution of the fluxes (icebergs and runoffs) averaged over the experimental period 1920-2014 is presented in Figure 1. Also, the reconstructed fluxes for different components of freshwater release, available for the period 1840 to 2016, is shown in Figure 2.

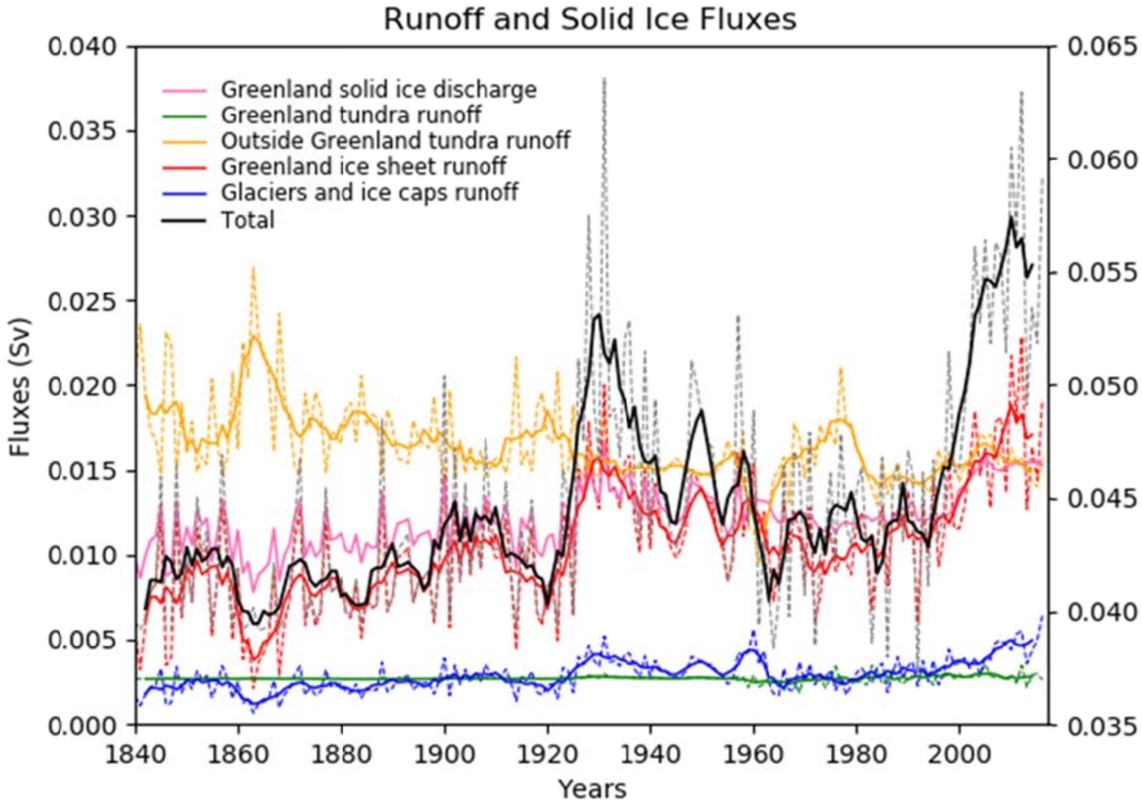

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Figure 2: Extended annual freshwater fluxes of Bamber et al. (2018) based on linear regression using Box and Colgan (2013) estimates. Solid lines are 5-years moving averages, dashed lines are the mean annual values. The total flux from all sources is shown by the solid black line plotted against the right-hand Y axis.

Finally, the freshwater fluxes have been interpolated also on the high-resolution grid (1/24°) of the regional model of the North Atlantic-Arctic domain based on NEMO 3.6. These fluxes can thus be used as forcing dataset for high-resolution simulations using this model, to better account for the freshwater fluxes that may be crucial for the fate of oceanic variations.

Development of historical climate simulations including Greenland ice sheet melting

Using the estimates of Greenland freshwater release described above, an ensemble of 10 climate simulations have been performed over the period 1920-2014. These simulations are based on the IPSL-CM6A-LR ocean-atmosphere coupled model. This model is the new version of the IPSL model, using a resolution of about 1° in the ocean (NEMO model version ORCA3.6 with 75 vertical levels) and 1.25 x 2.5° (latitude-longitude) in the atmosphere (with 79 vertical levels).

The historical simulations include observed external forcing from 1850 coming from anthropogenic emissions and natural forcing (volcanic eruptions, solar variations), as well as changes in the land-use. They do not properly include the effect of the Greenland ice sheet melting because the closure of the freshwater budget in climate models is complex and land-ice dynamics is very poorly resolved and not correctly representing the on-going large melting of Greenland ice sheet. The different members are starting from different initial conditions obtained from a preindustrial simulation, in order to sample internal variability. These different historical simulations are part of the IPSL contribution to CMIP6. Here, we use the same starting date as 10 of the 32 available historical simulations to start our simulations including observed melting from 1920 (called Melt ensemble in the following).

In practice, the runoff values coming from the atmospheric component of the climate model are overwritten in the ocean component NEMO with the average values presented in Figure 1 and spread over the locations shown in blue Figure 2 (top). Elsewhere coupled model runoff fluxes are used. No global rebalancing is applied, as Greenland ice sheet melting is a net input of water in the ocean coming from the ice sheet reservoir. As shown in bottom Figure 3, the runoff from our forcing zone in the Melting ensemble (blue) is of the same order of magnitude as the one from the output runoff in the Historical ensemble (black). In our experiment we are therefore not correcting much the mean bias in the runoff, which is low, but we are mainly correcting the trend and variability which is higher in the observations than what is computed by the model. This may be related to the ice dynamics which is not accounted for in the model parameterization (simple thermodynamical budget, *cf.* Swingedouw et al., 2007).

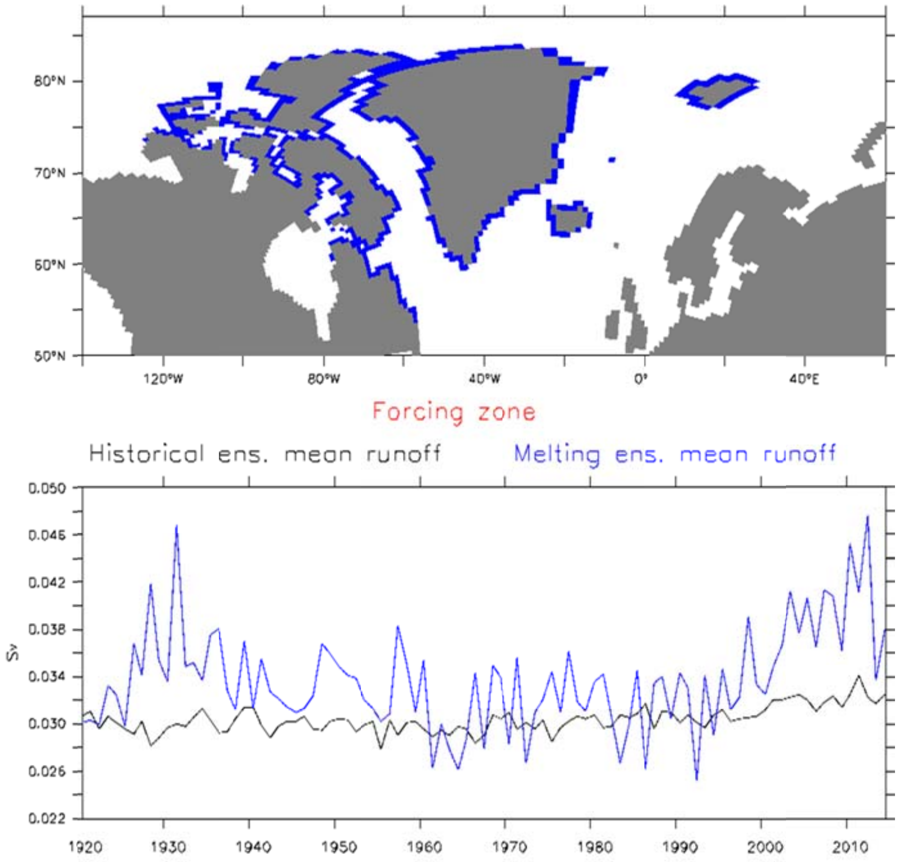

Figure 3: Top figure shows in blue the area around Greenland where runoffs are forced in the model. Bottom figure is a comparison of mean annual values of runoff fluxes from the two ensembles cumulated in the blue zone: Melting (blue line) and Historical (black line).

Regarding the iceberg melting fluxes, they are not explicitly resolved in the IPSL-CM6A-LR climate model, as indicated above. Yet, when the accumulated snow over the Greenland ice sheet exceeds three meters, the excessive freshwater flux is then equally distributed in the ocean north of 40°N following a 10-year smoothing (e.g. Marti et al., 2010). This can be considered as a very crude parameterization of the iceberg melting flux in the historical simulations. In the so-called melting runs, this redistribution is overwritten. For this, one has to disable the transmission of the calving values, mainly corresponding to iceberg fluxes, that are parameterized in the model. Iceberg melting fluxes (solid ice component from Figure 2, pink line) are forced in the melting ensemble in the zone described in Figure 1 by the reconstructed fluxes. The latent heat flux related with iceberg melting is here neglected. The difference between the resulting (observed) calving flux and that from the Historical in this zone is compensated in the usual region of iceberg melting i.e. north of 40°N. To account for the difference between the total calving flux in the historical simulations and that from Bamber et al. (2018), we compute the average of the calving flux in the historical ensemble over the period 1900-1920 north of 40°N, compute the difference with the total solid ice from Bamber et al. (2018) and then add this constant value north of 40°N except in the blue zone from Figure 1. By doing so, we are only correcting the trend of iceberg fluxes and not the mean state of the freshwater released by iceberg from Greenland, except concerning their location. For direct runoff from Greenland, this procedure was not necessary as the differences between observed and computed runoff in the historical over the period 1900-1920 was negligible.

As icebergs are considered as melted ice, these values are added to the runoff values in the same module of the ocean-ice model NEMO-LIM (Madec, 2015; Rousset et al., 2015) so that all freshwater inputs from Greenland ice sheet are taken into account. We mainly correct the trend in the freshwater fluxes around Greenland, so that the amount of runoff and solid ice fluxes is rapidly larger in the Melting experiment than in the Historical ensemble along the experiments (e.g. Fig. 3). We chose not to compensate this supplementary water elsewhere and have more freshwater fluxes going into the ocean in this area in the Melting runs than in the Historical ones. By doing so we better represent the ice sheet freshwater release in the ocean system.

It is also planned to include this melting in a data assimilation simulation with nudging towards observed SST and SSS. Nevertheless, this run has been delayed and is not ready yet. It is planned to be performed in fall 2019 and will serve as initial conditions for the climate hindcasts including freshwater release from WP4 to be performed in winter 2019-2020.

