Possible Links between Arctic Sea Ice Loss Events and Cold Eurasian Anomalies in Winter

Wenqin ZHUO1,2 and Zhina JIANG1*
1 State Key Laboratory of Severe Weather (LaSW), Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing 100081
2 College of Oceanic and Atmospheric Sciences, Ocean University of China, Qingdao 266100

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ABSTRACT

Recently, there have been two competing perspectives on the links of rapid sea ice retreat over the Barents–Kara Seas (BKS) and in midlatitude severe cold winters over Eurasia. By using the daily ECMWF reanalysis (ERA)-Interim dataset during 1979–2016, we reconcile two contrasting viewpoints, namely, if an upward turbulent heat flux appears and maintains several days after the rapid sea ice loss over the BKS in winter, a dipole structure which consists of a primary positive center of action around the Barents Sea with the other opposite-sign center of action over Eurasian continent is easily amplified, and consequently a cold anomaly over Eurasia will occur, but not vice versa. Our work casts light on the links between the Arctic sea ice loss and Eurasian cold winter anomalies by revealing the different responses of the surface turbulent heat flux (STHF) after rapid sea ice retreat on a daily basis.

Key words: sea ice retreat, cold winter anomalies, dipole structure, surface turbulent heat flux (STHF)

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1. Introduction

Arctic sea ice, as an important component of the climate system, has greatly melted in recent decades, mostly rapid in September (Serreze et al., 2007; Simmons, 2015; Wei et al., 2018). Together with the sea ice loss, rapid Arctic warming known as Arctic amplification (Screen and Simmonds, 2010) and frequent cold events over Eurasia and North America during winter have been observed, which trigger great interest of scientists in the climate variability (Screen, 2014; Kug et al., 2015; Wu et al., 2015).

Through regulating the exchange of energy between the ocean and atmosphere, the sea ice loss is anticipated to influence the atmospheric circulation and weather patterns (Deser et al., 2004, 2007; Honda et al., 2009; Liptak and Strong, 2014; Overland and Wang, 2015). Evidences showed that the varying Arctic sea ice conditions in autumn have an effect on large-scale atmospheric features during the following autumn and winter well beyond the Arctic (Francis et al., 2009; Liu et al., 2012; Lu et al., 2019). Tang et al. (2013) emphasized that the winter atmospheric circulation at high northern latitudes are sensitive to the sea ice loss in winter, but with different responses to the sea ice loss in autumn. Numerous studies suggested that the winter atmospheric circulation associated with the Arctic sea ice loss favors the occurrence of cold winter extremes at midlatitudes of the northern continents (Inoue et al., 2012; Mori et al., 2014, 2019a, b; Lu et al., 2016; Luo et al., 2016; Yao et al., 2017). For example, Mori et al. (2014) indicated that the probability of severe winters has increased because of sea ice reduction in Barents–Kara Seas. Mori et al. (2019a) reconciled the discrepancy between different models and observations and concluded that the magnitude of the forced surface temperature response to the sea ice loss and Eurasian cooling is systematically underestimated. Inoue et al. (2012) revealed that an anti-
cyclical anomaly prevails along the Siberian coast during light ice years over the Barents Sea, which is likely to cause the anomalous warm advection over the Barents Sea and cold advection over eastern Siberia. Luo et al. (2016) and Yao et al. (2017) further revealed that the recent large BKS warming increases the quasi-stationarity and persistence of Ural blocking, and then leads to more widespread Eurasian cold events, which further enhances the BKS warming. And then, Ma and Zhu (2019) showed that extreme cold events in East Asia may be an enhanced response to the extremely strong Ural blocking and surface Siberian high modulated by global warming. Lu et al. (2016) also indicated the frequency of the extreme cold events in Eurasia associated with strong anticyclones and blocking in the mid–high latitudes. It is revealed that this stationary Rossby wave is generated by the anomalous surface turbulent heat flux (STHF) as a result of the anomalous ice cover (Honda et al., 1999, 2009; Inoue et al., 2012; Ma et al., 2018).

