ENVIRONMENTAL RESEARCH
LETTERS

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RECEIVED
16 December 2021

REVISED
15 February 2022

ACCEPTED FOR PUBLICATION
15 February 2022

PUBLISHED
25 March 2022

LETTER

An extreme event of enhanced Arctic Ocean export west of Greenland caused by the pronounced dynamic sea level drop in the North Atlantic subpolar gyre in the mid-to-late 2010s

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Keywords: Arctic freshwater export, subpolar gyre, dynamic sea level, Davis Strait, Canadian Arctic Archipelago

Supplementary material for this article is available online

Abstract

The North Atlantic subpolar gyre influences the climate in many different ways. Here, we identified that it is also responsible for a recent extreme event of Arctic Ocean freshwater export west of Greenland. A shift in climate regimes occurred in the mid-2000s, with a significant negative trend in the dynamic sea level in the subpolar gyre since then. We found that the dynamic sea level drop induced a strong increase in freshwater export west of Greenland, in particular from 2015 to 2017, when the sea level was close to the minimum. Sea ice melting and atmospheric variability in the Arctic had only a small contribution to this event. As the exported water from the Arctic Ocean has low salinity and constituents of chemical tracers very different from those in the North Atlantic, such events might have impacts on the North Atlantic ecosystem and the climate as well. Our study suggests that such events might be predictable if the subpolar gyre sea level has certain predictability.

1. Introduction

The large-scale upper ocean circulation in the Arctic Ocean is characterized by the Transpolar Drift Stream and the anticyclonic Beaufort Gyre circulation, which carry low-salinity water from different sources, including river runoff, net precipitation (precipitation minus evaporation) and Pacific Water inflow (Serreze *et al* 2006, Haine *et al* 2015, Carmack *et al* 2016). On average, the salinity of the upper ocean water in the Arctic Ocean is lower than that in the North Atlantic, where it is exported to, so it is traditionally called Arctic freshwater. The excess Arctic freshwater is released into the North Atlantic through Arctic gateways both east and west of Greenland. The exported freshwater can influence the upper ocean salinity in the subpolar North Atlantic with potential impacts on ocean stratification, deep water formation, and thus the Atlantic Meridional Overturning Circulation (AMOC) and climate (Goosse *et al* 1997, McGeehan and Maslowski 2011, Karami *et al* 2021, Zhang *et al* 2021). Currently, the Arctic Ocean stores a large amount of freshwater compared to the mid-1990s (Polyakov *et al* (2013), Rabe *et al* (2014), Proshutinsky *et al* (2019), Wang *et al* (2019)), as shown in figure 1(b). This raises concerns about possible impacts on climate if anomalous freshwater is released into the North Atlantic. Furthermore, the export from the Arctic Ocean can also influence the ecosystem in the North Atlantic, including coastal North America, because the chemical constituents of the Arctic freshwater are different from those in the North Atlantic (Azetsu-Scott *et al* 2010, Hátún *et al* 2017).

