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Impact of Greenland orography on the Atlantic Meridional Overturning Circulation / Davini, P.; von Hardenberg, J.; Filippi, L.; Provenzale, A.. - In: GEOPHYSICAL RESEARCH LETTERS. - ISSN 0094-8276. - 42:3(2015), pp. 871-879. [10.1002/2014GL062668]

Availability:
This version is available at: 11583/2814812 since: 2020-04-22T12:04:10Z

Publisher:
AMER GEOPHYSICAL UNION

Published
DOI:10.1002/2014GL062668

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27 April 2024

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL062668

Key Points:
- The removal of Greenland ice sheet affects the intensity of the AMOC

Supporting Information:
- Supporting Information S1

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Citation:
Davini, P., J. von Hardenberg, L. Filippi, and A. Provenzale (2015), Impact of Greenland orography on the Atlantic Meridional Overturning Circulation, *Geophys. Res. Lett.*, *42*, 871–879, doi:10.1002/2014GL062668.

Received 2 DEC 2014
Accepted 13 JAN 2015
Accepted article online 16 JAN 2015
Published online 9 FEB 2015

Impact of Greenland orography on the Atlantic Meridional Overturning Circulation

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Abstract We show that the absence of the Greenland ice sheet would have important consequences on the North Atlantic Ocean circulation, even without taking into account the effect of the freshwater input to the ocean from ice melting. These effects are investigated in a 600 year long coupled ocean-atmosphere simulation with the high-resolution global climate model EC-Earth 3.0.1. Once a new equilibrium is established, a cooling of Eurasia and of the North Atlantic and a poleward shift of the subtropical jet are observed. These hemispheric changes are ascribed to a weakening of the Atlantic Meridional Overturning Circulation (AMOC) by about 12%. We attribute this slowdown to a reduction in salinity of the Arctic basin and to the related change of the mass and salt transport through the Fram Strait—a consequence of the new surface wind pattern over the lower orography. This idealized experiment illustrates the sensitivity of the AMOC to local surface winds.

1. Introduction

Greenland and its ice sheet represent one of the most relevant orographic barriers for the Northern Hemisphere westerly flow. Located between 60°N and 80°N, Greenland reaches an elevation of 3200 m, and it extends for more than 2500 km in the north-south direction and 1100 km in the east-west direction. This topographic relief, together with the high surface albedo, generates a cold interior and consequently has a relevant thermodynamical impact on transient air masses. The Greenland ice sheet represents also a freshwater reservoir equivalent to a global sea level rise of 7 m [*Gregory et al.*, 2004].

Given these characteristics, in the last decades the role of Greenland in the climate system has been at the center of scientific attention. The freshwater flux from a melting ice sheet has the potential to modify the Atlantic Meridional Overturning Circulation (AMOC) [*Driesschaert et al.*, 2007; *Vellinga and Wu*, 2008; *Vizcaíno et al.*, 2008]. In addition, the presence of Greenland perturbs the atmospheric flow and the pattern of stationary planetary waves, influencing the position of the negative center of action of the North Atlantic Oscillation (NAO) which is placed right downstream of Greenland [*Kristjánsson and McInnes*, 1999].

As a consequence, several authors have performed experiments modifying the Greenland orography in general circulation models (GCMs). Atmospheric-only (AGCM) simulations where Greenland was replaced by a flat surface at sea level showed a significant reduction of the stationary wave pattern of the Northern Hemisphere [*Petersen et al.*, 2004; *Dethloff et al.*, 2004]. *Junge et al.* [2005] also detected an eastward shift of the NAO and a reduction of the storm activity in the North Atlantic.

Coupled atmosphere-ocean simulations, in which the current Greenland orography was substituted with the bedrock lying beneath the ice sheet, found a warming over Greenland of up to 30°C in summer and of about 15°C in winter [*Lunt et al.*, 2004; *Toniazzo et al.*, 2004; *Stone and Lunt*, 2013]. Such warming can be only partially explained by the lower elevation of the new orography. While during summer the warming is strengthened by a positive snow albedo feedback, even involving sea ice retreat [*Lunt et al.*, 2004], during winter warm anomalies spread over the Western Arctic and they are associated with a cyclonic circulation that develops over Greenland [*Toniazzo et al.*, 2004; *Stone and Lunt*, 2013].

The experiments mentioned above were performed using GCMs with low horizontal resolutions (on the order of 3–4°C) and in many instances with fixed oceanic boundary conditions. Even when the simulations included an active ocean, the time of integration was of only a few decades and therefore an adjustment of the ocean circulation to the new conditions may not have been achieved.