However, there is an opposite perspective on the links between the Arctic sea ice retreat and midlatitude cold winters (Barnes, 2013; Sato et al., 2014; Sorokina et al., 2016; Blackport et al., 2019; Lu et al., 2019; Screen and Blackport, 2019a, b; Blackport and Screen, 2020). Sato et al. (2014) suggested that the links between the Barents Sea ice coverage and cold Eurasian winter are just a sector of a teleconnection pattern originating from the North Atlantic Gulf Stream region, which contrasts with the previously proposed atmospheric direct response to sea ice variability (Simmonds and Govekar, 2014). Later, Sorokina et al. (2016) indicated that it is the atmospheric variability that drives the observed variability in Barents Sea ice cover, as well as the “warm-Arctic–cold-Siberian” pattern. In addition, Sun et al. (2016) showed that the sea ice loss does not yield trends toward lower continental temperatures by using multiple models. McCusker et al. (2016) further concluded that the cooling over central Eurasia is due to sea–ice-independent internally generated circulation pattern with the atmosphere-only global climate model. Screen (2014) pointed out that the Arctic amplification actually reduces the subseasonal cold-season temperature variance. Blackport et al. (2019) also indicated that it is the anomalous atmospheric circulation that simultaneously drives cold midlatitude winters and mild Arctic conditions, and the reduced sea ice has little influence on cold winters over midlatitudes. Barnes (2013) indicated that the relationship between the Arctic amplification and midlatitude atmospheric circulation is complex and it is inappropriate to understand the role of Arctic alone. Dai and Song (2020) suggested that the impacts of Arctic amplification on climate are small beyond the high latitudes, and the statistical analyses cannot separate the impact of Arctic warming from other correlated factors. And lately, Screen and Blackport (2019a, b) as well as Blackport and Screen (2020) emphasized the negligible influence of Arctic sea ice loss on the atmosphere in midlatitudes and made a debate with Mori et al. (2014, 2019a), which aroused a hot discussion (Mori et al., 2019b). The above contrasting viewpoints indicated that the linkages between Arctic sea ice loss and midlatitude extremely cold anomalies are complex, which maybe depend on conditions of the sea ice loss and atmospheric state. In this study, from a synoptic viewpoint, rapid sea ice loss events in winter are first selected based on a daily sea ice index, and then by comparing different responses of the STHF and atmospheric circulation after the sea ice loss, we explore the possible relationships between the rapid sea ice retreat and cold anomalies over downstream continents.

2. Data and methods

2.1 Data

In this study, the daily mean ECMWF reanalysis (ERA)-Interim dataset is used during 1979–2016 (Dee et al., 2011), which includes the sea surface temperature (SST), sea ice concentration (SIC), 2-m surface air temperature (SAT), geopotential height, STHF (sensible plus latent), total column water vapor (TCWV), and zonal and meridional winds with a horizontal resolution of 1° latitude × 1° longitude. Besides, we also use STHF from the Objectively Analyzed air–sea Fluxes dataset (OAflux; https://oaflux.whoi.edu) in 1985 onward to check the accuracy of STHF in ERA-Interim, and similar results are obtained (omitted). The daily ECMWF SIC is adopted in this work, because it is in good agreement with that from the National Snow and Ice Data Center (NSIDC; Cavalieri et al., 1996) in variability (Park et al., 2015), however, which has daily data every other day during 1978–1988. Moreover, it also has consistent variability with Advanced Microwave Scanning Radiometer 2 (AMSR2) in winters of 2012–2016 in spite of smaller amplitude (omitted).

2.2 Methods

To see the Arctic SIC variability in winter, the daily standard deviation of SIC in December–February (DJF) is presented in Fig. 1a, which shows that the SIC has the greatest daily variability over BKS (70°–80°N, 15°–75°E). Therefore, in the following sections, we focus on the sea ice loss events over this region, which is concerned by many scientists (Luo et al., 2016; Sorokina et
al., 2016; Yao et al., 2017). Given the obvious warming trend over BKS (Wang et al., 2019), the SAT and SIC in this region have been linearly detrended.

