Intraseasonal melting of northern Barents Sea ice forced by circumpolar clockwise propagating atmospheric waves during early summer

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ABSTRACT

Arctic sea ice intraseasonal variation (ISV) is crucial for understanding and predicting atmospheric subseasonal variations over the middle and high latitudes but unclear. Sea ice concentration (SIC) over the northern Barents Sea (NBS) features large ISV during the melting season (Apr.-Jul.). Based on the observed SIC, this study finds that the NBS SIC ISV in the melting season is dominated by 30–60-day periodicity. The composite analysis, using 34 significant 30–60-day sea ice melting events during 1989-2017, demonstrates that the 30–60-day circumpolar clockwise propagating atmospheric waves (CCPW) is concurrent with the NBS SIC ISV, which features zonal wavenumber one along 65°N and a typical quasi-barotropic structure. Further analysis finds that the 30–60-day surface air temperature (SAT) evidently leads the SIC variations by nearly 6 days over the NBS, which is primarily caused by low-level meridional thermal advection linked with the 30–60-day CCPW. The positive anomaly of the downward sensible heat and longwave radiative fluxes, caused by the increased SAT and atmospheric moisture, play the dominant roles in melting the sea ice in the 30–60-day time scale over the NBS. The increased atmospheric moisture is mainly ascribed to the increased horizontal moisture advection influence by the 30–60-day CCPW. This study strongly suggests that the atmospheric ISV is a crucial precursor for NBS sea ice intraseasonal changes in boreal summer, and more accurate subseasonal predictions of atmospheric circulation, temperature, and moisture are indispensable for improving sea ice subseasonal prediction over the Arctic region.

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SIGNIFICANCE STATEMENT

Northern Barents Sea (NBS) sea ice intraseasonal variation (ISV) is crucial for understanding mid-high-latitude climate variations as well as the New trans-Arctic shipping prediction but lacks solid knowledge. This study found 30–60-day variation is the dominant ISV periodicity of NBS sea ice change during summer, which is essentially modulated by circumpolar clockwise propagating atmospheric waves. And the atmospheric wave-induced meridional thermal advection modulates the surface temperature and atmospheric moisture, causes the changes of downward sensible heat and longwave radiative fluxes, and eventually dominantly regulates the 30–60-day sea ice variations. The mechanism of sea ice ISV strongly suggests that accurately predicting the atmospheric fields is indispensable for obtaining more accurate sea ice subseasonal prediction.
1. Introduction

Arctic sea ice (ASI) undergoes significant decline due to global warming, particularly in the historical melting season (Comiso 2002; Holland et al. 2006; Rothrock et al. 1999; Serreze et al. 2003; Stroeve and Notz 2018; Stroeve et al. 2005). The future prediction indicates that the summer ice-free Arctic might even occur in the coming decades (Holland et al. 2006; Wang and Overland 2009), which will lead to the complete opening of the Arctic Passage for maritime transportation (Aksenov et al. 2017; He et al. 2012). Meanwhile, the change of ASI potentially influences the multi-time scale atmospheric variations in both higher (Ding et al. 2017; Sun et al. 2016; Vihma 2014; Wu et al. 2011) and lower latitudes (Perlwitz et al. 2015), and even triggers more frequent extreme events (Screen et al. 2015; Liu et al. 2012). Therefore, it is necessary to recognize and understand ASI changes at different time scales for better predicting the Arctic and lower-latitude weather-to-climate change.

The interannual variation of ASI has been found to be associated with different thermal-dynamical processes, including surface radiation (Ding et al. 2017), moisture transport related with tropical forcing (Dunn-sigouin et al. 2021), Arctic Oscillation (Overland and Wang 2010), North Atlantic Oscillation (Caian et al. 2018), Eurasian teleconnection pattern (Zhang et al. 2018a), low-frequency atmospheric forcing (Ding et al. 2017, 2019; Luo et al. 2021), and surface winds and ocean forcing (Grunseich and Wang 2016; Perovich et al. 2011; Zhang 2015). Accordingly, the ASI seasonal prediction has been widely explored based on dynamical models and statistical methods (Wang et al. 2013; Wei et al. 2021), which has been carried out in many operational centers and institutes and included in the Sea Ice Prediction Network (Scambos and Stammerjohn 2020).

However, the intraseasonal variation (ISV) of ASI is short of study, although its influence has been proved to be significant for the atmospheric subseasonal changes and prediction in both local and remote regions (e.g., Dai et al. 2019; Deser et al. 2007; Guan et al. 2020; Honda et al. 1999; Tyrlis et al. 2020; Wu et al. 2017; Zhang et al. 2020). In boreal winter, the sea ice has exhibited the strongest intraseasonal mode over the Atlantic and Pacific portions of the Arctic (Cavalieri and Parkinson 1987; Fang and Wallace 1994; Guan et al. 2020; Strong et al. 2009). The boreal winter Arctic sea ice

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concentration (SIC) ISV has been linked with the change of Ural Blocking (Chen et al. 2018; Gong and Luo 2017; Kim et al. 2021; Luo et al. 2016a), jet stream location (Barnes and Simpson 2017; McGraw and Barnes 2020), North Atlantic Oscillation (Luo et al. 2017, 2019; Strong et al. 2009), and propagating waves (Guan et al. 2020), which may cause the variation of downward longwave radiation (Chen et al. 2018; Guan et al. 2020, Park et al. 2015a,b) related to the change of poleward moisture fluxes (Woods and Caballero 2016; Zhong et al. 2018).

