Thermodynamic processes affecting the winter sea ice changes in the Bering Sea in the Norwegian Earth System Model

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Abstract. The Arctic sea ice has changed largely over the last decades and is expected to change in the future. In this study, we assess sea ice changes in the Pacific sector of the Arctic in an Earth System Model. In winter, the first Empirical Orthogonal Function of sea ice concentration in the Pacific sector of the Arctic based on observations are significantly opposite to that in the Atlantic sector during a period from 1976 to 2004, describing 13.4% of the total Arctic winter sea ice

15 variability. The similar pattern is also confirmed in the Norwegian Earth System Model (NorESM1-M) (15.8%). Thermodynamics is found to be vital to winter sea ice variability. In this study, we analyze the relationships between some thermodynamical processes (congelation ice, frazil ice, bottom and top ice melting, and conversion of snow to ice) and sea ice changes in the Bering Sea, based on the NorESM1-M coupled climate model results. All these studied thermodynamical processes can influence the variability in winter sea ice concentration and thickness in the Bering Sea. Considering the mean

20 seasonal cycle over the 30-year time period, conversion of snow to ice contributes about 69% to the increase in sea ice mass during winter in the Bering Sea, and it is thus the main source to the growth of the winter sea ice in NorESM1-M in the Bering Sea. On the interannual time scales, winter sea ice concentration and thickness variability in the Bering Sea are highly related with the studied thermodynamic processes. Among these thermodynamic processes, congelation ice shows the most important effect on the simulated variability in the Bering Sea, especially in the northeastern part.

25 **1 Introduction**

The changes in Arctic sea ice have profound effects on marine industries and ecosystems (Meier et al., 2014), beside these, recent studies also pointed out that sea ice could impact the weather and climate in lower latitudes (Gao et al., 2015). Therefore, improved understanding on the mechanisms which influence the Arctic sea ice and the reliable prediction of sea ice is of importance to local and global society. The change of the Arctic sea ice has been related to both the global warming

30 (Borgerson, 2008) and the natural variability (Johannessen et al., 2004). In terms of dynamic mechanisms, the Arctic sea ice change can be impacted by the radiative (e.g., albedo, clouds, water vapor) (Blanchet and others, 1995; Struthers et al., 2011)

and remote (both atmospheric and oceanic transports from lower latitudes) influences, such as the negative trend in the North Atlantic Oscillation (Ding et al., 2014). Furthermore, changes in sea ice export in the Fram Strait can contribute to changes in the Arctic sea ice (e.g., Langehaug et al., 2013; Smedsrud et al., 2011).

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In the Atlantic-sector, sea ice areas in the Barents Sea and the Greenland Sea changed more significantly during the period 1979-2010 (Cavalieri and Parkinson, 2012) than that in the Pacific-sector. Early observation-and-modelling based studies have suggested that the sea ice variability in the Atlantic-sector was affected by the Atlantic Ocean heat transport into the Arctic (Årthun et al., 2012; Miles et al., 2014; Zhang, 2015). In this study, we investigate mechanisms that can contribute to

40 sea ice variability in the Pacific-sector using a fully coupled Earth System Model. More specifically, we investigate thermodynamic processes that control the freezing and melting of sea ice (such as congelation ice, frazil ice, bottom and top ice melting, and conversion of snow to ice) and quantify their roles in the variability of winter sea ice in the Bering Sea (BS). The freezing (melting) of sea ice will absorb (release) heat, which is highly important to the air-sea heat exchange (Fichefet and Maqueda, 1997).

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In the Pacific-sector, the Bering Strait is the only gateway between the Arctic Ocean and the Pacific Ocean. The Bering Strait is about 85 km wide and 50 m deep. It is one of the shallowest straits in the world. The Pacific Ocean affects Arctic atmospheric temperature and sea ice by the oceanic heat transport from the Pacific Ocean through the Bering Strait (Woodgate et al., 2010). Although the oceanic heat transport from the Pacific Ocean to the Arctic Ocean is not as strong as

50 that from the Atlantic-sector, it can also impact the climate of Arctic (Muilwijk et al., 2018; Woodgate et al., 2006). Frey et al. (2015) used satellite data to investigate the divergence of sea ice area across the Bering, Chukchi, and Beaufort Seas and their relationships with the heat exchange between the lower troposphere and the sea surface over the years 2003-2010 (Frey et al., 2015; Li et al., 2014). They found that sea ice cover in the Chukchi has been thermally driven, and this in the Bering Sea has been driven by both wind and thermodynamics.

