Mapping of Active Frazil for Antarctic Coastal Polynyas, With an Estimation of Sea-Ice Production

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Abstract The importance of the area of active frazil and associated high sea-ice production in Antarctic coastal polynyas has been increasingly recognized in recent in situ and high-resolution satellite observations. However, the occurrence and spatial distribution of active-frazil area are not well understood. We present the first mapping of active-frazil area for Antarctic coastal polynyas, based on the thin ice algorithm of AMSR-E that discriminates active-frazil area. Mapping of sea-ice production is presented by taking account of active-frazil area. Active-frazil area is predominant along East Antarctica, particularly very close to the coast, locally leading to very high ice-production rates exceeding 20 m/yr. For frazil-dominant polynyas, estimated ice production is ∼20%–50% higher compared with previous studies. Analyses of all the major polynyas suggest that active-frazil extent depends on offshore wind and air temperature, while ice production is determined by offshore wind only.

Plain Language Summary Antarctic coastal polynyas, thin ice or open water areas, are regarded as sea-ice production factories. Cold and saline water rejection by high ice production generates dense water, some of which is transformed into the Antarctic Bottom Water, a key player in global thermohaline circulation. A polynya area is roughly classified into two ice types: thin solid ice area, which is a nearly uniform thin ice-covered area, and active-frazil area, which is a mixture of frazil/grease ice and open water formed by turbulent conditions. Although the active-frazil area has very high ice production, its high ice production has not been considered in previous ice-production estimates. In this study, we map active-frazil area and estimate ice production incorporating active frazil for Antarctic coastal polynyas for the first time, using an improved algorithm of satellite passive microwaves. Active-frazil area and associated ice production are found to be determined mostly by offshore wind, which explains the predominance of active frazil and high ice production in the east Antarctic coastal polynyas with strong offshore wind.

1. Introduction

Coastal polynyas are thin ice or open water areas formed by sea-ice divergence due to prevailing offshore winds and/or ocean currents (Morales Maqueda et al., 2004), which are ubiquitous around Antarctica during winter (Kern, 2009). Antarctic coastal polynyas are regions of intensive heat loss to the atmosphere and are often regarded as ice production factories. A large amount of brine rejection caused by the ice production generates dense shelf water (DSW), some of which can be a precursor of Antarctic Bottom Water (AABW). Therefore, ice production in coastal polynyas is a key factor in global thermohaline circulation and the resultant material cycles (e.g., Hoppema & Anderson, 2007).

Due to the importance of coastal polynyas, many studies have sought to develop algorithms to identify areas of thin ice with a thickness of <10–20 cm from satellite microwave radiometers, and estimated ice production based on a heat flux calculation using the derived ice thickness (e.g., Comiso et al., 2011; Iwamoto et al., 2014; Martin et al., 2004; Tamura et al., 2008). In these algorithms, ice thickness is estimated from the polarization ratio (PR) of the brightness temperatures (TBs) based on an empirical equation between PR and thin ice thickness. However, the PR-ice thickness relationship differs depending on the study area, and it has a relatively large statistical dispersion even within the same study area. Thus, ice production estimated from the derived thin ice thickness also has large uncertainty. Further, it has been shown that ice production estimated from previous algorithms does not correlate well with surface wind, with a correlation
coefficient of 0.01–0.47 for 13 major Antarctic coastal polynyas (Nihashi & Ohshima, 2015; referred to as NO2015 hereafter). Since the ice production in coastal polynyas is mainly governed by surface winds (e.g., Pease, 1987), the low correlation coefficient suggests the possibility that the previous algorithms do not represent thin ice thickness and sea-ice production well.

Thin ice (polynya) areas can be roughly classified into two ice types: active frazil, which is a frazil/grease ice area formed in turbulent conditions, and thin solid ice, which is a nearly uniform thin ice–covered area formed in calm conditions. Recently, Nakata et al. (2019) developed a classification method of the ice types from microwave data (see Text S1 for the details). Moreover, they examined the PR-thickness relationship for active frazil and thin solid ice separately, and found them to be very close to those of Martin et al. (2004) and NO2015, respectively. Based on these results, Nakata et al. (2019) combine the classification of active frazil and thin solid ice types and an estimation of ice thickness for each type.

