Intensification of the Atlantic Water supply to the Arctic Ocean through Fram Strait induced by Arctic sea ice decline

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Abstract

Substantial changes have occurred in the Arctic Ocean in the last decades. Not only sea ice has retreated significantly, but also the ocean at mid-depth showed a warming tendency. By using simulations we identified a mechanism that intensifies the upward trend in ocean heat supply to the Arctic Ocean through Fram Strait. The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water (AW) volume transport to the Nordics Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic AW layer, potentially contributing to the "Atlantification" of the Eurasian Basin. Therefore, the Nordic Seas can play the role of a switchyard for the Arctic sea ice decline to influence the Arctic heat budget at mid-depth.

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Key Points:

- The decline of Arctic sea ice reduces its export, thus increasing the salinity in Greenland Sea
- This reduces the sea surface height and speeds up the gyre circulation in Greenland and Nordic Seas
- The enhanced Atlantic Water transport intensifies the warming at Fram Strait and in the Arctic Ocean

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Abstract

Substantial changes have occurred in the Arctic Ocean in the last decades. Not only sea ice has retreated significantly, but also the ocean at mid-depth showed a warming tendency. By using simulations we identified a mechanism that intensifies the upward trend in ocean heat supply to the Arctic Ocean through Fram Strait. The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water (AW) volume transport to the Nordics Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic AW layer, potentially contributing to the "Atlantification" of the Eurasian Basin. Therefore, the Nordic Seas can play the role of a switchyard for the Arctic sea ice decline to influence the Arctic heat budget at mid-depth.

Plain Language Summary

The Arctic sea ice decline is among the key indications of the climate change, which has strong impacts on the environment, human beings and biodiversity. In this paper we found that the Arctic sea ice decline at surface can even cause Arctic Ocean warming at mid-depth by intensifying the upward trend of ocean heat supply to the Arctic Ocean through Fram Strait. The Nordic Seas play the role of a switchyard for the involved processes: The sea ice decline reduces the sea ice export through Fram Strait, which further increases the salinity in the Greenland Sea; Consequently, in the Nordic Seas the sea surface height decreases and the gyre circulation strengthens; These changes then increase the Atlantic Water inflow to the Nordics Seas and the Arctic Ocean, causing significant warming in the Atlantic Water layer of the Arctic Ocean. The changes in the ocean heat budget have strong implications on potential feedbacks to sea ice decline through basal melting in a future warming climate. The intensification of the Atlantic Water volume transport through Fram Strait can impact not only the Arctic heat budget, but also the nutrient budget and potentially the primary production.

1 Introduction

The Arctic Ocean is located at the northern end of the North Atlantic Overturning Circulation (AMOC), which carries ocean heat in the Atlantic Water (AW) from the North Atlantic through the Nordic Seas into the Arctic Ocean (Fig. 1a). The AW enters the Arctic Ocean through two gateways. The Barents Sea branch loses most of its heat to the atmosphere already over the shallow continental shelf in the Barents and Kara Seas (Smedsrud et al., 2013), whereas the Fram Strait branch supplies oceanic heat to the warm AW layer (about 200 - 700 m depth) of the Arctic Ocean (Aagaard & Carmack, 1989; Rudels, Jones, Anderson, & Kattner, 1994). Although the Arctic sea ice is isolated from the AW layer by the halocline, the ocean heat can penetrate to the surface and induce sea ice basal melting in certain regions (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov, Alexeev, Repina, Koldunov, & Smirnov, 2012; Onarheim, Smedsrud, Ingvaldsen, & Nilsen, 2014; Polyakov et al., 2010). Climate simulations for future scenarios indicate that deep convection might become common in the Arctic Ocean (Lique, Johnson, & Plancherel, 2018), which can bring ocean heat at mid-depth up towards sea ice.

Located at the northern end of the Northern Hemisphere freshwater cycle, the Arctic Ocean also receives a large amount of freshwater from precipitation, river runoff and the Pacific Water inflow (Serreze et al., 2006). The excess liquid freshwater is released to the North Atlantic on both sides of Greenland (Fig. 1a), while sea ice is mainly exported through Fram Strait (Serreze et al., 2006).

The Arctic Ocean has undergone pronounced changes during the past decades. At the surface, the sea ice has declined in both extent and thickness (Kwok et al., 2009; Stroeve et al., 2012). The sea ice decline results in a significant reduction in sea ice volume export through Fram Strait (Wang et al., 2019). Below the halocline, the AW layer has a warming tendency (Polyakov et al., 2013). The eastern Eurasian Basin was observed to have a weaker stratification in the halocline above a warmer AW layer in recent years in comparison to the climatological condition, a phenomenon termed as "Atlantification" (Polyakov et al., 2017). The warming trend in the AW layer was observed upstream in the AW inflow at the Fram Strait (Beszczynska-Moeller et al., 2012).

Previous studies suggest that temperature anomalies travel from the North Atlantic through the Nordic Seas into the Arctic Ocean (Gerdes, Karcher, Kauker, & Schauer, 2003; Hatun, Sando, Drange, Hansen, & Valdimarsson, 2005; Holliday et al., 2008; Årthun & Eldevik, 2016). It was recently shown that local processes such as the Greenland Sea Gyre circulation also influence the northward AW transport and the temperature at the Fram Strait (Chatterjee et al., 2018). However, dynamical processes responsible for the