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The decrease of Arctic sea ice since 1979 has shown temporal and spatial differences. Cavalieri and Parkinson (2012) studied the changes and trends of Arctic sea ice area and extent from 1979 to 2010, and they found that the decrease of sea ice area in the BS mainly occurs in autumn and winter. From the first Empirical Orthogonal Function (EOF1) and the associated time series from observation-based sea ice concentration (Figure 1), it has been found that the trend of winter sea

60 ice concentration in the BS is opposite to that of in other Arctic marginal seas on the interannual time scales. The spatial characteristics of EOF1 pattern are significantly different from that in other Arctic marginal seas, such as the Greenland Sea and Barents Sea (Figure 1). The EOF1 pattern based the observations (1976 to 2004) explains 13.4% of the total variability of the Arctic sea ice in winter, which is the dominant pattern. In the Norwegian Earth System Model (NorESM1-M), the similar EOF1 pattern is also found, which can explain about 15.8% of the Arctic winter sea ice variability. This shows that

65 the model can reflect different sea ice variability in the Atlantic and Pacific Arctic.

In the Arctic, the growth of congelation ice and frazil ice, bottom and top ice melting and the conversion of snow to ice are vital to the development of sea ice (Hunke et al., 2010; Lange et al., 1989). Therefore, it is necessary to study these factors that potentially can have a large effect on the winter sea ice changes in the BS.
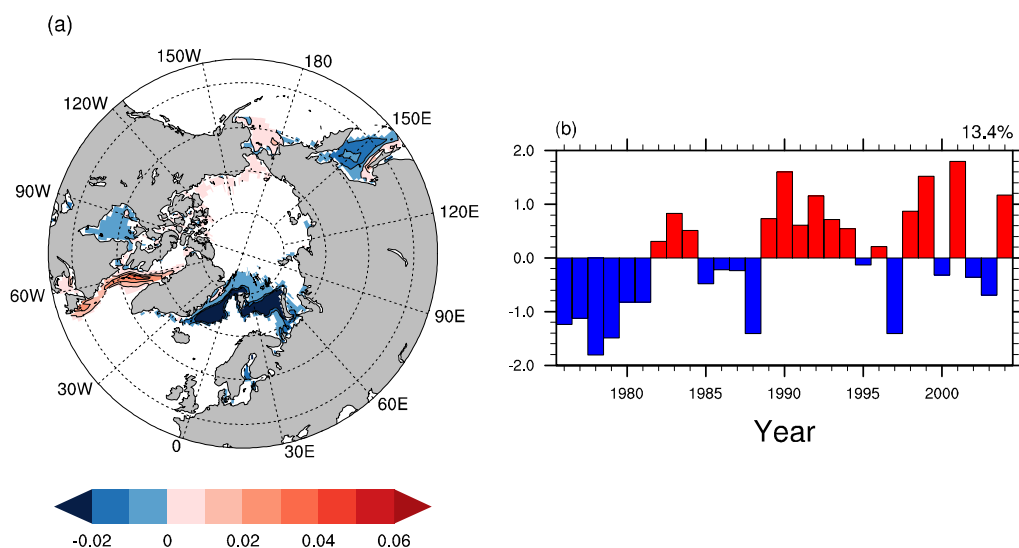
Figure 1: First EOF spatial pattern (a) and the associated time series (b) of winter Arctic sea ice concentration in the from 1976 to 2004 based on the observations, variation of the sea ice concentration is explained by theEOF1, 13.4%.

The manuscript is organized as follows. In Section 2, we describe the data, model, and methods used. In Section 3, we investigate the sea ice freezing and melting processes in the winter time from 1976 to 2004 and quantify how these thermodynamic processes impact the sea ice concentration and thickness in the BS by using model results and datasets from the Met Office HadIey Center. In Section 4, we discuss and conclude our results.

2 Data and methods

2.1 Observation based and reanalysis data

Mean sea ice concentration is from the Met Office HadIey Center HadISST. The data is a monthly global sea ice concentration on a 1-degree latitude-longitude grid, which is from 1870 to 2017 (Langehaug et al., 2017). A detailed description of the dataset is given in Rayner et al. (2003). In this study, we choose the nearly 30-year time period from 1976 to 2004 and compare it with model simulations, in order to evaluate the models' performance. The data before 1979 is not as accurate as that after it because of the higher resolution data in the later period (Johannessen et al., 1999). The sea ice extent is defined as the area where sea ice concentration is as least 15% (Årthun et al., 2017). The area with sea ice concentration over 90% is considered to be fully sea ice covered.

Due to the limitations of sea ice thickness observation, we use assimilation data to estimate the simulations from the model. Monthly mean sea ice thickness is from Pan-Arctic Ice Ocean Modelling and Assimilation System (PIOMAS) (Lindsay, 2010; Zhang and Rothrock, 2003). The monthly sea ice thickness data is from 1978 to the present, and we choose the period
90   of 1978-2004. The spatial coverage of this data is only from 45 ºN to 90 ºN.