In boreal summer, a recent study reported two low-frequency intraseasonal periodicities (40–60-day and 70–80-day) of SIC changes in the late melting season (Aug.-Oct.) (Qian et al. 2020), but this study focused on the whole Arctic and the mechanism beneath them remained unclear. Few studies focus on the feature of ASI ISV during the early melting season, despite of its importance for the Arctic economy and transportation (Crépin et al. 2017). Several studies have attempted to make subseasonal prediction of the ASI for the melting season using a statistical model based on the strong intraseasonal autocorrelation (Wang et al. 2016) and their relations among sea ice, atmosphere and ocean (Wang et al. 2019). However, the physical mechanism causing the ASI ISV has been not clarified. Several studies have attempted to investigate the causes for the ASI intraseasonal changes from the following aspects: the ASI ISV can be modified by Madden-Julian Oscillation (MJO) (Henderson et al. 2014); low-level winds associated with anomalous anticyclonic flow over the Arctic mediate the intraseasonal retreating rate of sea ice in summer 2010 and 2011 (Ogi and Wallace 2012); and the September ASI was modified by warm wind advection and anomalous high temperatures in previous months of 2007 (Comiso et al. 2008). However, these studies mainly focus on case events and the effect of tropical intraseasonal teleconnection. A comprehensive picture of ASI ISV and associated physical causes based on long-term historical records are lacking in summer. Additionally, since the high-latitude atmospheric circulations and temperature have shown ISV signals in both troposphere (Barnes and Simpson 2017; Graves and Stanford 1989; Huang 2008; Hu...
et al. 2016; Yang et al. 2013; Zhu and Yang 2021) and stratosphere (Gao and Stanford 1987) in boreal summer, whether and how the high-latitude atmospheric boreal summer ISVs link with the ASI subseasonal variations is also elusive and worthwhile to be studied.

In particular, the Barents Sea (BS) undergoes the most significant changes among Arctic sub-regions due to global warming (Stroeve and Notz 2018), which will lead to the opening of the New trans-Arctic shipping route (Smith and Stephenson 2013). The BS is a key region linking the Arctic to lower latitude weather-to-climate changes (Luo et al. 2016a) and the region where sea ice variability is significant in all seasons (Yang et al. 2016; Wang et al. 2019). In winter, the changes of sea ice over the BS can influence the Eurasian blocking events and the extreme cold events (Dai et al. 2019; Gong and Luo 2017; Kim and Son 2020; Luo et al. 2016b). The spring-summer sea ice anomalies over the BS can trigger extreme weather events in the following season over the middle and lower latitudes of the Northern Hemisphere (Chen et al. 2020; Deng et al. 2020; Han et al. 2021; He et al. 2018; Zhang et al. 2018b). Most researches focus on winter and decadal-to-interannual time scales, and few studies pay attention to summer and intraseasonal time scale. Therefore, a deepened understanding of the BS sea ice ISV during the melting season can provide more useful information for New trans-Arctic shipping prediction and understanding mid-high-latitude climate variations (Screen et al. 2015).

To fill the scientific gap about the BS sea ice ISV in boreal summer, this study aims to investigate the major feature of sea ice ISV over the BS and its linkage with atmospheric ISV. The paper is organized as follows. Section 2 describes the datasets and the methods. Section 3 addresses the dominant intraseasonal mode of SIC over the BS and the selection of the significant events and key regions. The northern BS (NBS) SIC ISV and associated atmospheric travelling waves are presented in section 4. The mechanism for the sea ice ISV over the BS is proposed in section 5. The role of wind-
driven dynamical and ocean thermal processes is discussed in section 6, and the conclusion is finally given in section 7.