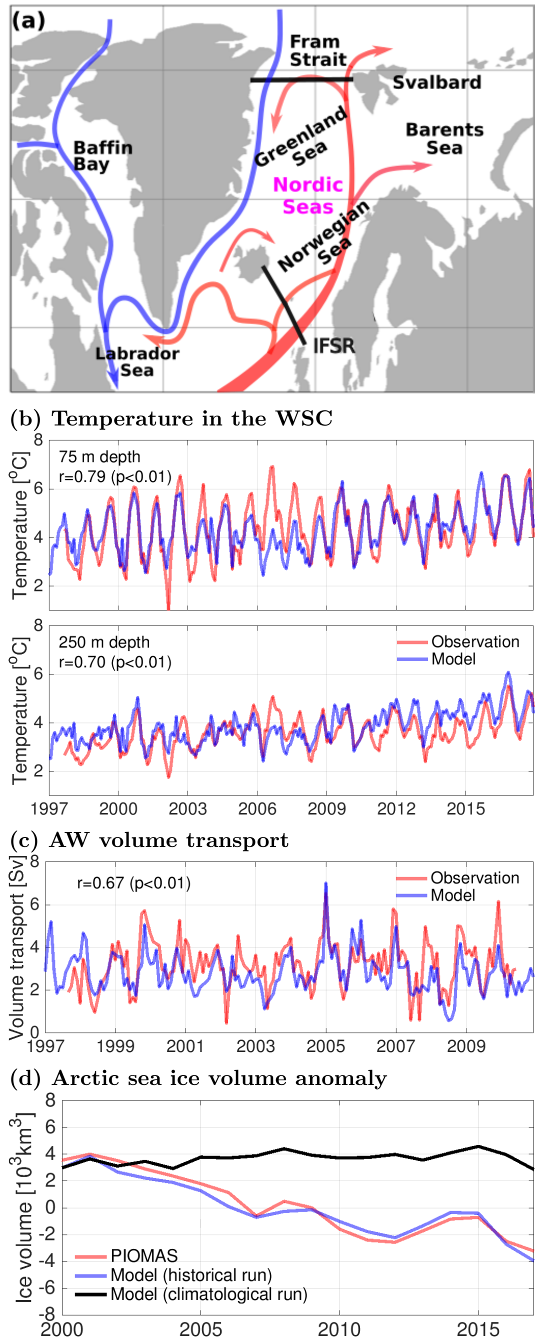

Figure 1. (a) Schematic of Arctic Ocean – North Atlantic exchange currents. The red arrows indicate the currents carrying the Atlantic Water, and the blue arrows indicate freshwater export from the Arctic Ocean. The Fram Strait and Iceland-Faroe-Scotland Ridge (IFSR) are indicated with black lines. (b) Temperature in the West Spitsbergen Current (WSC) core (averaged over the three easternmost moorings) at different depths in Fram Strait in the historical run and mooring observations. The Fram Strait mooring observations are described by Beszczynska-Moeller et al. (2012) and von Appen et al. (2016) . (c) Atlantic Water (AW, $>$ 2°C) volume transport in the WSC at the Fram Strait in the historical run and observations. The observed volume transport and the argument for the temperature threshold of the AW are provided by Beszczynska-Moeller et al. (2012). (d) Anomaly of Arctic sea ice volume in the PIOMAS reanalysis (Schweiger et al., 2011) and in the two model runs. The anomalies of PIOMAS and the historical run are referenced to their respective mean values averaged over the shown period, and the anomaly of the climatological run is referenced to the mean value of the historical run.

recent upward trends in AW temperature and ocean heat transport at Fram Strait are not fully understood.

In this study we discovered a mechanism that significantly intensifies the upward trends of AW temperature and volume transport at Fram Strait. We found that the Arctic sea ice decline and the resultant reduction in sea ice volume export change the ocean salinity, sea surface height (SSH) and the cyclonic gyre circulation in the Greenland Sea and Nordic Seas, which thus strengthens the AW volume and heat supply to the Arctic Ocean.

2 Model setups

The Finite Element Sea ice Ocean Model (FESOM, Wang et al., 2014) is employed in this study. It works on triangular unstructured meshes for both its ocean and sea ice components. The global model grid is the same as the high-resolution setup evaluated by Wang, Wekerle, Danilov, Wang, and Jung (2018). It has 4.5 km horizontal resolution (grid size) in the Arctic Ocean and 24 km in the North Atlantic. In most other parts of the global ocean the resolution is about 1 degree. This model configuration can reasonably represent the Arctic sea ice and ocean hydrography compared to observations and coarser model setups (Wang, Danilov, Jung, Kaleschke, & Wernecke, 2016; Wang, Wekerle, Danilov, Koldunov, et al., 2018; Wang, Wekerle, Danilov, Wang, & Jung, 2018).

The atmospheric reanalysis data of JRA55-do v.1.3 (Tsujino et al., 2018) are used to drive the model in a historical (hindcast) run. To elucidate the role of Arctic sea ice decline, we conducted a sensitivity experiment (called climatological run hereafter). In this run we replaced the historical thermal forcing fields (near-surface air temperature, shortwave and longwave radiation fluxes) with their climatological values inside the Arctic Ocean, which is defined by its four gateways (Fram Strait (79°N), Davis Strait (66°N), Bering Strait (66°N) and the Barents Sea Opening (20°E)). The climatological forcing is obtained by averaging the JRA55 data from 1970 to 1999 for each 3h segment, so the temporal frequency is 3-hourly in both the JRA55 historical and climatological forcing data. Winds remain the same (the historical forcing) in the two runs.

By using the climatological thermal forcing over the Arctic Ocean, we can eliminate the Arctic sea ice declining trend in the climatological run (see section 3). The impact of the sea ice decline on the ocean can be revealed by comparing the two runs.

Two AW dye tracers are used to better illustrate the difference between the two runs. One is injected into the AW layer at the Iceland-Faroe-Scotland Ridge (IFSR), the other at Fram Strait. Their values are restored to one in these two gateways during the simulations. Their concentration indicates the proportion of AW in the water mass. We also introduce a passive tracer representing the meltwater from sea ice melting in the Nordics Seas. It enters the ocean through surface flux (m/s), which equals the water flux from sea ice melting, and is then subject to ocean advection and mixing. By spatially integrating this passive tracer over a chosen region, we can get the volume of sea ice meltwater in this region. Considering a box with volume V and salinity s_2, which is the mean salinity after part of the box volume (denoted as α) is replaced by sea ice meltwater, we have the following equation of salt balance:

$$s_{ice}\alpha + s_1(V - \alpha) = s_2 V, \tag{1}$$

where s_1 is the mean salinity in the box if sea ice meltwater would not have entered. The sea ice salinity in the model is $s_{ice} = 4$. Then we can get

$$\Delta s = s_2 - s_1 = -(s_2 - s_{ice})\alpha/(V - \alpha), \tag{2}$$

which is an approximation for the effect of sea ice meltwater on salinity changes in the box. We will use this passive tracer to assess the influence of sea ice meltwater on the salinity in the Greenland Sea.

The historical run is integrated from 1958 to 2017. The climatological run branches off from the historical run in 2001 and is conducted until 2017, covering the recent period of strong sea ice decline. The passive tracers mentioned above are added starting from 2001 in both runs.

3 Results

The AW temperature in the West Spitsbergen Current (WSC) at the Fram Strait, measured by the mooring array described by Beszczynska-Moeller et al. (2012) and von Appen et al. (2016), has a strong seasonal variability and an upward trend in recent years (Fig. 1b). The historical run reasonably reproduces the observed temperature variation. The observed warming trend in the WSC core (averaged over the three easternmost moorings between 8°E and 8.7°E) is about 0.5 °C/decade at both the 75 m and 250 m depths (von Appen, 2019; von Appen, Beszczynska-Möller, Schauer, & Fahrbach, 2019). The simulated trends are 0.54 °C/decade and 0.69 °C/decade at these two depths, respectively. The AW volume transport in the WSC (east of 5°E) at Fram Strait estimated by Beszczynska-Moeller et al. (2012) based on mooring observations is also well reproduced in the model (Fig. 1c). Furthermore, the model well represents the declining trend of both the Arctic sea ice volume (Fig. 1d) and extent (not shown) in the studied period. We also evaluated the model against available observations and reanalysis for the sea ice volume export through Fram Strait (Kwok, Cunningham, & Pang, 2004; Ricker, Girard-Ardhuin, Krumpen, & Lique, 2018; Selyuzhenok, Bashmachnikov, Ricker, Vesman, & Bobylev, 2019; Spreen, Kern, Stammer, & Hansen, 2009), the sea surface height (SSH) in the Greenland Sea (Müller, Dettmering, et al., 2019; Müller, Wekerle, et al., 2019), and salinity in the Greenland Sea (Brakstad, Våge, Håvik, & Moore, 2019) (see figures in the online Supporting Information). The comparisons show that the historical run can well represent the variability of the quantities relevant to this study. In the following, we will explore whether and how the Arctic sea ice decline can influence the AW temperature and volume transport at the Fram Strait by comparing the two simulations.

3.1 Historical thermal forcing strengthens AW inflow

When applying climatological atmospheric thermal forcing over the Arctic Ocean, the declining trend of sea ice volume (Fig. 1d) and extent (not shown) is eliminated. The climatological run retains some small interannual variability in sea ice related to, for example, the variability in winds.