Development of off-line simulations including passive tracers released around Greenland

The spread of the additional freshwater from Greenland can be best traced using a passive tracer released at the locations of Greenland freshwater sources, proportional to the amount of runoff discharge from Greenland at each time step and each grid cell at the Greenland coast. The spreading of this tracer is governed only by physical processes of advection and diffusion like the bulk of the meltwater from Greenland. The tracer is implemented in the model as a passive conservative tracer which is advected by ocean circulation. It is transported into the North Atlantic basin by IPSL-CM6A-LR physical fields using a classical advection-diffusion equation.

Analysis of the simulation by use of statistical approaches and comparison with IPSL-CM6A large-ensemble of historical simulations and oceanic observations

The historical and melting ensembles have been analyzed using ensemble mean to highlight the forced signal either from external forcing (Historical ensemble) or also including the impact of observed Greenland ice sheet melting (Melting ensemble). These forced signals, as well as the internal variability from the model evaluated with the help of individual members, have been compared to available observations, namely the SST from HadISST (Rayner, 2003) and ERSST (Huang et al., 2015), the SSS data from EN4 (Good et al., 2013) and Friedman et al. (2017).

Development of a high-resolution simulation of the ocean over the recent decades

A 1/24° ice-ocean model configuration of the Arctic Ocean and the Atlantic Subpolar Gyre, based on NEMO 3.6 (cf. deliverable D2.2 for a more detailed description of the model) is used to analyze the response of the ocean to the Greenland freshwater release. The study compares two simulations differing by the freshwater inputs. In the control experiment, a constant climatological runoff is applied, whereas in the sensitivity experiment, the reconstruction of Greenland and Arctic ice sheet melting from

Bamber et al. (2018) is implemented. The freshwater sources are interpolated on the model grid following the same algorithm as that used for the IPSL-model. However, in contrast to the IPSL model, the melt water resulting from solid ice discharge is not spread offshore using the Altiberg distribution. The control simulation extends from 2004 to 2017 while the sensitivity experiment is still running and therefore only available from 2004 to 2013. There is no restoring of the surface salinity to observations, which is a crucial point to correctly evaluate impacts of the melting. Still, the lateral boundary conditions are kept unchanged between the two experiments but the boundaries are far enough from the release area that the sensitivity of the convection sites can be considered unaltered by these conditions. In order to follow the spreading of the Greenland fresh water supply over the surrounding ocean, the ocean domain around Greenland has been divided into 9 sub-domains roughly following the contours of the main basins and shelf regions (Figure 4a). The total freshwater released to each of the sub-domains is presented in Figure 4b for the two experiments. As expected, the largest fresh water fluxes are found along the western coast of Greenland, collecting into Baffin Bay and in the Labrador Sea. Large fluxes are also found on the East Greenland shelf. After 10 years, the cumulative input of freshwater over the whole domain is 3000 km^3 larger in the sensitivity than in the control experiment.

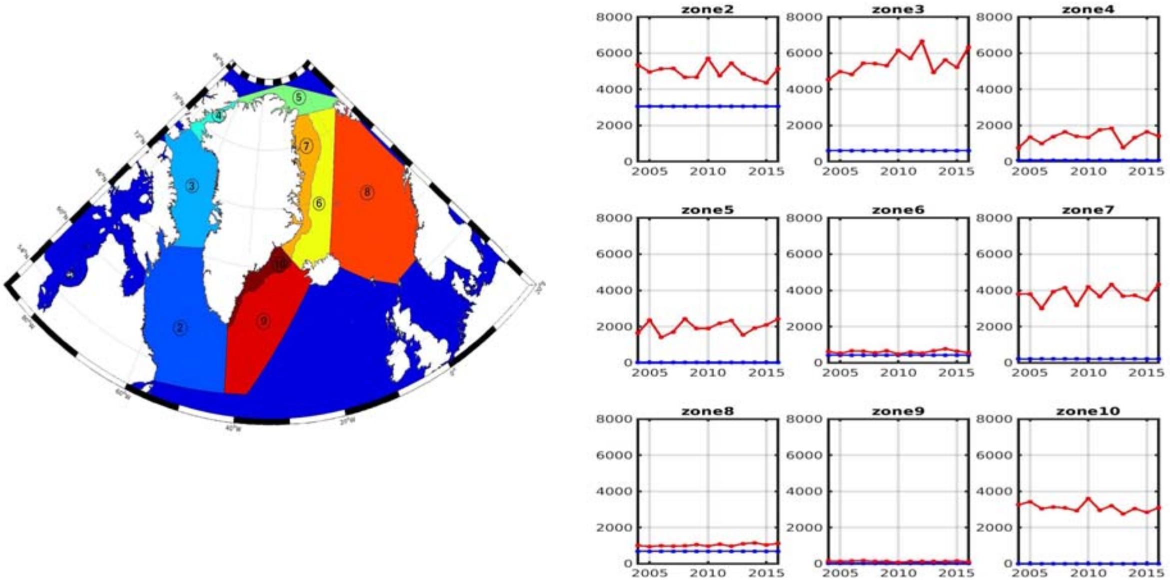

Figure 4: On the left side, the 9 sub-domains where individual freshwater budgets are computed. On the right side: Mean annual freshwater flux (in m^3/s) summed up over each sub-domain in the (blue) control and (red) sensitivity experiments.

Main results achieved

Impacts of Greenland melting on the ocean since 1920 in a coupled climate model

Short introduction

Over the last decades, ice sheet melt and outlet glacier discharge are increasing which is changing the freshwater budget of the Arctic and North Atlantic (Boning et al., 2016). A few recent analyses have addressed the physical and biogeochemical impact of the increased freshwater fluxes from the Greenland ice sheet (Boning et al., 2016; Gillard et al., 2016; Yang et al., 2016). Former studies suggested that these fluxes may have modified the stratification in the Labrador Sea. Nevertheless, considerable variability in the North Atlantic does not allow one to make strong conclusions relying on observations only. For instance, deep convection resumed in the Labrador Sea in 2014-2016 according to observations (Yashayaev and Loder, 2017).

A recent study uses SST fingerprints from the Atlantic Meridional Overturning Circulation (AMOC) to detect a possible weakening of the AMOC in the recent decades (Caesar et al., 2018). This suggests that the AMOC may have weakened since around the 1950s by 3 ± 1 Sv. Such a weakening has also been suggested from sortable silt, a proxy record of deep current intensity, and may have been unprecedented over the last 1500 years (Thornalley et al., 2018). Nevertheless, the causes of this weakening are still unclear. Some studies speculated it may be related to the on-going melting of Greenland (Rahmstorf et al., 2015). An extensive discussion of this issue is provided in chapter 6 of the recently released Special Report on the Ocean and the Cryopshere in a Changing climate (SROCC) report to which people from this deliverable contributed as lead authors.

Up to now, no simulation of coupled ocean-atmosphere General Circulation Model have been performed to evaluate the impact this melting may have on the ocean dynamics, and if it can explain the supposed weakening of the AMOC as suggested by Caesar et al (2018). This is what has been done here.

Results

To evaluate the pathway of the freshwater released in the melting ensemble, we present the trajectory of the tracer at the surface in Figure 5. It reveals a rapid spreading of the freshwater tracer into the Labrador Sea, with an accumulation along the west coast of Europe. A small area in the Labrador Sea (around 59.5°N, 55°W) and the Irminger Sea seem to be by-passed by the freshwater but the signal may also disappear because of vertical mixing in these convection zones.

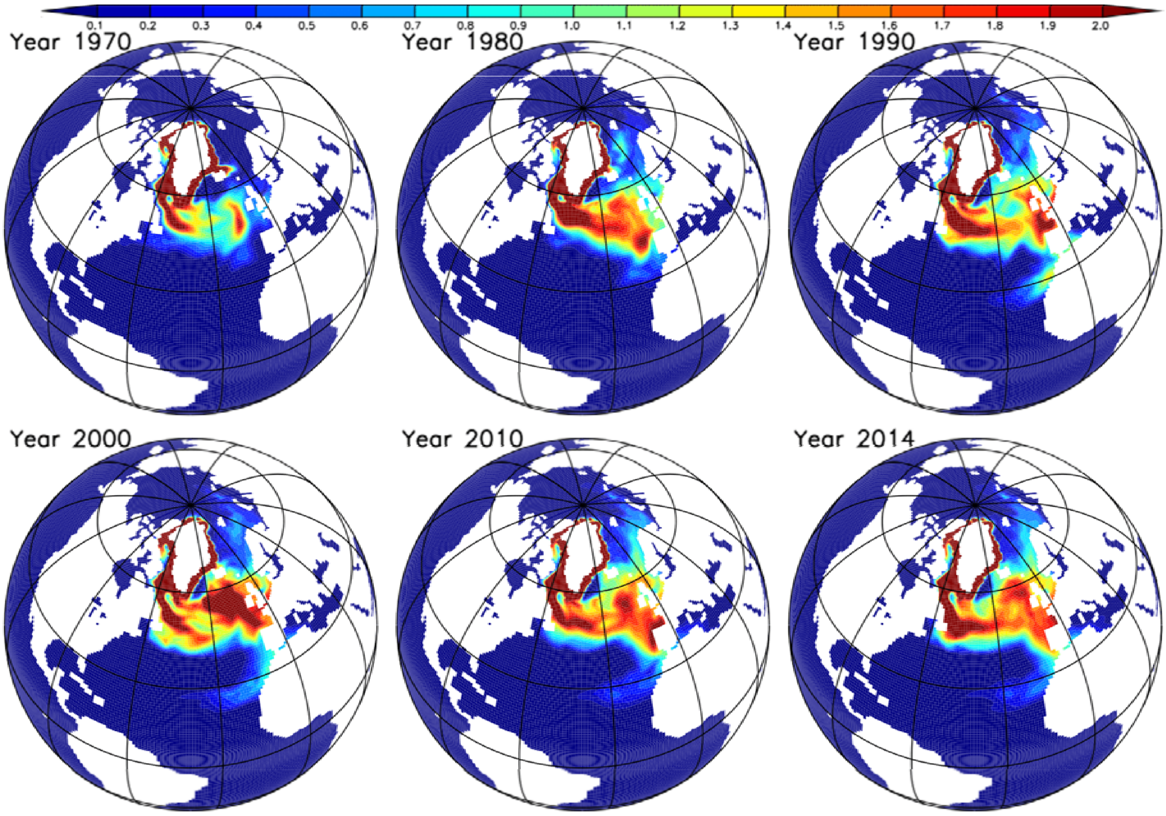

Figure 5: Evolution of tracer concentration from year 1970 to 2014 using off-line tracer computation.

The signature of the melting is isolated from the differences between the historical and melting ensemble means. The impact of the observed melting of Greenland ice sheet on Sea Surface Salinity (SSS) over the whole period of simulation (1920-2014) is presented in Figure 6. The additional freshwater released in the melting ensemble creates a large (>1 psu) and significant (95%) surface freshening in Baffin Bay that travels South of the subpolar gyre towards the subtropical gyre (Figure 6, left) with far lower amplitude (<0.2 psu). In the Arctic Ocean, there is a strong positive (>0.2 psu) SSS difference signal which can be the result of a modification of the North Atlantic circulation, and an increase of the quantity of saltier Atlantic waters towards the North Pole. Such a fingerprint of freshwater release around Greenland has been found in previous idealized hosing experiments from 6 different models (Swingedouw et al. 2013), which highlights the robustness of this signal. It is explained by an increase of Atlantic water towards the Arctic and not by local freshwater adjustment related with sea ice for instance (cf. Swingedouw et al. 2013, also checked in these simulations). Such a signal might be already detectable in the Arctic, but the available SSS data are not long enough to validate this. Concerning the Sea Surface Temperature (SST), we observe in Figure 6 (right) a cooling signal in the subpolar gyre, in the Nordic and Barents seas and also along the Canary Current. Overall, the signal is relatively weak and amounts to less than 0.2°C over the subpolar gyre, where it is the most widespread.

