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LETTER

# Long-lasting impact of winter North Atlantic Oscillation on Barents-Kara sea ice anomaly in recent decades

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**Keywords:** winter NAO, BK sea ice, long-lasting impact, air-sea-ice response

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## Abstract

In this paper, the long-lasting impact of the winter North Atlantic Oscillation (NAO) on Arctic sea ice is investigated using reanalysis data, with focus on the Barents–Kara (BK) sea where the air-sea-ice response is closely associated with the interdecadal shift in the northern action center of the NAO. A significant negative correlation between the winter NAO and the late autumn BK sea ice has been dominant since the early 2000s, which is in sharp contrast to the extremely weak correlation before the late 20th century. When the northern center of the NAO retreats westward, a prevailing low-level southerly wind anomaly creates significant positive air temperature anomalies over the BK sea, and the induced ocean current strengthens the northward transport of warm sea water, resulting in a positive BK upper-layer ocean temperature anomaly and a negative sea ice anomaly until early spring. Entering summer, the preexisting less-than-normal sea ice causes the amount of solar shortwave radiation absorbed by the upper-layer sea water to significantly increase and thereby continues to warm up the upper layer of sea water and reduce the sea ice. The warmed sea water enables the negative sea ice anomaly to last until late autumn owing to its relatively large specific heat capacity. Thus, the NAO in the previous winter exerts a long-lasting impact on the BK sea ice.

## 1. Introduction

The Arctic—home to the coldest, shallowest, and smallest ocean in the world—is an important component of the global climate system. As a critical part of the Arctic ocean, sea ice significantly regulates the radiation, heat, and momentum exchange between the atmosphere and ocean, and impacts the mid-high latitude (e.g. Budikova 2009, Honda *et al* 2009, Wu *et al* 2009, 2013, 2015, 2017, Jaiser 2012, Li and Wu 2012, Liu *et al* 2012, Li and Wang 2013, Gao *et al* 2015, Sorokina *et al* 2016, Smith *et al* 2017, He *et al* 2018, Kim and Kim 2020, Savelieva 2020) and tropical climate (e.g. Liu *et al* 2004, Chen *et al* 2020, Kim *et al* 2020).

As a key factor affecting the Arctic climate, the Barents-Kara (BK) sea has some of the greatest sea ice variability on various time scales in the Arctic (Deser *et al* 2000, Vinje 2001, Divine and Dick 2006). The high air-sea temperature difference in the BK sea (Simonsen and Haugan 1996) dominates the seasonal heat budget of the Arctic atmosphere, making it the most active area of air–sea exchange and a hot spot affecting the high-latitude climate system (Serreze *et al* 2006, Smedsrud *et al* 2013). The North Atlantic Ocean is connected to the Arctic Ocean through the BK sea and can exchange heat and energy with the Arctic Ocean through the Gulf Stream, North Atlantic Current, and Norwegian Atlantic Slope Current (Polyakov *et al* 2005). Sato *et al*

(2014) revealed that a poleward shift of the sea surface temperature (SST) front over the Gulf Stream can induce warm southerly advection and thereby reduce sea ice in the Barents sea. Numerical results have also shown that the interannual variability and long-term decrease in the Arctic sea ice area reflect the variation in the inflow of the North Atlantic Current (Arthun and Schrum 2010, Arthun *et al* 2012, Koenigk and Brodeau 2014).

Atmospheric circulation over the North Atlantic and Arctic is also crucial to connecting the Arctic sea ice to the middle-to-high latitude region (Zhang *et al* 2012, Gerber *et al* 2014, Chen and Luo 2017, Ding *et al* 2017). As the dominant climate mode in the North Atlantic region, the North Atlantic Oscillation (NAO) has great impacts on the entire North Atlantic-Arctic region (Hurrell *et al* 2003). Ogi *et al* (2003) showed that the summertime weather in East Asia is closely associated with the NAO during the previous winter. Rodwell *et al* (1999) also highlighted the impact of the NAO on the Arctic sea ice cover in the Barents sea during the winter. A negative NAO coupled with a positive tropical SST anomaly can lead to negative temperature anomalies in the high latitude and polar regions (Ding *et al* 2014, Peings and Magnusdottir 2014).

Previous studies have pointed out the evident interdecadal change in the spatial pattern of the NAO (Luo *et al* 2010a, 2010b), which leads to changes in the relationship between the NAO and the Arctic sea ice export (Hilmer and Jung 2000) and climate variability (Lu and Greatbatch 2002). However, few studies have focused on the long-lasting impact of the winter NAO on Arctic sea ice across seasons. In this study, we aimed to determine the long-lasting association between the Arctic sea ice anomaly and the winter NAO and proposed a plausible mechanism for the NAO sustainably effect on the sea ice. Moreover, a recent study revealed the weakening and westward retreat of the northern center of the NAO in the past two decades (Zuo *et al* 2016). The interdecadal variations in this association were also investigated.