2. Datasets and methods

a. Datasets

This study used SIC retrieved from passive microwave data to describe the ISV of ASI, which is obtained from the National Snow and Ice Data Center (NSIDC) Climate Data Record of SIC (version 3) based on a combination of the National Aeronautics and Space Administration (NASA) Team algorithm (Cavalieri et al. 1984) and NASA Bootstrap algorithm (Comiso and Sullivan 1986). The SIC dataset from NSIDC has a spatial resolution of 25 km and covers 48.4°N–90°N. Since this dataset is only available every 2 days before 1989 (Yang and Magnusdottir 2017), this study intentionally uses the historical record of 29 years from 1989 to 2017. The relevant atmospheric and surface fields are obtained from the daily ERA-Interim reanalysis dataset of the European Center for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011), including geopotential height at 950hPa (GHT950), 850 hPa (GHT850), 500 hPa (GHT500), and 200 hPa (GHT200), zonal and meridional wind, and temperature, specific humidity, vertical $p$-velocity ($\omega$) from 1000 hPa to 300 hPa, surface air temperature (SAT), skin temperature, surface zonal and meridional wind speed at 10m, surface net solar radiation (SR), longwave radiation (LR), surface sensible heat flux (SHF), and surface latent heat flux (LHF), with a 1.5° × 1.5° latitude/longitude spatial resolution, and the data provided on model levels. ECMWF also provides diabatic and physics tendencies from the forecast model. We also use the NSIDC daily 25-km EASE-Grid sea ice motion dataset (Tschudi et al. 2019) and obtain sea ice thickness (SIT) data from the Pan-Arctic Ice Ocean Modeling and Assimilation System (Zhang and Rothrock 2003). For the oceanic thermal effect analysis, the ocean variables, including potential temperature and salinity with 14 levels in the upper 135m, are obtained from the National Centers for Environmental Prediction (NCEP) Climate
Forecast System Reanalysis (CFSR; Saha et al. 2010) from January 1989 to March 2011 and CFS Version 2 from April 2011 to December 2017 (Saha et al. 2014) with the resolution of 0.5° × 0.5°, following Sato and Inoue (2018).

b. Methods

To extract the specific ISV and process the daily data, two steps are taken based on previous studies (Yang et al. 2010; Gao et al. 2017). The ISV component is obtained from the “raw” daily time series by first removing the climatology of individual year and then removing the annual mean of anomalies, and next using 5-day running mean to remove signals fewer than 10 days. To identify the dominant periodicity, the power spectrum analysis through Fast Fourier Transform (FFT) with a tapered window (Bingham et al. 1967) is applied to the time series of ISV component for each grid or domain average. This time series covers 29 consecutive melting seasons (Apr. to Jul.) with a total of 3538 days (29 × 122 = 3538) from 1989 to 2017. The associated statistical significance test is carried out according to a red noise standard spectrum from the first-order Markov Model (Gilman et al. 1962). The priori/posteriori 95% confidence can be calculated according to evaluating the inverse chi-squared distribution. The effective degree of freedom is estimated based on Leith (1973), the formulation of \( v \) given by:

\[
v = -\frac{1}{2} n \ln[R],
\]

where \( n \) is 3538 and \( R \) is the lag one-pentad autocorrelation coefficient. And this method has been widely used in previous studies (e.g., Wei et al. 2019; Yang and Li 2016; Yao and Tong 2020; Zhu and Yang 2021). The Butterworth band-pass filter is used to extract the specific intraseasonal component of each variable.

The temperature tendency equation is used to diagnose the contribution of different terms to the change of SAT associated with the SIC variations. The temperature tendency equation for the specific intraseasonal component implemented in the reanalysis model, following Clark and Feldstein (2020), is shown in Eq. (1):

\[
\left( \frac{\partial T_a}{\partial t} \right)' = \left( -u \frac{\partial T_a}{\partial x} - v \frac{\partial T_a}{\partial y} \right)' - \left( \frac{\partial T_a}{\partial \eta} \right)' + \left( \frac{k T_a w}{p} \right)' + P_r' + Res' \quad (1)
\]

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where the prime denotes the specific intraseasonal component, the temperature may change in response to horizontal temperature advection $-u \frac{\partial T_a}{\partial x} - v \frac{\partial T_a}{\partial y}$, vertical temperature advection $-\eta \frac{\partial T_a}{\partial \eta}$, adiabatic warming $\frac{k T_a w}{p}$, and diabatic heating $P_T$, where the diabatic heating term $P_T$ is composed of longwave radiation heating/cooling, shortwave radiative heating/cooling, and latent heat release and vertical mixing. The $Res$ term is a residual accounting for the analysis increment, and for any inconsistencies between Eq. (1) and the precise equation that is implemented by ECMWF.

To evaluate energy fluxes over the ice upper surface, according to Hoffman et al. (2008), Stott (2011), and Kuipers Munneke et al. (2018), the surface energy budget of an ice surface can be written as Eq. (2):

$$M = SR + LR + SHF + LHF + G \quad (2)$$

where $M$ is the energy flux available for melting, $SR$ and $LR$ are the surface net shortwave radiation and longwave radiation, $SHF$ and $LHF$ are the sensible and latent heat flux, and $G$ is the energy flux in the ice. Here, $G$ consists of the flux due to the penetration of the shortwave radiation into the ice and the conductive heat flux through ice ($G_s$). The estimated penetration of the shortwave radiation into the ice is calculated by $0.4I_o \times (1 - a_I)SR_{in}$, where $SR_{in}$ is the incoming fluxes of shortwave radiation, the shortwave ice albedo $a_I$ is set at 0.50, and the fraction of the net incident shortwave radiation penetrating the uncovered upper surface $I_o$ is around 17% (Maykut and Untersteiner 1971; Parkinson and Washington 1979). By calculation, the value of the shortwave radiation into the ice is very small (-0.10 W m$^{-2}$ on average). Thus, $G$ can be represented by $G_s$ (the conductive heat flux through the ice) calculated by $k_I (T_B - T_{sfc})/h_I$ based on Parkinson and Washington (1979), where the thickness of the ice $h_I$ is taken from the previous time step, the thermal conductivity of the ice $k_I$ is set at a constant 2.04 W m$^{-1}$K$^{-1}$, $T_{sfc}$ is the surface temperature, and the temperature at the bottom of the ice $T_B$ is assumed to be 271.2K representing the freezing point of
seawater (Maykut and Untersteiner 1971; Bryan et al. 1975). Note that all energy fluxes are specific intraseasonal components, and the positive values represent that the energy fluxes are directed toward the surface.