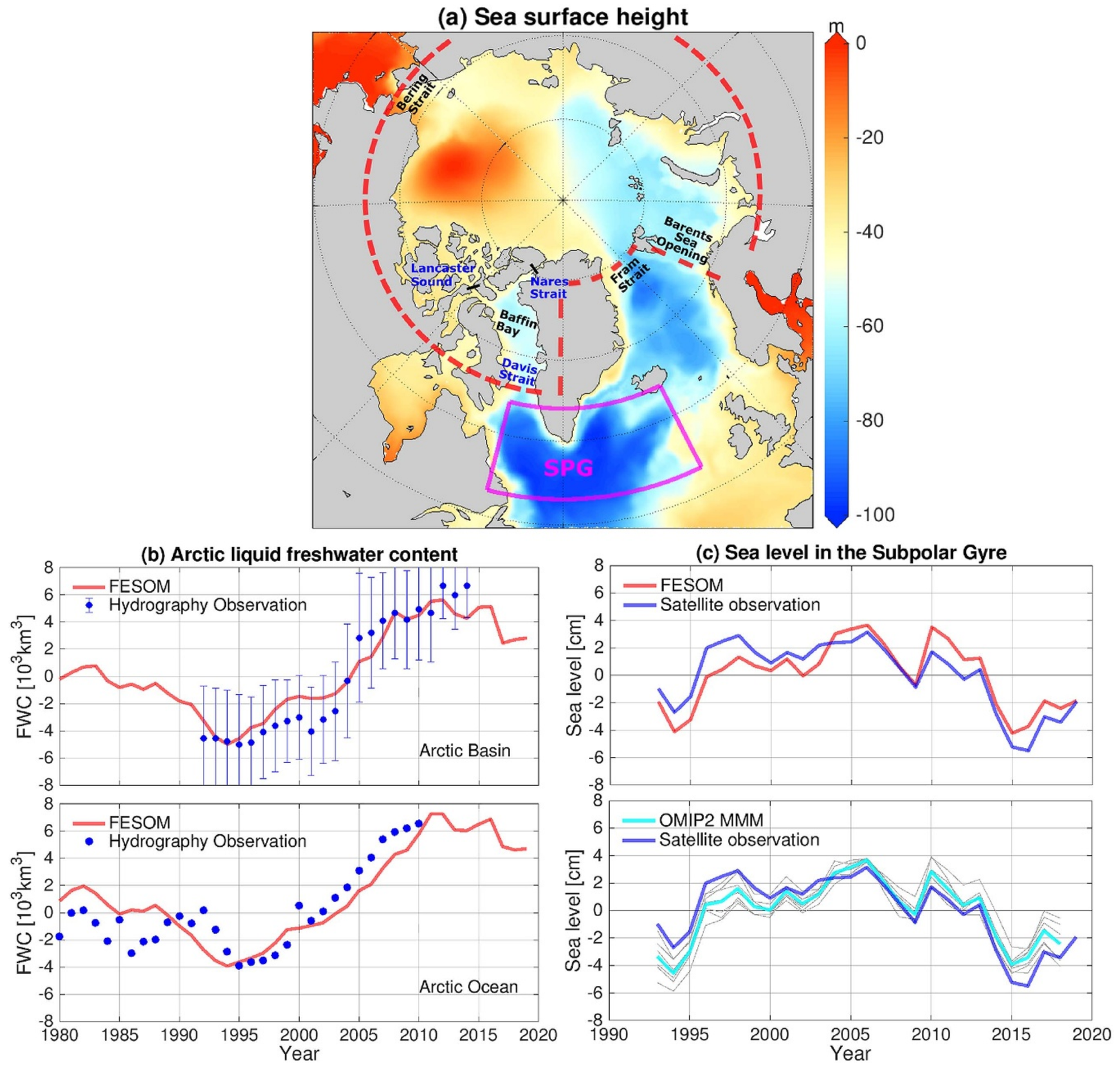

Figure 1. (a) Mean SSH simulated in FESOM. The Arctic gateways are indicated. The red dashed line indicates the Arctic boundary for applying atmospheric forcing in the sensitivity experiments. The magenta box denotes the North Atlantic subpolar gyre. (b) Liquid FWC anomalies in the Arctic deep basin (upper) and Arctic Ocean (lower) in FESOM historical simulation and observations (Polyakov *et al* 2013, Rabe *et al* 2014, Wang *et al* 2019). (c) Anomalies of SSH averaged in the subpolar gyre in the FESOM historical simulation (upper) and OMIP2 (Griffies *et al* 2016) simulations (lower). The satellite observation (Pujol *et al* 2016) is also shown. The individual OMIP2 model results are shown with thin gray curves, and their multi-model-mean (MMM) is shown with the thick cyan line.

The accumulation and release of Arctic Ocean freshwater were suggested to be driven by quasi-decadal variability in the wind regime (cyclonic versus anticyclonic) in the Arctic (Proshutinsky and Johnson 1997, Maslowski *et al* 2000, Zhang *et al* 2003, Condron *et al* 2009). The phase of the large-scale atmospheric circulation mode (represented by the Arctic Oscillation or North Atlantic Oscillation) can modify the distribution of Arctic freshwater export between gateways (Steele and Ermold 2004, Lique *et al* 2009, Aksenov *et al* 2010, Jahn *et al* 2010, Wang *et al* 2021), which can further influence the imprint of the exported freshwater on upper ocean stratification in the subpolar North Atlantic (Komuro and Hasumi 2005, Wang *et al* 2018).

West of Greenland, Arctic freshwater passes the narrow straits of the Canadian Arctic Archipelago and then leaves Baffin Bay through the Davis Strait (Melling *et al* 2008, Peterson *et al* 2012, Curry *et al* 2014, Münchow 2016); see the map in figure 1(a). The variability of this export is largely determined by the sea-level difference between the two ends (one on the Arctic side and the other on the Baffin Bay side) of each of the two main straits in the Canadian Arctic Archipelago (Kliem and Greenberg 2003, Houssais and Herbaut 2011, McGeehan and Maslowski 2012, Wekerle *et al* 2013, Lu *et al* 2014, Wang *et al* 2017). The export transport is correlated with the North Atlantic Oscillation index on interannual timescales (Jahn *et al* 2010, Houssais and Herbaut 2011, Wekerle *et al* 2013), while local wind and sea ice conditions in the Canadian Arctic Archipelago region can also influence the export transport (Grivault *et al* 2018). On monthly timescales, the flow through the Davis Strait and Nares Strait can reverse its direction temporarily to become Arctic inflow when the sea surface height (SSH) along the western coast of Greenland is strongly increased under the condition of an extremely high Greenland Blocking Index (Myers *et al* 2021). Previous studies also suggest that the signal of sea-level changes south of Greenland can propagate quickly through fast waves to the northern Baffin Basin and influence the Arctic export (Houssais and Herbaut 2011, Wekerle *et al* 2013).

Between the mid-2000s and mid-2010s, a negative trend in the dynamic sea level in the subpolar North Atlantic was observed in satellite altimetry measurements (figure 1(c)), which was mainly due to the steric height decrease and associated with cooling, strengthening and widening of the subpolar gyre (Chafik *et al* 2019). The cooling of the subpolar gyre could be mainly attributed to the reduction in meridional ocean heat transport (Piecuch *et al* 2017, Foukal and Lozier 2018), possibly due to the weakening of the AMOC in this period (Zhang and Zhang 2015, Robson *et al* 2016). The anomalously strong wintertime North Atlantic Oscillation in 2015 and 2016 intensified the deep convection in the Labrador Sea, which, after multiyear preconditioning, led to the highest density of the Labrador Sea Water since the mid-1990s (Yashayaev and Loder 2017). This may have also contributed to the SSH minimum observed in these years.

Did the conspicuous dynamic sea level drop in the mid-to-late 2010s considerably influence the Arctic freshwater export west of Greenland? If it did so, how significant was the influence compared with the effect of the atmospheric forcing inside the Arctic in that period? In this study, we used numerical simulations to answer these questions.

