ENVIRONMENTAL RESEARCH
LETTERS

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To cite this article: Lingling Suo *et al* 2017 *Environ. Res. Lett.* **12** 074004

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
25 November 2016

REVISED
28 March 2017

ACCEPTED FOR PUBLICATION
31 March 2017

PUBLISHED
28 June 2017

LETTER

Sea-ice free Arctic contributes to the projected warming minimum in the North Atlantic

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Keywords: sea-ice free Arctic, North Atlantic warming minimum, AMOC weakening, regional climate change, atmosphere–ocean interaction

Supplementary material for this article is available online

Abstract

Projected global warming is not spatially uniform and one of the minima in warming occurs in the North Atlantic (NA). Several models from the Coupled Model Intercomparison Project Phase 5 even projected a slight NA cooling in 2081–2100 relative to 1986–2005. Here we show that, by our simulations performed with the Bergen Climate Model (BCM), an autumn (September to November) sea-ice free Arctic (SIF) contributes to the NA warming minimum by weakening the Atlantic meridional overturning circulation (AMOC). The role of the air–sea interaction in the response to the SIF, which has not been widely discussed in the literature, has been highlighted by the results presented in this study.

1. Introduction

Climate model projections of the global warming in the late 21st century are not spatially uniform. The strongest warming occurs over the Arctic and a warming minimum is located in the North Atlantic (NA warming minimum) covering the Labrador Sea and extending to the mid-latitude NA (Collins *et al* 2013). Nearly all models projected a NA warming minimum and several models even projected a NA cooling, as reported in the IPCC Fifth Assessment Report (IPCC AR5) (Collins *et al* 2013, IPCC 2013). Possible causes of the NA warming minimum that have been discussed in previous studies include deep ocean convection in the Labrador Sea region (Lazier *et al* 2002), which has been proposed as an explanation of the slower ocean surface warming there (Manabe *et al* 1990). It is highly possible that the Atlantic meridional overturning circulation (AMOC) will weaken over the 21st century in association with the general global warming (Collins *et al* 2013). A reduction of the AMOC coincides with a cooling over the sub-polar region of the North Atlantic (Rahmstorf *et al* 2015) which could be a reason for the reduced warming intensity over the sub-polar NA.

It has been projected that the autumn Arctic sea-ice will probably disappear after the mid-21st century due to the strong Arctic warming projected for this period (Collins *et al* 2013, Overland and Wang 2013). It has been suggested that the disappearance of the Arctic sea-ice and the associated higher sea surface temperature (SST) in the Arctic in autumn will drive a negative Arctic Oscillation, increased precipitation, and warming over the Arctic in autumn (Suo *et al* 2016). A change in atmospheric circulation over the NA has the potential to modulate the ocean circulation: indeed it has been suggested that the negative North Atlantic Oscillation (NAO) in winter may act to weaken the AMOC (Delworth and Zeng 2015, Lohmann *et al* 2009). Furthermore, the net surface freshwater flux over the Atlantic region is also related to a weakening of the AMOC (Dahl *et al* 2005). Therefore a change in the AMOC may be expected if the autumn Arctic sea-ice decline leads to a change in the net surface freshwater flux (precipitation minus evaporation).

However, most of the previous studies on the impact of Arctic sea-ice decline are based on atmospheric general circulation model (AGCM) simulations which neglect the air–sea coupling. Those studies which used fully coupled models found that the air–sea coupling intensified and extended atmospheric responses to the Arctic sea-ice decline, but these studies did not address the ocean circulation change and how changes to the ocean circulation played a role in atmospheric responses (Deser *et al* 2015, Deser *et al* 2016, Petrie *et al* 2015, Semmler *et al* 2016, Blackport and Kushner 2016). Tomas *et al* (2016) investigated the atmospheric response to sea-ice reduction with and without ocean heat transport and found that the responses with ocean heat transport are more symmetric about the equator. How the changes in the ocean bridge the Arctic sea-ice decline and atmosphere response needs further study.