2.2 Model outputs

We use the Norwegian Earth System Model (NorESM1-M) (Bentsen et al., 2013) from Norway. We will assess the model outputs in terms of simulated sea ice concentration, and sea ice thickness in the BS in winter.

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NorESM1-M outputs used in this study can be obtained on the website of Coupled Model Intercomparison Project Phase 5 (https://esgf-node.llnl.gov/login/?next=/ac/subscribe/CMIP5%2520Research/) (Taylor et al., 2012). Here we use the historical experiment from 1850 to 2004. To be consistent with reanalysis data, we choose model outputs from 1976 to 2004 of the historical experiments. In addition, the winter in this study refers to December, January, and February.

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In the Atlantic Arctic, the NorESM1-M overestimates the winter sea ice concentration in most areas, while it underestimates the sea ice concentration in the Bering Sea (Figure 2). Compared to the winter sea ice concentration differences between model outputs and HadISST datasets in the Greenland and Barents Seas (over 0.3), the differences in the Bering Sea are relatively smaller (less than 0.3). The deviations of winter sea ice concentration appear to be larger in the west of Sea of
105   Okhotsk.
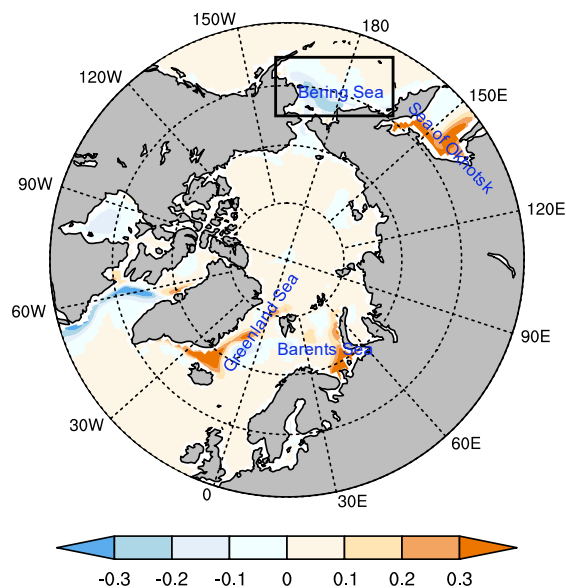
Figure 2: Distributions of deviations of mean winter sea ice concentration between NorESM1-M outputs and the reanalysis datasets from HadISST in the winter from 1976 to 2004 in the Arctic. The black box embraces the Bering Sea (59-68°N and 0-18°W), blue shading represents that sea ice in the model is less than that in the observations, orange represents that sea ice in the model is larger than that in the observations.

The time series of winter area-averaged sea ice thickness in the BS (59°N~68°N, 0°~18°W) from NorESM1-M and PIOMAS are shown in Figure 3. In the BS, sea ice thickness in winter simulated by the model is about 0.15 m, and the result of PIOMAS is about 0.19 m. And the standard deviation of two time series is only about 0.04.
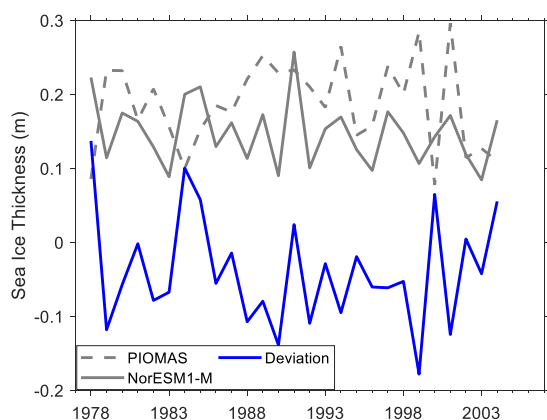
Figure 3: Time series of area-averaged sea ice thickness (m) of PIOMAS (gray dotted line), NorESM1-M (gray solid line) and the deviation between NorESM1-M and PIOMAS (blue line) in winter from 1978 to 2004 in the BS.

The aim of this study is to investigate roles of thermodynamic processes in sea ice. To do so, several thermodynamic processes in sea ice including the congelation and frazil growth of sea ice, top and bottom melting in the BS have been
120 analyzed. All of these variables are available from the CMIP5 archive and have been investigated earlier in NorESM1-M, but in the Atlantic sector and in the central Arctic Ocean (Sandø et al., 2014). The frazil ice is made of random and discoid ice crystals and is formed in cool turbulent water near the surface of the seawater (Gow and Tucker, 1991), which is often formed on the surface in oceans when the weather is much cold (Daly, 1994). As the accumulations of frazil, the sheets of ice will become thicker, then shape in the form of platelets on the bottom of an established ice cover depending on the
125 weather conditions (Gow et al., 1987), which is called congelation ice (Ackley et al., 1990). When the congelation ice is increasing to a certain extent, solid ice can be finally formed (Weeks and Ackley, 1986). The congelation growth of ice is much slower than the frazil growth of ice because overlaying ice would hinder heat release into the air (Bauer and Martin, 1983). Further, the volume of congelation ice may determine an ice floe (Maykut, 1978) . Air temperature and sea surface salinity determine the time of the sea water to sea ice (Cox and Weeks, 1988) . When the air temperature is very low, the
130 ocean may release heat into the atmosphere (Kim et al., 2019), and then the first-year ice would be formed.