2. Model and data

The Finite Element Sea-ice Ocean Model (FESOM 1.4, Danilov *et al* 2004, 2015, Wang *et al* 2008, 2014) was employed in this study. It is a global unstructured-grid ocean general circulation model that allows one to conveniently refine the grid in selected regions. The employed model setup has a nominal horizontal resolution of about 1° in most parts of the global ocean. The resolution is increased to 24 km north of 45°N, and further increased to 4.5 km in the Arctic Ocean. With this resolution, the model can reasonably reproduce the observed transport variability in Lancaster Sound and the Nares Strait (Wekerle *et al* 2013). The vertical grid spacing is 10 m in the upper 100 m and coarsened downward with 47 z-levels in total. The model is driven by the JRA55-do atmosphere reanalysis (Tsujino *et al* 2018) from 1958 to 2019. This model configuration has been used in different Arctic studies, with model assessments showing that the variability and trend of Arctic freshwater content (Wang *et al* 2019, Wang 2021), Arctic sea ice volume, extent and drift (Wang *et al* 2021, Wang*et al* 2021) and sea level in the Arctic Ocean and Greenland Sea (Wang *et al* 2020, Xiao *et al* 2020) can be reasonably represented.

Besides the aforementioned control run (called global_vari below), we carried out four sensitivity experiments to unravel the mechanisms driving the changes in Arctic Ocean export west of Greenland in the 2010s. They were run from 2010 to 2019, starting from the control run results at the end of 2009. In the first one (called AO_vari), the atmospheric forcing outside the Arctic was replaced by a repeat-year forcing (no interannual variability), while inside the Arctic the forcing remained to be the JRA55-do forcing. The setting in the second one (called notAO_vari) is opposite to the first one, with atmospheric forcing outside the Arctic being the JRA55-do forcing and the forcing inside the Arctic being the repeat-year forcing. The third one (called notAO_vari_wind) is similar to the second one, but the buoyancy forcing outside the Arctic was also replaced by the repeat-year forcing, so only winds outside the Arctic have interannual variability in this experiment. In the fourth sensitivity experiment (called no_vari), we applied repeat-year forcing everywhere on the globe. The Arctic boundary for separating the forcing domains is defined by the four Arctic gateways near the Davis Strait (66°N), Fram Strait (78°N), Barents Sea Opening (17°E) and Bering Strait (66°N) (see figure 1(a)). The simulations used in this study are summarized in table 1.

The repeat-year atmospheric forcing was prepared based on the JRA55-do forcing. We followed the recommendation of Stewart *et al* (2020) to use the one-year-long winds compiled from JRA55-do from May 1st, 1990 to April 30th, 1991, which represent a neutral state of the atmospheric circulation from a global perspective. For the atmospheric fields related to buoyancy forcing, we averaged the JRA55-do data from 2010 to 2019 for each 3 h segment. That is, the repeat-year forcing has the same temporal (3 h) and spatial (0.55°) resolution as the JRA55-do forcing.

We analyzed the ocean volume and freshwater transport through the Arctic gateways and the Arctic freshwater content (FWC). The Arctic FWC is defined as

$$\mathrm{FWC} = \int_A \int_D^0 (S_{\mathrm{ref}} - S)/S_{\mathrm{ref}}\,\mathrm{d}z\mathrm{d}A, \qquad (1)$$

where S is ocean salinity, S_{ref} is a reference salinity, D is the isohaline depth of $S = S_{\mathrm{ref}}$, and the integration is from depth D to the ocean surface over the Arctic area A. At each location, the FWC is equivalent to the amount of pure (zero-salinity) water required to be taken out from the ocean column so that the mean salinity in the ocean column is changed to the reference salinity. We took $S_{\mathrm{ref}} = 34.8$ psu, a value representing the Arctic Ocean mean salinity (Aagaard and Carmack 1989) and used in nearly all Arctic studies. We note that changing the reference salinity to 35 psu (a value closer to the mean surface salinity in

Table 1. List of simulations used in this study. The atmospheric forcing used inside and outside the Arctic is explained.

Experiment name	Forcing in the Arctic	Forcing outside the Arctic
global_vari	JRA55-do	JRA55-do
AO_vari	JRA55-do	repeat-year
notAO_vari	repeat-year	JRA55-do
notAO_vari_wind	repeat-year	wind: JRA55-do; buoyancy: repeat-year
no_vari	repeat-year	repeat-year

the northern North Atlantic) has very little impact on the variability of the FWC (anomaly from the temporal mean). The freshwater transport through an Arctic gateway transect is defined as

$$\mathrm{FWT} = \int_L \int_D^0 u_n (S_{\mathrm{ref}} - S)/S_{\mathrm{ref}}\,\mathrm{d}z\mathrm{d}L, \qquad (2)$$

where u_n is the ocean velocity perpendicular to the transect, and the integration is from depth D to the ocean surface over the transect length L. The observational estimates of FWC for the Arctic Ocean (Polyakov *et al* 2013) and the Arctic deep basin (Rabe *et al* (2014), Wang *et al* (2019)) were used to assess the model results. The deep basin is defined as the Arctic area where the bottom topography is deeper than 500 m.

To our knowledge, there are no published observational estimates of ocean volume and freshwater transport through the Davis Strait for the mid-to-late 2010s. We therefore also analyzed seven Ocean Model Intercomparison Project 2 (OMIP2) simulations available in the CMIP6 repository (table S1 available online at stacks.iop.org/ERL/17/044046/mmedia). They are global ocean sea-ice model simulations forced by the JRA55-do forcing (Griffies *et al* 2016). We will compare the FESOM control simulation with these OMIP2 simulations to see whether the variability of the Davis Strait transport is consistent among the models.

The DUACS DT2014 satellite altimeter data set (Pujol *et al* 2016) was used to assess the simulated SSH variability in the North Atlantic subpolar gyre (60°W to 15°W, 53°N to 64°N, indicated by the magenta box in figure 1(a)). The global mean trend of sea level was removed to investigate the regional dynamic sea level change.