Here we use both the Bergen Climate Model 2 (BCM) (Otterå *et al* 2009) and its atmospheric component ARPEGE Climat3 (ARPEGE) (Déqué *et al* 1994) to study the linkage between the projected autumn sea-ice free Arctic (SIF) and the NA warming minimum. We show that the NA warming minimum can be partly explained by the SIF and is related to the weakening of the AMOC driven by a SIF. This finding also demonstrates that the air–sea coupling should not be neglected in studies concerning the impacts of the sea-ice retreat.

2. Model simulations

We have used the BCM (Otterå *et al* 2009) and its atmospheric component ARPEGE (Déqué *et al* 1994) to explore the atmospheric response to the projected SIF. The model version used in this study improves upon the original version in a variety of aspects. Importantly, conservation properties of the ocean model have been largely improved by adopting an incremental remapping scheme (Dukowicz and Baumgardner 2000), and the single layer sea-ice model has been replaced with the multi category model GELATO (Salas Mélia 2002). The ARPEGE is run with a truncation at wave number 63 (TL63), a time step of 1800s, 31 vertical levels ranging from the surface to 0.01 hPa and a horizontal resolution of approximately 2.8°. The ocean component is a further developed version of the isopycnic-coordinate model, MICOM (Bleck and Smith 1990, Bleck *et al* 1992, Assmann *et al* 2010), configured for an average horizontal resolution of approximately 2.4°, which is enhanced in the tropics and in the Arctic, and a stack of 34 isopycnic layers with a bulk mixed-layer at the top.

A fully coupled control run (Ctrl) and a fully coupled future projection run (Proj) have been performed with the BCM. The Ctrl run is a 380 years experiment with all greenhouse gas concentrations fixed at the year 2000 level. The Ctrl run is used to provide the initial conditions for the Proj simulations. Proj is integrated for the period 2000 to 2100 using the IPCC SRES A2 (business-as-usual) emission scenario (Meehl *et al* 2007) and then continued for an additional 20 years in stabilization mode with the anthropogenic forcing agents fixed at 2100 levels (for instance with an atmospheric CO_2 level of 836 ppm). The autumn mean of Arctic sea-ice area in the last 20 years of the Proj simulation is below 1 million km^2, which is often used as the criterion to define sea-ice free conditions (Collins *et al* 2013, Overland and Wang 2013).

The future projected surface air temperature (SAT) changes in the Proj SIF period relative to the Ctrl are obtained as the difference between the mean of the last 20 years in the Proj and the corresponding 20-year mean in the Ctrl. The corresponding 20 years in the Ctrl is selected as the [N-19, N] years from the Proj starting point in the Ctrl (online supplementary figure S1(*a*)). N is the simulation length of the Proj. The appearance of the NA warming minimum in the Proj is not sensitive to the selection of the comparison period in the Ctrl (figure S1(*b*) available at stacks.iop.org/ERL/12/074004/mmedia).

A partially-coupled control run (CtrlCoup) and a partially-coupled Arctic sea-ice sensitivity experiment (SensCoup) have also been performed with the BCM. Here, partially coupled means that over the Arctic region the atmosphere ‘sees’ a prescribed surface climatology while the ocean ‘sees’ a freely developing atmosphere. The system remains fully coupled outside the Arctic region (figure S2(*a*)). Inside of the Arctic region, the boundary conditions (SIC and SST) are prescribed as the daily varying Ctrl climatology for the CtrlCoup during all seasons, and for the SensCoup during all the seasons except in autumn, while the Proj SIF conditions are prescribed in autumn for the SensCoup (see Suo *et al* 2016 for further details). The prescribed sea-ice thickness is processed in the same way as SIC, in agreement with the selection of SIC. Both the SensCoup and the CtrlCoup contain four ensemble members which started from different initial conditions that sample different phases of AMOC variability in order to reduce the possible influence of the AMOC initial status on the simulated responses. Each ensemble member was run for 120 years with prescribed yearly repeating daily SST and SIC in the Arctic. The solar irradiance is kept constant and greenhouse gas concentrations are kept at the year 2000 level.

Another group of control runs (CtrlAtmos) and sensitivity experiments (SensAtmos) performed with ARPEGE used the same conditions as the CtrlCoup and SensCoup except that the ocean and atmosphere are not coupled anywhere and the daily SSTs are fixed as in the Ctrl (see for more details see Suo *et al* (2016)). The CtrlAtmos and SensAtmos contain four 50-year-long ensemble members.