In the present work we explore this topic further and we show that the Greenland orography has a strong impact on the North Atlantic circulation, even when the effects of freshwater input from ice melting are

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discarded. To this end, we use a state-of-the-art GCM, performing a 600 year high-resolution coupled simulation where the current Greenland orography is replaced with that of the bedrock under the ice sheet. The resolution of the model (about 1° for the ocean and about 0.75° for the atmosphere) provides a rather detailed representation of the atmospheric and oceanic circulations in a highly sensitive region such as the North Atlantic and may be extremely important for properly capturing the response of the coupled climate system. Moreover, the large time of integration allows for adjustment of the ocean to the new atmospheric forcing.

Recent studies have shown that atmosphere-ocean feedbacks can be particularly relevant in this region. *Timmermann and Goosse* [2004] showed that removing the wind stress forcing induces a collapse of the AMOC. More recently, it has been shown that wind stress and air-sea fluxes anomalies in the subpolar North Atlantic can affect the AMOC intensity in both idealized models [e.g., *Schloesser et al.*, 2014] and GCMs. This can be caused by changes in the frequency of atmospheric blocking [*Häkkinen et al.*, 2011] or by anomalous phases of the NAO [*Lohmann et al.*, 2009; *Medhaug et al.*, 2012], generally mediated by changes in the strength of the Atlantic subpolar gyre [*Hátún et al.*, 2005].

For these reasons, we focus on the impact of orography-induced changes in the atmospheric circulation and on how these modify the ocean circulation, finally resulting in a global-scale change in the Northern Hemisphere.

2. Data and Method

In the present work we use the version 3.0.1 of the state-of-art atmosphere-ocean Global Circulation Model EC-Earth [*Hazeleger et al.*, 2010]. EC-Earth is based on the Integrated Forecast System (IFS, cycle 36r4) [*European Centre for Medium-Range Weather Forecasts*, 2009] atmospheric circulation model, developed by the European Centre for Medium-Range Weather Forecasts; on the Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land (H-TESSEL) land surface scheme [*Balsamo et al.*, 2009]; and on the Nucleus for European Modelling of the Ocean (NEMO) 3.3.1 oceanic circulation model [*Madec*, 2008] which includes the Louvain-la-Neuve Sea Ice Model (LIM3) sea ice model [*Vancoppenolle et al.*, 2012]. The atmospheric and oceanic components are coupled through OASIS3 [*Valcke*, 2013].

The atmospheric configuration of IFS adopted (T255L91) has a horizontal resolution of about 0.75° and 91 vertical levels, while the ocean/sea ice model grid is set at a horizontal resolution of about 1° and 46 vertical levels (ORCA1L46). For all simulations, well-mixed greenhouse gases and volcanic aerosol concentrations are fixed at the values of year 2000, according to the historical scenario of the Coupled Model Intercomparison Project Phase 5 (CMIP5) protocol [*Taylor et al.*, 2012].

We perform a 110 year spin-up starting from present-day conditions (World Ocean Atlas 2001) [*Conkright et al.*, 2002], followed by two different experiments. The first of the two simulations, hereafter named CONTROL, is a 300 year long reference experiment. Although the model has not reached full statistical stationarity after the spin-up, in this experiment the global oceanic temperature is showing a weak drift of only +0.07°C/300 years. The second simulation, hereafter named BEDROCK, is 600 years long. It has the same boundary and initial conditions but a different Greenland orography, simulating a situation where the Greenland ice sheet has been completely removed. The standard orography is replaced with that of the bedrock underlying the ice sheet, according to the ETOPO1 data set [*Amante and Eakins*, 2009], without accounting for any isostatic adjustment and applying a smoothing aimed at neglecting subgrid features. The Greenland orographies for the CONTROL and BEDROCK experiments are shown in Figure 1a.

In the BEDROCK experiment the surface albedo of Greenland has been changed accordingly, using the seasonal cycle of the snow-free albedo from the Siberian Tundra (averaged over 80°E–130°E, 60°N –65°N). The initial Greenland snow depth is set to zero.

3. Results

If not stated differently, the last 200 years of each simulation (model years 101–300 for CONTROL and 401–600 for BEDROCK) are discussed in the following.