3. Results

3.1. Control simulation

The FESOM control simulation reproduced the observed increase of Arctic FWC of about 10 000 km^3 from the mid-1990s to the beginning of the 2010s (figure 1(b)). Furthermore, the interannual variability of the dynamic sea level in the North Atlantic subpolar gyre in the satellite era is well represented in FESOM and in the OMIP2 models as well (figure 1(c)). The satellite observation and models agree that there was a negative trend in the dynamic sea level in the North Atlantic subpolar gyre after 2005, and the trend accelerated in the 2010s until reaching the sea-level minimum in 2015–2016.

The ocean volume transport and freshwater transport through the Davis Strait are consistent between the FESOM and the OMIP2 models for both the interannual variability and the event of enhanced export in the mid-to-late 2010s (figures 2(a) and (b)). There is a discrepancy in the exact year of maximum ocean volume transport among the OMIP2 models, but most of them show a maximum in 2015–2017, when the transport in FESOM is clearly larger than in other years. FESOM and most of the OMIP2 models show an increase in Davis Strait freshwater transport between 2011 and 2017. Overall, the FESOM results are very close to the OMIP2 multi-model-mean results (figures 2(a) and (b)). We note that the ocean volume transport and freshwater transport are significantly correlated over the 20-year period within each model, as also suggested in previous studies (Lique *et al* 2009, Jahn *et al* 2010, Wekerle *et al* 2013, Wang *et al* 2016), because the ocean volume transport variability largely determines the variability of the freshwater transport for the Davis Strait.

Both the FESOM and OMIP2 models simulated enhanced Davis Strait export in the mid-late 2010s (figures 2(a) and (b)), when the dynamic sea level in the subpolar gyre considerably dropped (figure 2(c)). This correlation implies a possible link between the sea-level drop in the subpolar gyre and the export increase in the Davis Strait, but statistics alone cannot exclude the possibility that in reality other dynamical processes caused or significantly contributed to the enhanced Davis Strait export. In the following we will use sensitivity experiments to unravel the key mechanisms responsible for the enhanced Davis Strait export in the mid-to-late 2010s.

3.2. Sensitivity experiments

The anomalies of ocean volume transport through the Davis Strait in the control simulation and in three of the sensitivity experiments (notAO_vari, AO_vari and no_vari) are shown in figure 3(a). The figure indicates that the increase in volume transport from 2015–2017 is mainly induced by the atmospheric forcing outside the Arctic. The volume transport interannual variability induced by the atmospheric forcing over the Arctic Ocean is relatively small in the 2010s.

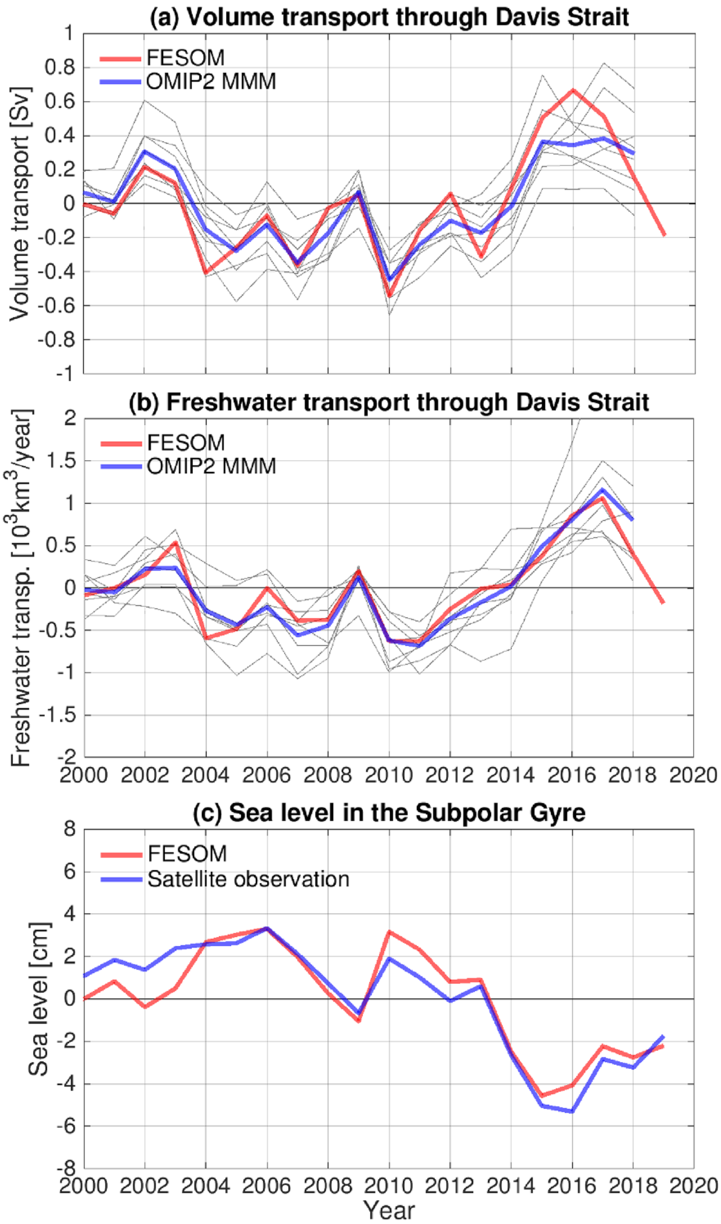

Figure 2. Anomalies of (a) volume transport and (b) freshwater transport through Davis Strait in FESOM historical simulation and OMIP2 (Griffies *et al* 2016) simulations. The individual OMIP2 model results are shown with thin gray lines, and their multi-model-mean (MMM) is shown with thick blue lines. Positive values indicate larger export. (c) Anomalies of SSH in the North Atlantic subpolar gyre in FESOM historical simulation and satellite observation (Pujol *et al* 2016). The subpolar gyre region is indicated in figure 1(a).