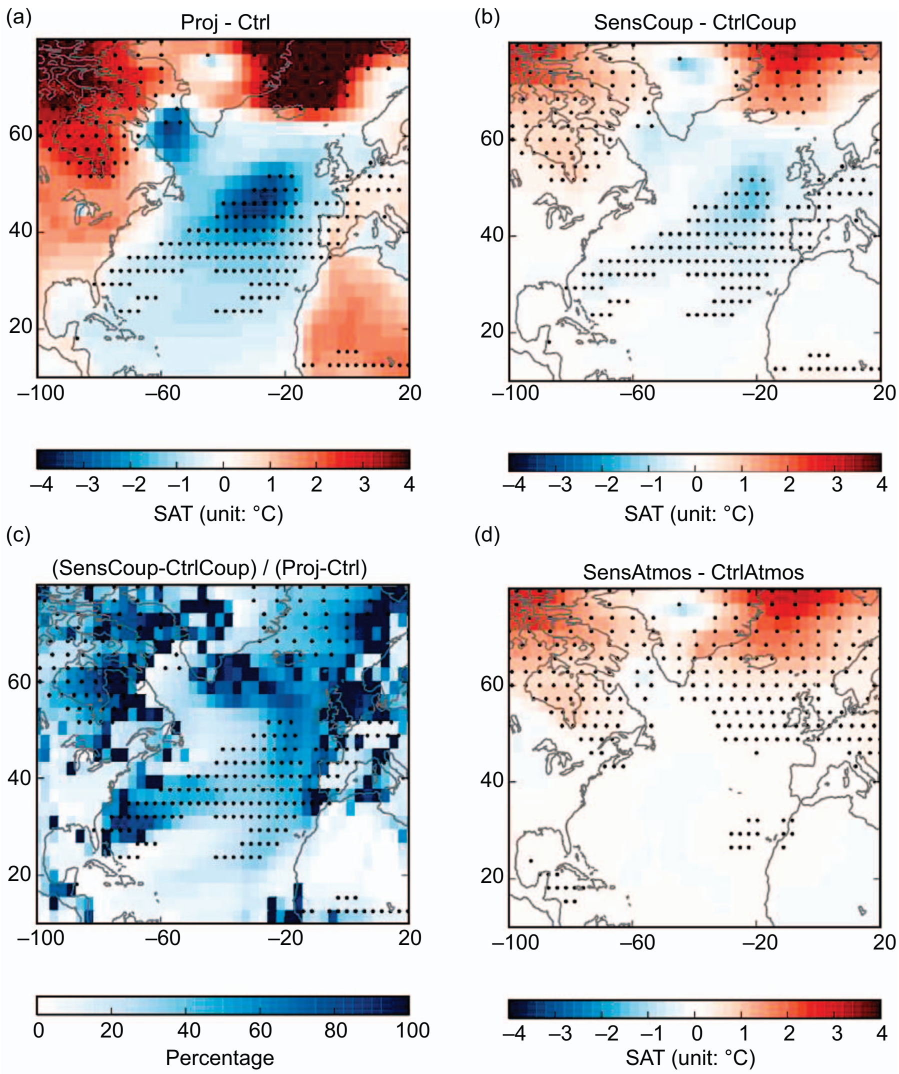

Figure 1. Annual mean SAT changes. (*a*) Deviation from the global mean of the difference between the Proj during the SIF period and the Ctrl, (*b*) in response to the SIF simulated with BCM, (*c*) ratios of (*b*) to (*a*) and (*d*) in response to the SIF simulated with ARPEGE. The percentage in regions where (*a*) and (*b*) show opposite signs is assigned to zero in (*c*). The dots in (*a–d*) show where the SAT responses to the SIF simulated with BCM/ARPEGE pass the 95% significance test.