Locally, the response of the model to the removal of the Greenland ice sheet is in agreement with previous studies (Figures 1b–1d). In BEDROCK, the surface over the Greenland landmass warms by about 8°C on a

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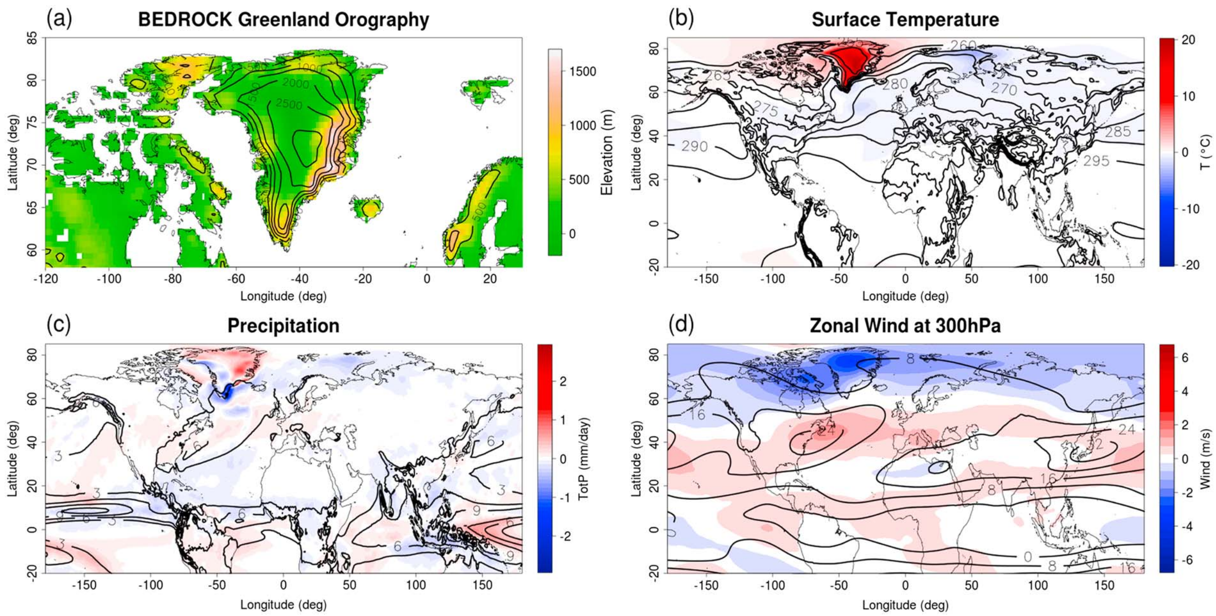

Figure 1. (a) CONTROL (contours) and BEDROCK (colors) orographies. Yearly mean of the last 200 years of simulations for (b) 2 m temperature, (c) precipitation, and (d) 300 hPa zonal wind. The CONTROL climatology (contours) and BEDROCK-CONTROL differences (colors) are shown. The significance of these changes (not shown) has been verified using a bootstrap technique.

yearly average (Figure 1b). A warming of several degrees is seen also around Greenland, with weaker and extended anomalies over the Western Arctic in winter and stronger and more localized anomalies in summer (not shown). The mechanisms leading to this new surface temperature pattern are similar to what was shown by *Toniazzo et al.* [2004] and *Stone and Lunt* [2013]. During summer, the imposed change of albedo favors the snow albedo and sea ice feedbacks that considerably reduce the snow and sea ice cover over Greenland and its surrounding seas. In this season the Greenland landmass warms by 13.8°C (with a maximum of 29.6°C), whereas the elevation feedback can account for only 8.4°C (assuming a standard atmospheric lapse rate of 6.4°C/1000 m and a mean elevation change of 1316 m). Conversely, during winter, the anticyclonic atmospheric circulation dominated by katabatic winds is replaced by a cyclonic circulation (Figures 2a and 2b). This cross-continental circulation advects the warm anomaly around Greenland, in particular spreading it on its westward side.

The absence of a high relief changes also the precipitation pattern over Greenland (Figure 1c). In BEDROCK, there is a net increase of precipitation over the northeastern part of Greenland, while it decreases over its southern tip (as seen also by *Dethloff et al.* [2004] and *Stone and Lunt* [2013]).

The wind field at 300 hPa becomes more zonal (Figure 1d), showing a less tilted and more penetrating Atlantic eddy-driven jet. A reduction in the magnitude of stationary eddies is also observed (not shown), in agreement with previous works [*Petersen et al.*, 2004; *Junge et al.*, 2005].

BEDROCK shows several large-scale changes which were not reported in past works. A poleward displaced subtropical jet, more evident over the Pacific and stronger in winter, is obtained (Figure 1d). Precipitation changes involve a slight southward displacement of the Intertropical Convergence Zone (ITCZ), which is evident looking at the dipoles over the Atlantic and Pacific oceans (Figure 1c). Those dipoles are stronger in summer and winter (not shown). Furthermore, an average cooling of −0.38°C (−0.54°C in winter) is observed over Eurasia (Figure 1b) (north of 45°N, between 0° and 180°E).