First, a daily standardized SIC index is constructed by averaging SIC anomalies over BKS. The anomaly of each variable is calculated by subtracting the 1979–2016 mean for each calendar day at each grid point. The SAT and STHF index over BKS are obtained in a similar way. A sea ice loss event is defined as a time period when the SIC index value is below −0.75 standard deviations for three or more consecutive days. If the beginning of an event occurs within 10 days at the end of the preceding event, the latter event is discarded. Thus, 30 sea ice loss events are identified during 37 winters of 1979–2016, which are listed in Table 1. Lag 0 for a sea ice loss event is defined as the onset day when the SIC index first reaches the criterion.

And then, in order to quantify the relationships between sea ice loss over BKS and Eurasian SAT, the correlation coefficients between SIC index over BKS and SAT are calculated (Fig. 1b). It shows that there is a significant positive correlation between SIC over BKS and SAT over the mid-Eurasian continent (40°–60°N, 60°–120°E), though there is also a strong significant negative correlation between SIC and SAT over BKS, which implies that, except the intense local interaction between the sea ice and atmosphere over BKS, there is also a close remote relationship between the sea ice over BKS and atmosphere over certain region of Eurasian continent. Accordingly, a standardized SAT index over Eurasia is constructed by averaging SAT anomalies over this region.

Therefore, in the following, composite analyses are performed to investigate the evolution of atmospheric variables associated with sea ice loss events over BKS. A Student’s t-test is used to evaluate the statistical significance of our composite calculations.

3. Possible links between sea ice loss and cold anomalies

To better see the relationship between the sea ice loss over BKS and cold anomalies over Eurasian continents, various atmospheric indices based on sea ice loss events are presented in Fig. 2. It is shown that the SIC index begins to drop significantly on lag −6 days and reaches its minimum value (−1.1 standard deviations) around lag +3 days. Afterwards, it goes back gradually and maintains about −0.8 standard deviations almost till lag +30 days. Accompanying with the sea ice loss, the “warm BKS–cold Eurasia” pattern appears from lag −2 to +23 days. Interestingly, two evident temperature drops are found for the SAT index over Eurasia during this whole period. One descent process of Eurasian temperature is between lag −2 and +6 days, reaching its minimum on lag 0 day, which is at the rapid descending stage of SIC. This “warm BKS–cold Eurasia” pattern can be explained as the result of internal driving of the atmospheric

![Figure 1](image_url)

**Table 1.** The onset date and life cycle (day) of 30 sea ice loss events over Barents–Kara Seas

| Onset date | Life cycle | Onset date | Life cycle | Onset date | Life cycle |
|------------|------------|------------|------------|------------|------------|
| 19830104   | 14         | 19960122   | 4          | 20090204   | 4          |
| 19840113   | 30+        | 20011201   | 16         | 20100121   | 21         |
| 19841211   | 30+        | 20041223   | 10         | 20111201   | 30+        |
| 19850222   | 24         | 20050125   | 30+        | 20120117   | 30+        |
| 19860131   | 6          | 20051206   | 12         | 20121201   | 30+        |
| 19900204   | 14         | 20060102   | 9          | 20140212   | 30+        |
| 19900219   | 7          | 20060111   | 30+        | 20151201   | 30+        |
| 19910131   | 13         | 20070109   | 9          | 20160129   | 30+        |
| 19930202   | 4          | 20071217   | 4          | —          | —          |
| 19930227   | 8          | 20071231   | 5          | —          | —          |
| 19950204   | 10         | 20080201   | 4          | —          | —          |

Note: + indicates that the life cycle exceeds 30 days.
variability (Inoue et al., 2012; McCusker et al., 2016; Sorokina et al., 2016; Blackport et al., 2019; Zhuo and Jiang, 2020). While for the second descending process of Eurasian temperature, it is between lag +11 and +23 days, reaching its minimum on lag +14 days and lagging 10 days of the minimum of sea ice, which puzzles us and makes us to wonder whether the previously melted sea ice could generate some influences on it. In the following, we hope that we can get some lights on the links between sea ice loss events and Eurasian cooling by exploring the mechanism of occurrence of this kind of cold anomaly.