2.3 Methods

All data during 1976-2005 have been detrended before we perform the correlation analysis. The correlation coefficients are tested by the standard student's t test (Santer et al., 2008) with α= 5 (5% significance level). Correlations between latent and sensible heat flux, shortwave heat flux and winter sea ice change in BS are very low, thus these factors will not be
135 considered in the following discussion.

We also calculate the correlations among the longwave heat flux, top and bottom melting of sea ice, congelation ice growth and frazil ice growth and conversion of snow to ice to understand their potential driving roles in the change of sea ice concentration and thickness. Herein, we choose the time series of thermodynamics from September to March during the
140 period of 1976-2004.

3 Results

3.1 Mean sea ice in winter

As the first step, we utilize the simulations from NorESM1-M to analyze the changes of winter sea ice mass (kg) along with the BS sea ice thermodynamic processes (Table1). By summarizing the total increase in sea ice mass (caused by
145 thermodynamic processes in sea ice) in winter (December, January, and February), in the BS, is about 6.29×10^{15} kg, while in the model winter sea ice mass increase (estimated by sea ice concentration, thickness, and grid area) is about 8.84×10^{15} kg. So, the five thermodynamic processes in sea ice take about 71% of the total winter sea ice increase in the BS. Among the

five processes, conversion of snow to ice is the most important one, and it can account for more than 97% of the sea ice changes caused by the thermodynamics, and 69% of the whole sea ice mass increase in winter in the BS.

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Also from Table 1, top ice melting in winter is much smaller than the other sea ice processes (10^{11} compared with 10^{13} in congelation and frazil ice, and bottom ice melting, and 10^{15} in conversion of snow to ice). We will therefore focus on the impact of congelation and frazil ice, bottom ice melting and conversion of snow to ice on the sea ice variability in the BS.

155   In terms of sea ice concentration, thickness, and grid area, sea ice mass increase is about 2.68×10^{15} kg (December), 3.49×10^{15} kg (January) and 2.67×10^{15} kg (February), where most increase in sea ice mass of the BS is found in January. Therefore, we focus on the spatial distribution of the local sea ice thermodynamics in January.

160   **Table 1: From 1976 to 2004, mean sea ice mass (kg) caused by congelation ice, frazil ice, conversion of snow to ice, bottom ice melting and top ice melting in December, January, and February in the Bering Sea**

	Dec	Jan	Feb
Congelation Ice	5.39×10^{13}	5.58×10^{13}	6.45×10^{13}
Frazil Ice	6.96×10^{13}	6.37×10^{13}	6.58×10^{13}
Snow to Ice	1.41×10^{15}	2.18×10^{15}	2.55×10^{15}
Bottom Ice Melting	-6.43×10^{13}	-6.65×10^{13}	-7.98×10^{13}
Top Ice Melting	-1.34×10^{11}	-6.23×10^{11}	-8.39×10^{11}

The mean spatial pattern for the four sea ice processes is shown in Figure 4a. The growth of congelation ice presents a gradual increase from south to north, and the frazil ice has the same feature. Bottom ice melting and conversion of snow to ice share the similar distribution, increasing from southeast to northwest, with a maximum value center located at