The AW volume transport at Fram Strait in the historical run is stronger than in the climatological run (by 10% averaged over the last 10 years, Fig. 2a). With time the AW temperature at Fram Strait also becomes higher in the historical run (by 6% averaged over the last 10 years, Fig. 2c). With regard to the Nordic Seas, it is the region along its northeastern boundary that has much higher temperature in the historical run (Fig. 2e). As a consequence of both higher volume transport and higher temperature, the oceanic heat supply to the Arctic Ocean through the Fram Strait is certainly higher in the historical run.

Although the difference of AW temperature at Fram Strait between the two runs is not very large compared to the mean AW temperature, its upward trends differ significantly. The mean warming trend of the AW at Fram Strait in the period 2001 – 2017

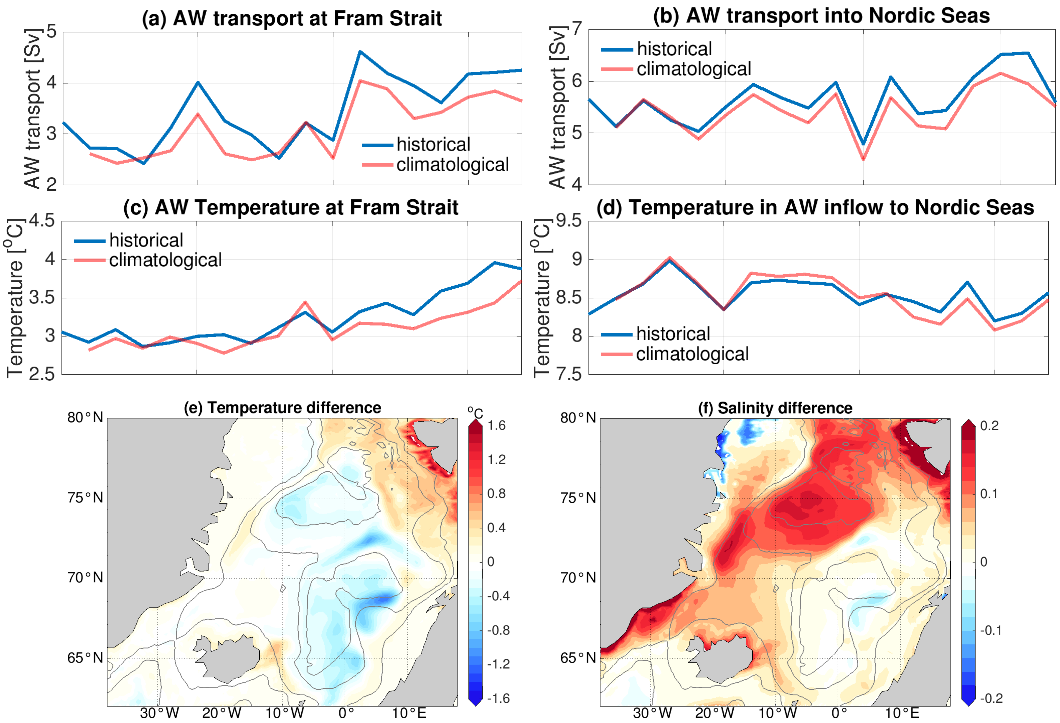

Figure 2. Atlantic Water volume transport through (a) Fram Strait (> 2°C) and (b) into the Nordic Seas at the Iceland-Faroe-Scotland Ridge (IFSR, > 4°C). The temperature threshold values were suggested based on observations by Beszczynska-Moeller et al. (2012) and Hansen et al. (2015) for the Fram Strait and Nordic Seas inflow, respectively. Atlantic Water temperature at (c) Fram Strait and (d) IFSR. (e) Difference of temperature between the two runs (historical minus climatological runs) averaged over the upper 300 m and the last 10 years. (f) The same as (e), but for salinity.

is 0.62 °C/decade and 0.41 °C/decade in the historical and climatological runs, respectively. That is, the AW warming trend at the Fram Strait is about 50% higher in the historical run. Besides, the upward trends of ocean volume transport in the historical run is 18% higher. The strengthened upward trends in the AW volume transport and AW temperature at Fram Strait in the historical run is attributed to the historical thermal forcing over the Arctic Ocean, which is the only model setting that is different between the two runs.

Moreover, the AW volume transport into the Nordic Seas through the IFSR is stronger in the historical run (Fig. 2b), although the difference in the ocean temperature at IFSR between the two runs is not pronounced (Fig. 2d and Fig. 2e). Averaged over the last 10 years, the AW volume transport through the IFSR in the historical run is 0.3 Sv higher than in the climatological run. This implies more oceanic heat supply from the North Atlantic to the Nordic Seas, which is consistent with the higher temperature in the northern Nordic Seas.

3.2 Sea ice decline as the driver

The above results indicate that the historical thermal forcing over the Arctic Ocean can enhance the AW volume transport into the Nordic Seas and the Arctic Ocean. In the following, we will show how the sea ice decline in the historical run leads to the difference in the AW temperature and transport at the Fram Strait between the two runs.

With historical thermal forcing, Arctic sea ice thins and the sea ice volume declines. As a consequence, the sea ice volume export through Fram Strait is lower (by about 20% averaged over the last 10 years, Fig. 3a). Sea ice melts on its way to the south, and the meltwater can penetrate into the Greenland Sea and influence the salinity therein. The salinity in the Greenland Sea is higher in the historical run (Fig. 2f,3b). Is this due to the reduction in the amount of sea ice and thus its meltwater in the historical run? Using Equation 2, the equivalent salinity change in the Greenland Sea associated with sea ice melting south of the Fram Strait can be estimated (Fig. 3c). Indeed, sea ice melting in the historical run has less negative contribution to the salinity than in the climatological run. We found that the difference in this equivalent salinity change associated with sea ice melting between the two runs can directly explain about 70% of the ocean salinity difference in the Greenland Sea between the two runs. Salinity in the Greenland

Sea can also be influenced by incoming AW from the Nordic Seas gyre circulation. However, the salinity of the AW in the gyre circulation upstream the Greenland Sea is similar in the two runs (Fig. 2f), and the amount of AW entering the Greenland Sea is nearly the same as illustrated by the concentration of the AW dye tracer released at IFSR (Fig. 3c). Therefore, the changes in sea ice export and thus in the amount of meltwater are the main reason for the salinity difference in the Greenland Sea between the two runs.

The salinity in the Greenland Sea is higher in the historical run, which leads to lower halosteric height, the major contribution to the total steric height difference between the two runs (Fig. 3d). As a result, the SSH in the Greenland Sea is lower in the historical run (Fig. 3e). Although the difference between the two runs is the most pronounced in the Greenland Sea, the SSH in the historical run is lower in most parts of the Nordic Seas (Fig. 3e,g). Accordingly, the cyclonic gyre circulation in the Greenland Sea and Nordics Seas is stronger in the historical run (Fig. 3f,h).

On the one hand, the lower SSH in the Nordic Seas in the historical run can lead to higher AW inflow through the IFSR, as suggested in previous studies (Sandø, Nilsen, Eldevik, & Bentsen, 2012). On the other hand, the stronger AW boundary current can increase ocean volume transport toward the Arctic Ocean through the Fram Strait, as suggested by Chatterjee et al. (2018) and Muilwijk et al. (2019). Both the higher AW inflow from the North Atlantic to the Nordic Seas and the stronger AW volume transport toward the Fram Strait increase the temperature in the WSC. As a consequence, the stronger AW volume transport through Fram Strait and the higher ocean temperature together can increase the oceanic heat supply to the Arctic Ocean.