## 2. Data and methodology

The monthly mean sea ice concentration (SIC) and SST data on a 1.0° × 1.0° grid were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1 (HadISST; 1870 to present; Rayner *et al* 2003). We focused primarily on the satellite era (1979 to present) since the available sea ice observations prior to the satellite era are quite limited both spatially and temporally and are presumably subject to a large uncertainty (Johannessen *et al* 2004). The atmospheric data were derived from the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) reanalysis 2 dataset (Kanamitsu *et al* 2002) on a 2.5° × 2.5° grid covering the period from 1979 to the present. The oceanic reanalysis data were obtained from the Simple Ocean Data Assimilation reanalysis dataset version 3.4.2 (Carton *et al* 2018, 2019) on an approximately 0.25° × 0.25° grid for 1980–2020. The monthly NAO index, which has been calculated by projecting the monthly observed anomaly field onto the monthly patterns (Barnston and Livezey 1987), was downloaded directly from the Climate Prediction Center/National Oceanic Atmospheric Administration website. All the analyses were carried out from 1980 to 2020. The anomaly was defined as the deviation from the climatological annual cycle for 1981–2010. To focus on the climatic variability, the long-term linear trend was removed prior to our analysis.

To identify the independent modes associated with the sea ice anomaly in the Arctic, empirical orthogonal function (EOF) analysis was applied to the SIC anomalies over the Arctic sector (poleward of 65° N). North's rule of thumb (North *et al* 1982) was used to test the significance of the EOF modes. Regression analysis was conducted using the derived EOF principal components (PCs) to retrieve the associated spatial patterns of the EOF. The center longitude of the northern center of the NAO pattern, which was obtained via 21 year sliding regression of the geopotential height anomaly at 500 hPa onto the winter mean NAO index, was utilized to represent the eastward shift or westward retreat of the northern center of the NAO. The anomalous horizontal ocean current was reconstructed using the wind stress in terms of the Ekman transport (Ekman 1905). The full details of the methodology are provided in supporting information S1. The statistical significance of the regression and correlation coefficients was assessed using the two-tailed Student's *t*-test.

## 3. Results

### 3.1. Interdecadal change in the relationship between the late autumn Arctic sea ice and the pre-winter NAO

To detect the long-lasting impact of the winter NAO on sea ice anomaly, the relationship between the late autumn Arctic sea ice and the pre-winter NAO was examined. First, EOF analysis was conducted from 1980 to 2020 to extract the independent mode of the October-November-December (OND) mean SIC anomaly. According to North's rule of thumb, only the first EOF mode (EOF1) is significantly separated, and it explains 29.1% of the total variance. The spatial pattern of the EOF1 (figure 1(a)) shows that the dominant negative sea ice anomaly in late autumn is mainly occurred over the BK sea area. Figure 1(b) shows the regression pattern of the OND SIC anomaly onto the previous winter-mean NAO index calculated by averaging the monthly index over December–January–February from 1979/80 to