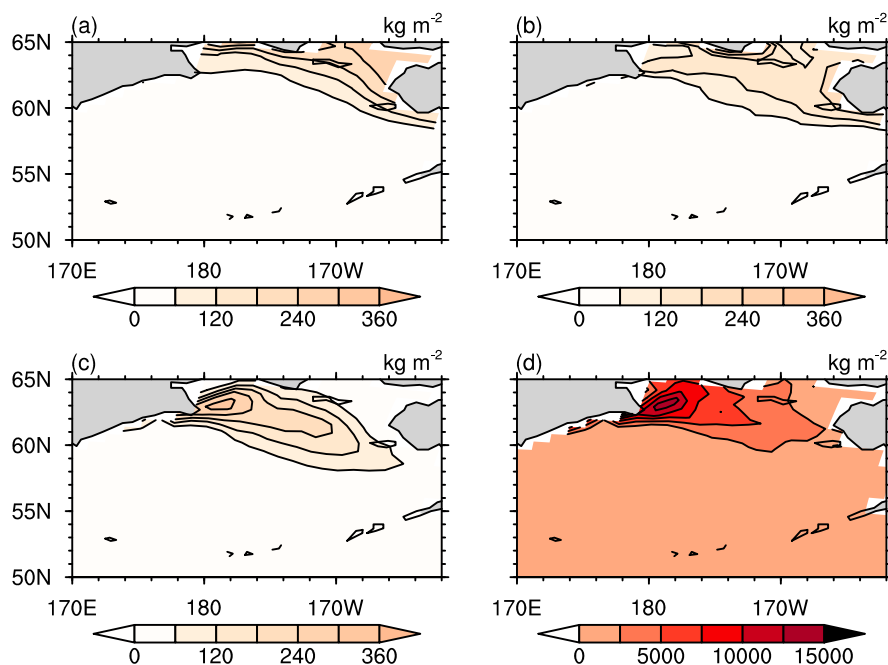
165   northwestern BS (Figure 4c and Figure 4d). We find that the area with most sea ice (bottom) melting is concentrated in the area with the largest sea ice growth (conversion of snow to ice). The magnitude of the conversion of snow to ice is much greater than that of other thermodynamic processes by means of their spatial distribution. The four spatial distributions show a common area of winter sea ice growth taking place mainly in the north of the BS, where the largest variability is found in the conversion of snow to ice in the northwest of BS.

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Figure 4: Averaged (a) congelation ice, (b) frazil ice, (c) bottom ice melting (absolute value), and (d) conversion of snow to ice during 1976–2004 (January), the actual value of bottom ice melting is negative.

3.2 The Relationship between the interannual variability of sea ice concentration and thickness and the thermodynamic Processes

175 The thermodynamic processes in sea ice may not immediately have effects on the changes of sea ice concentration and thickness. The possible situation is that the change in thermodynamic processes may be ahead of the change in sea ice, or they may lag behind sea ice variability. In the previous section, we found sea ice mass in the BS increases the most in January. Herein, we select the time series of surface air temperature, net downward longwave heat flux, and different sea ice processes for each of the months from September to March. In order to understand how these thermodynamic processes in

180 the BS affect sea ice variability in January, correlations between sea ice concentration and thickness, and time series of processes are studied to detect possible relationships. Figure 5 shows the correlation between sea ice concentration and thickness in January, and the sea ice thermodynamic processes in each of the months (September-March). The net downward longwave heat flux shows strong opposite correlation to the sea ice concentration (-0.93). In Figure 5, correlations between 30-year time series indicate that variabilities of sea ice concentration, congelation ice, frazil ice, bottom ice melting,

185 conversion of snow to ice, net downward longwave heat flux and surface air temperature in January are simultaneous. The correlation of sea ice concentration in the BS is with congelation ice (0.86), and the bottom ice melting (-0.75) and frazil ice (0.64), respectively (Figure 5a). However, variability of conversion of snow to ice has the smallest correlation with sea ice concentration in January (0.42), which suggests that it isn't vital to the variability of sea ice concentration in winter.

190 Characteristics of correlations between the BS sea ice thickness (in January), and thermodynamic processes (from September to March) are similar with that between sea ice concentration and thermodynamics. It can be found that correlations between sea ice thickness and bottom ice melting, congelation ice and conversion of snow to ice reach the maximum at the same time (Figure 5b). As for frazil ice, it is highly related with sea ice thickness variability both in December and January, and the correlation coefficients in two months are both about 0.56.

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In the above, we have shown that thermodynamic processes in sea ice are important for the increase of sea ice concentration and thickness in the BS in January. Regarding the highest correlations between sea ice concentration and thickness, the studied freezing and melting processes show immediate impacts on changes of sea ice concentration and thickness in the BS in January. The spatial distributions of correlations in January are presented in the following (Figure 6 and 7).

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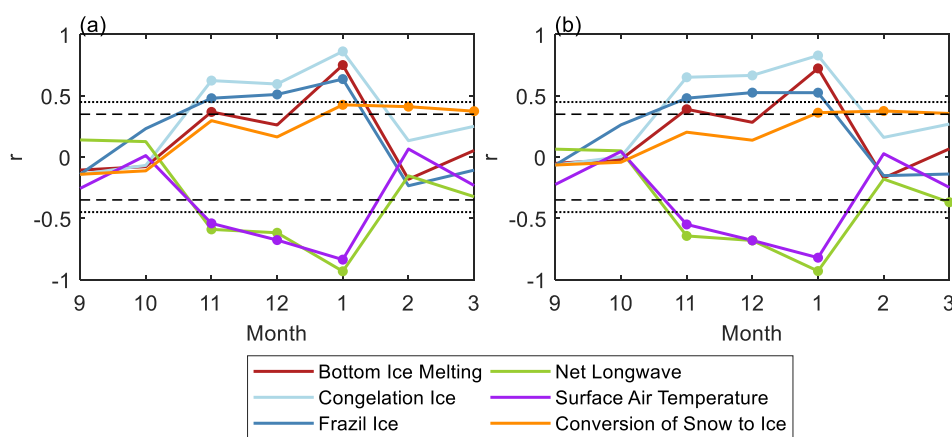