The wind stress curl over the Nordic Seas can influence the interannual variability of the AW inflow toward Fram Strait, thus the temperature variation in the Fram Strait (Chatterjee et al., 2018). Muilwijk et al. (2019) studied the response of the Nordic Seas to wind forcing variability using multi-model simulations. They modified the gyre circulation strength and SSH in the Nordic Seas by imposing wind anomalies over the Greenland Sea and found that the AW inflow from the North Atlantic into the Nordic Seas and the Arctic Ocean can be accordingly changed. Different to the processes investigated in those studies, the driver of the changes in the Nordic Seas between our two simulations is the reduction in Arctic sea ice export resulting from the on-going climate

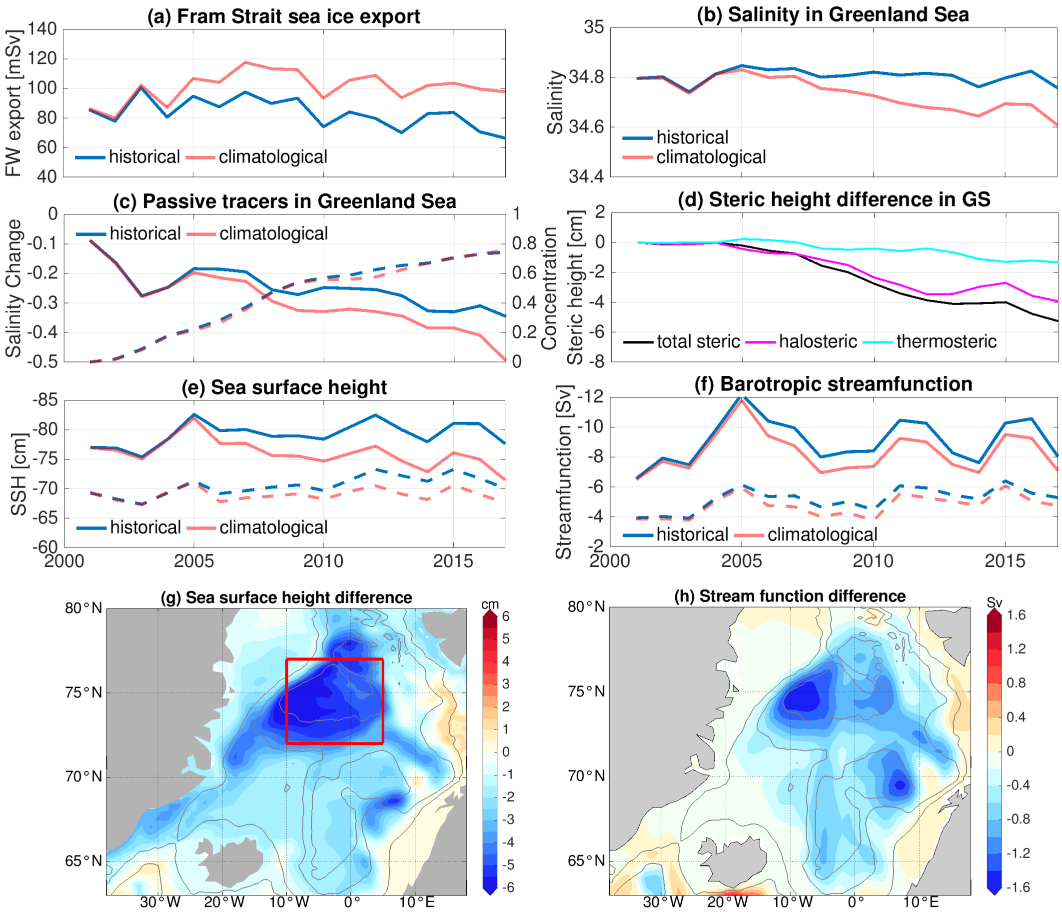

Figure 3. (a) Fram Strait sea ice freshwater export flux. (b) Salinity in the upper 300 m in the Greenland Sea (indicated with the red box in (g)). (c) Contribution to salinity changes in the upper 300 m of the Greenland Sea by sea ice melting in the Nordic Seas latitude range (solid lines) and the mean Atlantic Water dye tracer in the upper 300 m of the Greenland Sea (dashed lines). The equivalent salinity change is calculated using Equation 2. The dye tracer is released in the Atlantic Water layer at the Iceland-Faroe-Scotland Ridge (IFSR). (d) The difference of steric, halosteric and thermosteric height between the two runs (historical minus climatological, integrated from surface to bottom) averaged over the Greenland Sea. (e) Sea surface height (SSH) over the Greenland Sea (solid curves) and Nordic Seas (65°N – 77°N, dashed curves). (f) Barotropic streamfunction over the Greenland Sea (solid curves) and Nordic Seas (dashed curves). (g) SSH difference between the two runs (historical minus climatological) averaged over the last 10 years. The red box indicates the Greenland Sea region. (h) The same as (g), but for the barotropic streamfunction.

warming. The same wind forcing was used in our two simulations and the ocean surface stress over the Greenland Sea was not changed between the runs.

4 Discussions

4.1 Upward trends in AW temperature and transport at Fram Strait

Our simulations show that the AW temperature and volume transport at Fram Strait have upward trends even in the climatological simulation (Fig. 2a,c). However, there is no significant upward trend in the AW volume transport from the North Atlantic into the Nordic Seas in the climatological run, and the temperature in the AW inflow to the Nordic Seas even has a negative trend in both simulations (Fig. 2b,d). The latter is associated with the recent cooling of the subpolar North Atlantic (Josey et al., 2018). Therefore, for the studied period, the upward trends in the AW temperature and transport at Fram Strait in the climatological run are caused by the atmospheric forcing over the Nordic Seas rather than over the North Atlantic. On the one hand, the air-sea heat flux along the AW pathway in the Nordic Seas can modify the ocean temperature (Asbjornsen, Årthun, Skagseth, & Eldevik, 2019). On the other hand, stronger cyclonic atmospheric circulation over the Greenland Sea can strengthen the AW transport towards the Fram Strait and increase the temperature there (Chatterjee et al., 2018). In our study, the Arctic sea ice decline is discovered to be another important driver for the recent upward trends in the AW temperature and transport at the Fram Strait.

4.2 Resultant warming in the Arctic Ocean

As a result of stronger oceanic heat supply through Fram Strait in the historical run, the AW layer of the Arctic Ocean is warmer than in the climatological run (Fig. 4). The largest temperature difference between the two runs is located in the Eurasian Basin, while it is warmer also on the Canadian Basin side of the Lomonosov Ridge (Fig. 4b,e). The increased AW supply to the Arctic Ocean is clearly shown by the concentration of the dye tracer released at the Fram Strait (Fig. 4c,f).