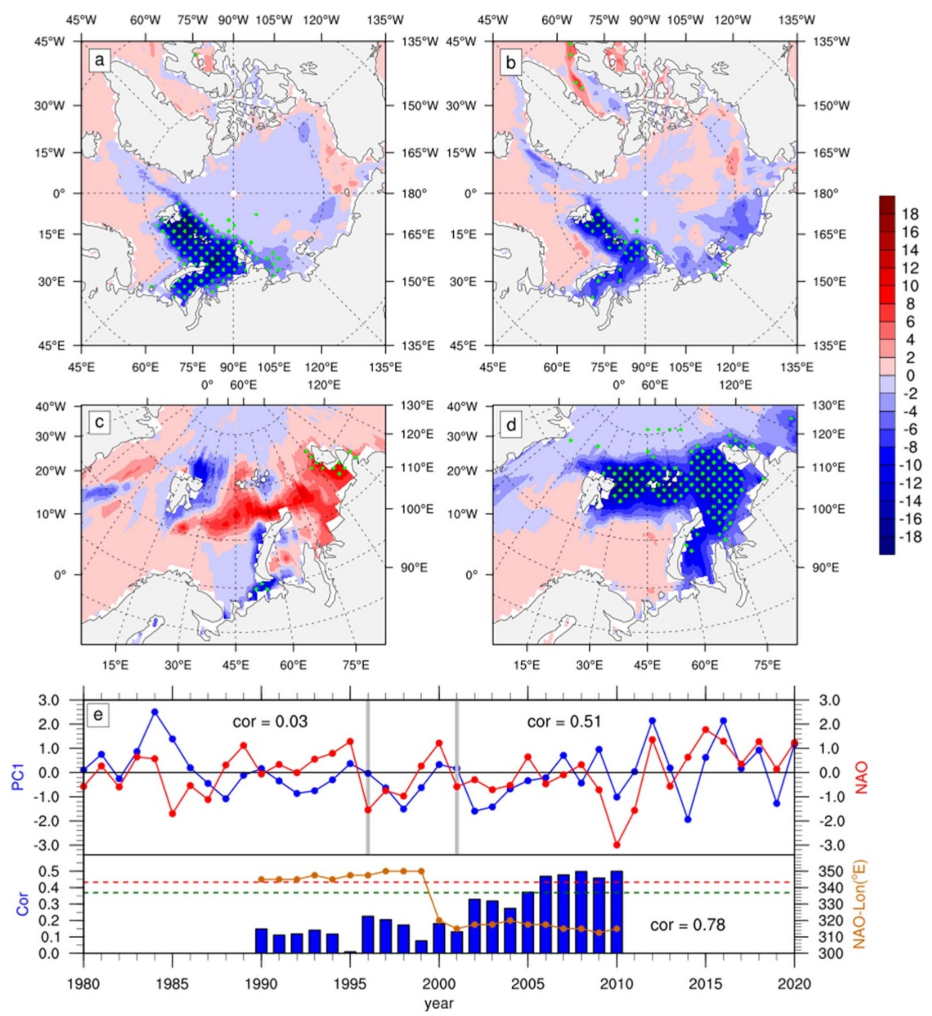

**Figure 1.** (a) Spatial pattern of the first EOF mode of the OND-mean SIC anomaly (shading, unit: %) poleward of 65° N. (b)–(d) Regression patterns of the OND-mean SIC anomaly (shading, unit: %) onto the pre-winter mean (DJF mean) NAO index during (b) 1980–2020, (c) 1980–1996, and (d) 2001–2020. (e) Normalized time series of PC1 (blue dot line), winter mean NAO index (red dot line), their 21 year sliding correlation coefficients (blue bar), and the center longitude of the northern center of the NAO (dark orange dotted line) where the dashed green (red) line indicates statistical significance at the 90% (95%) confidence level based on the two-sided Student's *t*-test. The green dots in (a)–(d) denote significance at the 95% confidence level based on the two-sided Student's *t*-test.

2019/20. The NAO is negatively correlated with the Arctic sea ice, and the area of significance is located in the BK sea. This regression pattern is quite similar to the EOF1 spatial pattern, implying an intrinsic relationship between the OND BK sea ice and the pre-winter NAO. The correlation coefficient between PC1 and the pre-winter NAO index is about 0.33, exceeding the 95% confidence level.

The sliding correlation with a 21 year moving window (figure 1(e)) between PC1 and the pre-winter NAO index was poor before the late 20th century, but it was significantly enhanced from the early 2000s onward (0.03 during 1980–1996 and 0.51 during 2001–2020, the latter is significant at the 95% confidence level). The difference in the correlation coefficients of the two periods is also significant at the 95% confidence level based on the Fisher *z* transformation (Fisher 1915), confirming the recently constructed impact of the winter NAO on the BK sea ice anomaly in recent decades. Figures 1(c) and (d) show the clear difference in the spatial patterns of the OND SIC anomaly regressed against the pre-winter NAO index during the two periods. During the first period, a positive SIC anomaly occurred in most of the BK sea but failed to pass the statistical significance test. Entering the second period, a significant negative SIC anomaly occurred in the entire BK sea, similar to those shown in figures 1(a) and (b).

A recent study demonstrated the weakening and westward retreat of the northern center of the NAO over the past two decades (Zuo *et al* 2016). As illustrated in figure 1(e), the center longitude of the northern center of the NAO exhibited a clear westward retreat at around 2000 (see also figure S1), accompanied by a marked increase in the sliding correlations between PC1 and the pre-winter NAO index. The correlation coefficient between the series of the sliding correlation and the NAO center