Figure 5: Correlations between sea ice concentration (a) and thickness (b) in January and bottom melting (red lines), congelation ice (sky blue lines), frazil ice (navy blue lines), net longwave heat flux (green lines), surface air temperature (purple lines), and the conversion of snow to ice (orange lines) from September to March from 1976 to 2004. Dots represent the correlations passing the
205 **95% significance test, the long-dotted lines represent 95% significance, and the shortly dotted lines represents 99% significance.**

3.2.1 Spatial distributions of the relationship between sea ice concentration and thickness and the thermodynamic processes

Figure 6 is the correlations map between sea ice concentration and congelation ice, frazil ice, bottom ice melting, conversion of snow to ice and surface air temperature in January. The pattern of surface air temperature against sea ice concentration

210 (Figure 6e) has negative correlation in the BS, with more pronounced area in the north-eastern part of the BS. This suggests that the increase in sea ice concentration decrease is accompanied decrease in surface air temperature in January. Also, opposite correlation patterns can be seen between sea ice concentration in January in the BS and congelation ice, frazil ice, bottom ice melting, conversion of snow to ice, as shown in Figure 6(a)-(d). The reason for this may be that in this region of the BS, sea ice cover is the only seasonal, and these thermodynamic processes in sea ice are correlated with the heat flux

215 balance over sea surface. Meanwhile, the correlations map between surface air temperature and congelation ice (Figure 7) shares similar pattern to Figure 5e, suggesting the modulating of surface air temperature on congelation ice, and therefore on the sea ice concentration (Figure 6a).

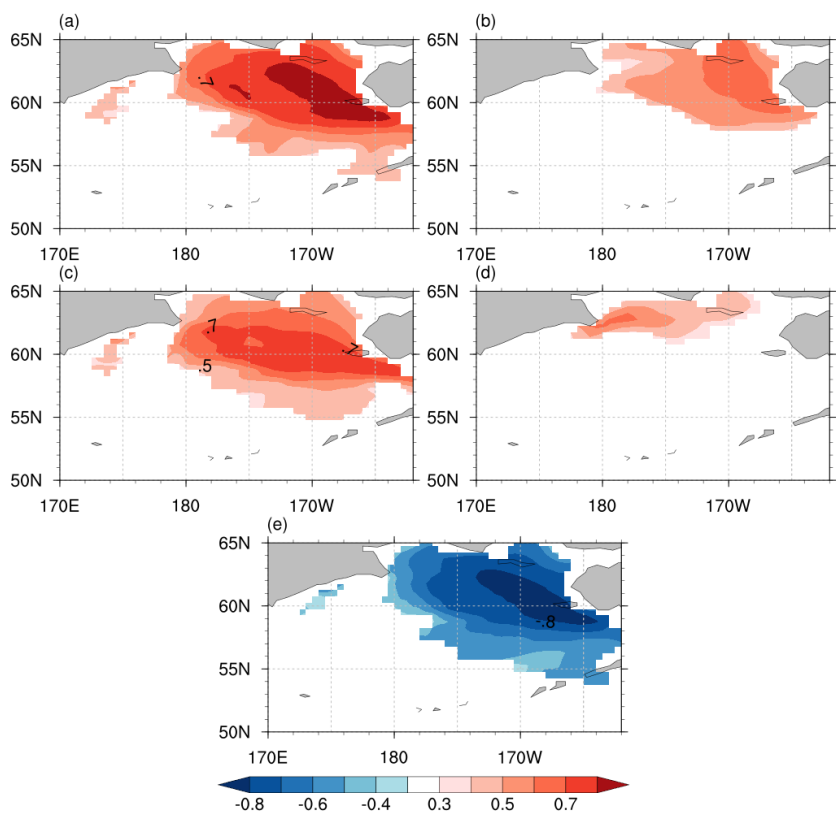



Figure 6: Significant correlations between sea ice concentration in January in the BS and congelation ice (a), frazil ice (b), bottom
220 **ice melting (c), conversion of snow to ice (d), and surface air temperature (e) from 1976 to 2004.**

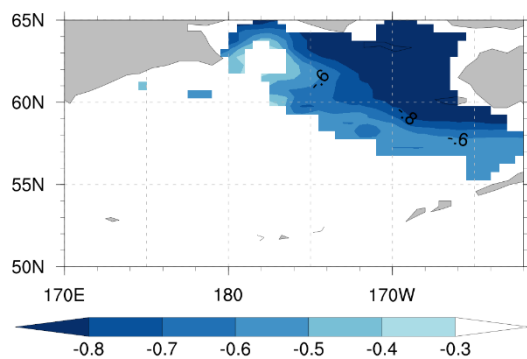



Figure 7: Significant correlations between congelation ice in January in the BS and surface air temperature from 1976 to 2004.