To examine the relative contribution of wind-driven dynamical processes to sea ice change, we calculate the regional averaged cumulative changes of SIT over the core region caused by sea ice motion, following the method in Park et al. (2015b) and Jiang et al. (2021). The wind-driven SIT change is calculated by the following Eq. (3):

$$\Delta h(j) \equiv \sum_i^j \delta h_i = - \sum_i^j \left[ \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) \right]_i \delta t_i$$  \hspace{1cm} (3)

where $\Delta h(j)$ denotes SIT change from Day $i$ to Day $j$, $\delta h_i$ denotes SIT change per day, $h$ represents SIT, $u$ and $v$ denote zonal and meridional ice-drift velocities, respectively. And the prime denotes the specific intraseasonal component.

To explore the ocean thermal effect on sea ice change, according to Shi et al. (2021) and Zhong et al. (2022), we estimate the oceanic thermal effect on sea ice in specific intraseasonal variation, using the following parametrized ocean-to-ice heat flux (OHF) equation, is shown in Eq. (4):

$$OHF = \rho_{ocean} c_p u_\ast C_H (T_{o5m} - T_{of})'$$ \hspace{1cm} (4)

where $\rho_{ocean}=1023$ kg m$^{-3}$ is a reference mixed layer density, $c_p=3980$ J/(°C kg) is the specific heat of seawater, $C_H=0.0057$ is the heat transfer coefficient (McPhee, 1992; McPhee et al. 2003), $T_{o5m}$ and $T_{of}$ are the ocean mixed layer temperature at the depth of ~5m and freezing point, and $u_\ast$ is friction velocity. Here, $T_{of}$ is a linear function of salinity $S$ given by: $T_{of} = -0.054 \cdot S$ (Shi et al. 2021; Vancoppenolle et al. 2007). And the prime denotes the specific intraseasonal component.

To understand the moisture change, the moisture flux convergence (MFC) is examined following He et al. (2017). MFC can be written as Eq. (5):

$$MFC = - \left( u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} \right)' - [q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)]'$$ \hspace{1cm} (5)

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where the advection term \((-u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y})\) represents the horizontal advection of the specific humidity, whereas the convergence term \([-q \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)]\) denotes the product of the specific humidity and horizontal mass convergence. Note that prime denotes the specific intraseasonal component.

To identify and define the significant specific periodic SIC events, we use three thresholds mentioned in Section 3. We use composite analysis to reveal the characteristics of specific periodical SIC variations and associated atmospheric circulation, and the physical processes related to specific periodical SIC variations at different phases, which has been used in many previous studies (Song and Wu 2019). Besides, the Student’s-\(t\) test is used to evaluate the statistical significance of composite analysis.

3. Dominant intraseasonal mode of SIC over the NBS and significant case selection during the melting season

According to the 29-year climatological daily variation of SIC (Fig. 1c), the sea ice melting over the BS region (70°N–80°N; 15°E–60°E) starts in Apr. and ends in Aug.–Sept.. In Aug.–Sept., the sea ice over the BS only covers fewer than half areas of the whole BS region and nearly reaches ice-free in Sept. (Fig. 1). Thus, the target period purposely removes the nearly ice-free months (Aug. and Sept.) and selects Apr.–Jul., called as the melting season hereafter. Shown as in Fig. 1b, the sea ice mainly concentrates over the NBS in Apr.–Jul.. Therefore, the target region of this study focuses the NBS (75°N–80°N, 15°E–60°E) region. Furthermore, we found, as shown in Fig. 2, the SIC intraseasonal variance averaged in 29-summer (Apr.–Jul.) has the maximum center in the NBS and accounts for 17%–37% of the total variance, with the maximum in Apr.
Fig. 1. (a) Geographical location of the BS in the Arctic region. The black rectangle roughly represents the BS region (70°N–80°N; 15°E–60°E). (b) Spatial distribution of climatological SIC (shading) over the BS from Apr. to Jul. during 1989-2017. The blue rectangle represents the NBS (75°N–80°N; 15°E–60°E). (c) Time series of climatological daily mean SIC averaged over the BS during 1989-2017. The light blue shading represents the melting season.

Fig. 2. Intraseasonal variance (shading) and intraseasonal fractional variance (contour: yellow for 15%, pink for 20%, blue for 25%) of SIC over the BS during the melting season. The black rectangles represent the NBS.