To resolve our doubts, 30 sea ice loss events are divided into two types. Type 1 sea ice loss event is with a Eurasian cold anomaly from lag +10 to +30 days, in which the value of SAT index over Eurasia less than 0 for at least 3 consecutive days. Thus, 15 cases are selected according to this definition. The left 15 sea ice loss cases are defined as Type 2 sea ice loss event. The SAT and STHF index differences of these two types of sea ice loss events are shown in Fig. 3. A significantly negative SAT index difference between Types 1 and 2 sea ice loss events can be observed from lag +16 to +23 days, reaching the minimum on lag +19 days, which means that these two types of sea ice loss events are distinctive according to the SAT index difference from lag +10 to +30 days.

Blackport et al. (2019) pointed out that during winters with a lower than average sea–ice area, when there is an upward STHF anomaly locally, the atmosphere is primarily driven by sea ice. Conversely, when STHF anomaly is downward, the atmosphere is driving the sea ice. The STHF index difference between Types 1 and 2 sea ice loss events in Fig. 3 also shows the significant upward from lag +4 to +11 days after the rapid sea ice loss but ahead of SAT dropping over Eurasia [note that the ECMWF sign convention for STHF is that positive (negative) values indicate a downward (upward) turbulent heat flux at the surface], which makes us suspect that the anomaly of STHF over BKS after the sea ice loss may be a determining factor of the following Eurasian cooling.

4. Mechanisms for cooling anomalies after sea ice loss

Before analyzing the role of sea ice loss on the atmosphere, the anomalous 500-hPa geopotential height and SAT fields with time are shown in Fig. 4. The “warm Arctic–cold Eurasia” pattern can be found at lag 0 day for both types of the sea ice loss events (Figs. 4a, f), though, which in Type 2 event is stronger. For Type 1 sea ice loss event, the cooling over Eurasia disappears on lag +5 days. Afterwards, another cold process occurs and reaches its maximum amplitude on lag +15 days, and then decays. However, for Type 2 sea ice loss event, only one Eurasian cold event can be observed at a monthly timescale, which reaches it maximum amplitude on lag +5 days and then decays. Correspondingly, at 500 hPa,
an anticyclonic anomaly prevails along the Siberian coast over the Barents Sea on lag 0 day for both types of sea ice loss events, which is likely to cause the anomalous warm advection over the BKS and cold advection over Eurasian continent. For Type 1 sea ice loss event, there is a wave train, which consists of a primary positive center around the Scandinavian Peninsula, with two other negative centers over Greenland and Eurasian continent, respectively. This wave train propagates westward and decays on lag +5 days. Afterwards, a similar wave-like pattern appears again on lag +10 days, which strengthens and reaches its maximum amplitude on lag +15 days. Its eastward propagation and decay imply the ending of the Eurasian cooling. However, for Type 2 sea ice loss event, although a similar wave train pattern can be seen on lag 0 day, it slowly propagates eastward and decays gradually. On lag +10 and +15 days, the positive center has moved to central Asia. In conclusion, it seems that the “warm Arctic–cold Eurasia” pattern is closely related with the anticyclone over Ural Mountain and its northern surroundings. The strengthening of the northwest–southeast tilted dipole structure over Northwest Eurasia after the sea ice loss is the most important factor contributing to the later continuous intrusion of cold air into midlatitude Eurasian continent.

To get some knowledge about the metling of sea ice, composites of the anomalous SIC fields for the two types of sea ice loss events are shown in Fig. 5, respectively. Comparatively, the negative SIC anomaly of Type 1 event is stronger and more persistent than that of Type 2 event. The negative SIC anomaly first appears over the northern Barents Sea on lag ~5 days. Afterwards, it extends southward, covering the northern and southeastern Barents Sea as well as southern Kara Sea. The SIC anomaly reaches its minimum value on about lag 0 (+5) days for Type 1 (2) events, respectively. After reaching its minimum value, the SIC anomaly for Type 1 event maintains at least until lag +15 days, but the SIC anomal-
aly for Type 2 event undergoes almost its life cycle to lag +15 days.