Without Arctic sea ice decline, the Eurasian Basin also has a warming tendency during recent years (Fig. 4d), because AW temperature and the volume transport at Fram Strait still have upward trends (Fig. 2a,c). The sea ice decline strengthens the Fram Strait inflow and increases the temperature, thus increasing the warming trend in the Arctic

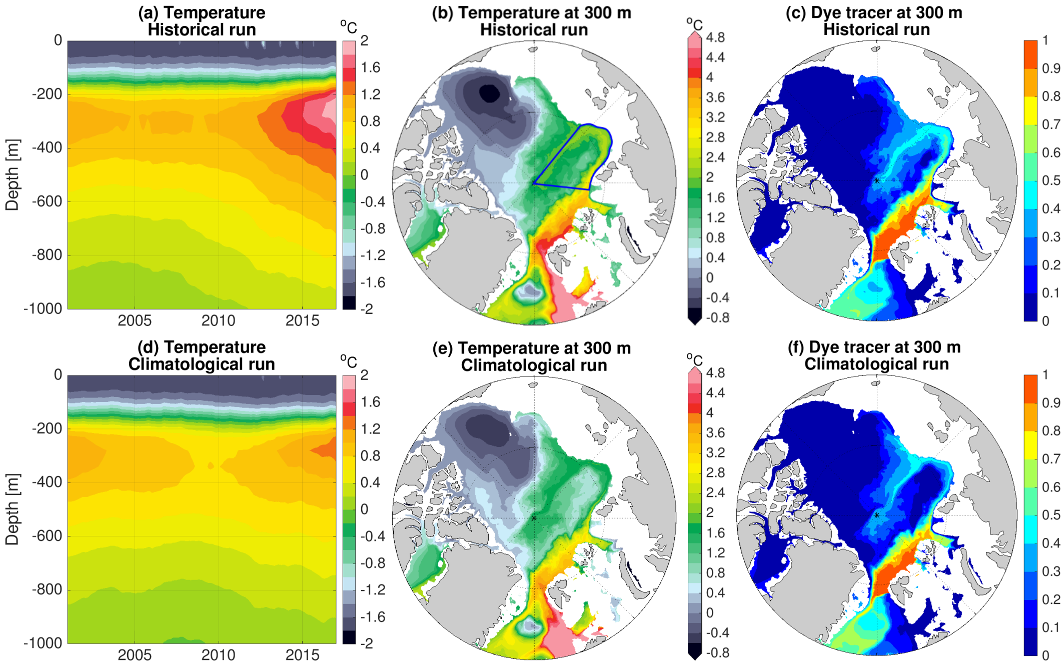

Figure 4. (a) Hovmöller diagram of temperature averaged over the eastern Eurasian Basin (indicated by the blue box in (b)) in the historical run. (b) Temperature at 300 m depth averaged over the last three years in the historical run. (c) Dye tracer at 300 m depth averaged over the last three years in the historical run; The tracer is released in the Atlantic Water layer east of 0°E at Fram Strait. (d)(e)(f) The same as (a)(b)(c), respectively, but for the climatological run.

Ocean (Fig. 4a). As some of the increased ocean heat from the Fram Strait induced by the sea ice decline is accumulated in the Arctic AW layer with time, the ocean warming trend inside the Arctic Ocean in the historical run is much stronger than in the climatological run (cf. Fig. 4a and 4d).

Sea ice decline not only increases the AW layer temperature as found in this study, but also significantly increases the salinity in the halocline of the Eurasian Basin by changing water mass spatial distribution (Wang et al., 2019). The two effects together can contribute to the Atlantification of the eastern Eurasian Basin observed by Polyakov et al. (2017).

The AW inflow through Fram Strait is also highly relevant for nutrient supply to the Arctic Ocean (Torres-Valdés et al., 2013). The processes we discussed imply that the Arctic sea ice decline can also influence oceanic primary productivity in the Arctic Ocean indirectly through changing the AW inflow, besides its direct impacts, for example, through changing light availability.

5 Conclusions

Observations show that the AW layer at Fram Strait and downstream inside the Arctic Ocean has become warmer (e.g., Beszczynska-Moeller et al., 2012; Polyakov et al., 2013). Using model simulations we found that the Arctic sea ice decline is one of the important drivers. The discovered driving mechanism is illustrated in Fig. 5. When sea ice declines, the Arctic sea ice volume export through Fram Strait decreases, which increases the salinity in the Greenland Sea. The halosteric height, thus the SSH, decreases in the Greenland Sea and Nordic Seas. The cyclonic gyre circulation in the Nordic Seas strengthens accordingly. The reduction of SSH and strengthening of the AW boundary current increases the AW transport into the Nordic Seas and the Arctic Ocean. The warming trends of the AW at Fram Strait and in the Arctic Ocean are thus intensified. In these processes, the Nordic Seas play the role of a "switchyard", while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the "switchgear".

Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010). Although ocean heat is important for the sea ice bud-

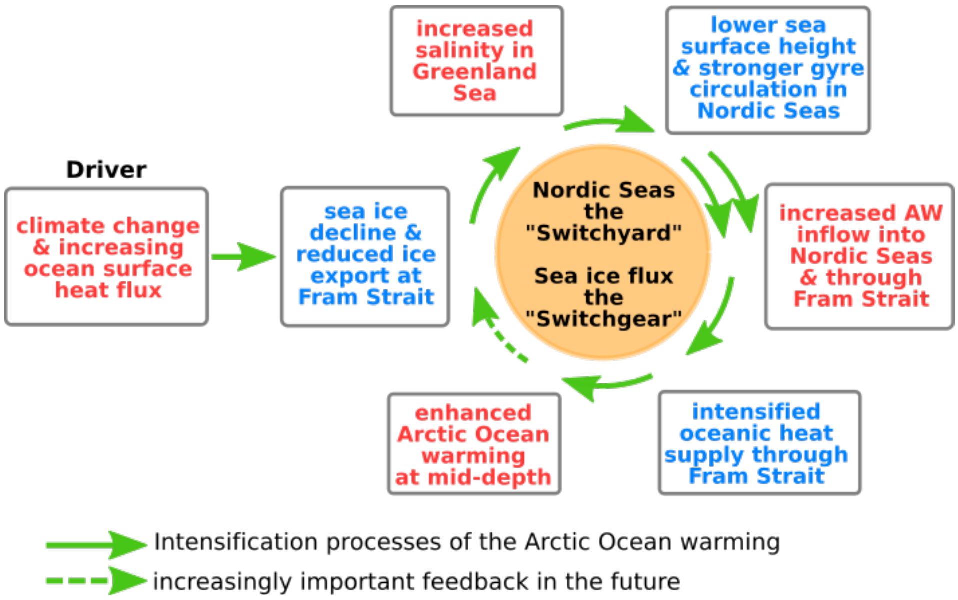

Figure 5. Schematic diagram illustrating the discovered mechanism that intensifies the warming of the Atlantic Water layer at the Fram Strait and in the Arctic Ocean at mid-depth.

get in the current climate, the air-sea heat flux still plays a dominant role (Olonscheck, Mauritsen, & Notz, 2019). However, if the ocean heat transport through Fram Strait continues to increase in the future, the induced basal melting on larger scales may reduce the sea ice volume export through Fram Strait more significantly. In this case, the feedback as depicted in Fig. 5 may play an increasingly important role in strengthening the AW heat inflow and Arctic sea ice decline.