The BCM simulated response to the SIF is defined as the ensemble mean of the differences in the 81–120 year mean between the SensCoup and the CtrlCoup. The last 40 years are selected because during this period the AMOC response to SIF has reached quasi-equilibrium. The SIF causes a weakening of the AMOC in the SensCoup relative to the CtrlCoup (see section 3). The weakening of the AMOC starts from the first decade with a decadal mean change of −0.4 Sv (1 Sv = 10^6 m^3s^{-1}), and this weakening intensifies during the first and second 40 years with a statistically significant ($\alpha = 0.05$) linear trend of −0.4 and −0.5 Sv decade^{-1} respectively, while there is no statistically significant ($\alpha = 0.05$) linear trend (−0.1 Sv decade^{-1}) during the last 40 years. For consistency, the ARPEGE simulated response is defined as the ensemble mean of the difference in the 40-years (11–50) mean between the SensAtmos and the CtrlAtmos.

The two-tailed Student's *t*-test has been used in this study to measure the significance of the responses.

3. Results

The simulated annual global mean SAT in the Proj SIF is 2.7 °C higher than in the Ctrl. The simulated warming is in the range of the 2081–2100 warming (RCP6.0) relative to 1986–2005 reported in the IPCC AR5 (Collins *et al* 2013). IPCC AR5 has reported that the projected annual and seasonal warming shows non-uniform spatial distribution with the strongest warming over the Arctic and a minimum warming over the NA (Collins *et al* 2013, IPCC 2013). After removing the globally-averaged SAT change, figure 1 (*a*) clearly shows that there is a much weaker warming over the NA compared to the global average, which is similar to the pattern reported in the IPCC AR5. The projected changes to the SAT over the NA relative to the global mean is more prominent in the boreal winter (December–January–February; DJF) and spring (March–April–May; MAM) than in summer (June–July–August; JJA)

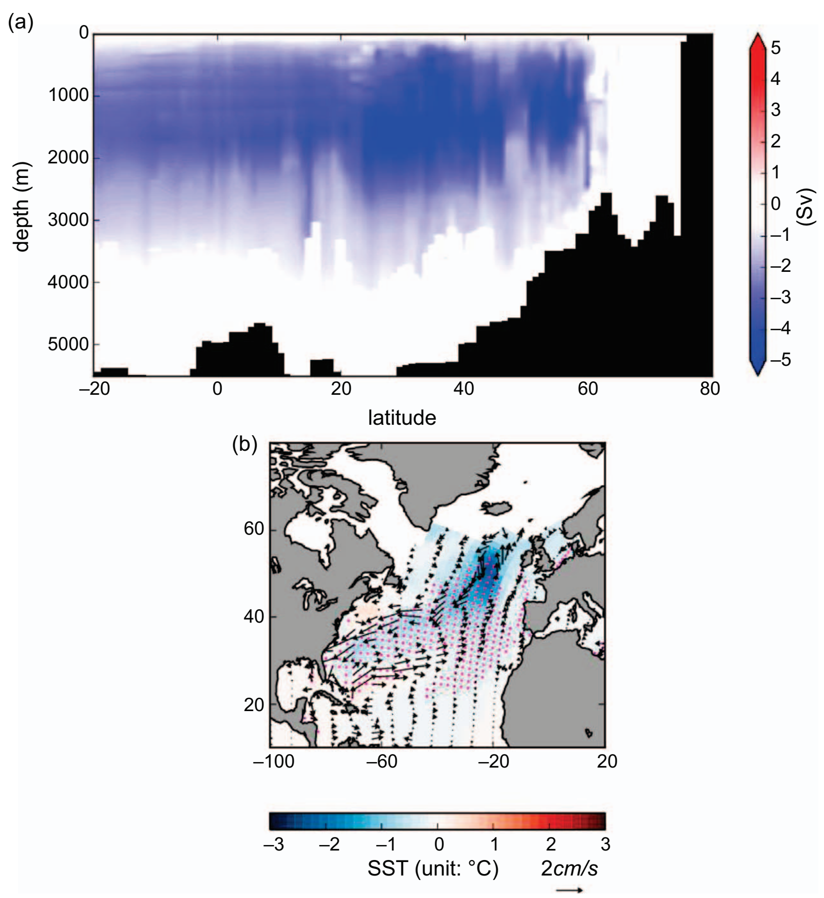

Figure 2. BCM simulated annual (*a*) stream function and (*b*) SST (colors) and ocean surface circulation (vectors) responses to the SIF in the SensCoup. In (*a*) only those responses which are significant at the 95% confidence level are shown and in (*b*) the SST changes which are significant at the 95% confidence level are marked by dots.

and autumn (September–October–November; SON) (figure S3(*a*)). In the central and northeastern NA, the difference in temperature change can reach −4.4, −4.1, −3.0, −2.2 and −3.4 °C in winter, spring, summer, autumn and in the annual mean respectively (figure S3(*a*) and figure 1(*a*)).