Similarly, there is a considerable decrease in sea surface temperatures (SSTs) over the North Atlantic, with a southward displacement of the North Atlantic current (Figure 2c) and a slight weakening of its intensity (not shown). Such colder SSTs, together with a stronger zonal flow (Figure 1d), are likely the cause of the cold anomalies over Eurasia (see also *Ridley et al.* [2005] and *Mikolajewicz et al.* [2007]). Indeed, such anomalies are stronger during wintertime (not shown). Owing to the same mechanism, sea ice concentration and thickness increase on the Barents Sea and the Eastern Arctic, while they decrease on the Western Arctic (not shown).

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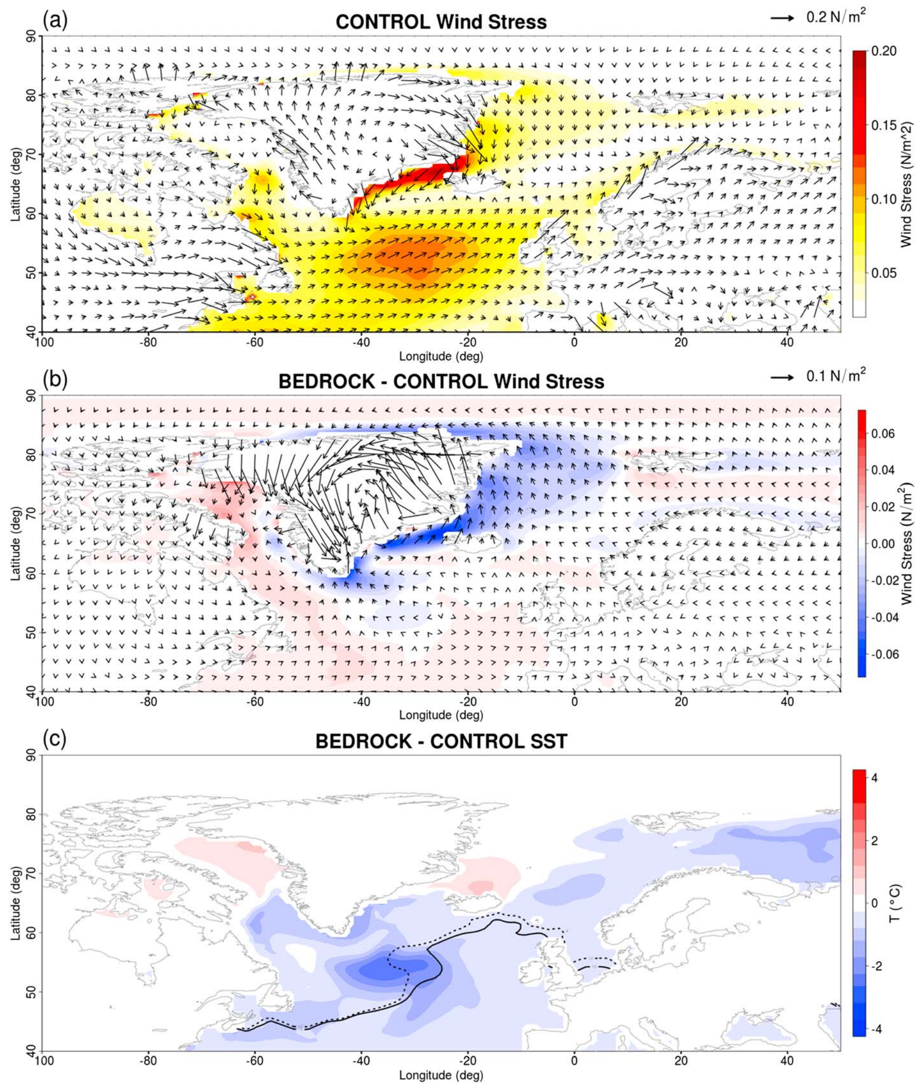

Figure 2. Wind stress direction (arrows) and intensity (colors, length of arrows) for (a) CONTROL and (b) BEDROCK-CONTROL differences. Wind stress intensity is shown only over sea in order to focus on the effect on the oceanic circulation. (c) BEDROCK-CONTROL SST differences. Lines represent the 10°C isotherm, representative of the North Atlantic current, for CONTROL (dashed line) and BEDROCK (solid line). All quantities have been averaged over the last 200 years of the simulations.

Globally, these findings show similarities with AGCM simulations with forced basin-scale cooling of the North Atlantic [*Sutton and Hodson*, 2007] but especially with coupled GCM experiments in which a reduction of the AMOC is obtained [e.g., *Zhang and Delworth*, 2005; *Vellinga and Wu*, 2008]. Indeed, the observed North Atlantic SST cooling is a common fingerprint in climate models, pointing to a slowdown of the AMOC [*Roberts et al.*, 2013].