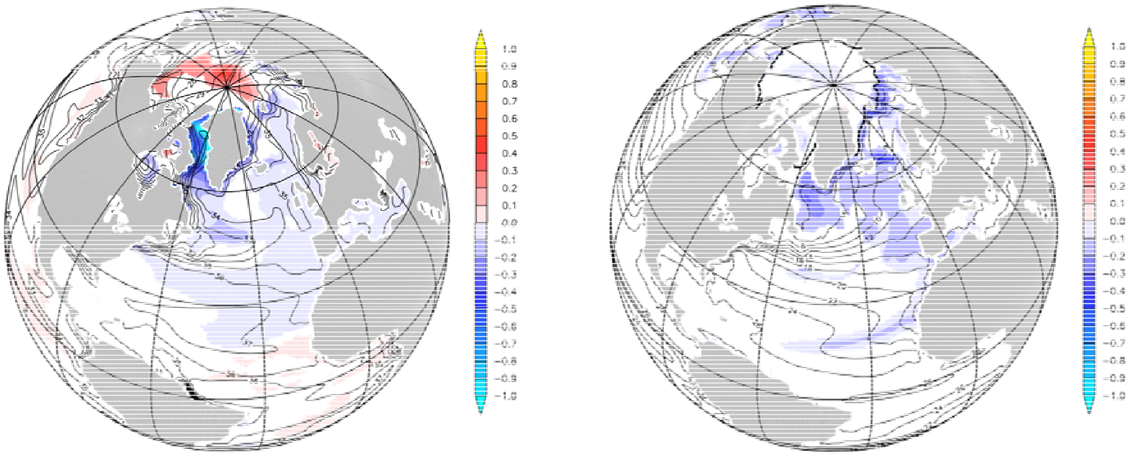

Figure 6: Shading shows the significant (95%) difference between Historical and Melting ensembles mean SSS (left) and SST (right) over the years 1920-2014. Contour lines are the mean state of the Historical ensembles mean SSS and SST (1920-2014 averaged).

Figure 7 highlights the difference in winter mixed layer depth (MLD) averaged over the whole period of the experiments. In the historical simulations, convection preferentially occurs in the Labrador and Nordic Seas with mixed layer depths exceeding 1000m on average over February-March-April. We also notice a less active convection site in the Irminger Sea. The impact of the observed Greenland ice sheet melting is a slight reduction of convective activity in the Labrador and Nordic seas, with mean differences exceeding 50 m in a few locations of these seas. On the other hand, the Irminger Sea convective activity is slightly enhanced by up to 20 m on average. This response in the Labrador and Nordic Seas is in line with the decrease in SSS that is not entirely compensated in density by the SST decrease (not shown). As a consequence, the density slightly decreases at the surface, which stabilizes the water column and diminishes the number and intensity of the convective events in winter. The increase of convection in the Irminger Sea can be related to the fact that this sea is only slightly impacted by the spread in freshwater release (cf. Figure 5) and is also associated with a modification of the surface currents that bring slightly more subtropical waters into the Irminger Sea in the Melting ensemble than in the Historical one (not shown).

The impact of this decrease in convective activity in the North Atlantic on the large-scale circulation can be seen in Figure 8. It shows a general decrease of the AMOC by up to about 0.5 Sv around 30°N latitude. The weakening is coherent over most of the basin but is generally weak and not significant in individual members. The same is true for MLD: there is a clear need of (at least) 10 members to correctly isolate the forced signal of the freshwater release, which remains small compared to the internal variability. This aspect is further highlighted below.

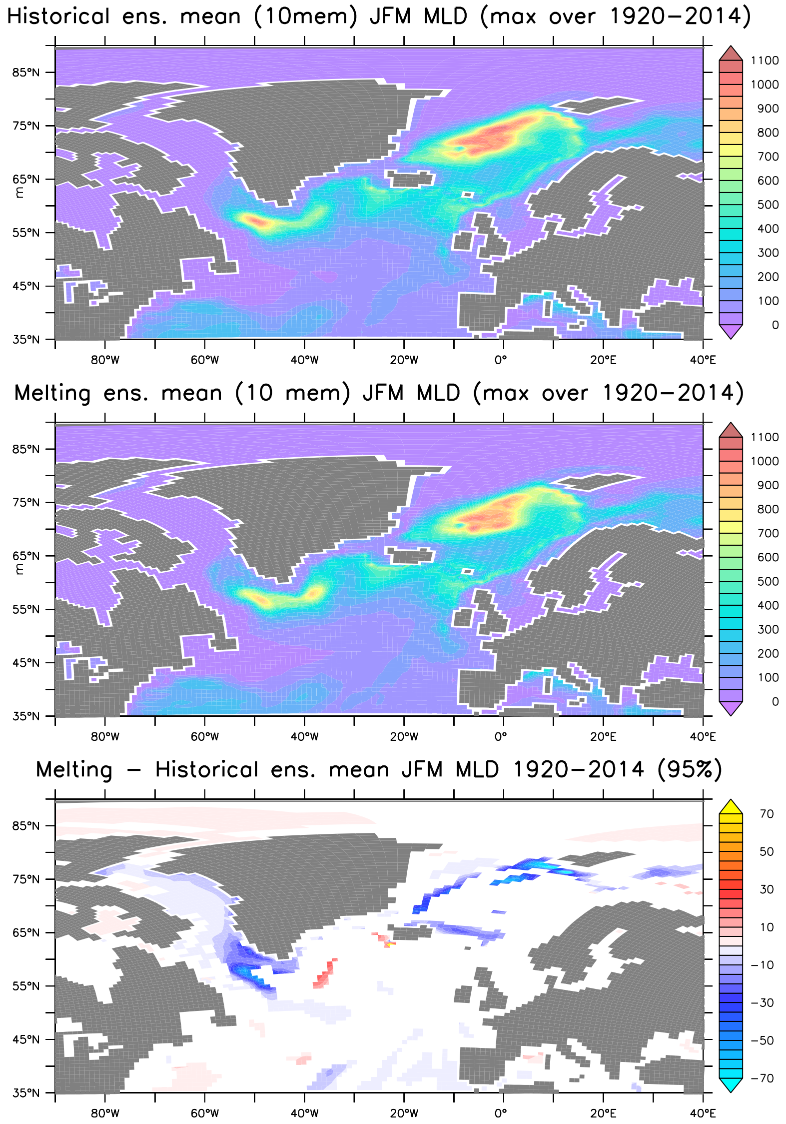

Figure 7: Top figure shows the mean state of the Historical ensemble maximum of winter (February-March-April) Mixed Layer Depth in the North Atlantic for the period 1920-2014. Middle figure shows the same variable for the Melting ensemble mean. Bottom figure is the significative (95%) difference between winter MLD for the same period.

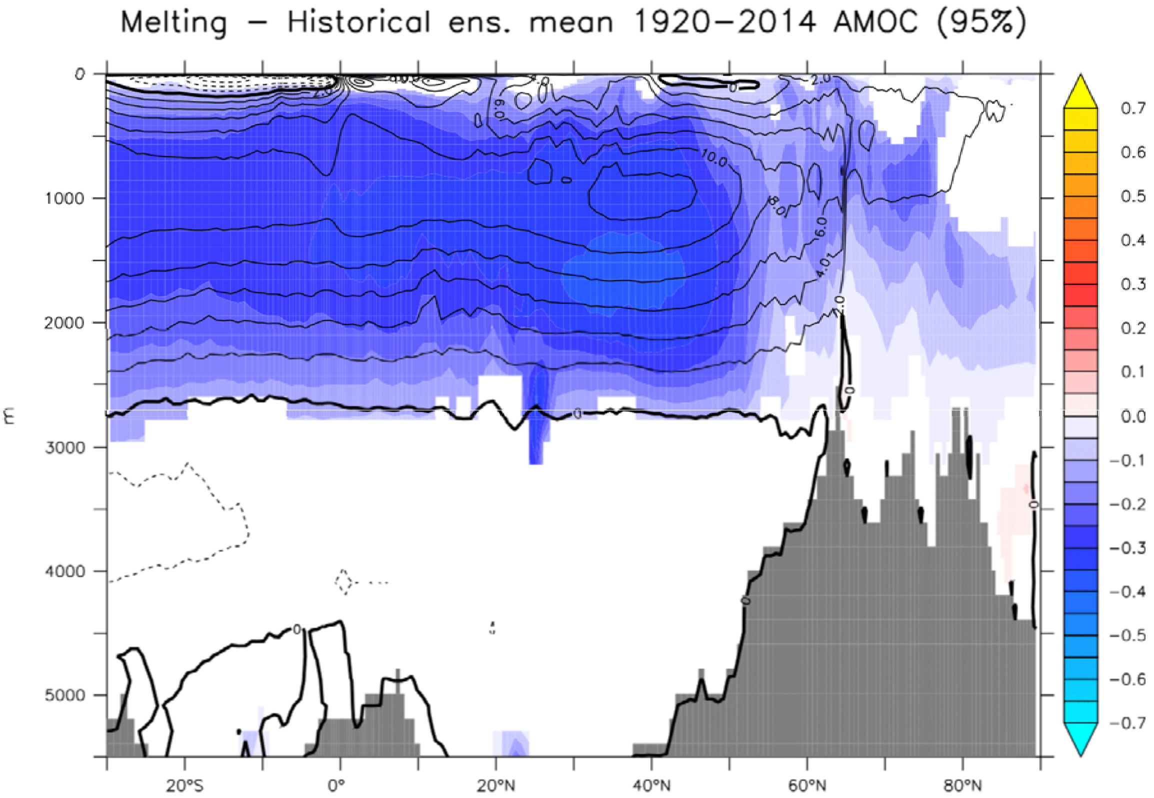

Figure 8: Colors are the significant (95%) difference between Historical and Melting ensembles mean Atlantic meridional stream-function for the period 1920-2014. Contour lines are the Historical ensemble time averaged (1920-2014) levels.

Comparison with ocean observations to evaluate the role of forced *vs*. internal variability

In order to evaluate the impact of the melting on the ability of the forced climate response to match with observed variations, we have compared the two ensembles with available SSS and SST observations. In Figure 9, we can see that the inclusion of the melting is bringing the ensemble mean of the Melting ensemble in between the two estimates from EN4 and Friedman et al. (2017), while the Historical ensemble mean trend is significantly higher than both observation-based estimates. Thus, it seems that the inclusion of the melting is bringing the forced signal closer to the observations of SSS trends in the subpolar region. For the SST, we notice on Figure 9, that both ensemble means exhibit a strong positive trend, while observation-based estimate from ERSST and HadISST show a slightly negative trend or slightly positive respectively, both of which are not significantly different from zero. Once again, the inclusion of the melting is thus bringing the forced signal closer to the observation, even though the improvement in terms of trend is very small and not significant at the 95% level but only at the 80% level.