A similar pattern is present in the BCM simulated response to the projected SIF (figure 1(*b*)). The responses are obtained as the difference between the ensemble mean of the SensCoup and the CtrlCoup. Following the SIF, the negative SAT response can reach −1.7, −1.9, −1.4, −1 and −1.5 °C over the central and northeastern NA in winter, spring, summer, autumn and in the annual mean respectively (figure S3(*b*) and figure 1(*b*)), which can counteract about 63, 70, 52, 37, 56% of the BCM projected global mean warming (2.7 °C) in the Proj.

The similarity between the SAT response to the SIF and the projected non-uniform warming implies that the SIF will cool down the NA in the course of global warming, and so contribute to the NA warming minimum. The ratios between the SAT response to the SIF and the non-uniform warming are between 30% and 60% over the central and northeastern NA in all the seasons and the annual mean (figure 1(*c*) and figure S3(*c*)).

How does the SIF contribute to the NA warming minimum? By the persistence and modulation of the atmosphere circulation responses? Or is it bridged by the ocean? When the atmosphere–ocean interaction is excluded there is no statistically significant decrease in SAT over the NA in response to the SIF in a non-coupled system like ARPEGE (figure 1(*d*) and figure S3(*d*)). That means the atmospheric circulation changes in response to the SIF do not directly reduce SAT over the NA. Such a comparison between the results from the BCM and the ARPEGE illustrates the essential role of the atmosphere–ocean interaction in the SIF impact on the NA climate.

Figure 2 shows the ocean circulation changes in response to the SIF. The weakening of the AMOC is clearly seen in the difference between the SensCoup and the CtrlCoup. In the mean of the last 40 years the stream function weakening is up to 5.1 Sv (figure 2(*a*)). The weakening of the AMOC is robust and appears in all the four ensemble members (figure S4). The weakening of the AMOC is associated with the weakening of the North Atlantic Current (figure 2(*b*)) which indicates a decrease in northward heat transport in the mid-latitude North Atlantic. The ocean surface circulation anomalies are collocated with the southwest–northeast tilting ocean surface