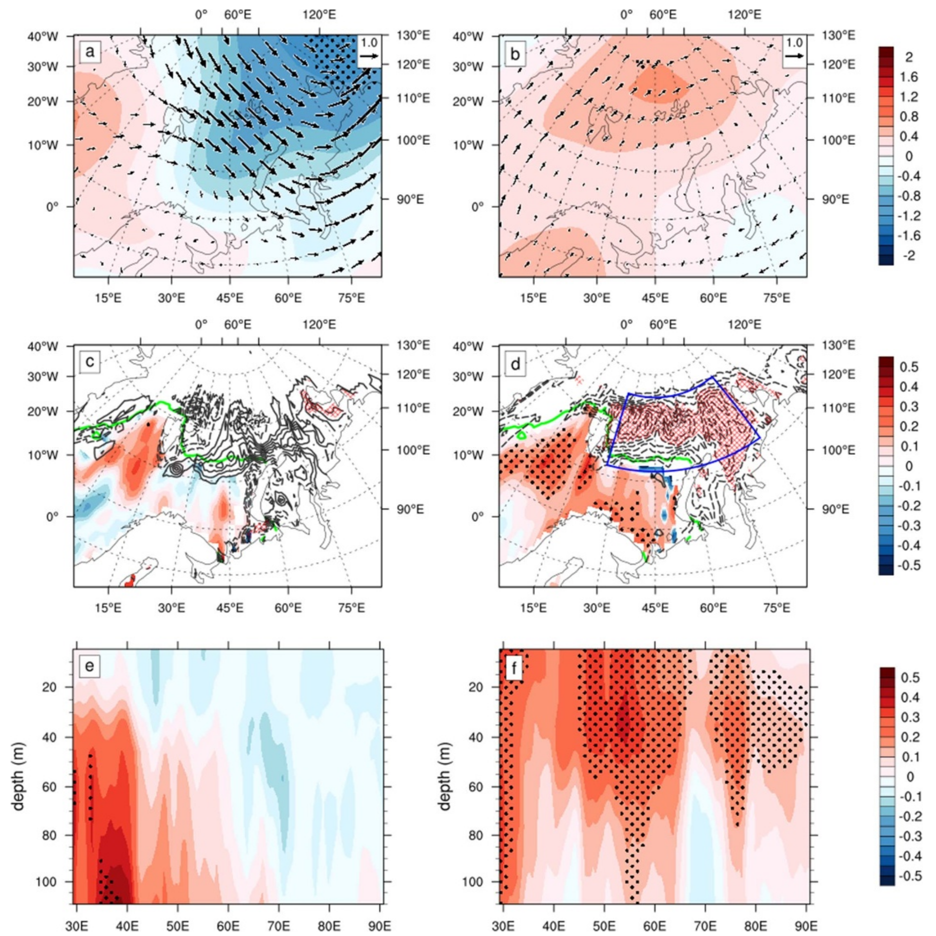

**Figure 2.** Regression patterns of the OND mean anomalous (a), (b) air temperature (shading, unit: °C) and horizontal wind (vectors, unit: m s$^{-1}$) at the 850 hPa isobaric level, (c), (d) SST (unit: °C) and SIC (contours, interval of 2%; zero contours are omitted), and (e), (f) meridional averaged oceanic temperature (unit: °C) over [76° N–83°N] (see blue box in figure 2(d)) above 120 m onto the pre-winter mean NAO index during (a), (c), (e) P1, and (b), (d), (f) P2. The thin red mesh in (c), (d) and black dots in (e), (f) denote significant SIC and temperature anomalies at the 95% confidence level based on the two-sided Student's *t*-test, respectively. The green contours in (c), (d) denote the 0.2 °C SST climatic isoline.

longitude is about 0.78, which is far greater than the threshold of 0.43 for the 95% confidence level. This suggests that the long-lasting impact of the winter NAO on the BK sea ice is highly associated with the east-west position of its northern action center. To determine the physical mechanisms of the long-lasting impact of the winter NAO on the BK sea ice anomaly, we divided the entire research period into two periods before and after 2000, namely 1980–1996 (referred to as P1) and 2001–2020 (referred to as P2). The 1997–2000 period was omitted to avoid interference with the results during the transition period.

We further investigated the atmospheric circulation and oceanic temperature to determine how the pre-winter NAO crossed more than half a year to impact the late autumn sea ice anomaly during P2 (figure 2), where the result for that during P1 was used for comparison. Because the NAO signal and its corresponding atmospheric circulation cannot last long due to the weak persistence of the atmospheric variations, the BK region exhibited insignificant weak negative and positive air temperature anomalies accompanied by wind anomalies at 850 hPa during P1 and P2, respectively. Although the SST in the HadISST dataset is not available for the area covered by sea ice, a significant positive SST anomaly still occurred near the region of the negative SIC anomaly during P2 (figure 2(d)) but was not visible during P1. This indicates that the ocean is more like an intermediary of the sustained impact from the previous winter relative to the atmosphere. Furthermore, the upper-layer ocean temperature above about 50 m was significantly positive during P2, corresponding to the evident negative sea ice anomaly in the region (figure 2(f)). During P1, the upper-layer ocean temperature was still inconspicuous (figure 2(e)). This suggests that the significant difference in the air-sea-ice response of the NAO occurred around 2000, and the winter NAO has exerted continuous impacts on the BK sea ice through the upper-layer ocean temperature in recent decades.