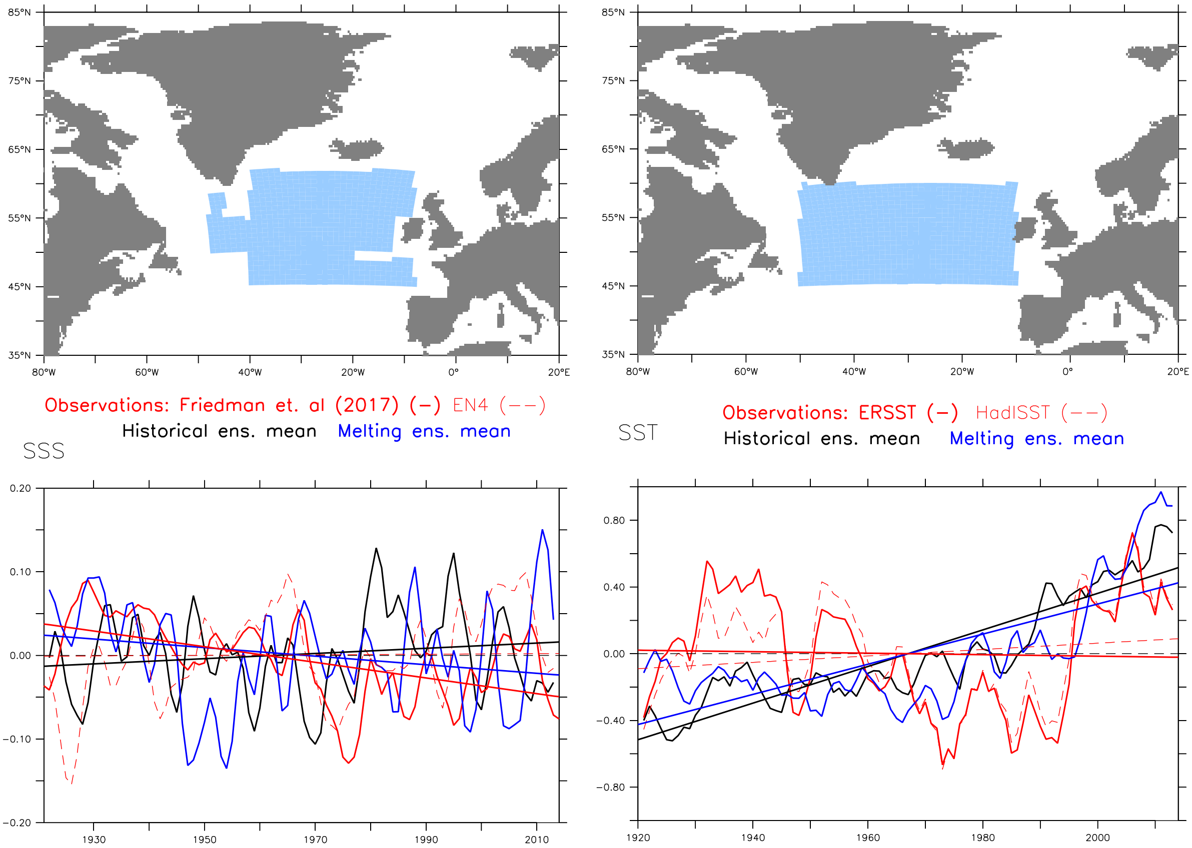

Figure 9: SSS (left) and SST (right) in observations (red), ensemble mean of historical simulations (black) and of melting simulations (blue) averaged over two different SPG boxes (depending on data availability) represented on the top. The linear trend over the period 1920-2014 is shown as well.

On top of this long-term trend, we have been interested in the capability of the different ensembles to reproduce prominent features of the variability of the SPG region over the last century. To analyze the decadal-scale variability of the SST in the region, we have smoothed the time series as shown in Figure 9. Also, to estimate if the ensembles can reproduce the cold blob in the SPG that started in the 2010s (Josey et al., 2018), we have extended the two ensembles from 2015 until 2100 using a ssp45 scenario. Five members for this extension have been performed at the moment. Figure 10 shows that before 1960, the simulated decadal variability is not in phase with the observed variability in either of the two ensembles. From 1960 and onward, we notice that the Melting ensemble is closer to the observations than the Historical ensemble. It reproduces the cooling trend in the 1960s and 1970s, the warming rebound in the early 1980s and the rapid warming of about 1°C around 1995. The exact timing of these different features is on the other hand not reproduced in the Historical ensemble that mainly shows a warming trend and a few cooling events closely following volcanic eruptions. A sliding window correlation with a 30-year window does indicate that the correlation is significant from the 1970s and onward in the melting ensemble, contrary to the Historical ensemble.

Finally, the cooling of the 2010s is not well reproduced in the two ensembles. Nevertheless, we notice in the late 2010s a cooling trend in both ensembles. Because it is also present in the historical simulation, this cooling trend does not seem to be related to the observed melting of Greenland. It may rather be related with the external forcing or a delayed response to it. This forcing is positive at that moment (2010-2020), with no large aerosol loading or decrease in solar irradiance and a large increase in greenhouse gas concentration (not shown). Thus, we argue that the cooling trend of the late 2010s is related with a dynamical response of the ocean. At this stage we can hypothesize the phasing of a decadal variability in response to radiative forcing of the former years, for instance due to volcanic eruptions (e.g. Swingedouw et al., 2015) or anthropogenic aerosols. A dedicated study using different detection-attribution ensembles and an in-depth analysis of the heat budget will be necessary to decipher the mechanisms at play and will be pursued during the last phase of the project.

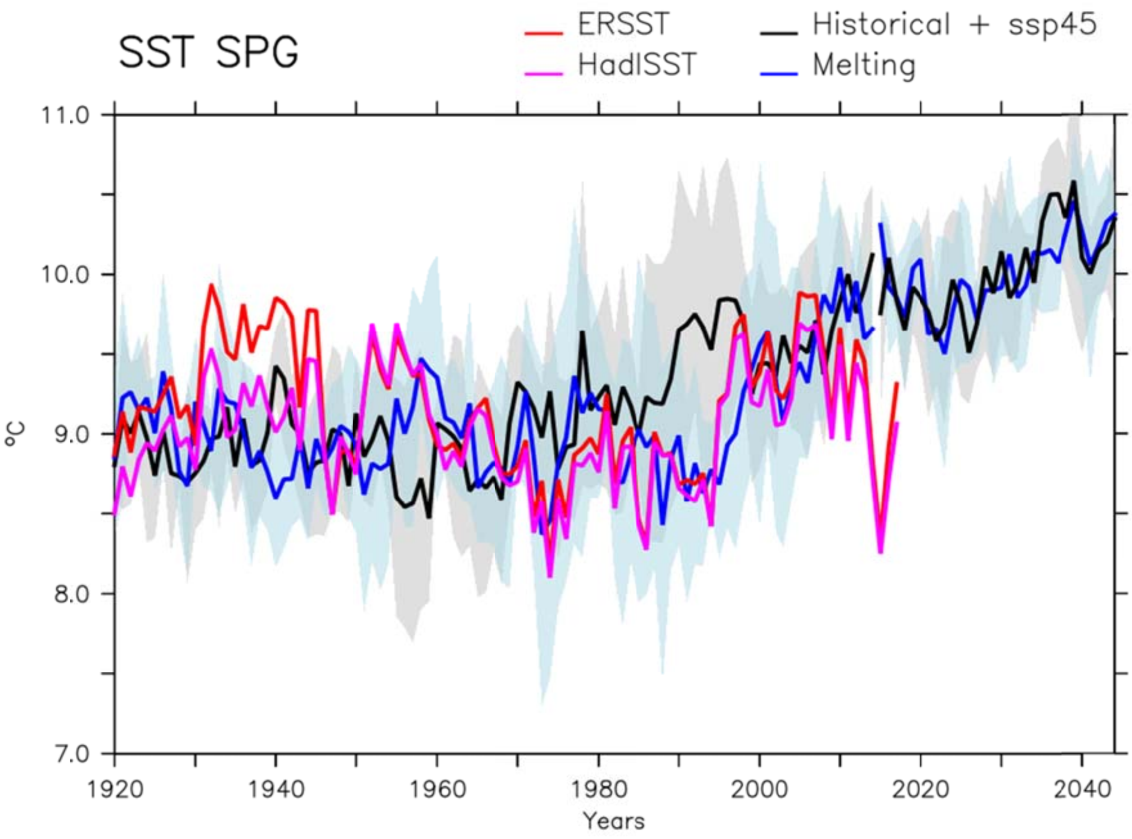

Figure 10: SST in the SPG region (cf. Figure 90) with 5-year running mean in red for ERSST, in pink for HadISST. The ensembles of historical simulation have been prolonged by ssp45, including or not an estimate of future melting (linear extrapolation). These new ensembles comprise only 5 members at the moment, and we thus show the corresponding 5-member ensemble mean for Historical and Melting ensembles. In black are historical and ssp45 without observed melting and in blue including the observed melting and its extrapolation.

Variability of the Arctic Ocean over the recent decades in a high-resolution 1/24° model

To analyze the impact of the increase in freshwater release, the freshwater content (FWC) of each sub-domain defined in Figure 4a has been computed. The freshwater content is defined as:

$$FWC = \iiint \frac{(Sr - S)}{Sr}.dV \qquad (1)$$

where S is the salinity, dV an elementary volume and $S_r = 34.8$ is a reference salinity.

The difference of freshwater content (FWC) between the sensitivity and the control experiments is shown for each sub-domain in Figure 11. The FWC is divided by the area of each sub-domain to enable comparison between these sub-domains. The largest increases of FWC are found in the Baffin Bay, Nares Strait and on the East Greenland shelf. In this figure, the cumulative fresh water input added in the sensitivity experiment is also displayed (red curve): we can thus deduce the relative influence of the FW transport divergence and surface freshwater flux on the evolution of the FWC for these sub-domains.