In the northeast of the BS, congelation ice, frazil ice, bottom ice melting and conversion of snow to ice in sea ice are

225 positively related with sea ice thickness, and surface air temperature are opposite (Figure 6 and 8). The amount of sea ice

freezing in January is much greater than the amount of ice melting (Figure 9), and bottom ice melting cannot lead the sea ice

loss in January. In the seasonally covered regions, there is no ice over the sea surface in the BS before winter, when more

frazil ice is formed in December and more sea ice is available to be melted, lower temperature and more freezing processes

lead to more sea ice finally. So, more frazil ice gives more ice to melt at the bottom and make sea ice thicker as a result, such

230 a positive correlation is therefore an indication of the coupled process between sea ice amount and these associated sea ice

freezing / melting process. The order which these processes happen is shown by the lead-lags between sea ice thickness in

January, and thermodynamic processes in Figure 5. For sea ice thickness in January, the highest correlation to frazil ice is

both in December and January (Figure 5b). Therefore, congelation ice is still the most important thermodynamic process to

the variability of sea ice thickness in the BS. As the case in sea ice concentration in January, congelation ice is found to be

235 the most important for winter sea ice thickness variability in the BS (Figure 8a) too.

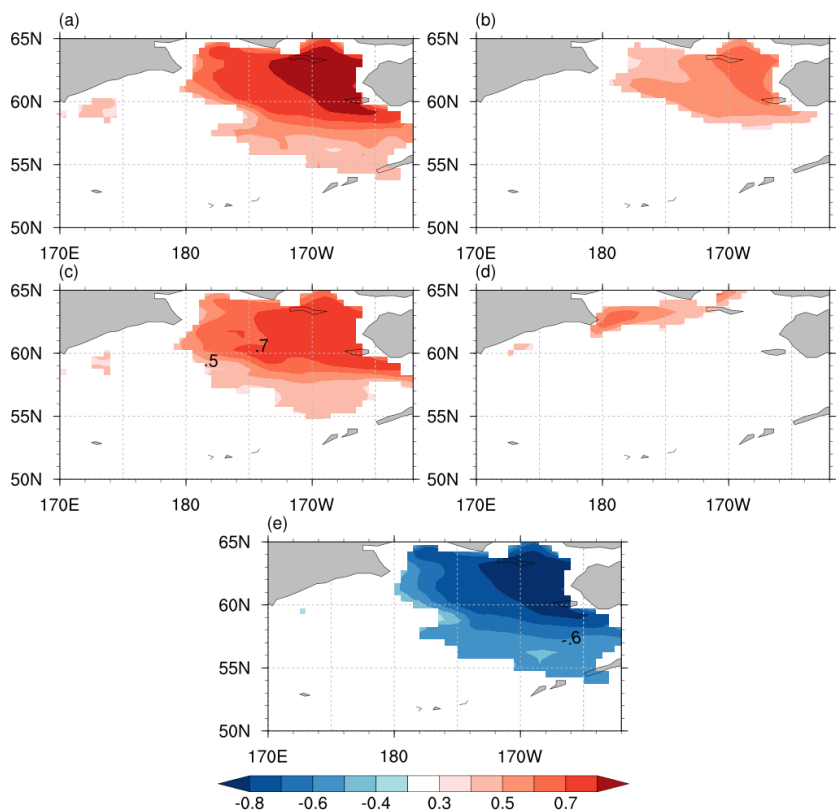
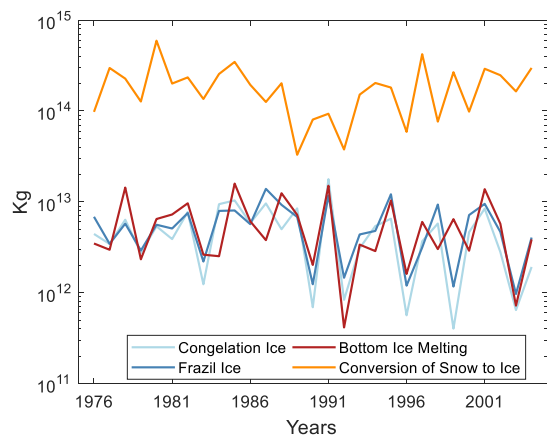



Figure 8: Significant correlations between sea ice thickness in January in the BS and congelation ice (a), frazil ice (b), bottom ice melting (c), conversion of snow to ice (d), and surface air temperature (e).