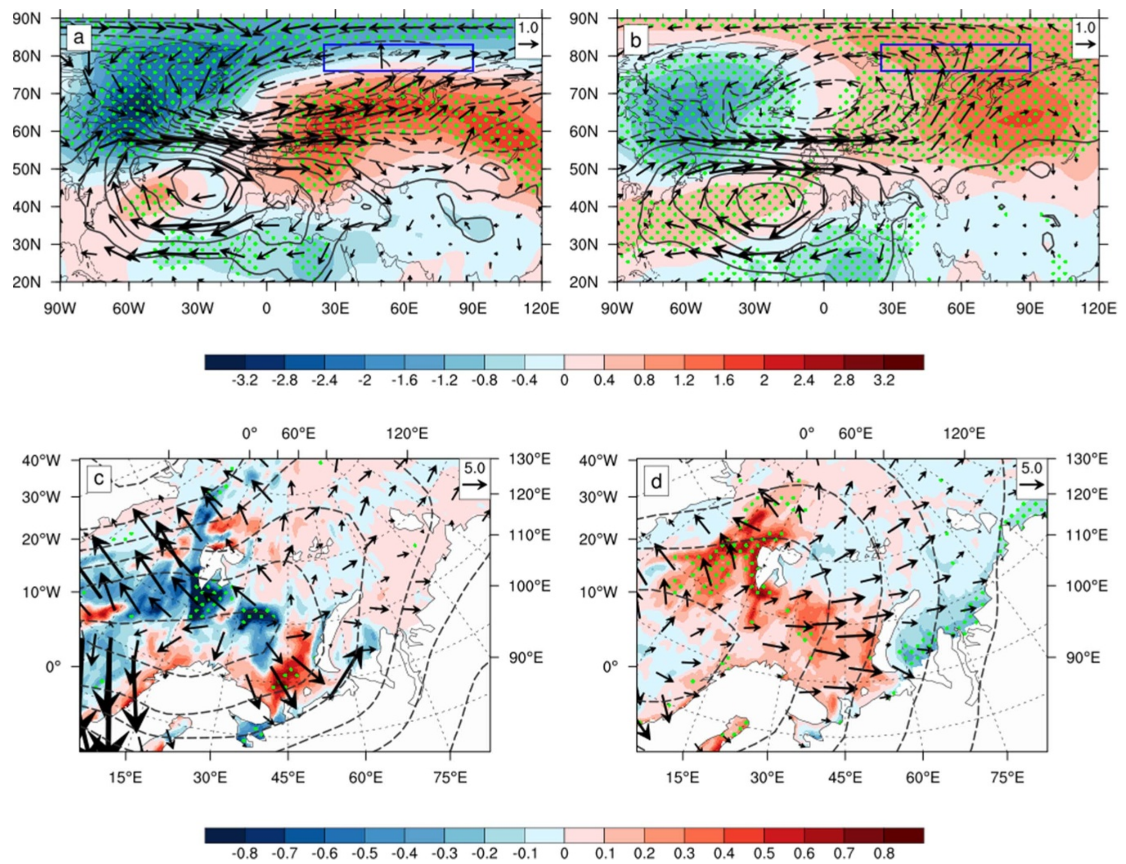

**Figure 3.** Regression patterns of the DJF-mean anomalous (a), (b) air temperature (shading, unit: °C) and horizontal wind (vectors, unit: m s$^{-1}$) at the 850 hPa isobaric level, and SLP (contours with an interval of 0.8 hPa), and (c), (d) reconstructed ocean current in terms of the Ekman transport (vectors, unit: cm s$^{-1}$), sea subsurface temperature integrated from depths of 0 m to 50 m (shading, unit: °C), and SLP (contours with an interval of 0.8 hPa) against the simultaneous NAO index during (a), (c) P1, and (b), (d) P2. The green dots denote the significant temperature anomaly above the 95% confidence level based on the two-sided Student's *t*-test. The blue solid box in (a), (b) denote the key area in the BK sea.