In CONTROL, the average value of the AMOC index (defined as the yearly maximum of the meridional stream function between 38° and 50°N and between 500 and 2000 m of depth) is 17.88 sverdrup (Sv) ($\sigma = 1.46$ Sv), in reasonable accordance with observations [*Cunningham et al.*, 2007]. As shown in Figure 3a, in BEDROCK this value is reduced to about 14 Sv after approximately 50 years. This is followed by a slow recover, but after 400 years it seems to stabilize around a value of 15.71 Sv ($\sigma = 1.36$ Sv; averages and standard deviations are computed over the last 200 years of each experiment).

There is an important difference between BEDROCK and the simulations in *Zhang and Delworth* [2005] and *Vellinga and Wu* [2008]: these were hosing experiments in which a strong freshwater forcing was applied in the North Atlantic to force the AMOC slowdown. Conversely, in BEDROCK the Greenland ice sheet has been

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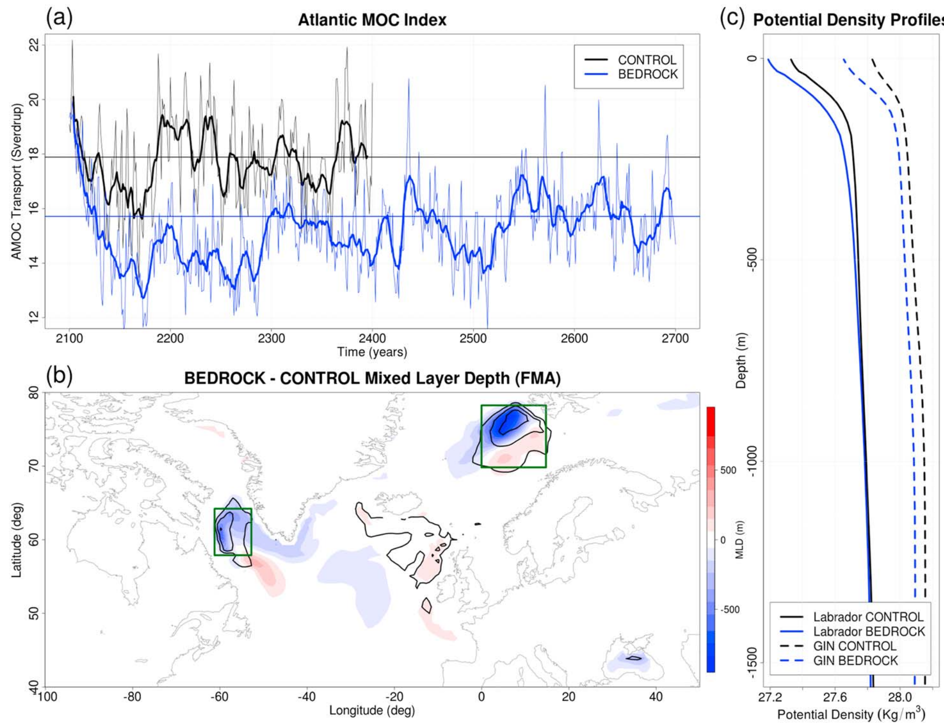

Figure 3. (a) AMOC transport for CONTROL (black) and BEDROCK (blue). Bold lines are 10 year running means. The AMOC index is computed as the yearly maximum of the meridional stream function between 38°N and 50°N and between 500 and 2000 m depth. Solid lines are the average over the last 200 years of the simulations. (b) Late winter (February-March-April) mixed layer depth for CONTROL (contours) and BEDROCK-CONTROL difference (colors). Mixed layer depth is defined as the level where the in situ density is increased by 0.03 kg/m^3 compared to the surface. (c) Potential density profiles for the Labrador and for the GIN sector. The corresponding regions are drawn as boxes in Figure 3b.

removed without including its equivalent freshwater contribution to the ocean. Moreover, the BEDROCK runoff over Greenland is slightly reduced with respect to CONTROL. Note that EC-Earth uses a simple runoff routing scheme, as a result of which runoff from Greenland is distributed rather uniformly in the surrounding ocean. For this reason, the change in the pattern of precipitation over Greenland (Figure 1c) cannot significantly affect the freshwater input to the ocean. In other words, the changes in the oceanic poleward heat transport observed in BEDROCK cannot be ascribed directly to modifications in the freshwater input to the ocean.

In EC-Earth simulations, the AMOC is characterized by two areas of deep water formation: one in the Labrador Sea and the other in the Greenland-Iceland-Norway (GIN) Seas, south of Svalbard. Figure 3b shows how in BEDROCK the AMOC slowdown is connected to the shallowing of the late winter (February-March-April) mixed layer depth in both areas.