To further verify the change of turbulent heat flux over BKS, Fig. 6 presents the anomalous STHF for these two types of sea ice loss events. For Type 1 sea ice loss event, a dipole flux anomaly is observed over BKS, with the negative values over the northern Novaya Zemlya and southern Kara Sea as well as positive values over the southern Barents Sea on lag −5 days, which strengthens on lag 0 day. This implies that there are complicated interactions between the sea ice and atmosphere during this period. However, from lag +5 to +10 days, upward turbulent heat fluxes dominate the BKS region, which means that the atmosphere is primarily driven by sea ice during this stage (Blackport et al., 2019). For Type 2 sea ice loss event, on the contrary, downward turbulent heat fluxes are observed over BKS from lag −5 to +15 days. That is to say, the atmosphere dominates the sea ice over BKS for almost three weeks. Comparatively, one thing is sure: the atmosphere drives sea ice before lag 0 day for these two types of events, and promotes the rapid sea ice loss. But then, the loss of sea ice gives feedback to the atmosphere for Type 1 event, while for Type 2 event, the atmosphere continues to drive the sea ice during the whole period, which may explain the different atmospheric responses after the sea ice loss for these two types of events.

As a common knowledge, the STHF anomalies are modulated by the sea ice extent. However, there is still one thing that we should keep in mind: The local atmospheric condition after the sea ice loss can determine the direction of the anomalous STHF. To further clarify this point, composites of the TCWV and 10-m horizontal wind vector for these two kinds of sea ice loss events

Fig. 5. Lead–lag composites of anomalous SIC fields based on (a–e) Type 1 and (f–j) Type 2 sea ice loss events. The dotted area indicates the anomaly of sea ice exceeding the 90% confidence level according to the Student’s t-test.
have been shown in Fig. 7. It can be seen that the TCWV over BKS for Type 1 event is less than that for Type 2 event after the sea ice retreat, while the divergence of 10-m wind for Type 1 event is stronger than that for Type 2. That is to say, the atmospheric condition for Type 1 sea ice loss event is more conducive to the turbulent heat loss from the ocean to atmosphere (Cayan, 1992).

Deser et al. (2004) revealed that one key process after the sea ice loss is the enhanced upward sensible and latent heat flux as well as subsequent diabatic heating in the lower troposphere. This diabatic heating can excite Rossby waves propagating vertically and then equatorward (Honda et al., 2009), whose timescale from the Arctic into midlatitudes is several days (Gong et al., 2020). Because the surface sensible and latent heat fluxes are commonly regarded as the driving source of equatorward propagating Rossby waves, in order to elucidate the impact of STHF over BKS on the atmospheric circulation, the three-dimensional wave activity flux (WAF; Takaya and Nakamura, 2001) after the sea ice loss from lag +6 to +15 days are illustrated in Figs. 8, 9 for Types 1 and 2 events, respectively. A southeastward propagating WAF from Barents Sea to Eurasian continent for Type 1 event, pretty evident on lag +12 and +15 days, can be found from the right column of Fig. 8, which corresponds to a wave-like pattern with the positive anomaly over BKS and negative anomaly over its downstream. Consistently, an upward WAF is seen over a narrow range around 45°E on lag +6 days, and then strengthens and expands to the scope of 45°–90°E at the following lags, as shown on the left column of Fig. 8. On the contrary, there is no WAF originating from Barents Sea for Type 2 sea ice loss event (Fig. 9). Only a sparsely weak southeastward WAF over the Eurasian continent can be

![Fig. 6.](image-url)
observed from lag +9 to +12 days, which originates from the northern Eurasian continent. That is to say, for Type 1 event, the weakened wave train on lag +9 days is further amplified by the transportation of wave activity after the sea ice loss, which makes the cooling anomaly appear again over Eurasia (Figs. 4, 8); for Type 2 event, however, the anticyclone over BKS is not strengthened, but propagates eastward (Fig. 9). Our work verifies the conclusion of Honda et al. (2009) that the anomalous upward STHF associated with the sea ice loss is the source of equatorward propagating Rossby waves.

