Intraseasonal Melting of Northern Barents Sea Ice Forced by Circumpolar Clockwise-Propagating Atmospheric Waves during Early Summer

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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 multiple 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 and dynamical processes, including surface radiation (Ding et al. 2017), moisture transport related with tropical forcing (Dunn-Sigouin et al. 2021), the Arctic Oscillation (Overland and Wang 2010), the North Atlantic Oscillation (Caian et al. 2018), the 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 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. 2016b), jet stream location (Barnes and Simpson 2017; McGraw and Barnes 2020), the 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 and 70–80 days) of SIC changes in the late melting season (August–October) (Qian et al. 2020), but that 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 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, 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 traveling 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 conclusions are 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 the NSIDC has a spatial resolution of 25 km and covers 48.4°–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 dataset of the European Center for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011), including geopotential height at 950 hPa (GHT950), 850 hPa (GHT850), 500 hPa (GHT500), and 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 subregions due to global warming (Stroeve and Notz 2018), which will lead to the opening of new trans-Arctic shipping routes (Smith and Stephenson 2013). The BS is a key region linking the Arctic to lower-latitude weather-to-climate changes (Luo et al. 2016b) 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. 2016a). 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 research focuses on winter and decadal-to-interannual time scales, and few studies pay attention to summer and the 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- to high-latitude climate variations (Sreen 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 traveling 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 conclusions are given in section 7.
200 hPa (GHT200), zonal and meridional wind, and temperature, specific humidity, vertical $p$ velocity ($\omega$) from 1000 to 300 hPa, surface air temperature (SAT), skin temperature, surface zonal and meridional wind speed at 10 m, surface net solar radiation (SR), longwave radiation (LR), surface sensible heat flux (SHF), and surface latent heat flux (LHF), with a 1.5° x 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 135 m, 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° x 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. 2018). The ISV component is obtained from the “raw” daily time series by first removing the climatology of the individual year and then removing the annual mean of anomalies, and next using a 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 (April–July) with a total of 3538 days (29 x 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. 1963). The a priori/a 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), with the formulation of $\gamma$ given by $\gamma = -(1/2)n\ln(R)$, where $n$ is 3538 and $R$ is the lag-1-pentad autocorrelation coefficient. 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 bandpass 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):

\[
\frac{\partial T_a'}{\partial t} = -\left( \frac{\partial T_a}{\partial x} - \nu \frac{\partial T_a'}{\partial y} \right) - \left( \frac{\partial T_a}{\partial y} \right) + \frac{k_T a w}{p} + P_T + \text{Res}',
\]

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 \(-\eta \frac{\partial T_a}{\partial y}\), adiabatic warming \(k_T a w/p\), 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

\[
M = SR + LR + SHF + LHF + G,
\]

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 \((G_i)\). The estimated penetration of the shortwave radiation into the ice is calculated by 0.4\(I_o\times(1-a_I)SR_{in}\), 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 \((-0.10\ \text{W m}^{-2}\ \text{on average})\). Thus, \(G\) can be represented by \(G_i\) (the conductive heat flux through the ice) calculated by \(k_I(T_B - T_{sc})/h_I\) based on Parkinson and Washington (1979), where the thickness of the ice \(h_I\) is taken from the previous time step, thermal conductivity of the ice \(k_I\) is set at a constant 2.04 W m\(^{-1}\) K\(^{-1}\), \(T_{sc}\) is the surface temperature, and the temperature at the bottom of the ice \(T_B\) is assumed to be 271.2 K 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 equation:

$$\Delta h(j) \equiv \sum_{i} \delta h_i = -\sum_{i} \left[ \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) \right] \delta t_i,$$

(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, and $u$ and $v$ denote zonal and meridional ice-drift velocities, respectively. 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 parameterized ocean-to-ice heat flux (OHF) equation, shown in Eq. (4):

$$\text{OHF} = \rho_{\text{ocean}} c_p \mu (T_{o5m} - T_{o5m})^\prime,$$

(4)

where $\rho_{\text{ocean}} = 1023 \text{ kg m}^{-3}$ is a reference mixed layer density, $c_p = 3890 \text{ J (°C kg}^{-1})^{-1}$ is the specific heat of seawater, $C_H = 0.0057$ is the heat transfer coefficient (McPhee 1992; McPhee et al. 2003), $T_{o5m}$ and $T_{o5m}$ are the ocean mixed layer temperature at the depth of $\sim 5$ m and freezing point, and $u$ is friction velocity. Here, $T_{o5m}$ is a linear function of salinity $S$ given by $T_{o5m} = -0.054 \times S$ (Shi et al. 2021; Vancoppenolle et al. 2007). 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

$$\text{MFC} = -\left[ \frac{\partial q}{\partial x} + \frac{\partial q}{\partial y} \right]^\prime - \left[ q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right]^\prime,$$