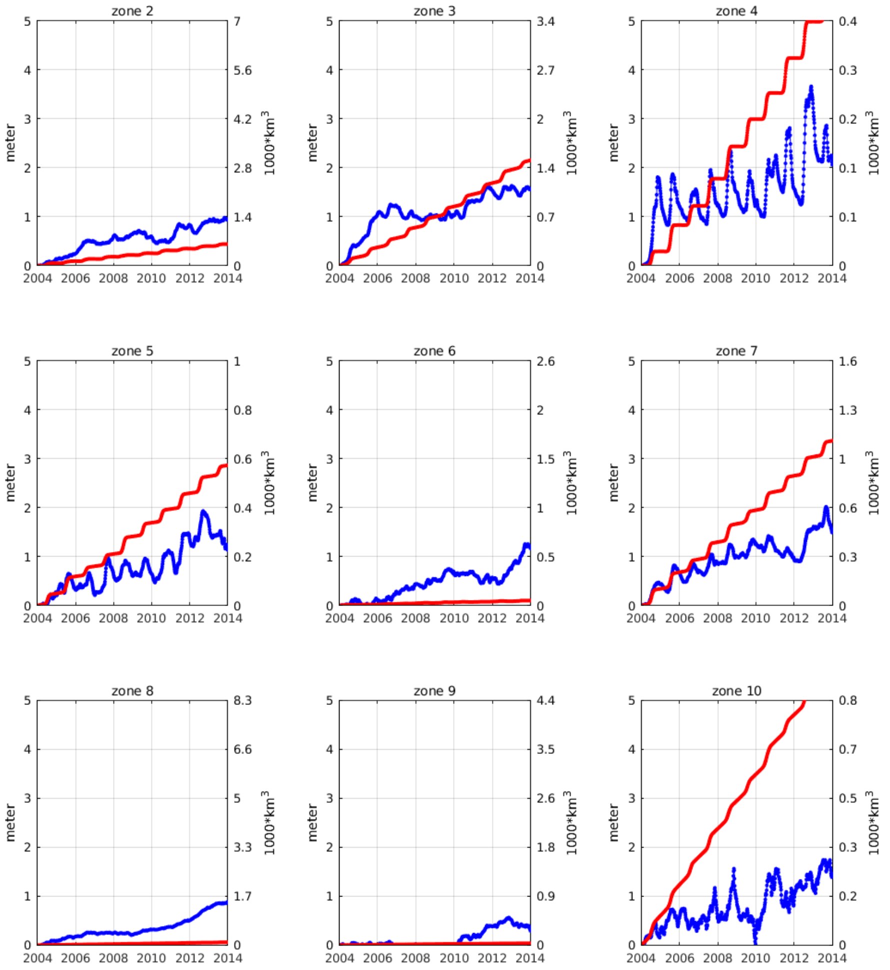

Figure 11: Difference of fresh water content (blue) and cumulative fresh water release (in red, in meter and 1000 km^3 respectively) in each sub-domain between the sensitivity and the control experiments. Region numbers correspond to those in Figure 4: 2: Labrador Sea, 3: Baffin Bay, 4: Nares Strait, 5: North Greenland, 6: Greenland-Iceland Sea, 7: East Greenland shelf, 8: Norwegian Sea, 9: Irminger Sea, 10: southeast Greenland shelf.

On the East Greenland shelf, even if there is a large increase of the FWC, part of the Greenland freshwater discharge is advected outside the domain. Indeed, the horizontal maps of the annual mean FWC (Figure 12) suggests that the Jan Mayen Current and the East Icelandic Current advect the FW into the Iceland and southern Norwegian Seas (zones 6 and 8) and contribute to the increase of the FWC in these regions (Figure 11). A moderate signature of increased FWC is also detected in the Norwegian Current. In the Baffin Bay (zone 3), FW is imported from outside this domain during the first 5 years before being released. In the Labrador Sea, the influence of the increased FW export through Davis Strait after 2005 is consistent with the increase of FWC on the Labrador shelf in the following two years (Figure 12). Starting in 2008, substantial FW anomalies are found in the interior Labrador Sea suggesting that the FW accumulated on the shelf starts to penetrate into the basin. The change in FWC is mainly due to the decrease in salinity in the upper 100 meters (not shown). The input of freshwater during that period amounts to 1200-1400 km^3 and is slightly less than half of a typical Great Salinity Anomaly event (Hakkinen, 1993). The freshening of the upper layers leads to a reduction of the convection area and shallower winter mixed layer (Figure 13). By comparison, there is no detectable response of the winter mixed layer in the Icelandic Sea despite some FW accumulation there. This lack of response is attributed to too strong upper stratification in this region in the control experiment. In the Norwegian Atlantic Current, an increase of the winter mixed layer depth can be observed but the response is weak.

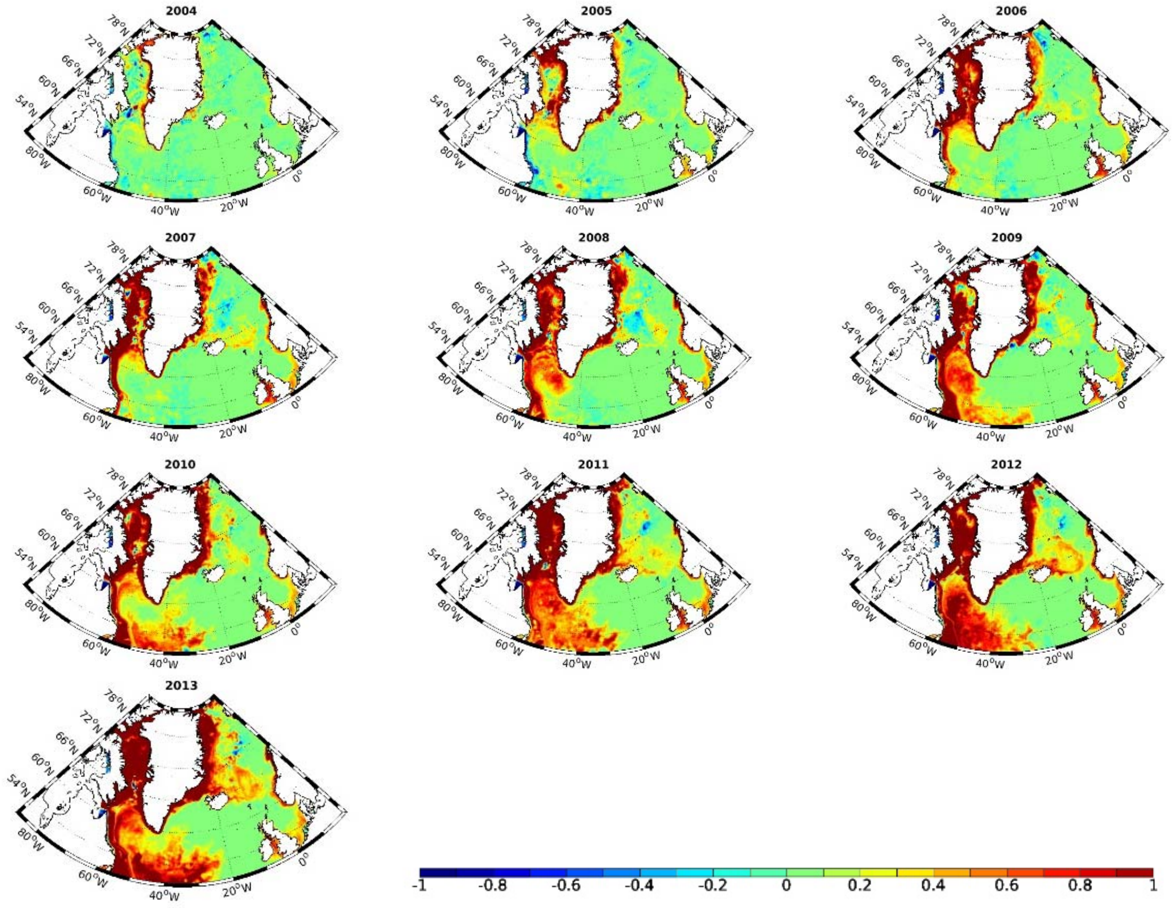

Figure 12: Difference in the freshwater content (in meters) between the control and sensitivity experiments.

These forced ice-ocean simulations and the coupled climate model simulations give a similar qualitative picture of the ocean response. However, as already noticed in previous studies, the response in the interior Labrador Sea, including the impact on the convection activity, is stronger in the forced simulations. Part of the discrepancy may be due to the fact that we compare a single forced model realization with an ensemble mean of the coupled simulation. Another candidate for the enhanced response of the Labrador Sea is most probably to be found in the higher resolution and therefore greater ability of the forced model to represent the transport of freshwater from the boundaries into the interior basin. A detailed analysis of the transports through key sections is currently in progress and will provide quantitative estimates of these effects.

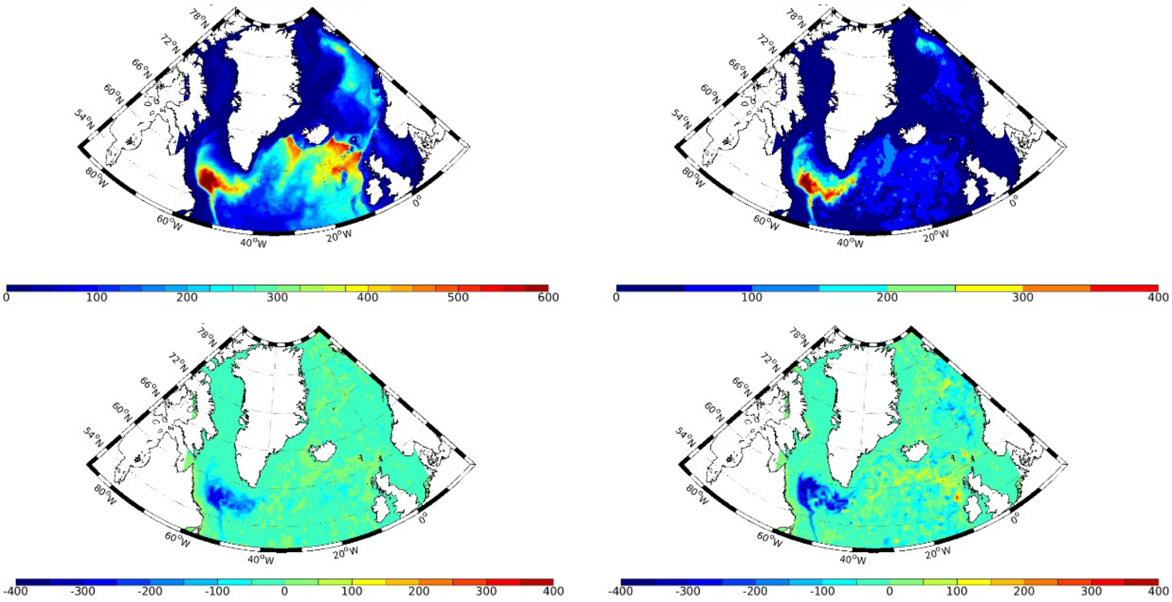

Figure 13: Winter (JFM) mixed layer depth (in meter): (upper panel) multiyear (2004-2013) average (left) and standard deviation (right); (lower panel) difference between the control and sensitivity experiments shown for the multiyear (2004-2013) average (left) and last year of the experiment (right)

Progress beyond the state of the art

First estimate of the forced response to observed Greenland melting over the historical era

As mentioned earlier, there is considerable debate in the community concerning the potential weakening of the AMOC and its causes (cf. 2019 SROCC report chapter 6). While it has been speculated that the freshening of the Atlantic by melting of land ice may have played a considerable role (Yang et al. 2016, Rahmstorf et al. 2015), a few ocean-only simulations usually starting from 1960 and after have shown that this melting may have a negligible impact on the AMOC (Böning et al. 2016, Dukhovskoy et al. 2019). Nevertheless, these simulations used a restoring of salinity at the surface which may limit the impact of the melting and were not coupled to an atmosphere to integrate potential coupled feedbacks.