In addition, to check the opinion proposed by Sato et al. (2014), the climatological and anomalous SST over the Atlantic Ocean for these two types of sea ice loss events are shown in Fig. 10. An interesting phenomenon is that the SST anomaly over the Gulf Stream especially over the SST front is significantly positive, as well as that over BKS, which is consistent with Sato et al. (2014). However, from Fig. 8, we know that the WAFs over Eurasian continent are originating from Barents Sea, not the Gulf Stream. Though a northeastward WAF from Gulf Stream on lag +12 days can be seen, it is very weak and is not transported to BKS, which is not consistent with Sato et al. (2014).

5. Conclusions and discussion

In this work, we try to reconcile two competing perspectives on the links between the rapid sea ice retreat over the Barents–Kara Seas (BKS) and in midlatitude severe winters over Eurasia, in which one stresses that the recent severe Arctic sea ice loss contributes to more frequent cold winters (Inoue et al., 2012; Mori et al., 2014, 2019a, b; Luo et al., 2016; Yao et al., 2017; Ma et al., 2018) and the other regards winter cold events over continents and Arctic sea ice loss are the results of internal atmospheric variability (Barnes, 2013; Sato et al., 2014; Sorokina et al., 2016; Blackport et al., 2019; Screen and Blackport, 2019a, b; Blackport and Screen, 2020). The ERA-Interim daily reanalysis dataset during 1979–2016 is used to do the composite analysis. Sea ice loss events over BKS are selected based on a daily sea ice index. Cold Eurasian anomalies after the sea ice loss are analyzed from a synoptic viewpoint. The previous study has shown that the cooling over continent during the fast decreasing stage of sea ice is considered as the results of internal atmospheric driving (Zhuo and Jiang, 2020). In this work, our focus is on the cold winter anomalies lagging the minimum SIC about 10–30 days. The results show that in winters, if an anomalous up-
ward STHF appears during the rapid sea ice loss stage and maintains several days even after the minimum sea ice anomaly, a dipole structure, which consists of a primary positive center of action around the Barents Sea with the opposite-sign center of action over Eurasian continent, is easily triggered or amplified, and consequently the cold anomaly will reoccur over some regions of the Eurasian continent, but not vice versa. Whether Arctic sea ice loss has effect on Eurasian cold winter anomalies or not is determined by the responses of STHF after rapid sea ice retreat which influenced by the lower tropospheric atmospheric condition (Bateni and Tajfar, 2017). Therefore, the condition of STHF after sea ice loss is needed to be further explored in the future, which will help us better understand interactions between the atmosphere and its underlying surface, and accordingly improve the predictability of climate variability.

Besides, it is noted that our work is based on a daily analysis. On a decadal timescale, the linkage between the sea ice loss and severe cold winters can also be explained. That is, under the global warming condition, if the upward turbulent heat fluxes over BKS often appear after the sea ice loss, severe Eurasian cold winters will occur more frequently. That is why, in recent decades, the upward turbulent heat fluxes, Arctic sea ice loss, and frequent severe cold winters are observed (Inoue et al., 2012; Mori et al., 2014; Ma et al., 2018). Otherwise, cold Eurasian winters seem to be determined by the sea–ice-independent internal atmospheric circulation (McCusker et al., 2016; Sun et al., 2016; Blackport et al., 2019; Screen and Blackport, 2019a, b; Blackport and Screen, 2020).
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Fig. 9. As in Fig. 8, but for Type 2 sea ice loss event.
Fig. 10. Lead–lag composites of SST (K) climatology (contour) and anomaly (shaded) fields over Atlantic based on (a–d) Type 1 and (e–h) Type 2 sea ice loss events. The dotted area indicates the anomaly of SST exceeding the 90% confidence level according to the Student's t-test.

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