The volume transport in the case without interannual variability in the atmospheric forcing (no_vari) is not steady in time, indicating that the ocean is in a state adjusting to the repeat-year forcing. When taking the variability associated with this adjustment into account, combining the notAO_vari and AO_vari results largely recovers the result of the control run (figure 3(b)).

The high freshwater export through the Davis Strait in 2015–2017 can be mainly attributed to the atmospheric forcing outside the Arctic too, as revealed by the freshwater transport time series from different simulations (figure 3(c)). The freshwater transport in 2017 is slightly higher than in 2016 in the control run, which has contribution from the local maximum in 2017 associated with the Arctic atmospheric forcing as shown by the AO_vari run. In the AO_vari run, the variability of the freshwater transport could be due to both the Arctic wind forcing and salinity changes associated with sea ice changes. However, this part of the variability is relatively small compared with the total variability in the control run, and has little contribution to the event of strongly increased freshwater transport in the 2010s (figure 3(c)). Similar to the ocean volume transport, combining the freshwater transport anomalies in the sensitivity experiments recovers that in the control run (figure 3(d)).

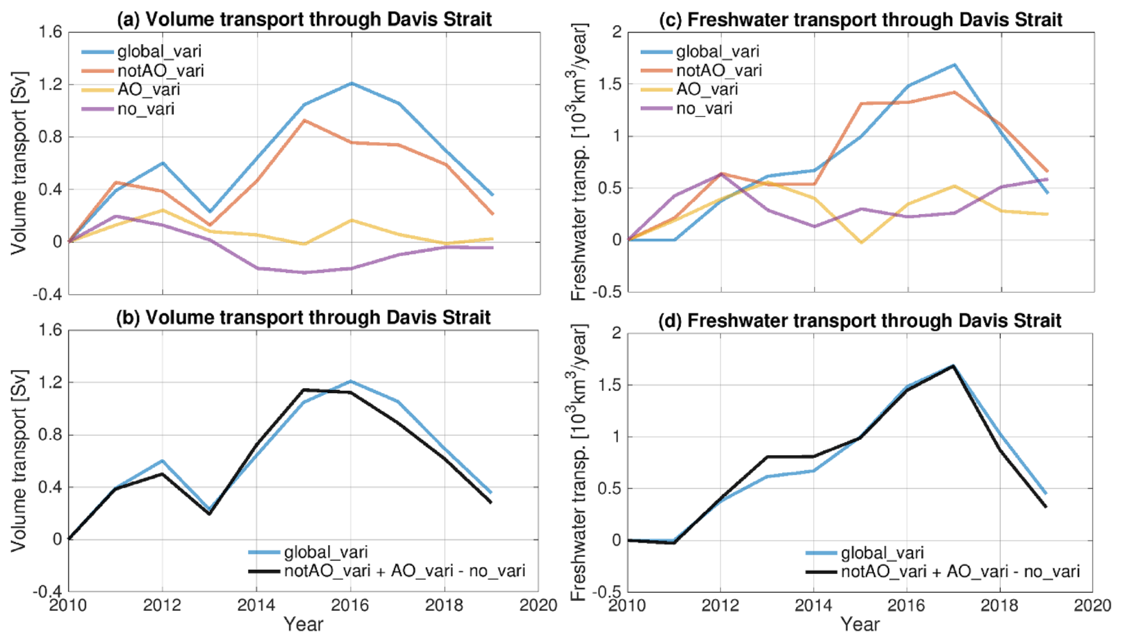

Figure 3. (a) and (b) Anomalies of volume transport through Davis Strait. (c) and (d) Anomalies of freshwater transport through Davis Strait. The upper panels show the results from individual experiments, while the lower panels show that the control run (global_vari) results can be recovered when combining the results from the individual sensitivity experiments. The anomalies are referenced to the first year (2010) of the studied period. Positive values indicate larger export.

The SSH anomaly in 2015–2017 relative to the mean over the 2010s in the notAO_vari simulation reveals the mechanism driving the enhanced Davis Strait export in this period (figure 4(a)). The anomaly of the sea-level drop in the subpolar gyre propagates to the northern Baffin Bay along the western coast of Greenland, thus increasing the ocean export through the Canadian Arctic Archipelago. As the SSH anomaly mainly propagates into the western Nares Strait, a larger part (about two-thirds) of the increase in the ocean volume transport is due to the increase in the Nares Strait transport (figure 4(c)). This is consistent with the previous finding that sea-level changes in the Labrador Sea have the largest impact on the Nares Strait transport (Wekerle *et al* 2013).

There are pronounced SSH dipole anomalies in the central Arctic in notAO_vari, in which there is no interannual variability in the atmospheric forcing over the Arctic Ocean (figure 4(a)). Very similar patterns are also found in the notAO_vari_wind simulation (figure 4(b)) and in the no_vari simulation as well (not shown), so they are manifestations of the Arctic Ocean adjustment to the repeat-year forcing. As the variation in the Davis Strait transport in no_vari is clearly smaller than that in notAO_vari (figures 3(a) and (c)), the presence of the ocean adjustment where the repeat-year forcing is applied does not influence our main conclusions.

The notAO_vari_wind simulation further confirms that the sea-level drop in the subpolar gyre is the main driver of the enhanced ocean export through the Davis Strait in 2015–2017. In this simulation, the winds outside the Arctic Ocean have interannual variability, but do not induce a strong sea-level drop in the subpolar gyre (figure 4(b)). Accordingly, it does not simulate a pronounced increase in the Davis Strait export (figure 4(d)).