Furthermore, they considered a short time frame, while large melting was already estimated to have occurred in the 1920 (Box and Colgan 2013).

Thus, our ensemble provides for the first time an estimate in a state-of-art coupled climate model (which participates to the CMIP6 exercise) of the impact of the largest part of land-ice melting in the Arctic regions. Results show that the forced impact of this melting is relatively modest, notably in regard of the internal variability of the model, estimated thanks to the large ensemble of historical simulations. For instance, the estimated weakening of the AMOC due to the melting is estimated to be less than 0.5 Sv, while estimate from Caesar et al. (2018) proposed a weakening of 3 ± 1 Sv over the historical era. The weakening due to Greenland ice sheet melting would represent, if our model-based estimate is correct, less than 15% of the total weakening signal estimated by Caesar et al. (2018).

The external forcing can also lead to a weakening of the AMOC without any melting of Greenland ice sheet. Indeed, as assessed in SROCC report (chapter 6), the weakening of the AMOC in CMIP5 models over the historical era is 1.4 ± 1.4 Sv. These CMIP5 models do not include the observed melting and may strongly underestimate it as it is the case in the IPSL-CM6A-LR model, due to a very poor representation of land ice processes. Thus, about half of the reconstructed weakening of the AMOC from Caesar et al. (2018) may be explained by externally forced signal from CMIP5 models. Nevertheless, the spread remains large here and we should highlight that in the IPSL-CM6A-LR large ensemble, the forced weakening signal is very close to zero, which means that, in this particular model, any weakening might be only related with land ice melting and might only represent about 15% of the estimated weakening signal. On the other hand, the internal variability is very large in this model and capable of explaining a large fraction of the (3 Sv) reconstructed weakening, with some members exhibiting weakening up to 2 Sv over the historical era. Nevertheless, even by including Greenland melting, a weakening of 3 Sv cannot be obtained. A few members enter the error bar of the estimate, and are mainly driven by internal variability rather than external forcing or observed melting of Greenland ice sheet. From this model, we thus argue that internal variability might be the best candidate to explain the reconstructed weakening of the AMOC. Nevertheless, this result is almost surely model dependent since some CMIP5 models do show a substantial AMOC weakening over the historical era, but not related with Greenland ice sheet melting. We thus conclude that the on-going melting of the Greenland ice sheet might have played a limited role in the potential recent AMOC weakening (which also remains debatable, since there are no direct measurements), while external forcing or internal variability is able to explain such a weakening.

Evaluation of the influence of Greenland melting on decadal ocean variability

The impact of the observed Greenland ice sheet melting on decadal variability has not been evaluated up to now. There have been a few hypotheses stating that the on-going melting might explain some of the cooling signal observed in the North Atlantic (e.g. Rahmstorf et al., 2015; Yang et al., 2016), but no proper attribution. Here, we have shown that, in addition to explaining a slight part of the SSS and SST trend, this melting may interact with other external forcing to bring a forced component of the decadal variability observed in the North Atlantic. In particular, the 1995 rapid warming in the subpolar gyre appears in our simulation to have a considerable fraction of variance forced by the melting. The understanding of this signal is not very clear at the moment and will be one of the focus the last year of the project. It could be interpreted as a delayed warming trend that is present in the Historical ensemble. The implications of this result for the decadal prediction are potentially crucial and , if true, argue for inclusion of an estimate of the observed melting in the initialized simulations and hindcasts. The melting product that we deliver here, starting in 1920, and based on Bamber et al. (2018) and Box and Colgan (2013) estimation, but adapted to AOGCM grid, is an important tool to go in that direction. It would be (at the least) used in the IPSL-EPOC decadal prediction system within WP4.

Response of the ocean to the freshwater discharge in a high-resolution 1/24° ocean model.

Böning et al. (2016) found a small effect of the freshwater discharge from the Greenland ice sheet on the convection in the Labrador, suggesting however, that this impact may be enhanced in the future with the increasing trend of the discharge. In our sensitivity experiment, the freshwater input from the new estimate of Bamber et al. (2018) is roughly twice that used in Böning et al. (2016) experiment, and it also includes the fresh water release from glaciers and ice caps outside Greenland. The larger input and the absence of surface salinity restoring to climatology, may contribute to the larger response obtained in our simulation: after 10 years of additional freshwater discharge, the convection is drastically reduced in the Labrador Sea and surface salinity anomalies of up to 0.4-0.6 can be found in the northern Labrador Sea (compared to the 0.1-0.2 decrease found in Böning et al., 2016). Thus, the potential impact of Greenland ice sheet melting might be larger than expected by former estimates from ocean-only models or from the coupled ocean-atmosphere model with relatively low-resolution in the ocean. The sensitivity experiment displays a larger increase of the SSH in the western Subpolar gyre (Figure 14), which may result from the freshwater input, but the barotropic streamfunction shows no clear evidence of changes in the gyre circulation. These changes might emerge on longer timescale.

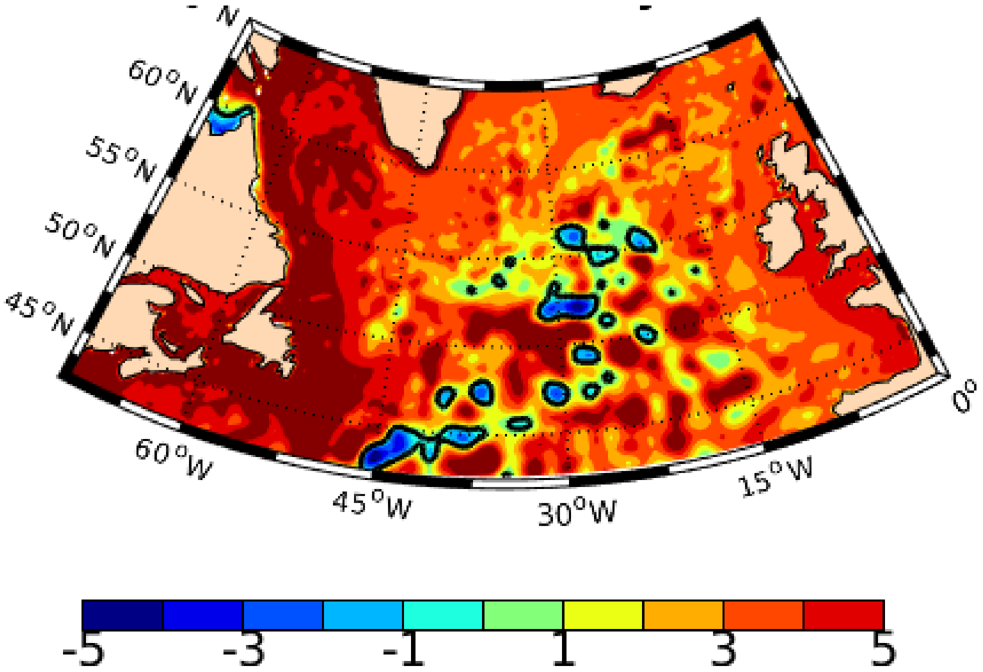

Figure 14: Sea surface height averaged over the period 2004-2013 (in cm). Difference between the sensitivity and the control experiments.

On the other hand, we find little impact of the fresh water release on the dense overflows, and potentially on the lower limb of the overturning (Fig. 15). Whether this is due to the lack of model sensitivity to the surface FW forcing in the overflow source region in the Iceland Sea or to the weak influence of the released FW in the Norwegian Current (another source of overflow water) is still under investigation. Note that unfortunately our limited area model would not allow us to evaluate the ultimate impact of the above changes on the AMOC.

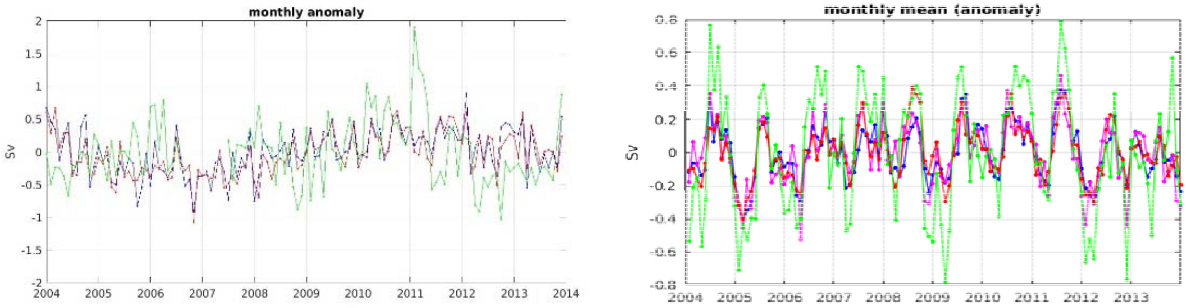

Figure 15: Transport anomaly of dense water overflow in (left) the Denmark Strait (DS) and (right) the Faroe Bank Channel (FBC). Observations (from Jochumsen et al. (2017) for DS and Hansen and Østerhus (2007) for FBC) in green, control and sensitivity experiments in blue and red respectively.

Impact

<u>How</u> has this work contributed to the expected impacts of Blue-Action?

Improve capacity to predict the weather and climate of the Northern Hemisphere, and make it possible to better forecast of extreme weather phenomena

Improve stakeholders' capacity to adapt to climate change

The analysis of literature performed within this deliverable has strongly contributed to the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC[1]) report for which Didier Swingedouw (CNRS-EPOC) was lead author of the chapter 6: "Extremes, Abrupt Changes and Managing Risks".

The topic of the impact of freshwater release from Greenland melting on the North Atlantic has been discussed within a dedicated subsection (n° 6.7.1.2). Also, a detailed assessment of the potential impact of a substantial weakening of the AMOC has been provided in section 6.7.2 and most notably the Figure 6.10 that is shown below. In that respect, **the work done in this deliverable has clearly impacted the IPCC SROCC report and the message delivered to the policymakers e.g. statement A2.7 and B2.7 from the summary for policymakers.[2]**