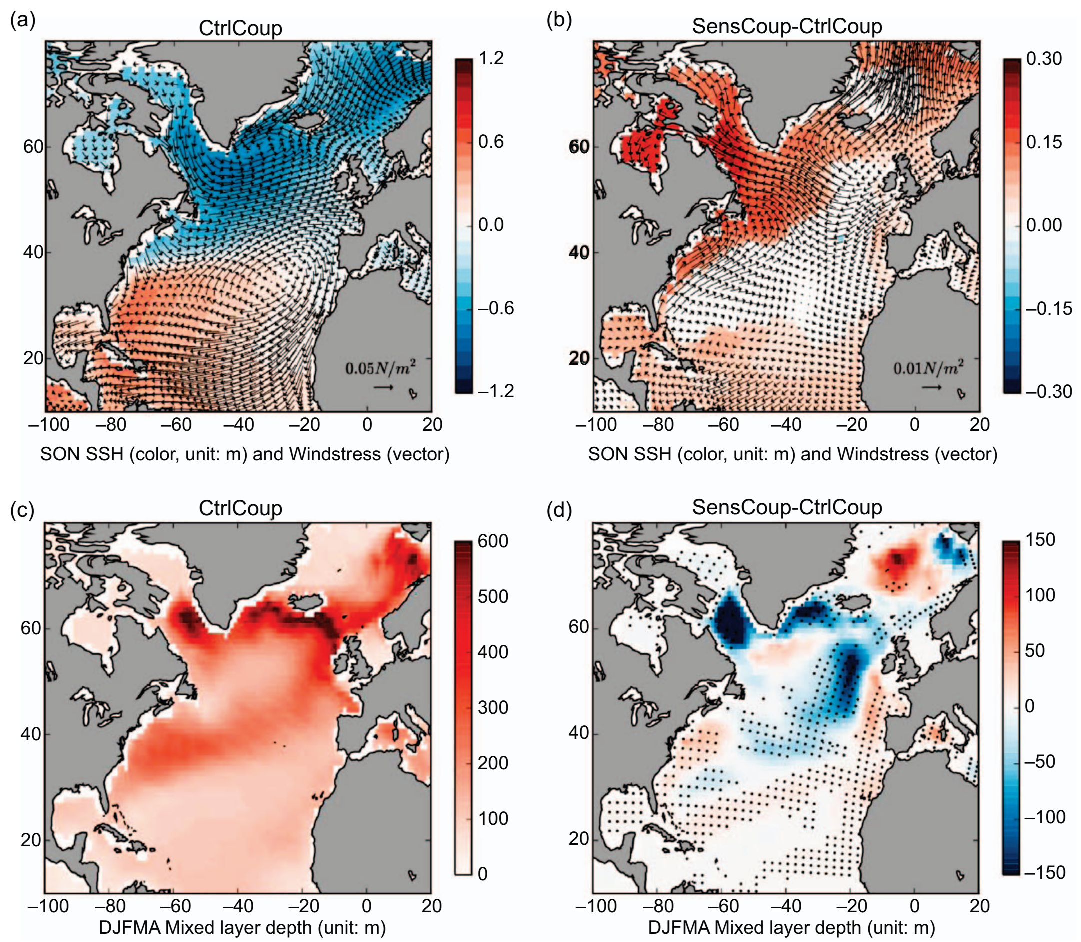

Figure 3. BCM simulated SON sea surface height (SSH, color) and windstress (vector) (*a*) in CtrlCoup 20 years mean and (*b*) responses to the SIF in SensCoup, and DJFMA mixed layer depth (*c*) in CtrlCoup 20 years mean and (*d*) responses to the SIF in the SensCoup. The responses which do not pass the 95% significance test are not shown in (*b*). In (*d*) the responses which are significant to the 95% confidence level are marked by dots. SON: September–October–November mean. DJFMA: Mean of extended winter (December–April) which is the season with clear open ocean convection in the BCM.

cooling over the NA which supports the hypothesis of a previous study that the future projected SST changes in the NA might be closely overlapped with the local surface ocean circulation change (Xie *et al* 2010). The statistically significant lower SST and weakened surface ocean circulation can be found in all the seasons and in the annual mean with the negative SST response reaching −2.8, −2.7, −1.8, −1.7 and −2.3 °C over the central and northeastern NA in winter, spring, summer, autumn and in the annual mean respectively (figure S5 and figure 2(*b*)). Thus, the SIF drives a weakening of the AMOC and consequently contributes to the NA warming minimum.

How does the SIF drive a weakening of the AMOC? Previous studies have indicated that a negative NAO appears in response to the Arctic sea-ice decline in autumn (Vihma 2014, Suo *et al* 2016). The sea-level pressure (SLP) response to the SIF in autumn shows a significantly weaker Icelandic low, in agreement with previous studies (figure S6). The weakened Icelandic low appears in both the BCM and the ARPEGE simulated SLP response. This has been associated with the intense heat flux release from the ocean and the warmed near surface atmosphere in the Arctic (Suo *et al* 2016). The wind stress in the CtrlCoup is cyclonic and located over the sub polar gyre in autumn (figure 3(*a*)). Associated with the weakened Icelandic low the wind stress anomalies are anticyclonic over the sub polar NA in autumn (figure 3(*b*)). Such reduced wind stress forcing causes a weakened sub-polar gyre (positive anomalous sea surface height (SSH) figure 3(*b*)). In winter, the SLP response shows a similar pattern as in autumn but with fewer locations having statistically significant responses over the NA region (figure S6), and this SLP response sustains the similarly anomalous wind stress forcing over the sub-polar gyre. Such positive SSH responses over the sub-polar gyre persist into the following spring and summer (figure S7). Deep convection in the CtrlCoup (as indicated by the ocean mixed layer depth during winter and spring) occurs mainly in the Labrador Sea and the Nordic seas (figure 3(*c*)). Associated with the weakened sub polar gyre, the intensity of the deep convection over the Labrador Sea and the sub polar NA becomes reduced (figure 3(*d*)) which contributes to the weakening of the AMOC. The phonemes shown here are in agreement with the previous studies although they