The atmospheric circulation over the Arctic Ocean was predominantly in an anticyclonic regime in the past two decades, so a large amount of liquid freshwater was accumulated inside the Arctic Ocean (Haine et al., 2015; Proshutinsky et al., 2009; Rabe et al., 2014). In this situation, although the sea ice export through Fram Strait decreased significantly, liquid freshwater export from the Arctic Ocean was not changed that much by the sea ice decline (Wang et al., 2019). However, if the atmospheric circulation over the Arctic Ocean changes to a cyclonic regime, or if precipitation in high latitudes increases significantly in the future warming climate (Carmack et al., 2016), enhanced liquid freshwater export might interfere with the processes we discussed. In a warming climate, the strength of the AMOC may decrease (e.g., Cheng, Chiang, & Zhang, 2013), which can also influence the AW transport to the Nordic Seas. It requires further studies to understand how different processes will impact the Arctic Ocean heat budget jointly in the future climate. To this end, we propose that the Nordic Seas may remain an important switchyard for changes of the Arctic Ocean owing to their location connecting the Arctic Ocean and the North Atlantic.

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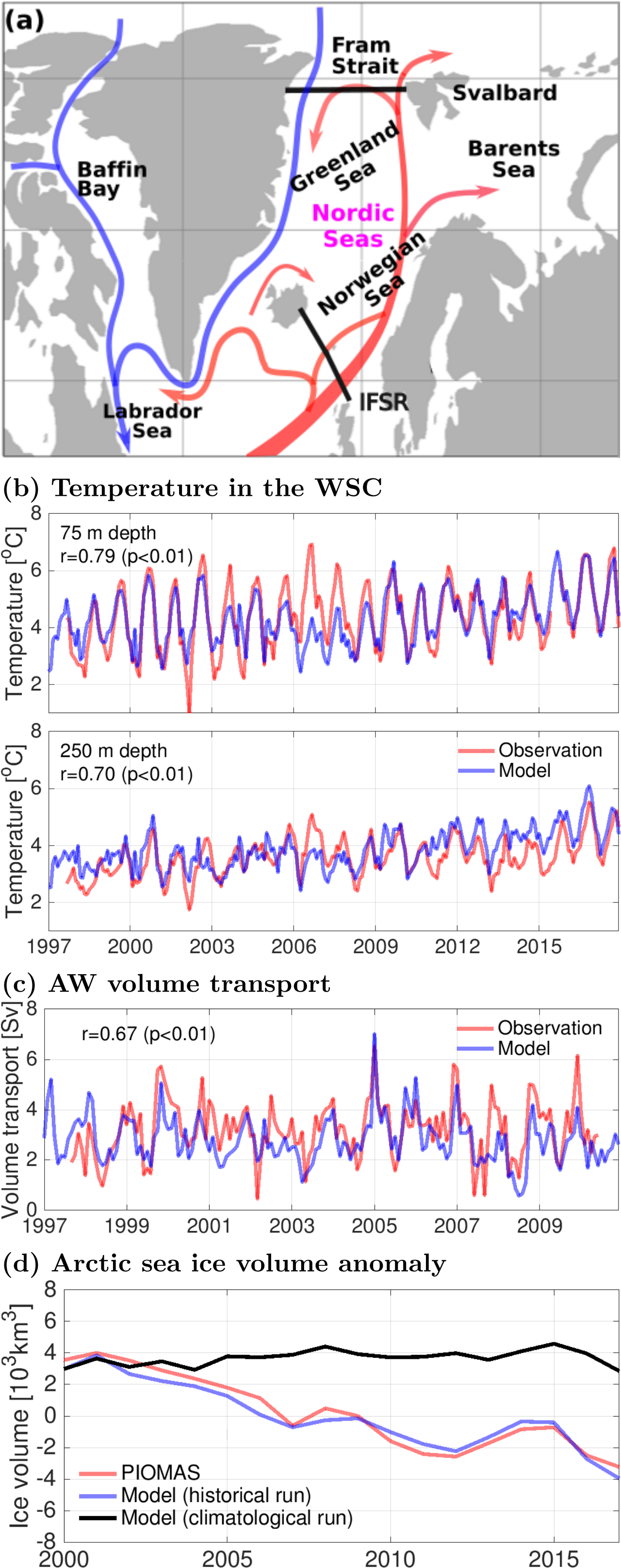
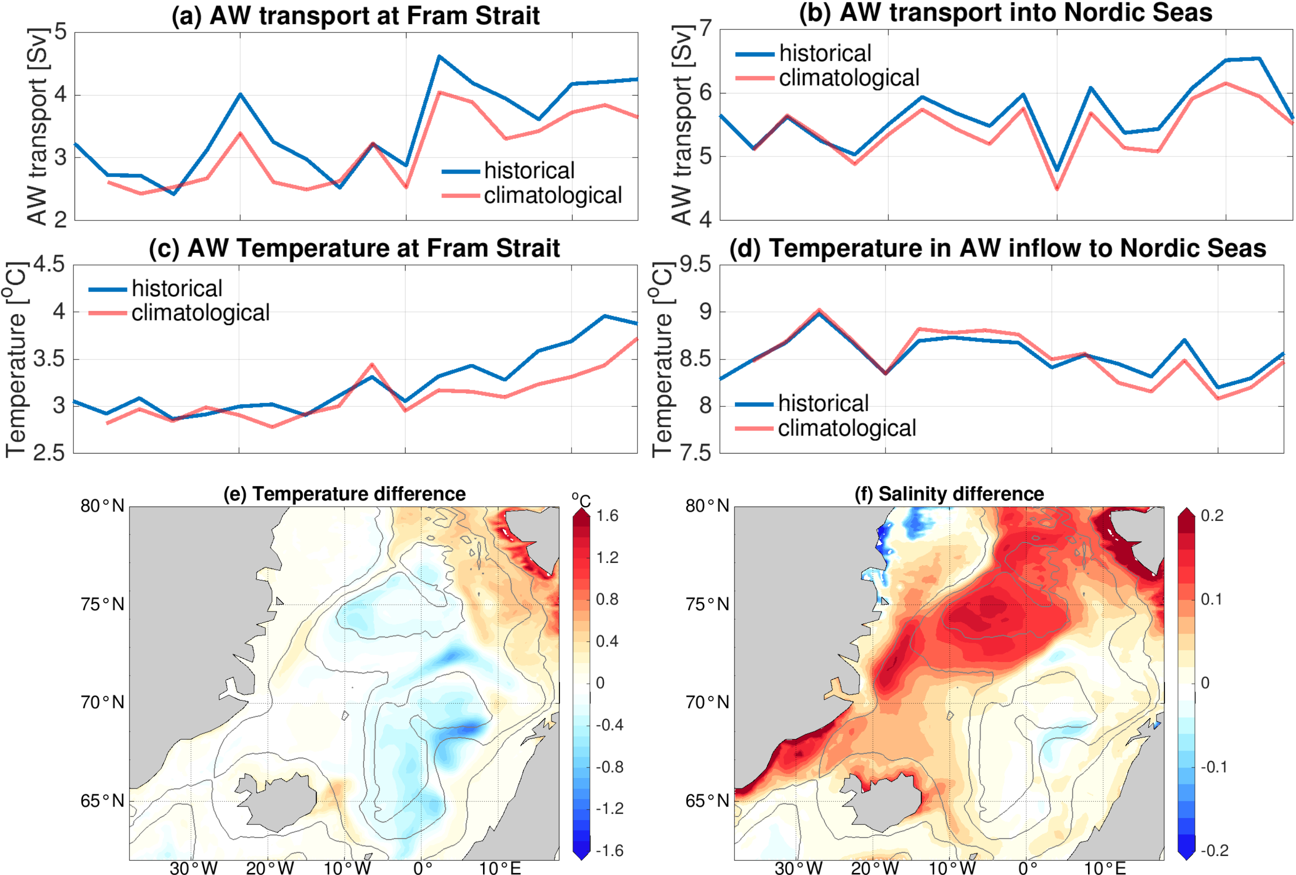
Figure1.