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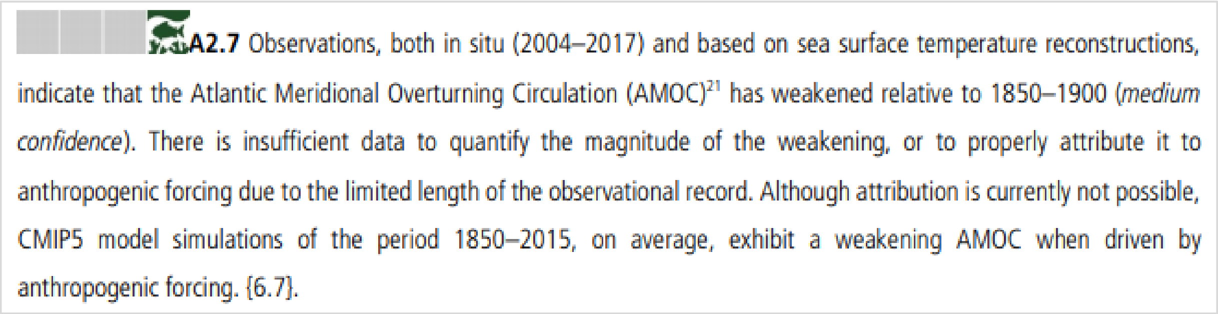
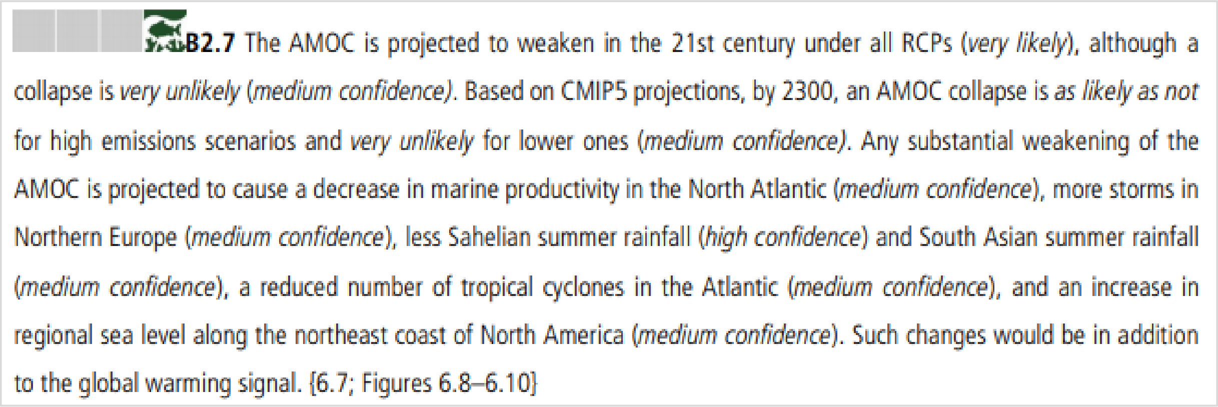
[1] https://www.ipcc.ch/srocc/home/

[2] https://www.ipcc.ch/srocc/download-report/
Summary for Policymakers https://report.ipcc.ch/srocc/pdf/SROCC_SPM_Approved.pdf



A2.7 Observations, both in situ (2004–2017) and based on sea surface temperature reconstructions, indicate that the Atlantic Meridional Overturning Circulation (AMOC)[21] has weakened relative to 1850–1900 (*medium confidence*). There is insufficient data to quantify the magnitude of the weakening, or to properly attribute it to anthropogenic forcing due to the limited length of the observational record. Although attribution is currently not possible, CMIP5 model simulations of the period 1850–2015, on average, exhibit a weakening AMOC when driven by anthropogenic forcing. {6.7}.

Statement A2.7 of the Summary for Policymakers. Copyright: IPCC SROCC 2019



B2.7 The AMOC is projected to weaken in the 21st century under all RCPs (*very likely*), although a collapse is *very unlikely* (*medium confidence)*. Based on CMIP5 projections, by 2300, an AMOC collapse is *as likely as not* for high emissions scenarios and *very unlikely* for lower ones (*medium confidence)*. Any substantial weakening of the AMOC is projected to cause a decrease in marine productivity in the North Atlantic (*medium confidence*), more storms in Northern Europe (*medium confidence*), less Sahelian summer rainfall (*high confidence*) and South Asian summer rainfall (*medium confidence*), a reduced number of tropical cyclones in the Atlantic (*medium confidence*), and an increase in regional sea level along the northeast coast of North America (*medium confidence*). Such changes would be in addition to the global warming signal. {6.7; Figures 6.8–6.10}

Statement B2.7 of the Summary for Policymakers. Copyright: IPCC SROCC 2019

As a consequence, the literature assessment performed in this deliverable helps to improve stakeholders' capacity to adapt to climate change through a better knowledge of the risk of the diversity of climate change in the North Atlantic sector, notably related with the freshwater release from Greenland ice sheet (cf. section 6.7.1.2 of the SROCC report).

The idea of developing a kind of story-telling approach has also emerged within the on-going Sixth Assessment Report (AR6), to better communicate the potential impact of a large change in the AMOC (depicted in Figure 14, a replicate of Figure 6.10 from SROCC report) on the different adaptation options depending on the future response of the AMOC, in response notably to Greenland ice sheet melting.

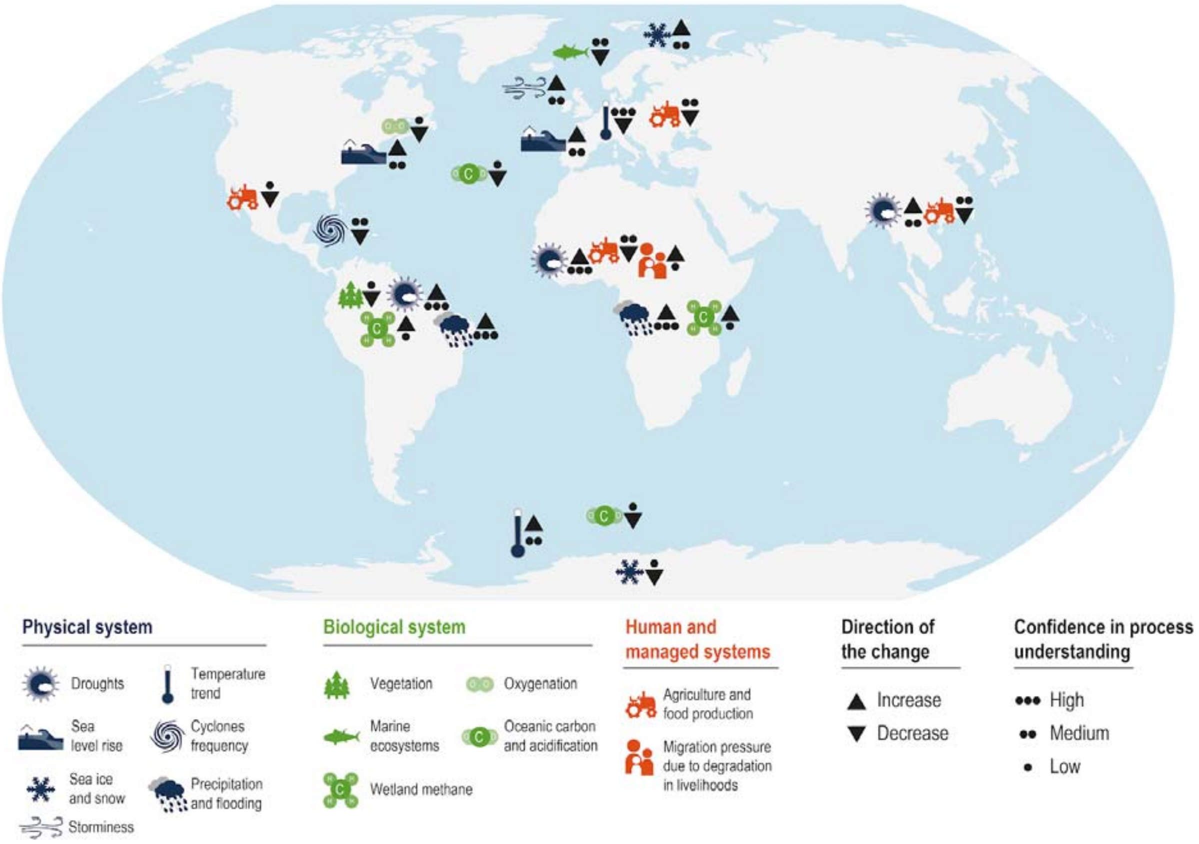


Figure 14: Infographic on teleconnections and impacts due to Atlantic Meridional Overturning Circulation (AMOC) collapse or substantial weakening. Changes in circulation have multiple impacts around the Atlantic Basin, but also include remote impacts in Asia and Antarctica. Reductions in AMOC lead to an excess of heat in the South Atlantic, leading to increased flooding, methane emissions and drought, and a concomitant negative impact on food production and human systems. In the North Atlantic region hurricane frequency is decreased on the western side of the basin, but storminess increases in the east. Marine and terrestrial ecosystems, including food production, are impacted while sea-level rise is seen on both sides of the Atlantic. The arrows indicate the direction of the change associated with each icon and is put on its right. An assessment of the confidence level in the understanding of the processes at play is indicated below each icon. Reproduction of Fig. 6.10 of SROCC report (copyright: IPCC SROCC 2019).

Contribute to a robust and reliable forecasting framework that can help meteorological and climate services to deliver better predictions, including at sub-seasonal and seasonal time scales

The development of a product of observed freshwater release and its integration in the IPSL-CM6A climate model will benefit the decadal prediction system using this model. The results shown in this deliverable highlight that this melting may have played a crucial role for the decadal variability in the North Atlantic. Such a result may transform our understanding of recently observed decadal variability in the North Atlantic and it is thus targeted to publish it in a high-profile journal, after producing a few more members to further strengthen the results obtained and better evaluate the signal to noise ratio.

This meltwater forcing is thus planned to be integrated in the initial simulation from the decadal prediction system using IPSL-CM6 as well as its hindcast as is planned (and in progress) in WP4. It will be also proposed to any institutes that want to include it in its DCPP activities.

This will thus lead potentially to an improved capacity to predict the weather and climate of the Northern Hemisphere.

Improve the capacity of climate models to represent Arctic warming and its impact on regional and global atmospheric and oceanic circulation

The comparison of the results of the high-resolution experiments with previous studies based on high resolution model suggests that proper estimates of the Greenland freshwater forcing is necessary to anticipate the magnitude of the response of the overturning circulation.

Impact on the business sector

- The potential improvements that will be brought to the IPSL-EPOC decadal prediction system may be of help to improve climate services that can feed several economic sectors (agriculture, business, insurance estimate…). Indeed, such bridges between decadal prediction and climate services are now developed all over Europe.
    - At CNRS-EPOC, **a climate service related with viticulture** is being developed based on former IPSL decadal prediction system. It is using statistical correction techniques (quantile-quantile) in collaboration with the private company The Climate Data Factory ([3]) and the institute specialized in viticulture, the Institut des Sciences de la Vigne et du Vin- Science Institute of Vine and Wine, in Bordeaux ([4]).
    - At CNRS-IPSL, **the focus is more globally on the European region**, as shown for example from the involvement of two authors of this deliverable in the project EUCP "European Climate Prediction system" ([5]) dedicated to climate predictions over Europe.
- The application of a statistical correction and downscaling to the potentially improved IPSL-EPOC decadal prediction system (evaluation still on-going) will allow us to refine the climate services that are developed, which are based on the integration of a phenological model of the grapevine. The information deduced from the skill of the decadal prediction system will then be proposed to various vineyards and may thus have a potential beneficial effect on the business sector through an improved estimate of risk and better adaptation measures.

Lessons learned and Links built

- One of the key results of this deliverable concerns the potential large role of internal variability in explaining the recent trend in SST in the North Atlantic. This result highlights the potential large

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[3] https://theclimatedatafactory.com/

[4] https://www.isvv.u-bordeaux.fr/fr/

[5] https://www.eucp-project.eu, funded by H2020

benefit of decadal prediction systems, which are indeed aiming at capturing and predicting the signal from this internal climate variability. It will feed both the WP2 and WP4 in Blue-Action.