(5)

where the advection term $(-q \frac{\partial q}{\partial x} - q \frac{\partial q}{\partial y})$ represents the horizontal advection of the specific humidity, whereas the divergence term $(-q \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})$ 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). 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-yr climatological daily variation of SIC (Fig. 1c), the sea ice melting over the BS region (70°–80°N, 15°–60°E) starts in April and ends in August–September. In August–September, the sea ice over the BS covers less than half the whole BS region, which becomes nearly ice-free in September (Fig. 1). Thus, the target period purposely removes the nearly ice-free months (August and September) and selects April–July, referred to as the melting season. As shown in Fig. 1b, the sea ice mainly concentrates over the northern Barents Sea (NBS) in April–July. Therefore, the target region of this study focuses on the NBS (75°–80°N, 15°–60°E) region. Furthermore, we found, as shown in Fig. 2, that the SIC intraseasonal variance averaged over 29 summers (April–July) has the maximum center in the NBS and accounts for 17%–37% of the total variance, with the maximum in April.

To investigate the dominant intraseasonal periodicity of the SIC over the NBS, we apply a power spectral analysis to the 29-summertime series of SIC intraseasonal component averaged over the NBS (Fig. 3). There are three significant intraseasonal variation periods, roughly in 15–30, 30–60, 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 shown in Fig. 4 (shading), overlapped with the 30–60-day (the 60–90- and 15–30-day components are ignored here) component. Taking the 30–60-day component as an example, the definition of a significant positive 30–60-day SIC event follows three thresholds that refer to the previous methods (Rui and Wang 1990; Gao et al. 2018; Zhu and Yang 2021): 1) the values of two valleys (negative minimum) and one peak (positive maximum) exceed 0.8 times the standard
30–60-day component & the intraseasonal component

![Graph showing time series of SIC intraseasonal component and 30–60-day SIC](image)

**Fig. 4.** Time series of SIC intraseasonal component (red/blue bars) on the left y axis and 30–60-day SIC (black solid lines) on 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 check mark denotes the significant event according to the given three thresholds.

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 a similar strategy but for the specific filtered band, 24 significant 15–30-day events and 9 significant 60–90-day

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deviation 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; and 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.

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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, the 30–60-day components are the dominant ISV mode of NBS sea ice, which is the focus of this study.

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 in the online supplemental 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-day intervals based on a composite analysis of 34 significant 30–60-day SIC events, as shown in Fig. 5, which clearly demonstrates the 30–60-day melting temporal evolution of SIC over the NBS. On day 0, the 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 0.02, the averaged intraseasonal SIC anomaly changes from 0.05 to −0.06, and the area-averaged total

![Fig. 5. Composite temporal evolution of 30–60-day SIC (shading) on days 0–18 with 2-day 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.](image-url)

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

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Dates</th>
<th>Duration (days)</th>
<th>Event category</th>
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<th>Duration (days)</th>
<th>Event category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11 Apr–1 Jun 1989</td>
<td>51</td>
<td>Negative</td>
<td>18</td>
<td>21 Apr–31 May 2001</td>
<td>40</td>
<td>Negative</td>
</tr>
<tr>
<td>2</td>
<td>10 Apr–16 May 1990</td>
<td>36</td>
<td>Negative</td>
<td>19</td>
<td>11 May–22 Jun 2001</td>
<td>42</td>
<td>Positive</td>
</tr>
<tr>
<td>3</td>
<td>7 Mar–18 Apr 1991</td>
<td>42</td>
<td>Negative</td>
<td>20</td>
<td>30 Mar–9 May 2003</td>
<td>40</td>
<td>Negative</td>
</tr>
<tr>
<td>5</td>
<td>11 Mar–17 Apr 1993</td>
<td>37</td>
<td>Positive</td>
<td>22</td>
<td>7 May–11 Jun 2007</td>
<td>35</td>
<td>Negative</td>
</tr>
<tr>
<td>9</td>
<td>3 May–14 Jun 1996</td>
<td>42</td>
<td>Positive</td>
<td>26</td>
<td>30 Apr–3 Jun 2010</td>
<td>34</td>
<td>Negative</td>
</tr>
</tbody>
</table>
FIG. 6. Composite temporal evolution of 30–60-day (a) GHT850 (contours; gpm; interval: 5 gpm), (b) GHT500 (contours; gpm; interval: 10 gpm), and (c) GHT200 (contours; gpm; interval: 10 gpm) on days 0–18 with 2-day 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. Letter A denotes the center of anticyclonic anomaly and letter C denotes the cyclonic anomaly. The maps are on polar-stereographic projections and include all latitudes poleward of 60°N.
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 that the accuracy of SIC datasets for the summer is ±15%, according to the NSIDC report (https://nsidc.org/data/G02135/versions/3), then the contribution of 30–60-day SIC variations to the total sea ice melting is 28%–51%.