### 3.2. Mechanism of the long-lasting impact of pre-winter NAO on BK sea ice anomaly in recent decades

Since the upper-layer ocean temperature is a crucial carrier of the impact of the winter NAO on the BK sea ice more than half a year later, we investigated how the winter NAO warms the sea water and melts the sea ice continuously. The winter NAO-induced simultaneous atmospheric and oceanic circulations are illustrated in figure 3. A striking difference between P1 and P2 is the zonal position of the northern center of the NAO, which is clearly illustrated by the low-level wind and sea-level pressure anomalies. The south center of the NAO also shows difference, but not as obvious as the north center. During P1, the NAO northern action center stretches eastward. The Bk sea is located near the center of the NAO northern cyclone. Zonal wind anomalies with different directions on the north and south sides of the BK sea and relatively weak meridional wind anomalies make the air temperature anomalies in this region inconspicuous. Entering P2, the NAO northern action center shifted westward. The Bk sea was located on the east side of the NAO northern cyclone. The prevailing southerly wind anomaly caused significant warm air temperature anomalies throughout the BK sea (see blue box in figures 3(a) and (b)).

In addition to the atmospheric circulation anomalies, the oceanic circulation was also significantly different during P1 and P2. The mean major current (figure S2) in BK sea is a poleward extension of the Gulf Stream and the North Atlantic Warm Current through the Norwegian Atlantic Slope Current (Polyakov *et al* 2005), which is conducive to bringing warm sea water from the middle to high latitudes through the Barents sea opening in the sub-polar region. During P1, due to the eastward position of the northern center of the NAO, the anomalous ocean current in terms of the Ekman transport reconstructed using the wind stress generally diverged from the overall northern cyclone of the NAO, and the induced upturning compensation of the deep cold water created a the negative upper-layer ocean temperature anomaly near the BK sea, which favored sea ice formation and retention (figure 3(c)). Entering P2, with the westward shift of the northern action center of the NAO, the anomalous ocean current strengthened the northward transport of warm sea water into the

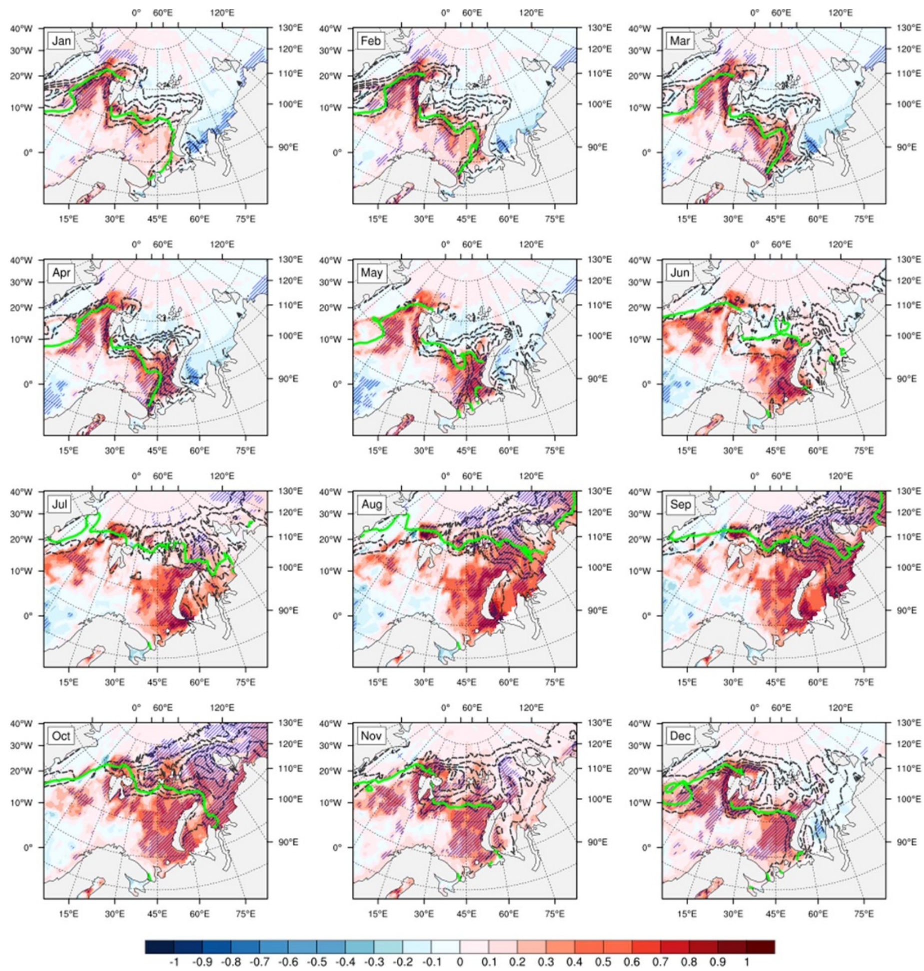

**Figure 4.** DJF-NAO-index-regressed patterns of January-December SIC (contours, interval of 2%; zero contours are omitted), and sea subsurface temperature anomalies integrated from depths of 0 m – 50 m (shading, unit: °C) during P2. The blue slashes denote significant sea subsurface temperature anomalies above the 95% confidence level based on the two-sided Student's $t$-test. The green contour denotes the 0.2 °C SST climatic isoline.