- The potential improvements that will be brought into the IPSL-EPOC decadal prediction system are planned to also feed the EUCP project, which is aiming at developing authoritative near-term projections (next 40 years) of the climate, bringing together, with a seamless approach, decadal predictions and projections.
- The lessons from Blue-Action WP3 then potentially benefit, on the longer-term, the Copernicus climate change services.

Contribution to the top level objectives of Blue-Action

This deliverable contributes to the achievement of the following objectives and specific goals indicated in the Description of the Action, part B, Section 1.1: http://blue-action.eu/index.php?id=4019

Objective 1 Improving long range forecast skill for hazardous weather and climate events

By improving the freshwater budget of the simulations over the historical era, this WP aims to improve the IPSL-EPOC decadal prediction system using the IPSL-CM6A model. In particular it has been shown here that the 1995s rapid warming event in the subpolar may be to a large amount forced by the combined effect of external forcing and Greenland ice sheet melting.

Objective 2 Enhancing the predictive capacity beyond seasons in the Arctic and the Northern Hemisphere

The decadal changes in the Arctic-North Atlantic sector are partly driven by freshwater release from land ice melting as shown by our results. Thus, the inclusion of this melting and future estimate might improve our predictive capacity, which will be further explored in WP4.

Objective 6 Reducing and evaluating the uncertainty in prediction systems

By quantifying the potential impact of the Arctic land ice melting, we have further estimated the error that may be introduced by neglecting this process, as shown in the comparison with observations made in the result section. The comparison of a climate model and a high-resolution sea ice-ocean model also suggests that the climate model underestimates the impact of the land ice melting on ocean circulation.

Objective 7 Fostering the capacity of key stakeholders to adapt and respond to climate change and boosting their economic growth

By participating in the IPCC SROCC report, results from the topic touched in this deliverable have been disseminated largely towards key stakeholders, who may possibly better account for the uncertainty related with the risk of abrupt changes in the North Atlantic.

Objective 8 Transferring knowledge to a wide range of interested key stakeholders

By diffusing within IPCC SROCC report, the knowledge gained in this deliverable has undoubtedly been transferred to a wide range of key stakeholders.

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Dissemination and exploitation of Blue-Action results

Dissemination activities

Type of dissemination activity	Name of the scientist (institution), title of the presentation, event	Place and date of the event	Type of Audience	Estimated number of persons reached	Link to Zenodo upload
Participation to a workshop	Didier Swingedouw (CNRS), Presentation "Potential for abrupt changes in the Atlantic Ocean Circulation: insights from climate models, space and in situ observations". Invited overview for the ISSI workshop.	Bern (CH), 15-18 April 2019	Scientific Community (higher education, Research)	30	http://doi.org/10.5281/zenodo.3062628
Participation to a conference	Didier Swingedouw (CNRS) Presentation on "Quand les courants marins changent de cap", Palais de la Decouverte.	Paris (FR), 20 March 2019	General public	80	http://doi.org/10.5281/zenodo.3060273
Participation to an event other than a conference or workshop	Didier Swingedouw (invited by CNRS): HDR thesis of G. Gastineau. Decadal climate variability: mechanisms and impacts.	Paris (FR), 18 January 2019	Scientific Community (higher education, Research)	40	http://doi.org/10.5281/zenodo.2669405
Organisation and participation to a	Didier Swingedouw (CNRS) presentation of "Impacts of the observed melting of Greenland ice sheet and Arctic land ice over the	Bordeaux (FR), 27-28 May 2019	Scientific Community (higher education,	70	https://zenodo.org/record/3470994

conference	North Atlantic in a climate model", CMIP6 workshop.		Research)		
Participation to a workshop	Didier Swingedouw (CNRS) presentation of: "Tipping point of the climate system: risk, impact and resilience strategy for society" Colloque *Resilience*.	Bordeaux (FR), 3-4 April 2018	Scientific Community (higher education, Research)	50	https://zenodo.org/record/3471456
Participation to a conference	Didier Swingedouw (CNRS) presentation of: "Le changement climatique peut-il augmenter le risque de gelées tardives ?" .Journées des Oenologues	Bordeaux, (FR), 16 March 2018	Industry	300	https://zenodo.org/record/3471462
Participation to a workshop	Didier Swingedouw (CNRS) presentation of: “Changement abrupt de climat en Atlantique Nord” for the visit of Alain Juppé (former prime minister of France)	Bordeaux (FR), 16 March 2017	Scientific Community (higher education, Research), Policy makers	30	https://zenodo.org/record/3471537
Video	Seminar (video associated on the web) by Didier Swingedouw (CNRS) presentation of: "Le jour d'apres est-il pour demain ? Quels risques pour le climat en cas de changement rapide de la circulation oceanique en Atlantique Nord" French Ministry for ecologic transition and solidarity.	Paris (FR), 21 December 2017	Policy makers	100	https://zenodo.org/record/3471517
Other	Marion Devilliers (CNRS-EPOC), Poster “Impacts of the observed melting of Greenland ice sheet and Arctic land ice over the North Atlantic in a climate model” (poster)	Vienna (AT), 7-12 April 2019	Scientific Community (higher education, Research)	50	https://doi.org/10.5281/zenodo.3467549
Organisation of a conference	Didier Swingedouw (CNRS) “Observing and understanding the Atlantic Meridional Overturning Circulation”	Plouzané (FR)	Scientific Community (higher education, Research)	100	https://www.epoc.u-bordeaux.fr/indiv/Didier/public_html/COLLOQUE/Final/
Other	Marion Devilliers (CNRS-EPOC): Poster “Impacts of the observed melting of Greenland ice sheet and Arctic land ice over the North Atlantic in a climate model”	Brest (FR), 24-27 June 2019	Scientific Community (higher education, Research)	30	https://www.zenodo.org/communities/blue-actionh2020/

Peer-reviewed articles

Title	Authors	Publication	DOI	Is Blue-Action correctly acknowledged?	Open Access granted
Abrupt cooling over the North Atlantic in modern climate models	Sgubin G., Swingedouw D., Drijfhout S., Mary Y. and Bennabi A.	*Nature Communications* 8, no 14375.	DOI: 10.1038/ncomms 14375	Yes	Yes
Impact of freshwater release in the Mediterranean Sea on the North Atlantic climate	Swingedouw D. Colin C., Eynaud F., Ayache M., Zaragosi S.	*Climate Dynamics*	https://doi.org/10.1007/s00382-019-04758-5.	Yes	Yes

Other publications

These are the publications currently in preparation, submitted, in review, accepted:

- Swingedouw D., Conversi A., Bartsch A., Ifejika Speranza C., Durand G., Jamet C*.,* Beaugrand G., Early warning from space for a few key tipping points in physical and biological systems, and in societies, *Review in Geophysics,* In preparation
- Devilliers M., Swingedouw D., Mignot J., Deshayes J., Garic G., Ayache M., A realistic Greenland and surroundings melting in a coupled climate model, Climate Dynamics, In preparation

These are the publications of those involved in this deliverable.

- Moffa-Sanchez, P., E. Moreno-Chamarro, D. J. Reynolds, P. Ortega, L. Cunningham , D. Swingedouw, D. E. Amrhein, J. Halfar, L. Jonkers, J. H. Jungclaus, K. Perner, A. Wanamaker and S. Yeager (2019) Variability in the northern North Atlantic and Arctic oceans across the last two millennia: A review/ *Paleoceanography*, 34:1399-1436.
- Sgubin G. , Swingedouw D., Garcia de Cortazar-Atauri I.,Ollat N. and van Leeuwen C. (2019) The Impact of Possible Decadal-Scale Cold Waves on Viticulture over Europe in a Context of Global Warming. *Agronomy*, 9, 397; doi:10.3390/agronomy9070397.
- Swingedouw D. Colin C., Eynaud F., Ayache M., Zaragosi S. (2019) Impact of freshwater release in the Mediterranean Sea on the North Atlantic climate. *Climate Dynamics*, published online https://doi.org/10.1007/s00382-019-04758-5.
- Colin C. et al. (2019) Millennial-scale variations of the Holocene North Atlantic mid-depth gyre inferred from radiocarbon and neodymium isotopes in cold water corals. *Quat. Sc. Rev.* 211, 93-106.
- Etourneau J. et al. (2019) Ocean versus atmosphere control on ice shelf vulnerability along the eastern Antarctic Peninsula. *Nature Communications* 10, Art. No 304.
- Eynaud F., Mary Y., Zumaque J., Wary M., Gasparotto M-C., Swingedouw D., Colin C. (2018) Compiling multiproxy quantitative hydrographic data from Holocene marine archives in the North Atlantic: A way to decipher oceanic and climatic dynamics and natural modes? *Global and Planetary Changes* 170, pp. 48-61.

- Ayache M. Swingedouw D., Mary Y., Eynaud F., Colin C. (2018)AMOC variability over the Holocene: A new reconstruction based on multiple proxy-based SST records.*Global and Planetary Changes* 170, pp. 172-189.
- Crosta X., Crespin J., Swingedouw D., Marti O., Masson- Delmotte V., Etourneau J., Goosse H., Braconnot P., Yam R., Brailovski I., Shemesh A. (2018) Ocean as the main driver of Antarctic ice sheet melting during the Holocene. *Global and Planetary Changes* 166, pp. 62-74.
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- Menegoz M., Cassou C., Swingedouw D., Bretonniere P.-A., Doblas-Reyes P. (2018) Modulation of the climate response to a volcanic eruption by the Atlantic Multidecadal Variability. *Climate dynamics* 51 (5-6), pp. 1863-1883.
- Sgubin G. Swingedouw D., Dayon G., GarcÃa de Cortazar-Atauri I., Ollat N., Bois B., Page C., Van Leeuwen C. (2018) The risk of tardive frost damage in French vineyards in a changing climate. *Agricultural and Forest Meteorology* 250, pp. 226-242.
- Bouttes N., Swingedouw D., Roche D., Sanchez-Goni M. and Crosta X. (2018) Response of the carbon cycle to the different orbital configurations of the last 9 interglacials. *Climate of the past*, 14, pp. 239-253.
- Cruz, P., Winkel T., Ledru P.-P., Bernard C., Egan N., Swingedouw D., Joffre R. (2017) Rainfed agriculture thrived despite climate degradation in the pre-hispanic arid andes. *Science advances* 3 (12), no e1701740.
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- Sgubin G., Swingedouw D., Drijfhout S., Mary Y. and Bennabi A. (2017) Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications* 8, no 14375.
- Germe A., Sevellec F., Mignot J., Swingedouw D., Nguyen S. (2017) Do oceanic initial state uncertainties matter for near term climate prediction? *Climate Dynamics* 48 (1-2) 353-366.

Uptake by the targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is the general public (PU) is and is made available to the world via CORDIS.

This is how we are going to ensure the uptake of the deliverables by the targeted audiences:

- Through dissemination at relevant scientific events (EGU…).
- Through dissemination to relevant non scientific audiences, such as civil society, businesses and policy makers via IPCC SROCC report and events like the one reported in Blue-Action deliverable D8.8 Societal Engagement Knowledge Exchange Nr. 2, on Ocean observations and predictions in response to the climate emergency.