To investigate the dominant intraseasonal periodicity of the SIC over the NBS, we apply a power spectral analysis to the 29-summer time series of SIC intraseasonal component averaged over the NBS (Fig. 3). There are three significant intraseasonal

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variation periods, roughly in 15–30 days, 30–60 days, and 60–90 days. Their area-averaged fractional variances over the NBS account for 32.83%, 49.24%, and 9.78% of the total intraseasonal variance, respectively.

The year-by-year intraseasonal SIC variations averaged over the NBS are demonstrated in Fig. 4 (shading), overlapped with 30–60-day (60–90-day and 15–30-day are ignored here) component. Taking 30–60-day component as an example, the definition of a significant positive 30–60-day SIC event follows the three thresholds which refer to the previous methods (Rui and Wang 1990; Gao et al. 2017; Zhu and Yang 2021): (1) the values of two valleys (negative minimum) and one peak (positive maximum) exceed 0.8 times standard deviations of the 30–60-day component, which ensures the selected event is significant; (2) the raw data removing the slow climatological annual cycle must exceed 0.8 standard deviations for three consecutive days, which ensures the selected event is also significant in unfiltered data; (3) the persistent days with positive values around the peak should be within 15–30 days, which ensures that the duration of the event is 30–60 days. The criteria for selecting the significant negative SIC events are similar but opposite. Here each 30–60-day negative event cycle has two maximum positive anomalies and one minimum negative anomaly, which includes the melting as the first half cycle (a period between the day of the first maximum positive anomaly and the day of the minimum negative anomaly) and the freezing as the second half cycle (a period between the minimum negative anomaly date and the second maximum positive anomaly date), and the start (end) date is defined as the first (the second) maximum positive anomaly.

Eventually, 34 significant 30–60-day SIC events (16 positive events and 18 negative events) are selected, as shown in Table 1. Following the similar strategy but for the specific filtered band, 24 significant 15–30-day events and 9 significant 60–90-day events are also selected, which are both fewer than the number of 30–60-day events. Based on both fractional variance and the number of significant events compared with
the other two ISV periodical modes, 30–60-day components are the dominant ISV mode of NBS sea ice, which is the focus of this study.

![Power spectrum of intraseasonal SIC over the NBS during the melting season](image)

**Fig. 3.** The power spectra of the intraseasonal SIC over the NBS during the melting season (black line); the red solid line denotes the Markov red noise spectrum, the blue/green dashed line represents a priori/posteriori 95% confidence. The x-axis has been rescaled using the natural logarithm of frequency.

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Fig. 4. Time series of SIC intraseasonal component (red/blue bars) in the left y-axis and 30–60-day SIC (black solid lines) in the right y-axis averaged over the NBS during each melting season from 1989 to 2017. Dashed black (orange) lines represent 0.8 standard deviation of 30–60-day SIC (intraseasonal component of SIC) of each melting season. The black “✓” denotes the significant event according to the given three thresholds.

<table>
<thead>
<tr>
<th>30–60-day events No.</th>
<th>Dates</th>
<th>Duration (d)</th>
<th>Event categories</th>
<th>30–60-day events No.</th>
<th>Dates</th>
<th>Duration (d)</th>
<th>Event categories</th>
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</table>

Table 1. The 34 significant 30–60-day events with their occurrence dates, duration days and event categories.

4. Dominant ISV of sea ice over the NBS and associated atmospheric intraseasonal wave

The average duration (between the start date and end date) of SIC 30–60-day variations over the NBS is 40.5 days, as shown in Table 1. Because we found the freezing process is almost the mirror image of the melting process in the 30–60-day variations (see Fig. S1 of supplementary material), the following study focuses on the melting processes of SIC 30–60-day variations over the NBS. First, we investigate the 30–60-day melting process of sea ice from the maximum positive anomaly (Day 0) to the minimum negative anomaly (Day 20) with 2 days intervals based on a composite analysis of 34 significant 30–60-day SIC events, as shown in Fig. 5 clearly demonstrates the 30–60-day melting temporal evolution of SIC over the NBS. On Day 0, 30–60-day SIC component has its positive maximum centered over the southeastern NBS. From Day 0 to Day 10, the 30–60-day positive sea ice anomaly gradually
decreases and reaches nearly normal on Day 10. Afterward, the sea ice melts persistently from Day 12 to Day 18 and reaches its minimum. During the melting process of 30–60-day SIC evolution, the area-averaged 30–60-day SIC anomaly changes from 0.04 to -0.04, the averaged intraseasonal SIC anomaly changes from 0.05 to -0.06, and the area-averaged total SIC decreases from 0.67 to 0.45 within 20 days. Thus, the amplitude of 30–60-day SIC reduction accounts for 73% of the SIC intraseasonal change and 36% of the total SIC change. If we consider the accuracy of SIC datasets for the summer is ±15%, according to the NSIDC report (https://nsidc.org/data/G02135/versions/3), the contribution of 30–60-day SIC variations to the total sea ice melting is 28%–51%.