Correlation analysis in CONTROL suggests that the AMOC index is especially associated with convective processes in the Labrador Sea. The correlation between the AMOC and the mixed layer depth in the Labrador Sea presents a maximum of 0.55 at a lag of 2 years (with AMOC following), while it is only 0.22 (no lag) in the GIN Seas (similar values are obtained for BEDROCK).

Potential density profiles reported in Figure 3c show that there is an increase of buoyancy in the upper layers, particularly in the Labrador Sea. Figure 4a, which plots the upper ocean (depth averaged between 0 and 350 m) salinity anomalies of BEDROCK with respect to CONTROL, shows that those changes can be ascribed to changes in salinity. There is a freshening in the Labrador and GIN Seas, but this is particularly strong in the Arctic Ocean. Larger negative salinity anomalies are observed in the Eastern Arctic (about −3 practical salinity units (psu)), while in the Beaufort Gyre the freshening is of about −0.5 psu. Density anomalies show similar patterns, whereas temperature does not (not shown), suggesting that salinity is the driver for density changes in the entire Arctic basin.

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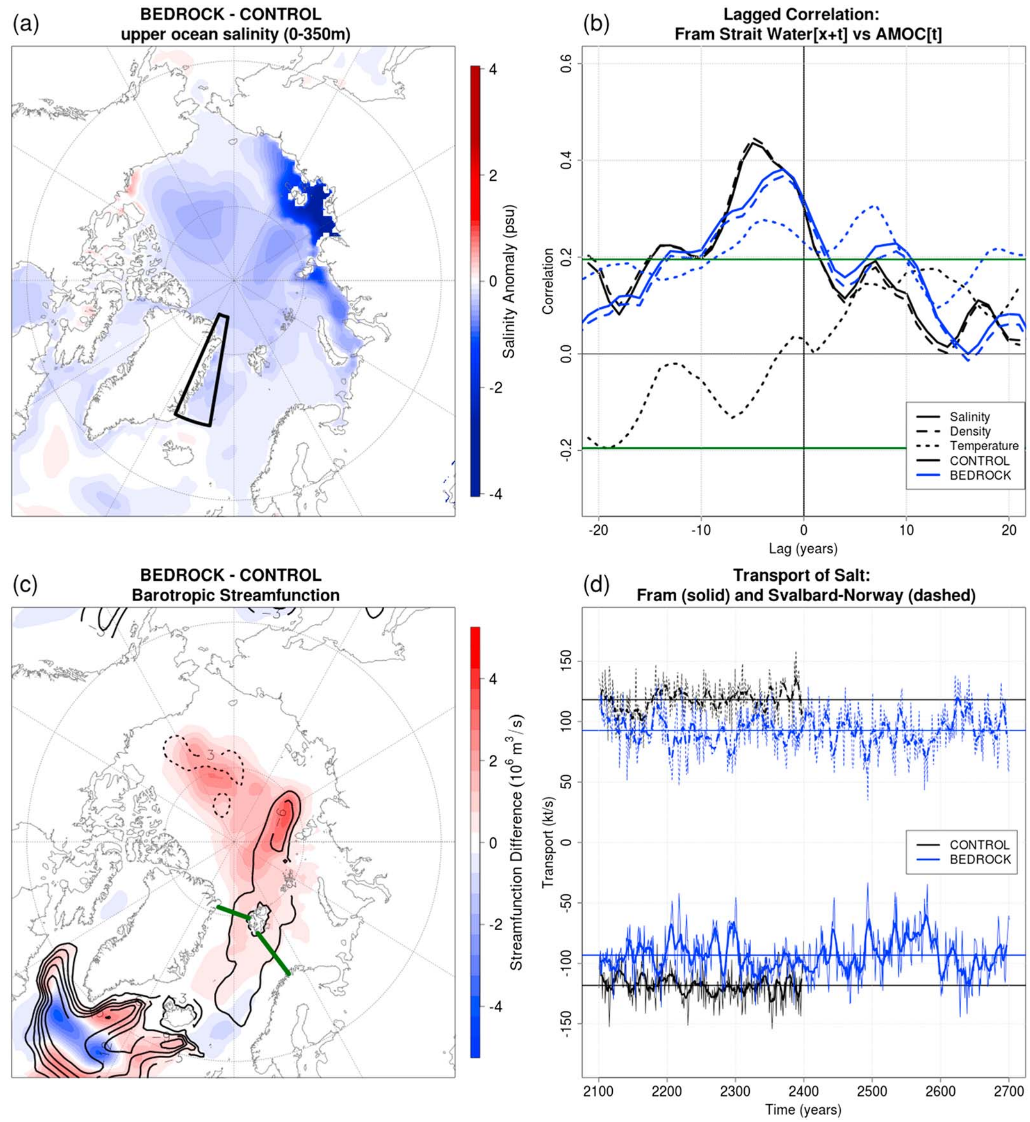