4. Discussions

In the notAO_vari simulation, the enhanced ocean volume export through the Davis Strait in 2015–2017 is largely counterbalanced by the decrease in the ocean volume export through the Fram Strait (figure 5(a)). The freshwater export through the Fram Strait also decreases in this period, partially compensating for the increase in the freshwater export through the Davis Strait (figure 5(b)). In the AO_vari simulation, the ocean volume transport is anticorrelated between the Fram Strait and the Barents Sea Opening (figure 5(c)), while the freshwater export through the Fram Strait has an increasing trend in the 2010s, with the largest export in 2017 (figure 5(d)).

In the control simulation, the anticorrelation between the Davis Strait volume transport and the Fram Strait volume transport (obvious in notAO_vari) and the anticorrelation between the Barents Sea Opening volume transport and the Fram Strait volume transport (obvious in AO_vari) are still present, but less pronounced (figure 5(e)) because of the mixture of different controls from inside and outside the Arctic. Our sensitivity experiments with geographically decomposed atmospheric forcing thus also helped to better reveal the relationship of volume transport between different Arctic gateways.

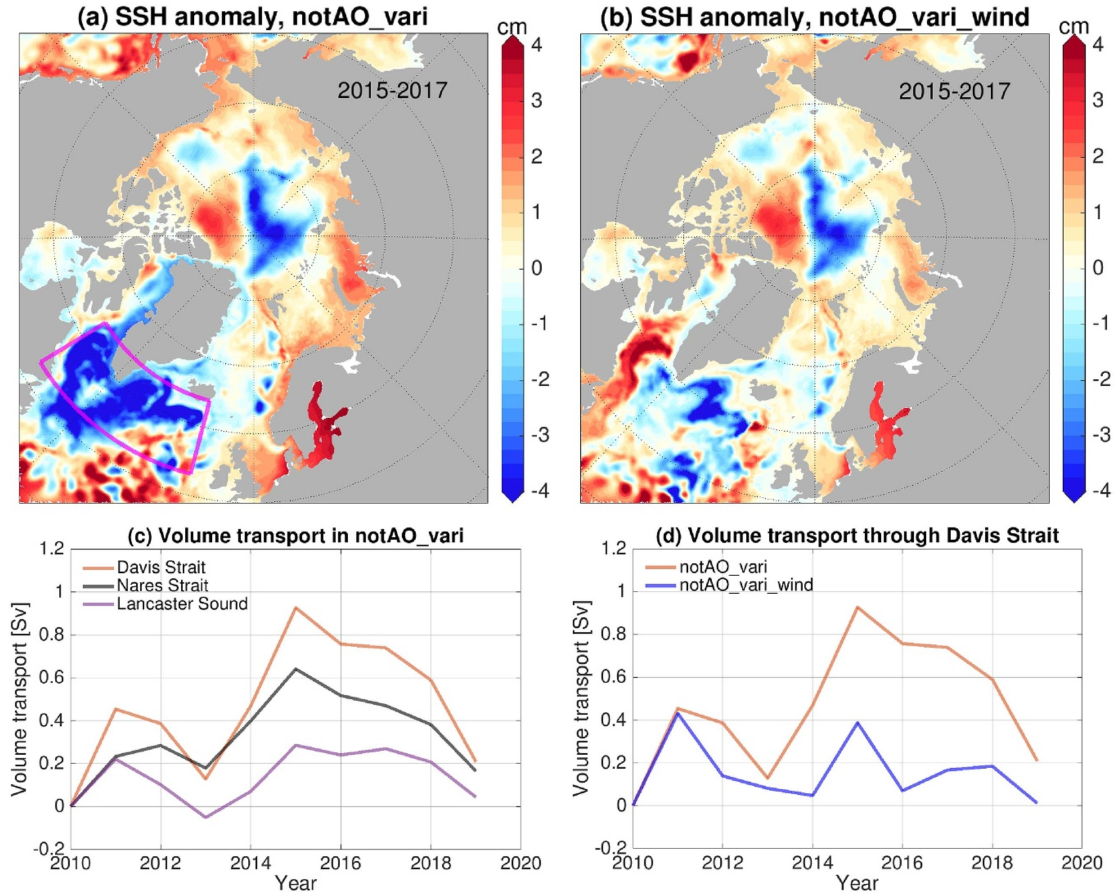

Figure 4. Anomaly of SSH in 2015–2017 relative to the mean over the 2010s in the (a) notAO_vari and (b) notAO_vari_wind simulations. (c) Anomalies of volume transport through Davis Strait and the two main straits of the Canadian Arctic Archipelago in the notAO_vari simulation. (d) Anomalies of volume transport through Davis Strait in notAO_vari and notAO_vari_wind simulations. The anomalies of the time series are referenced to the first year (2010) of the studied period; positive volume transports indicate larger export. The magenta box in (a) indicates the North Atlantic subpolar gyre region.