Fig. 5. Composite temporal evolution of 30–60-day SIC (shading) on Day 0–18 with 2 days intervals based on the significant 30–60-day SIC events. The gridded shows the results above the 95% confidence level. The black rectangles represent the NBS.

Concurrent with the 30–60-day melting processes of sea ice over the NBS, we examine the associated tropospheric atmospheric variations. Taking the GHT850 as an example, as shown in Fig. 6a, the most remarkable feature is a circum-polar clockwise propagating wave (CCPW), with zonal wavenumber one. As shown in Fig. 6, the anomalous low center moves westward, starting from northern Europe, propagating via Norwegian Sea, Greenland Sea, and Arctic Archipelago, and traveling over Baffin Bay, Chukchi Sea, East Siberian Sea, and the Laptev Sea, eventually finishing a circum-polar circle (see the other half cycle in Fig. S2 of supplementary material). The CCPW is significantly intensified over the northern Ural Mountains and

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the northern North Atlantic but weakened over the Chukchi Sea and the East Siberian Sea. A similar spatial structure occurs in both the middle and upper troposphere (Fig. 6b–c). Therefore, the 30–60-day CCPW typically features a barotropic structure. Note that the tropospheric southerly wind anomaly reaches its maximum in Day 8–14 over the NBS, which leads to the minimum of SIC by 6–10 days. The circumpolar clockwise traveling mode in summer has been reported in our recent study (Zhu and Yang 2021), and the earlier study by Branstator (1987) also reported the similar traveling waves but occurring in fall and winter.

Fig. 6. Composite temporal evolution of 30–60-day (a) GHT850 (contour; gpm; interval: 5 gpm), (b) GHT500 (contour; gpm; interval: 10 gpm), and (c) GHT200 (contour; gpm; interval: 10 gpm) on Day 0–18 with 2 days intervals based on the significant 30–60-day SIC events. The red (blue) contours present the positive (negative) values. Yellow shading shows the results above the 95% confidence level. The black rectangles represent the NBS. “A” denotes the center of anticyclonic anomaly and “C” denotes the cyclonic anomaly. The maps are on polar-stereographic projections and include all latitudes poleward of 60° N.
5. Mechanism for the 30–60-day sea ice variation over the NBS

The close relationship between sea ice and atmospheric anomalies is remarkable over the BS in their 30–60-day variations as mentioned above. Here we investigate their physical linkage. Fig. 7 illustrates the composite temporal evolutions of 30–60-day components for SIC and SAT averaged over the NBS. The most important feature is that the maximum positive SAT anomaly appears nearly at Day 14, which leads to the minimum SIC anomaly by 6 days during the melting period. The remarkable lead-lag relationship indicates the ISV of atmospheric temperature, which may play an important role in regulating the sea ice ISV.

![Fig. 7. Composite temporal evolution of the NBS area-averaged 30–60-day SIC (red line) and SAT (℃) (yellow line) based on the significant 30–60-day SIC events. The dots indicate the anomalies are significant at the 99% confidence level.](image)

We first investigate the causes of SAT increase using the composite near-surface temperature tendency equation of the 30–60-day component, following Eq. (1). To unify each term of near-surface temperature budget analysis, we purposely use the lowest model-level variables, which is approximately (based on the hydrostatic equation) 10 meters above the surface (Berrisford et al. 2009) and can represent the near-surface conditions. The 950 hPa variables are also applied to confirm the results. As a result, the warm horizontal advection dominantly exhibits a significant positive contribution to the increased temperature as shown in Fig. 8, which reaches its maximum (1.7 K day⁻¹) at Day 12–14. Correspondingly, we find the southerly anomaly of surface wind at 10 meters reaches its maximum (1.8 m s⁻¹) over the NBS at Day 12–14 as shown in Fig. 9, which is in phase with the CCPW addressed in Fig. 6. Therefore, the increased surface temperature is mainly caused by the warm advection associated
with circum-polar clockwise propagating 30–60-day waves. Meanwhile, we also notice that the diabatic heating exhibits a large negative contribution (-1.5 K day\(^{-1}\)) to the increased temperature at the near-surface atmosphere, which suggests a net heating transport downward from the lower-level atmosphere to the surface is significant.

**Fig. 8.** Composite temporal evolution of temperature tendency equation on the lowest model level averaged over the NBS based on the significant 30–60-day SIC events. The legends from left to right are temperature tendency (K day\(^{-1}\)) (black bars), horizontal advection of temperature (K day\(^{-1}\)) (red bars), diabatic heating (K day\(^{-1}\)) (yellow bars), vertical advection of temperature + adiabatic warming (K day\(^{-1}\)) (green bars), and Res (K day\(^{-1}\)) (purple bars) respectively.

**Fig. 9.** (a) Composite temporal evolution of 30–60-day SAT (shading, °C) and surface wind at 10m (vector, scale at right bottom) on Day 4–14 with 2 days intervals based on the significant 30–60-day SIC events. The black rectangles represent the NBS. (b) Composite temporal evolution of the NBS area-averaged 30–60-day surface meridional wind (m day\(^{-1}\)) (red bars) based on the significant 30–60-day SIC events.