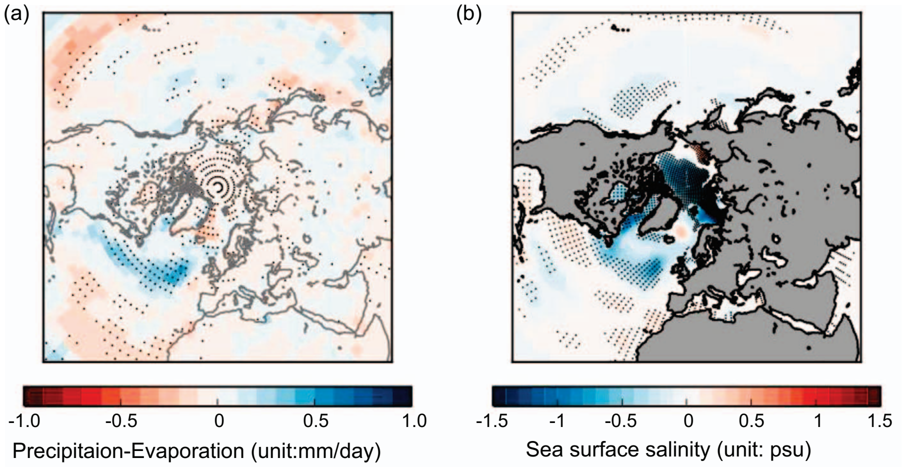

Figure 4. BCM simulated annual (*a*) precipitation minus evaporation and (*b*) sea surface salinity responses to the SIF. The responses which can pass the 95% significance test are marked by dots.

showed that the negative NAO in winter weakens the AMOC by altering the sub-polar gyre, while here the weakened Icelandic low happens mainly in autumn (Delworth and Zeng 2015, Lohmann *et al* 2009).

In addition, the net surface freshwater flux (precipitation minus evaporation) increases over the NA current region in response to the SIF (figure 4(*a*)). Such increased freshwater forcing can decrease ocean surface salinity over the sub-polar NA (figure 4(*b*)), especially when taken together with the reduced northward salt transport which accompanies a weakened AMOC. The freshening of the ocean surface layer also occurs in the Arctic Ocean (figure 4(*b*)). The atmosphere is warmed in areas where the prescribed sea-ice is free, which leads to a melting of the simulated sea-ice in the partial-coupling system. Such sea-ice reduction occurs quickly at the beginning of the SensCoup and the sea-ice area keeps stable during the simulation (figure S2(*b*)). Thus, the freshwater injected into the Arctic Ocean associated with sea-ice melting is released almost as a pulse at the beginning of the SensCoup, which causes a freshening in the central Arctic (figure S2(*c*)). Such a freshening pattern which is associated with a weakened AMOC is in agreement with the previous study of Bethke *et al* (2006). The seasonal freshwater flux and the sea surface salinity responses are similar to the annual responses (figure S8).

The freshening of the sub-polar NA and the Arctic Ocean is an important contributor to the weakening of the AMOC (Dahl *et al* 2005, Otterå *et al* 2004). In Otterå *et al* (2004), an additional 0.3 Sv freshwater was continuously added over the Nordic seas and the Arctic Ocean in the BCM during the 150 years integration, which simulated a maximum AMOC reduction of about 6 Sv over the first 50 years, followed by a gradual recovery to a level comparable to the control simulation. In contrast, the released freshwater into the central Arctic associated with the sea-ice melting happens mainly in the first year of the SensCoup, and the simulated Arctic sea-ice remains at a stable level (figure S2(*b*)). Therefore there is no continuous extra freshwater released into the central Arctic during the simulation when the simulated Arctic sea-ice is stable. On the other hand, the simulated Arctic sea-ice volume loss, which is obtained as the difference between the 120-year-mean sea-ice volume in the CtrlCoup and the SensCoup, is about 4.2×10^3 km^3. This amount of freshwater is equivalent to about 0.1 Sv over 1 year, 0.3% of the total amount in Otterå *et al* (2004). But the mean of the last 40 years of the AMOC weakening in the SensCoup is about 4.1 Sv, 68% of the maximum AMOC reduction simulated in Otterå *et al* (2004) and no AMOC recovery is shown in our study. Thus the gradually intensified weakening of the AMOC is mainly driven and sustained by the wind stress responses in the SensCoup.