BK sea, resulting in a positive BK upper-layer ocean temperature anomaly and the negative sea ice anomaly (figure 3(d)).

In winter, the NAO heats the BK region through atmospheric and oceanic circulations, reducing the sea ice and warming the upper-layer sea water. As revealed above, the upper-layer ocean temperature is crucial to the continuous impact of the winter NAO on the BK sea ice. Figure 4 shows the regression patterns from January to December of the SIC and sea subsurface temperature averaged from 0 to 50 m against the pre-winter NAO index during P2, in which the 0.2 °C SST climatic isoline is utilized to represent the ice-water line. The results show that the atmospheric and oceanic circulations associated with the winter NAO can only last until early spring (figure S3). Under the influence of the NAO, the ocean currents continue to transport warm water from the lower latitudes into the BK sea, and the warmed air further contributes to the warming of the sea water near the BK area through sensible heat transport (figure S4). The combined effect of the two causes a continuous reduction in sea ice before early spring, while the warm upper-layer sea water, along with the ice-water line, continues to advance northward. After spring, the signal of the NAO weakens, but the shrinking sea ice acts as a memory of the impact of the pre-winter NAO. During the summer, when the polar region receives perpetual daylight, the preexisting less-than-normal sea ice enhances the light transmittance of the ice sheet, causing the amount of solar shortwave radiation absorbed by the upper-layer sea water to significantly increase during the polar day (figure S5), and thereby, it continues to warm up the upper-layer sea water and reduce the sea ice. The ice-water line also advances towards the polar region until September, with significant negative sea ice anomalies appearing north of Novaya Zemlya. Reentering the freezing season, the negative BK sea ice anomaly can stay below normal until the late autumn due to the high persistence of the increase in the temperature of the upper-layer of the ocean. This is illustrated by the fact that the ice-water line resumes southward migration from October to November, but the positive

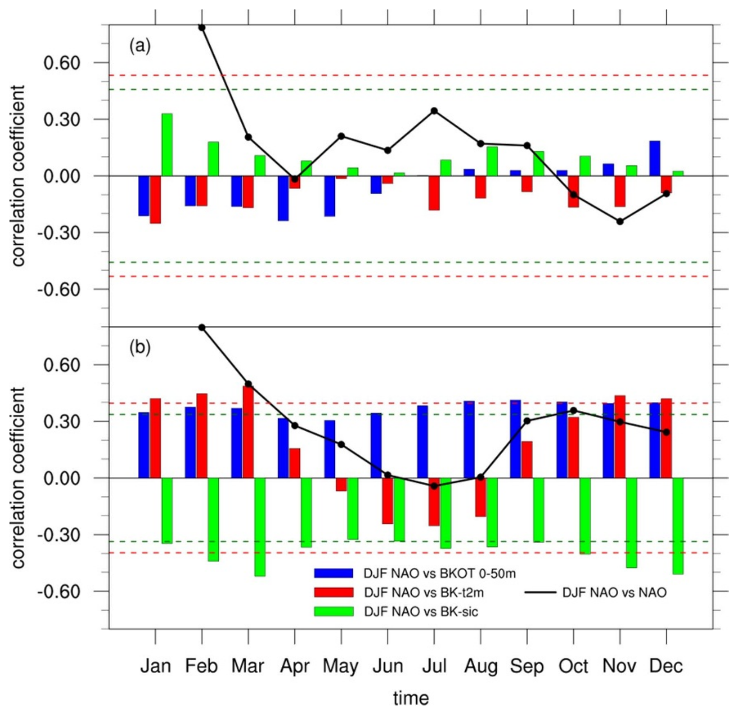


**Figure 5.** Lag correlations between pre-DJF mean NAO index and monthly BK t2 m, BK 0–50 m ocean temperature (OT), BK SIC and NAO indices during (a) P1, and (b) P2. The dashed red (green) line denotes statistical significance at the 95% (90%) confidence level.

upper-layer ocean temperature anomaly still controls the BK area north of the ice-water line. The contribution of the long-wave radiation and latent heat to the entire process is relatively negligible (figures not shown).