The increase in the Fram Strait freshwater export induced by atmospheric forcing inside the Arctic (seen in AO_vari) and the decrease in the Fram Strait freshwater export induced by atmospheric forcing outside the Arctic (seen in notAO_vari) largely compensate each other when forcing variability is kept globally (in the control run). Therefore, the most pronounced variation in freshwater export in the control run is in the Davis Strait (figure 5(f)). As we found in this study, the Davis Strait freshwater export is anomalously high in the mid-to-late 2010s, which is mainly due to the sea-level drop in the subpolar gyre. Although the Arctic sea ice volume decreased on average in this period, which was a positive source for the Arctic Ocean liquid FWC, the Arctic Ocean liquid FWC still reduced in the late 2010s (figure 1(b)). This should be mainly due to the enhanced freshwater export through the Davis Stait, as freshwater transport through other Arctic gateways did not change as much as that through the Davis Strait (figure 5(f)). However, even without the impact of the atmospheric forcing outside the Arctic Ocean, the Arctic Ocean would still have had enhanced freshwater export in the mid-to-late 2010s, mainly through the Fram Strait (figure 5(d)). Due to the sea-level drop in the subpolar gyre, the most strongly enhanced freshwater export actually occurred in the Davis Strait, instead of the Fram Strait. Therefore, the distribution of freshwater export between the gateways is significantly influenced by the atmospheric forcing outside the Arctic Ocean. Changes in the export routes were suggested to have significant impacts on deep convection and dense water formation (Komuro and Hasumi 2005, Wang *et al* 2018).

In the AO_vari simulation, the freshwater export is not correlated with net ocean volume transport in the Fram Strait (cf figures 5(c) and (d)), implying that salinity changes play an important role in determining the Fram Strait freshwater export in this case. The strongest Fram Strait freshwater export in AO_vari is in 2017, which is associated with a negative salinity anomaly in the Fram Strait (figure S1(a)) as a consequence of the cyclonic atmospheric circulation regime over the Arctic Ocean (figure S1(c)). In the control (global_vari) run, the sea-level drop in the subpolar gyre increases the ocean volume export west of Greenland and reduces the export through the Fram Strait, so the negative salinity anomaly in the

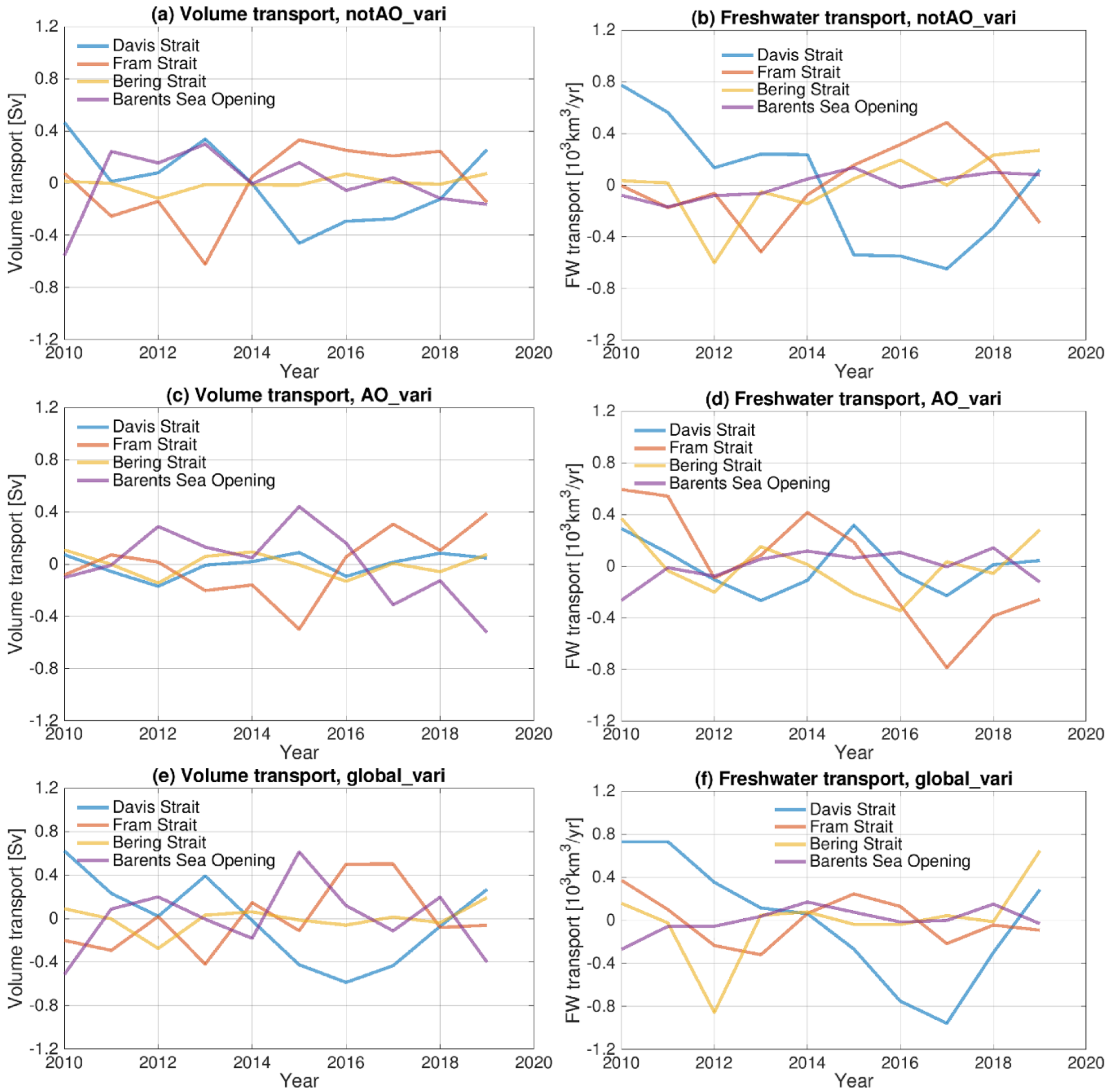

Figure 5. Anomaly of (a) ocean volume transport and (b) freshwater transport through the four Arctic gateways in notAO_vari. (c) and (d) The same as (a) and (b), but for AO_vari. (e) and (f) The same as (a) and (b), but for the control simulation global_vari. Note that in this figure Arctic outflow is negative and inflow is positive. The simulations are explained in table 1 and in the method section.