4. Conclusions and discussions

A coupled climate model BCM and its atmospheric part ARPEGE have been employed to study the impact of the future projected SIF on the NA climate. The study presented here emphasizes the role of ocean–atmosphere interaction on the SIF impact, which has not been widely discussed. It has been found that the SIF contributes to the projected NA warming minimum by weakening the AMOC. The weakened AMOC is driven and sustained by the weakened wind stress over the sub polar gyre associated with a weaker Icelandic low in autumn, and is accompanied by a freshening of the ocean surface layer in the sub-polar North Atlantic Ocean.

In our SensCoup simulation the atmosphere gets warmer in the Arctic in response to the SIF conditions. Subsequently, the simulated Arctic sea-ice area was reduced about 45% compared to that in the CtrlCoup (figure S2(*b*)). That means the method used in this study injects less freshwater into the Arctic Ocean, compared to the other approaches that have been used to define the sea-ice conditions e.g. by altering the long wave radiation (Deser *et al* 2015) or albedo (Blackport and Kushner 2016) in order to emulate sea-ice free conditions. The impact of freshwater release associated with the SIF intensifying the weakening of the AMOC, driven by the mechanisms mentioned in this study, needs further study.

Our study focuses on the responses to the sea-ice free Arctic in the autumn. The sea-ice conditions in other seasons are held constant as a control. The sea-ice reduction in the Nordic seas during the winter season can also trigger a negative NAO (Liptak and Strong 2013, Magnusdottir *et al* 2004) which might reinforce the weakening of the AMOC. The excluding of the sea-ice reduction in the other seasons is another possible reason why the NA warming minimum in the SensCoup is weaker than that in the Proj.

There are also other possible contributors to the NA warming minimum. The surface warming in response to increased CO_2 is generally slower over ocean than over land (Sutton *et al* 2007) because of the oceans' higher heat capacity, more efficient evaporative cooling, and accompanying cloud feedback (Sejas *et al* 2014). Furthermore, the deep ocean mixing in the Labrador Sea and the sub-polar NA could also slow down the ocean surface warming. But there is a question as to how much these factors can contribute to the NA warming minimum.

Observations since the satellite era have shown a substantial decline in autumnal Arctic sea-ice extent (Comiso *et al* 2008). Direct observations also indicate that the AMOC has been weakening since 2004 at a rate of 0.5 ± 0.2 Sv year^{-1} (Robson *et al* 2014). But the autumn NAO shows no clear trend and the winter NAO shows a clear positive trend after the 1980s (www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). The suggested mechanism in this study may have not been in operation or successfully observed. Further, the sea-ice reduction during recent decades is smaller in magnitude and different in distribution than that in the models, which might be a reason for such a disagreement.

The role of the air–sea interaction in the response to the SIF has been highlighted by the results presented in this study. Similarly, the air–sea coupling is also a key in transferring the spring Arctic sea-ice impact onto the East Asian summer monsoon (Guo *et al* 2014). Since the NA cooling in response to the SIF is seen throughout the whole year it has the potential to cause longer-lag-time climate impacts which also need further study.

Acknowledgments

This work has been supported by the Research Council of Norway through the BlueArc project (207650/E10), the European Union 7th Framework Programme (FP7 2007–2013) through the NACLIM project (308299) and the National Natural Science Foundation of China (41375083). This work also contributes to the NordForsk-funded project GREENICE (61841): Impacts of Sea-Ice and Snow-Cover Changes on Climate, Green Growth, and Society and the EU H2020 Blue-Action project (727852). Computational and storage resources for this work have been provided by NOTUR (nn2343k) and NORSTORE (ns9015k).

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