The described heating effect of the NAO on the BK and the surrounding seas is the key to its continuous influence on the sea ice anomaly. As was previously mentioned, the northern action center of the NAO was located more eastward during P1, which prevented it from having an evident impact on the BK sea in the beginning. Therefore, the regression patterns of the January-December SIC and the upper-layer ocean temperature anomalies during P1 (figure S6) were insignificant in the BK region. To understand the interdecadal change in the physical process causing the described long-lasting impact of the winter NAO on the BK sea ice, the evolved air–sea–ice responses to the winter NAO over the BK area (see blue box in figure 2(d)) during P1 and P2 were investigated (figure 5). The persistence of the winter NAO was weak during both periods and could only last until early spring. During P1, the simultaneous air-sea-ice response to the winter NAO was extremely weak, so it could hardly establish a long-lasting relationship. Entering P2, the winter NAO increased the ocean and air temperatures around the BK sea, which contributed to the development of a significant negative sea ice anomaly from winter to early spring. After late spring, the air response decreased as the NAO signal weakened, but the significant positive ocean temperature persisted. The warmed sea water enabled the negative sea ice anomaly to last until the freezing season in late autumn and finally established the long-lasting impact of the NAO in the previous winter on the BK sea ice. In addition, recent studies have demonstrated the change in winter NAO persistence (Liu and He 2020, Wu and Chen 2020). Here, comparing P1, the NAO showed a relatively high persistence during P2, which positively contributed to a more sustained impact on BK air-sea-ice interaction, and thus conducive to establishing the long-lasting impact.

## 4. Summary and discussion

The global climate system has significantly changed in recent decades, establishing some new relationships between the atmosphere, ocean, and sea ice. In this study, it was found that a long-lasting impact of the winter NAO on the BK sea ice anomaly has been gradually established in recent decades. A particularly sharp contrast in the relationship between the winter NAO and the late autumn BK sea ice was identified between the periods of 1980–1996 (P1) and 2001–2020 (P2). Further study suggests that this sharp contrast was closely linked to the zonal shift of the northern action center of the NAO at around 2000.

The air-sea-ice response to the winter NAO was quite different during P1 and P2. During P1, due to the eastward location of the northern center of the NAO, the BK sea exhibited an inconspicuous response in terms of the air temperature, and the ocean current induced by the wind stress was insufficient to reduce the sea ice. During P2, with the westward shift of the northern action center of the NAO, a prevailing southerly wind anomaly caused significant positive air temperature anomalies throughout the BK sea. In addition, the induced ocean current strengthened the northward transport of warm sea water from low latitudes into the BK sea, resulting in a positive BK upper-layer ocean temperature anomaly and a negative sea ice anomaly until early spring with the weakening of the NAO signal. Entering summertime, the preexisting less-than-normal sea ice enhanced the light transmittance of the ice sheet, causing the solar radiation absorbed by the upper-layer sea water under the sea ice to significantly increase during the polar day, and thereby, it continued to warm the upper-layer sea water and reduce the sea ice. The warmed sea water enabled the negative sea ice anomaly to last until late autumn owing to its slow attenuation, finally establishing the long-lasting impact of the NAO in the previous winter on the BK sea ice.

In this study, the preceding winter NAO was linked to the subsequent BK sea ice anomaly through air-sea-ice interactions. It should be noted that the North Atlantic-Arctic air-sea interaction is sensitive to interdecadal change, and some interdecadal variabilities, such as the Atlantic Multidecadal Oscillation (AMO), can significantly impact the dynamic ocean-atmosphere coupling (Wills *et al* 2019). Luo *et al* (2010a), (2010b) pointed out that an eastward shift of the Atlantic storm-track eddy activity that is associated with the eastward extension of the Atlantic jet stream is a possible cause of the whole eastward shift of the center of action of the NAO. AMO can influence the baroclinity by modulating the temperature gradient, and thus affecting the eddy activity. However, it needs sufficient observation diagnosis and numerical experiments to investigate. Besides, the Atlantic meridional overturning current is also an important component of the Atlantic oceanic thermohaline circulation, which has been found at its weakest in recent decades (Caesar *et al* 2021). In addition, interdecadal change has also been identified in the properties of the El Niño-Southern Oscillation (ENSO) since around 2000 (McPhaden 2012), which has been suggested to be evidently consistent with the change in the type of ENSO (Wang and Ren 2017). The types and longitudinal position of the ENSO have been revealed to be particularly influential to the NAO (Zhang *et al* 2015, 2019a), and the stability of the ENSO-NAO relationship is evidently modulated by the AMO (Zhang *et al* 2019b). The roles that such interdecadal modulation factors play in the NAO-Arctic sea ice relationship are worthy of further investigation. Associated with forcings from local and outside oceans, there may be some other mechanisms modulating the long-lasting impact of the winter NAO on the subsequent evolution of the sea ice. Further validation is needed to reveal these hypotheses and detailed mechanisms in future studies.

## Data availability statement

No new data were created or analyzed in this study.


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