Figure 4. (a) Salinity difference between BEDROCK and CONTROL depth averaged between 0 and 350 m. (b) Lagged correlation between salinity and density in the Fram Strait water (identified by the box in Figure 4a) and the AMOC index. Green lines identify the 95% statistical significance levels computed by the Student's *t* test. (c) Barotropic stream function for CONTROL (contours) and BEDROCK-CONTROL difference (colors). (d) Transport of salt for BEDROCK (blue) and CONTROL (black) through the Fram strait (solid line) and through the Svalbard-Norway section (dashed line). Bold lines are the 10 year running means, and horizontal lines represent their averages over the last 200 years of each simulation. The two sections are identified by the solid green lines in Figure 4c.

Arctic currents are known for exporting water from the Fram Strait (between Greenland and Svalbard). This water is then transported southward along the coast by the East Greenland, West Greenland, and Labrador currents into the Labrador Sea. Given the constant average positive freshwater input (due to precipitation and runoff) and to the weak evaporation, Arctic waters are less saline than Atlantic waters. Together with sea ice export, the total flux through the Fram Strait represents thus a net freshwater export.

Such Arctic freshwater export, both liquid and solid, has been shown to be a key driver for AMOC variability [e.g., *Jungclaus et al.*, 2005; *Koenigk et al.*, 2006]. We tested the role of sea ice export through the Fram Strait finding in BEDROCK a reduction of about 15% (0.049 Sv in CONTROL). This specific mechanism should thus favor an increase of salinity in the Labrador Sea, contrary to that found in BEDROCK.

Conversely, the negative salinity anomalies seen in the Arctic for BEDROCK can be tracked following the path of the main boundary currents from the Beaufort Gyre along the coast of Greenland up to the areas

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where deep water is formed in the Labrador Sea. The lagged correlation in Figure 4b indicates that salinity and density fluctuations of the upper ocean waters in the Fram Strait lead the changes in the intensity of the AMOC by a few years. It is therefore reasonable to conclude that the reduction of the AMOC is driven by the Arctic liquid water export through the Fram Strait and that the reduction in sea ice export is not large enough to counterbalance this effect.

But why has the Arctic become significantly less saline in the BEDROCK experiment? The Arctic salinity is controlled by several factors, such as changes in the sea ice volume or in the total freshwater flux (given by precipitation (P), minus evaporation (E), plus runoff (R), minus net sea ice export water equivalent (I), $P-E+R-I$). However, a major role is played by variations in the salt and mass fluxes across the Arctic ocean boundaries [e.g., *Zhang et al.*, 1998; *Häkkinen and Proshutinsky*, 2004; *Köhl and Serra*, 2014].

In BEDROCK, no significant changes can be observed in the Arctic $P-E+R-I$ or in sea ice volume. However, Figure 2b shows a notable reduction of wind stress along the Fram Strait. This reduces the cyclonic wind stress curl over the GIN Seas and weakens the associated cyclonic wind-driven circulation that drives the Arctic/Atlantic water exchange, as suggested by the changes in the barotropic stream function (Figure 4c). This leads to a reduction of the exchanges between the Arctic and Atlantic oceans.

This behavior can be illustrated by a simplified Arctic/Atlantic box model, where in a steady state the mass and salt fluxes across the boundaries can be written as

$$F_{\text{in}} + F_{\text{freshwater}} - F_{\text{out}} = 0 \qquad s_{\text{Atlantic}}F_{\text{in}} = s_{\text{Arctic}}F_{\text{out}} \tag{1}$$

where F_{in} is the liquid water flux entering the Arctic, F_{out} is the liquid water flux exiting the Arctic, $F_{\text{freshwater}}$ is the freshwater flux ($P-E+R-I$), and s is the salinity in the Atlantic and the Arctic oceans.

Thus, we can write

$$s_{\text{Arctic}} = \frac{s_{\text{Atlantic}}F_{\text{in}}}{F_{\text{in}} + F_{\text{freshwater}}} \tag{2}$$

This means that a weaker oceanic mass transport through the boundaries implies a reduction of the salinity in the Arctic ocean. Further details on the box model (and a more general nonsteady version including the contribution from the Pacific ocean) can be found in the supporting information.