(a)
Fram Strait
Svalbard
Baffin Bay
Greenland Sea
Barents Sea
Nordic Seas
Norwegian Sea
IFSR
Labrador Sea
(b) Temperature in the WSC
75 m depth
r=0.79 (p<0.01)
Temperature [°C]
250 m depth
r=0.70 (p<0.01)
Observation
Model
1997 2000 2003 2006 2009 2012 2015
(c) AW volume transport
r=0.67 (p<0.01)
Volume transport [Sv]
Observation
Model
1997 1999 2001 2003 2005 2007 2009
(d) Arctic sea ice volume anomaly
Ice volume [10³km³]
PIOMAS
Model (historical run)
Model (climatological run)
2000 2005 2010 2015

Figure2.



(a) AW transport at Fram Strait
AW transport [Sv]
5
4
3
2
historical
climatological
(b) AW transport into Nordic Seas
AW transport [Sv]
7
6
5
4
historical
climatological
(c) AW Temperature at Fram Strait
Temperature [°C]
4.5
4
3.5
3
2.5
historical
climatological
(d) Temperature in AW inflow to Nordic Seas
Temperature [°C]
9.5
9
8.5
8
7.5
historical
climatological
(e) Temperature difference
°C
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
80°N
75°N
70°N
65°N
30°W
20°W
10°W
0°
10°E
(f) Salinity difference
0.2
0.1
0
-0.1
-0.2
80°N
75°N
70°N
65°N
30°W
20°W
10°W
0°
10°E

Figure3.