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To investigate which downward fluxes in the air-ice interface are dominant, we calculate the surface energy budget of an ice upper surface, following Eq. (2), as shown in Fig. 10. As a result, both the downward SHF and the downward LR are dominant positive contributors to the anomalous surface warming in 30–60-day time scale. The $G$ represented by $G_s$ has a relatively small negative value, which can be roughly ignored compared with other atmospheric heat fluxes. In addition, the downward LHF anomaly has a positive contribution to surface warming but plays a secondary role compared with the downward SHF and LR.

![Surface energy budget](image)

**Fig. 10.** Composite temporal evolution of surface energy budget terms averaged over the NBS based on the significant 30–60-day SIC events. The legends are downward LR (W m$^{-2}$) (red bars), upward LR (W m$^{-2}$) (green bars), SHF (W m$^{-2}$) (yellow bars), LHF (W m$^{-2}$) (blue bars), SR (W m$^{-2}$) (black bars), and $G_s$ (purple bars), respectively. And the positive values represent that the energy fluxes are directed toward the surface.

We further diagnose the factors causing the 30–60-day variations of the above-mentioned three major contributors. The increased downward SHF relies on increased temperature difference (difference between SAT and skin temperature) and enhanced surface wind speed, which both reach their maximum values at Day 12 (Fig. 11a). The increased LHF is caused by specific humidity difference (difference between that of surface air and saturation specific humidity of skin temperature) and surface wind speed (Fig. 11c). The increased downward LR is related to increased vertically integrated MFC which is integrated from 1000hPa to 300hPa (Fig. 11b; purple line) as many previous studies have mentioned (Gong and Luo 2017; Guan et al. 2020; Park et al. 2015a; Woods and Caballero 2016). Meanwhile, we calculate the mean temperature

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anomaly in 30–60-day time scale, averaging in the vertical column between 1000 hPa and 300 hPa. The results also suggest that the increased downward LR is contributed by the increased mean temperature in the vertical column. The vertically integrated MFC intensifies and reaches the maximum on the upstream side of the intensified anticyclone from Day 8 to Day 10 (Fig. 6), accompanied by the increased southerly wind. Meanwhile, as shown in Fig. 11d, the moisture advection term dominantly contributes to the increase of the vertically integrated MFC according to Eq. (5). That means the strengthened southerly wind anomaly caused by the CCPW brings warmer and moist air from the lower latitudes to the polar region over the NBS.

![Fig. 11](image)

**Fig. 11.** Composite temporal evolution of the NBS area-averaged 30–60-day (a) SHF (W m\(^{-2}\)) (red line), temperature difference (°C) (purple line), and surface wind speed (m s\(^{-1}\)) (blue line); (b) downward LR (W m\(^{-2}\)) (red line), MFC (kg m\(^{-2}\)) (purple line) vertically integrated from 1000 hPa to 300 hPa, and air temperature (°C) (blue line) vertically averaged between 1000 hPa and 300 hPa; (c) LHF (W m\(^{-2}\)) (red line), specific humidity difference (10\(^{-9}\) kg kg\(^{-1}\)) (purple line), and surface wind speed (m s\(^{-1}\)) (blue line); (d) Composite temporal evolution of the NBS area-averaged 30–60-day advection term (kg m\(^{-2}\)) (purple bars), and convergence term (kg m\(^{-2}\)) (yellow bars) vertically integrated from 1000 hPa to 300 hPa based on the significant 30–60-day SIC events. The dots indicate the anomalies are significant at the 99% confidence level.

### 6. Role of wind-driven dynamical and ocean thermal process

To confirm if the atmospheric surface thermal process associated with the atmospheric intraseasonal CCPW is the dominant process causing sea ice melting in 30–60-day time scale, we further examine the effect of wind-driven dynamical forcing...
and ocean thermal process. First, because the SIT has a similar dominant intraseasonal periodicity (30–60-day) with SIC (see Fig. S3a of supplementary material) and the temporal evolution of the SIT 30–60-day component is almost in phase with the variations of the SIC anomaly over the NBS (see Fig. S3b of supplementary material), the wind-driven role on changing SIC can be estimated by its influence on SIT. Following the method in Park et al. (2015b) and Jiang et al. (2021), the wind-driven SIT 30–60-day change is calculated using Eq. (3). As shown in Fig. 12, the result shows that the wind-driven dynamical effect slightly causes the increase of SIT in the 30–60-day time scale, which is opposite with the 30–60-day sea ice melting process (SIT decrease). Therefore, the wind-driven dynamical effect on melting the NBS sea ice can be ignored in 30–60-day time scale.

Fig. 12. Composite temporal evolution for the total change of sea ice thickness (cm) (red line), and wind-driven 30–60-day anomalous sea ice thickness (cm) (blue line) over the NBS.