Fram Strait is reduced, while a stronger negative salinity anomaly is produced along the export pathway in Baffin Bay (figure S1(b)) compared to the AO_vari case. Therefore, importantly, to understand salinity changes in the Fram Strait and in the East Greenland (Coastal) Current we also need to consider the sea level in the subpolar gyre and the atmospheric forcing over the North Atlantic, besides local and Arctic forcing.

We found that the Nares Strait transport is particularly sensitive to the changes in the subpolar North Atlantic. As the North Atlantic circulation will experience dramatic changes in a warming climate (Weijer *et al* 2020), the ocean transport through the Nares Strait will very possibly change accordingly. The sensitivity of the Nares Strait transport to the subpolar North Atlantic might be the reason for the early emergence of forced changes in the Nares Strait freshwater transport as seen in climate model simulations (Jahn and Laiho 2020).

Local wind stress over the Canadian Arctic Archipelago, with dependence on local sea ice conditions, may also influence the ocean throughflow in the straits of the Canadian Arctic Archipelago (Grivault *et al* 2018). Winds southwest of Greenland can influence the SSH along the western coast of Greenland, thus influencing the throughflow in the Nares Strait (Myers *et al* 2021). The AO_vari and notAO_vari_wind simulations did not obtain the profound increase in the Davis Strait export as simulated in notAO_vari and the control run, indicating that local winds are not the main driver for this event. As we showed, this recent event of high freshwater export west of Greenland reflects decadal variability in response to the decadal variability of the dynamic sea level in the subpolar gyre. It remains to be seen whether winds over the Arctic Ocean, across the Canadian Arctic Archipelago and along the Greenland coast can play a more important role on interannual and decadal timescales in other periods. As for the fate of the Arctic freshwater after leaving Baffin Bay, it was found that the routing of the Arctic freshwater can be significantly influenced by changes in the intra-basin ocean circulation in the North Atlantic driven by wind variability (Holliday *et al* 2020).

Different processes were suggested to be responsible for the strengthening of the subpolar gyre and the related dynamic sea level drop in the 2010s, including buoyancy forcing and wind stress curl (Robson *et al* 2016, Piecuch *et al* 2017, Chafik *et al* 2019). Understanding these processes is beyond the scope of this paper. However, our simulations do show that wind variability alone cannot produce the sea-level drop in the subpolar gyre in the mid-to-late 2010s (compare figures 4(a) and (b)). This result clearly indicates the importance of buoyancy forcing.

5. Summary

In this study, we found that there was an extreme event of high freshwater export west of Greenland from the Arctic Ocean in the mid-to-late 2010s, and identified that the sea-level drop in the North Atlantic subpolar gyre was the main driver for this event. Our finding is based on a suite of independent global ocean-ice model simulations and dedicated sensitivity numerical experiments.

We carried out ocean-ice model sensitivity simulations with interannual variability of the atmospheric forcing only retained inside the Arctic or outside, in addition to a historical hindcast simulation. We found that the atmospheric forcing outside the Arctic is the main driver for the variability of the Arctic Ocean freshwater export west of Greenland in the 2010s. The atmospheric forcing outside the Arctic, through influencing the sea level in the North Atlantic subpolar gyre and thus along the western coast of Greenland, strongly modifies the gateways of Arctic freshwater export. The observed prominent dynamic sea level drop in the subpolar gyre in the mid-late 2010s was well reproduced in the model. It strongly increased the Arctic freshwater export through the Davis Strait. Although this tended to cause a reduction in the Arctic freshwater export through the Fram Strait, the contemporary Arctic cyclonic wind regime led to a compensation for this reduction, causing the variation in the Fram Strait freshwater export to be relatively small in the mid-to-late 2010s compared to that in the Davis Strait.

Our study suggests that the dynamic sea level in the subpolar gyre may serve as a predictor for the strength of Arctic export west of Greenland. Considering the possible link of the ocean temperature in the subpolar gyre with the AMOC strength and their predictability on decadal timescales (e.g. Zhang and Zhang 2015, Zhang *et al* 2019), certain predictability of the dynamic sea level in the subpolar gyre and thus of the Arctic Ocean freshwater export west of Greenland is expected. Providing predictions for the Arctic freshwater export would be very beneficial for society due to its potential impacts on the upper ocean salinity in the northern North Atlantic and the ecosystem along the eastern coast of North America. To this end, a better understanding of the mechanisms driving the variability of Arctic freshwater export is still required. In this study, we only focused on the recent extreme event of freshwater export west of Greenland in the 2010s. We need to know whether the revealed main dynamical control on the freshwater export in the 2010s can explain other major events in the past and whether this mechanism will remain important compared to other mechanisms in a warming climate. In particular, meltwater from the Greenland ice sheet can enter the subpolar gyre circulation (Dukhovskoy *et al* 2016, Gillard *et al* 2016, Luo *et al* 2016). In a climate much warmer than today, a large release of Greenland ice sheet meltwater could cause a strong freshening and thus a dramatic increase in the dynamic sea level in the northern North Atlantic (e.g. Wang *et al* 2012). Therefore, there may be more factors that can influence the long-term trend of ocean transport between the Arctic Ocean and sub-Arctic seas.

Data availability statement

The OMIP2 data are available from https://esgf-index1.ceda.ac.uk/projects/cmip6-ceda/. The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.5735462 .

Acknowledgments

The authors thank the two reviewers for their helpful comments. This work was supported by the German Helmholtz Climate Initiative REKLIM (Regional Climate Change and Humans), and by the German Federal Ministry for Education and Research (BMBF) within the EPICA project (Grant No. 03F0889A). The simulations were carried out at North German Supercomputing Alliance (HLRN).

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