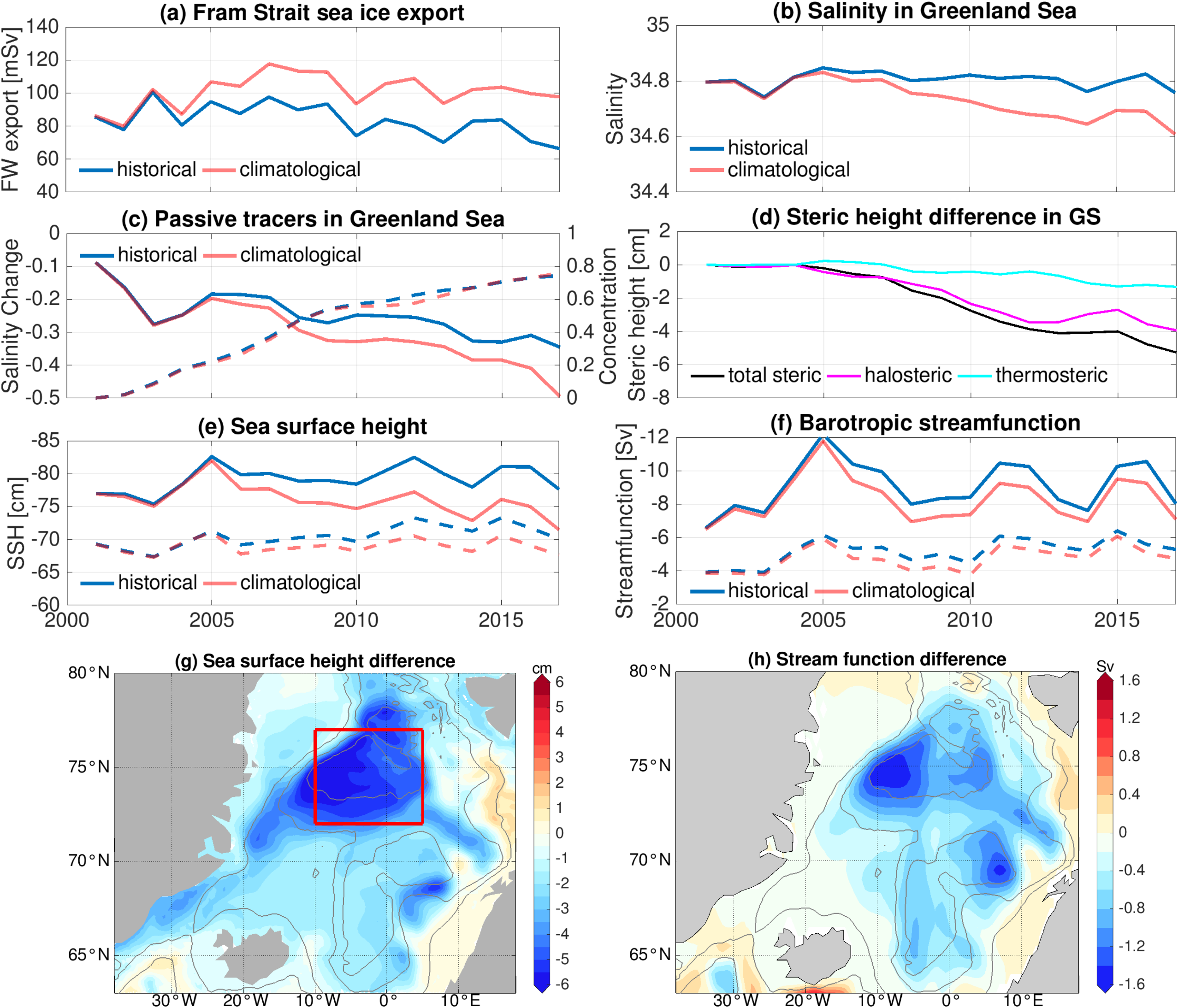
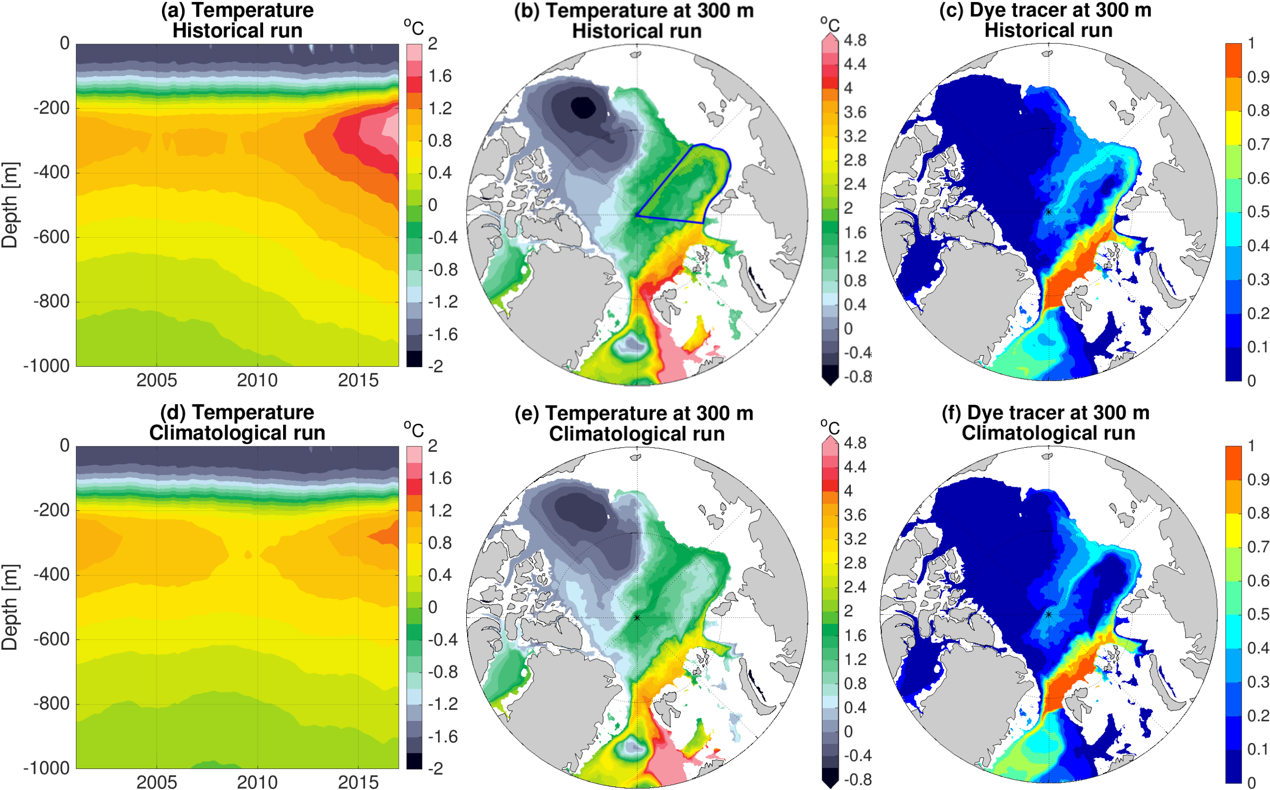
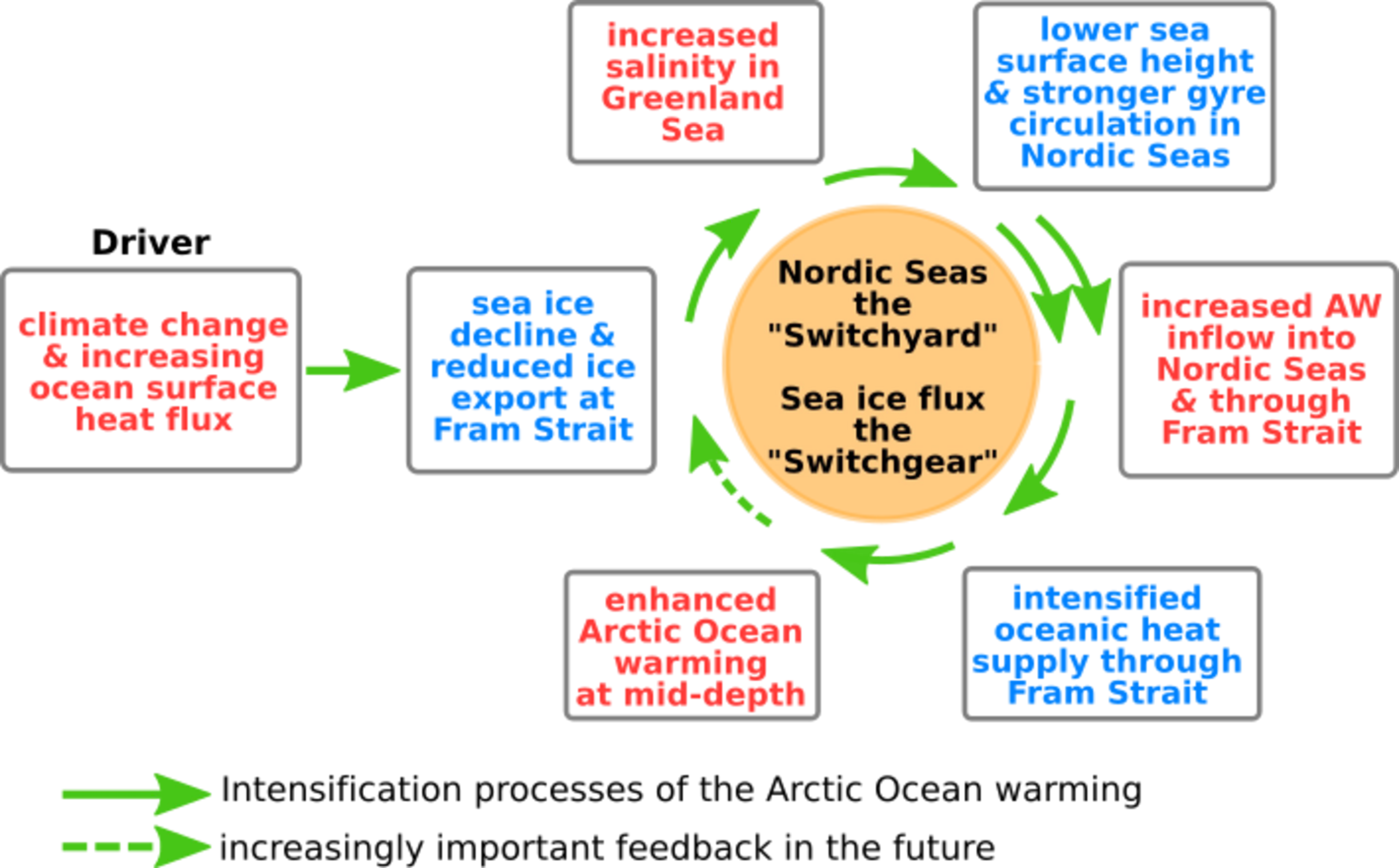

(a) Fram Strait sea ice export
FW export [mSv]
historical
climatological
(b) Salinity in Greenland Sea
Salinity
(c) Passive tracers in Greenland Sea
Salinity Change
Concentration
(d) Steric height difference in GS
Steric height [cm]
total steric
halosteric
thermosteric
(e) Sea surface height
SSH [cm]
(f) Barotropic streamfunction
Streamfunction [Sv]
(g) Sea surface height difference
cm
(h) Stream function difference
Sv
80°N
75°N
70°N
65°N
30°W
20°W
10°W
0°
10°E

Figure4.



(a) Temperature
Historical run
(b) Temperature at 300 m
Historical run
(c) Dye tracer at 300 m
Historical run
(d) Temperature
Climatological run
(e) Temperature at 300 m
Climatological run
(f) Dye tracer at 300 m
Climatological run
Depth [m]
°C
0
-200
-400
-600
-800
-1000
2005
2010
2015
2
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
-2
4.8
4.4
4
3.6
3.2
2.8
2.4
2
1.6
1.2
0.8
0.4
0
-0.4
-0.8
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure5.


Driver
climate change & increasing ocean surface heat flux
sea ice decline & reduced ice export at Fram Strait
increased salinity in Greenland Sea
lower sea surface height & stronger gyre circulation in Nordic Seas
Nordic Seas the "Switchyard"
Sea ice flux the "Switchgear"
increased AW inflow into Nordic Seas & through Fram Strait
intensified oceanic heat supply through Fram Strait
enhanced Arctic Ocean warming at mid-depth
Intensification processes of the Arctic Ocean warming
increasingly important feedback in the future