Exchanges between the Arctic and other oceans operate through four different sections: Pacific water enters through the Bering Strait, and Atlantic water enters through the Svalbard-Norway section. Arctic outflows are moving across the Canadian Archipelago and the Fram Strait. In BEDROCK, negligible changes in the oceanic mass transport are observed across the Bering Strait and the Canadian Archipelago (Table S1 in supporting information). Conversely, there is a decrease on the order of 25% through the Svalbard-Norway section and the Fram Strait: In CONTROL the oceanic mass fluxes into the Arctic are 3.40 Sv in the Svalbard-Norway section and −3.47 Sv in the Fram strait. These are reduced to 2.66 Sv and to −2.66 Sv, respectively, in the BEDROCK simulation. We find a negligible change in $F_{\text{freshwater}}$ (from 0.109 Sv in CONTROL to 0.106 Sv in BEDROCK). The reduced oceanic mass transport is associated with smaller salt fluxes (Figure 4d). This implies that, according to (2), a new equilibrium with a fresher Arctic has been established.

In BEDROCK, oceanic salt and mass transport through the Fram Strait is reduced over the first few years of the simulation (Figure 4d); this strengthens the idea of a wind-induced change in transport, driven by the new atmospheric circulation developed over the lower orography in BEDROCK. Conversely, the salt transport into the Arctic decreases only after 20–30 years from the beginning, suggesting a delayed oceanic response driven by the conservation of mass.

4. Discussion and Conclusions

In this work we have analyzed the effect of the removal of the Greenland ice sheet on the North Atlantic circulation with a fully coupled, high-resolution GCM. Whereas local differences, driven by circulation changes and a darker surface albedo, are in agreement with previous works [e.g., *Dethloff et al.*, 2004; *Toniazzo et al.*, 2004], we find an important slowdown of the AMOC by about 12%. In agreement with this weakening of the meridional overturning an increase in the atmospheric poleward heat transport (not shown) and a shift of the ITCZ and of the jet streams are observed. A similar increase of atmospheric

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transport in response to a reduction of the AMOC was already observed by *Zhang and Delworth* [2005] and *Vellinga and Wu* [2008], in experiments in which the AMOC was reduced forcing the Atlantic with an extra freshwater input.

The mechanism leading to this new equilibrium can be summarized as follows. The lowering of the Greenland orography modifies the high-latitude wind pattern, forcing a cyclonic anomaly that weakens the surface winds along the eastern coast of Greenland. The anomalous wind stress curl weakens the wind-driven circulation in the GIN Seas slowing the Eastern Greenland current. Consequently, a smaller transport of mass through the Fram Strait is observed. In order to conserve mass, less water is transported into the basin through the Svalbard-Norway section. Since the salt content in the Arctic is strongly related to the Atlantic inflow [e.g., *Häkkinen and Proshutinsky*, 2004; *Köhl and Serra*, 2014], a decrease in the salinity of the basin is initiated. The freshening is greatest along the pathway of the Atlantic water. In the first 20–30 years of the simulations the Arctic responds, decreasing its salinity and finally reaching a new equilibrium.

Arctic currents move fresher waters across the Fram Strait, reaching the Labrador Sea. Here they increase the buoyancy in the region where deep waters are formed, leading to the slowdown of the AMOC. As a consequence, the North Atlantic cools, favoring the formation of cold temperature anomalies also over Europe and Asia. The reduction of the AMOC is finally followed by a response of the atmosphere, which changes the meridional and zonal circulation balancing the global poleward heat transport.

This mechanism shares many similarities with the one highlighted by *Köhl and Serra* [2014], although in our case the wind stress changes affect the intensity of outflow from the Fram Strait and not from the Canadian Archipelago. Indeed, our oceanic model shows weak sensitivity in that region, and this can be caused by the oceanic horizontal resolution which may be insufficient to solve the complex bathymetry on the western side of Greenland. A higher oceanic resolution may also improve the representation of the eddies and boundary currents in the subpolar North Atlantic, affecting the regional buoyancy.

However, our idealized experiment confirms the striking role of the atmosphere-ocean coupling at high latitudes, showing how a local warming can actually lead to hemispheric cooling. Even though we must keep in mind that the observed results can be model dependent, we have shown that local changes in the atmospheric circulation are able to modify the oceanic circulation, which in turn leads to a new global atmospheric circulation. This is particularly interesting if we consider that Greenland occupies roughly 1.45% of the Earth's landmass. A similar large-scale change was not reported in past works working at lower resolution, suggesting that the role of oceanic and atmospheric resolution can be fundamental for properly representing the full sequence of feedbacks in action in this region.

Acknowledgments
Data from EC-Earth simulations are available upon request from the authors. This work has been funded by the Project of Interest "NextData" of the Italian Ministry of Education, University and Research (MIUR) (http://www.nextdataproject.it).

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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