Second, we attempt to examine the oceanic thermal effect on the 30–60-day melting of sea ice. On one hand, we estimate the ocean-ice interface thermal flux using the parametrized OHF equation based on Eq. (4) (Shi et al. 2021; Zhong et al. 2022). Since the value of friction velocity $u_*$ has large uncertainties with different estimated values (ranging from 0.002 m/s to 0.02m/s and usually using 0.006m/s as a measured average) (e.g., Morison et al. 1987, Shi et al. 2021, Andreas et al. 2010). As shown in Fig. 13a, the OHF over the NBS is negative during the early melting period from Day 0 to Day 12, which denotes that the positive heat anomalies are transported downward.

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from ice-ocean interface to ocean mixed layer imposing a negative effect on sea ice melting. The OHF becomes positive and contributes to intraseasonal sea ice melting during the late melting period from Day 13 to Day 20. Overall, given the whole intraseasonal sea ice melting process (Day 0–Day 20), the OHF is a slightly negative contributor to the domain-averaged sea ice melting in the 30–60-day time scale. On the other hand, we compare the temporal evolutions of the SIC, $T_{o5m}$, and oceanic mixed-layer temperature ($T_{omix}$). Here, the mixed layer is defined as the depth at which the potential density exceeds the reference layer (5m) by 0.03 kg m$^{-3}$ (Song and Zhang 2020; Yurganov et al. 2021). Obviously, the warming peaks of both the $T_{o5m}$ and $T_{omix}$ lag the decrease of SIC by 3 days shown as in Fig. 13b, which are opposite with the advanced warming SAT ahead of decreased SIC mentioned in section 5. The lagged warming of near-surface oceanic temperature against SIC melting further confirms that the NBS area-averaged ocean is passively heated by the interface-to-ocean downward thermal effect, especially in the early melting period, rather than warms the sea ice in the 30–60-day component. Hence, generally, the ocean thermal effect is not dominant in the intraseasonal sea ice melting over the NBS.

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Fig. 13. (a) Composite NBS area-averaged 30–60-day ocean-to-ice heat flux (W m\(^{-2}\)) of day-by-day and melting-process (Day 0–20) mean (red dots represent the value as \(u_*=0.006\text{m/s}\) and blue bars represent values ranging from \(u_*=0.002\text{m/s}\) to \(u_*=0.02\text{m/s}\)). (b) Composite temporal evolution of the NBS area-averaged 30–60-day SIC (red line), \(T_{\text{to5m}}\) (℃) (purple line), and \(T_{\text{omix}}\) (℃) (orange line) based on the significant 30–60-day SIC events. The crosses indicate the peak value days.

7. Conclusion

The SIC ISV is most significant over the NBS in the summer melting season (from Apr. to Jul.), with the dominant periodicity of 30–60 days. Concurrent with 30–60-day sea ice variations, an evident 30–60-day atmospheric wave propagates clockwise, encircling the north polar region. The deepened physical analysis uncovers their close linkage. The ISV of the NBS sea ice forced by intraseasonal atmospheric waves has been summarized in the schematic diagram (Fig. 14): in 30–60-day time scale, an anomalous CCPW causes anomalous meridional circulation over the BS (taking southerly wind anomaly as an example here), which brings both warm advection and moisture air. The warming atmosphere and increased moisture enhance the downward SHF and downward LR as the first order, and LHF as the secondary order, which eventually warm the surface and melt the NBS sea ice. The ocean thermal contributor from sea ice lower-surface becomes positive in the late stage of melting processes, which actually needs to be given more accurate estimation based on numerical modeling in the future.
Fig. 14. Schematic diagram for the physical process of 30–60-day sea ice decrease over the NBS during the melting season.

In conclusion, this study emphasized that the sea ice subseasonal variations are dominantly regulated by atmospheric intraseasonal waves, which strongly suggests that the accurately subseasonal prediction of atmospheric circulation and associated SAT are crucial for improving subseasonal prediction of sea ice in the Northern Atlantic sector of the Arctic. This study provides a new perspective for how to improve the subseasonal prediction of both the Arctic Sea ice and the mid-lower-latitude atmosphere. Other scientific issues that arise from our study are worthwhile to be studied include the causes for the other sea ice ISV (15–30-day and 60–90-day), the coherent variations with other areas in the Arctic and lower-latitudes, the sea ice feedback to the atmosphere in intraseasonal time scale. Examining if the modeling can simulate the realistic sea ice-atmosphere interaction in models is also crucial in future work.

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Data Availability Statement.

The ERA-Interim reanalysis data can be freely accessed on this website (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/). The NSIDC data can be freely accessed on this website (https://nsidc.org/data/G02202/versions/3). And the SIT reanalysis data from Pan-Arctic Ice Ocean Modelling and Assimilation System can be freely accessed on this website (http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/data/model_grid), and the NSIDC daily 25-km EASE-Grid sea ice motion dataset can be freely accessed on this website (https://nsidc.org/data/g02202/versions/3/). And the NCEP Climate Forecast System Reanalysis (CFSR) data can be freely accessed on this website (NCAR’s RDA (ucar.edu)).

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