240 **Figure 9: Time series of congelation ice (sky blue lines) (kg), frazil ice (navy blue lines) (kg), bottom melting (red lines) (kg) and the conversion of snow to ice (orange lines) (kg) in January from 1976 to 2004.**

4 Discussion

In the pan-Arctic, due to lack of extensive observations of congelation ice, many studies are based on the results of the model. We only study the relationships between thermodynamic processes and winter sea ice concentration and thickness in

245 the BS. The results show that in the NorESM1-M, congelation ice is an important process to winter sea ice variability in the BS. Congelation ice growth is controlled by the difference between sea ice temperature at the bottom and sea surface temperature. However, how congelation sea ice and other thermodynamic processes affect winter sea ice change in long-term is not very clear. More quantitative analysis needs to be done in further study. Besides thermodynamic processes, dynamics like ice drift and northwesterly wind (Rodionov et al., 2005) may also affect the sea ice variability in some certain.

250 The weaken Aleutian Low strengthen the northwesterly wind and promote icing as a result. Recently winter sea ice increase in the BS is driven by both thermodynamic and dynamic processes (Frey et al., 2015).

From 1976 to 2004, conversion of snow to ice can contribute about 69% of the winter mean sea ice mass increase in the BS. It implies that snow on sea ice is a factor worth noting. Many studies also find that snow on sea ice seems important to the

255 sea ice thickness (Blazey et al., 2013; Riche and Schneebeli, 2013). In the Pacific Arctic, the postponement of sea ice formation in early winter cause delays in snow accumulation over the first-year sea ice, but the increase in storm activities contributes to a large amount of snow cover (Sato and Inoue, 2018). During early winter, some short period snowfall events directly cause the following thermodynamic processes in sea ice (Sturm et al., 2002). Sea ice thickness in the Canadian Basin is negatively correlated with snow depth (Howell et al., 2016). It turns out that the key factor of sea-ice growth is the amount

260 of snow rather than surface air temperature. Sato and Inoue (2018) confirmed this importance of snow depth by the thermodynamic sea-ice model. At the end of the ice melt season, the decrease in snow depth is often accompanied by an

increase in sea ice thickness. The reason is that the snowmelt driven by the atmosphere results in greater conductive ocean heat loss through the upper layer of ice (Bigdeli et al., 2020). Now, there is a lack of detailed observations and it is difficult to assess the ability of simulating snow cover and snowmelt in climate models. In the future, we need use more observations

265 to better understand the effect of snow on the sea ice variability in the Arctic.

5 Conclusions

In terms of the long-term mean, the simulations of winter sea ice concentration and thickness in the BS in NorESM1-M are close to reanalysis data from 1976 to 2004. We have studied winter mean changes of sea ice and thermodynamic processes in sea ice in the BS in the NorESM1-M. First, the increase of sea ice mass in the BS is mainly caused by congelation ice,

270 frazil ice, and conversion of snow to ice. Thermodynamic processes can contribute about 71% of the winter sea ice mass increase in the BS. It is worth noting that conversion of snow to ice can account for more than 97% of the sea ice increase caused by the thermal processes, and 69% of the whole sea ice mass variability in winter.

On the inter-annual time scales, in January, thermodynamic processes in sea ice are significantly correlated with the sea ice

275 concentration and thickness in the BS. Congelation ice, frazil ice, bottom ice melting and conversion of snow to ice respond immediately to changes of sea ice concentration and thickness. Congelation ice is the most vital to the variability of sea ice concentration (0.86) and thickness (0.83) in the northeast of the BS. Congelation ice is highly correlated with surface air temperature. This is because frazil ice is formed earlier than congelation ice and form a thin layer of ice over the seawater. Then, the sheet of ice can hinder the heat exchange between the atmosphere and the ocean. As a result, the ice growth is

280 conducted by the temperature difference between the bottom ice and the cold air. Therefore, congelation ice is closely related to the change of surface air temperature. Lastly, this study finds that thermodynamic processes in sea ice have a dominant impact on winter sea ice variability in the BS. It gives a better understanding of sea ice changes in an Earth System Model.

Data variability

All data can be gotten on the website (https://esgf-node.llnl.gov/login/?next=/ac/subscribe/CMIP5%2520Research/).

285 **Author contributions**

HLZ conducted the research and wrote the manuscript. YQG, HLR, LY, and DG supervised the work together. All authors reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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