Concurrent with the 30–60-day melting processes of sea ice over the NBS, we examine the associated tropospheric atmospheric variations. Taking GHT850 as an example, as shown in Fig. 6a, the most remarkable feature is a circumpolar clockwise-propagating wave (CCPW), with zonal wavenumber 1. As shown in Fig. 6, the anomalous low center moves westward, starting from northern Europe, propagating via the Norwegian Sea, the Greenland Sea, and the Arctic archipelago, and traveling over Baffin Bay, the Chukchi Sea, the East Siberian Sea, and the Laptev Sea, eventually finishing a circumpolar circle (see the other half cycle in Fig. S2). The CCPW is significantly intensified over the northern Ural Mountains and 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 (Figs. 6b,c). Therefore, the 30–60-day CCPW typically features a barotropic structure. Note that the tropospheric southerly wind anomaly reaches its maximum during days 8–14 over the NBS, which leads to the minimum 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.

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. Figure 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.

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 are approximately based on the hydrostatic equation) 10 m 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 dominates positive contribution to the increased temperature as shown in Fig. 8, which reaches its maximum (1.7 K day⁻¹) at days 12–14. Correspondingly, we find the southerly anomaly of surface wind at 10 m reaches its maximum (1.8 m s⁻¹) over the NBS at days 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 circumpolar 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 that a net heating transport downward from the lower-level atmosphere to the surface is significant.

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.

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 1000 to 300 hPa (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 anomaly on a 30–60-day time scale, averaging in the vertical column between 1000 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.

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 days) with SIC (see Fig. S3a in the online supplemental 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), the wind-driven role in 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 to 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 on a 30–60-day time scale.

Second, we attempt to examine the oceanic thermal effect on the 30–60-day melting of sea ice. On the one hand, we estimate the ocean–ice interface thermal flux using the parameterized OHF equation based on Eq.(4) (Shi et al. 2021; Zhong et al. 2022). The value of friction velocity $u_*$ has large uncertainties with different estimated values (ranging from 0.002 to 0.02 m s$^{-1}$ and usually using 0.006 m s$^{-1}$ 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 from the 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 to day 20), the OHF is a slightly negative contributor to the domain-averaged sea ice melting on the 30–60-day time scale. On the other hand, we compare the temporal evolutions of the SIC, $T_{0.5m}$, and oceanic mixed-layer temperature ($T_{o_{mix}}$). Here, the mixed layer is defined as the depth at which the potential density exceeds the reference layer (5 m) by 0.03 kg m$^{-3}$ (Song and Zhang 2020; Yurganov et al. 2021). Obviously, the warming peaks of both the $T_{0.5m}$ and $T_{o_{mix}}$ lag the decrease of SIC by 3 days shown as in Fig. 13b, which are opposite to 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 warming 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.

7. Conclusions

The SIC ISV is most significant over the NBS in the summer melting season (from April to July), with a 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 is summarized in a schematic diagram (Fig. 14); on a 30–60-day time scale, an anomalous CCPW causes anomalous meridional circulation over the BS (taking the 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 second order, which eventually warm the surface and melt the NBS sea ice. The ocean thermal contributor from the lower surface of the sea ice 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.

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 North 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- to lower-latitude atmosphere. Other scientific issues that arise from our study that deserve study include the causes for the other sea ice ISV (15–30 and 60–90 days), the coherent variations with other areas in the Arctic and lower latitudes, and

![Fig. 13](image1.png)

**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 (days 0–20) mean (red dots represent the value of $u_*$ = 0.006 m s$^{-1}$ and blue bars represent values ranging from $u_*$ = 0.002 to 0.02 m s$^{-1}$). (b) Composite temporal evolution of the NBS area-averaged 30–60-day SIC (red line), $T_{5cm}$ (°C; purple line), and $T_{omix}$ (°C; orange line) based on the significant 30–60-day SIC events. The crosses indicate the peak value days.

![Fig. 14](image2.png)

**Fig. 14.** Schematic diagram for the physical process of 30–60-day sea ice decrease over the NBS during the melting season.
the sea ice feedback to the atmosphere in intraseasonal time scale. Examining if the modeling can simulate the realistic sea–atmosphere interaction in models is also crucial in future work.

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