Recently, based on in situ observations, Thompson et al. (2020) have revealed the dominance of frazil ice in supercooled water in the Terra Nova Bay polynya (TNBP) under prevailing katabatic wind conditions. They further showed that heat loss, and thus sea-ice production, are significantly higher than those from satellite passive microwave data. Several studies using synthetic aperture radar images have also shown that the active-frazil area is predominant in the Antarctic coastal polynyas under strong wind conditions (Ciappa & Pietranera, 2013; Nakata et al., 2015, 2019). In addition, Haumann et al. (2020) have shown observational evidence that, during the ice-formation season in the Southern Ocean, surface-induced supercooling widely occurs, which would be accompanied by frazil-ice formation.

As in other previous algorithms, Nakata et al. (2019) used the thermal ice thickness, which is suitable for calculating heat flux and sea-ice production (Kashiwase et al., 2019). The thermal ice thickness is defined as the thickness for which the calculated total heat flux would be realized if the ice thickness were uniform in the satellite footprint. Nakata et al. (2019) indicated that the thermal ice thickness in an active-frazil area is much thinner than that of thin solid ice (Figure S1b), implying that active frazil has much higher sea-ice production rate because conductive heat flux of sea ice is inversely proportional to the thermal ice thickness in a simple thermal conductivity equation. For accurate estimates of polynya ice production, detection of the active-frazil area and an appropriate estimate of ice production there are indispensable. However, because the ice thickness in an active-frazil area cannot be represented in the previous algorithms, sea-ice production has likely been underestimated, particularly for regions where active frazil is predominant.

One purpose of this study is to reveal where and to what degree active frazil occurs in Antarctic coastal polynyas by using the algorithm developed by Nakata et al. (2019). In this study, we focus only on coastal polynyas where the algorithm has been validated. We then provide the mapping of sea-ice production, taking account of high ice production in active-frazil areas. Many polynya models have treated the polynya extent under the assumption that the frazil ice produced in a coastal polynya moves offshore faster than pack ice and accumulates at the polynya edge (e.g., Biggs et al., 2000; Lebedev, 1968; Ou, 1988; Pease, 1987; Willmott et al., 1997). More precisely, these models have considered the area of the polynya as an active-frazil area. In this paper, we use this concept of a polynya to examine the relationships of the extent of the active-frazil area and sea-ice production with atmospheric factors.

### 2. Data and Method

We have created daily data for ice type, thin ice thickness, and sea-ice production in the Southern Ocean during winter (March–October) for the period 2003–2010, using the AMSR-E thin ice algorithm developed by Nakata et al. (2019). We assume that sea-ice production occurs only in the grid cells assigned as areas of thin ice by the algorithm. Because the daily averaging process of TBs sometimes causes misclassifications of ice types in coastal polynyas, we used the AMSR-E/Aqua Level 2A (L2A) global swath spatially resampled TBs at 89 and 36.5 GHz with a spatial resolution of about 14 × 8 km without averaging, instead of daily mean TBs. First, we interpolated all AMSR-E L2A TB data onto the National Snow and Ice Data Center polar stereographic grid with a spatial resolution of 6.25 km, using a Gaussian weighting function. Then, we classified the sea-ice region into thick ice, thin solid ice, and active frazil by a linear discriminant method using the TBs at 36 and 89 GHz (see Text S1 for further details). Next, ice thickness for active frazil (h_a) and thin solid ice (h_s) are estimated from PR defined as \((T_{B_a}−T_{B_s})/(T_{B_t} + T_{B_b})\), where \(T_{B_t}\) and \(T_{B_b}\) are the

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vertically and horizontally polarized TBs at 36.5 GHz, using Equations 1 and 2, respectively (see Figure S1b for their graphs):

\[
h_a = \exp\left(\frac{1}{596 PR - 11.8}\right) - 1.008, \quad PR > 0.05
\]

\[
h_s = \exp\left(\frac{1}{72 PR}\right) - 1.06, \quad PR > 0.06
\]

Regions of land and landfast sea-ice were masked out using the land and landfast ice mask data with a resolution of about 6.25 km, obtained from the fast ice detection algorithm by NO2015. We also masked out regions with ice concentration of <30% as open water areas, using the enhanced NASA Team (NT2) algorithm with a spatial resolution of 12.5 km (Markus & Cavalieri, 2000).

Daily averaged sea-ice production rate \( V_t \) in a given grid cell is calculated as follows:

\[
V_t = R_a \times V_a + R_s \times V_s.
\]

where \( R_a \) and \( R_s \) are daily occurrence rates for active frazil and thin solid ice, respectively; \( V_a \) (m s\(^{-1}\)) and \( V_s \) (m s\(^{-1}\)) are ice production rates for active-frazil and thin solid ice areas, respectively.

The AMSR-E scanning sensor observes a given grid cell by about 3–4 and 7–8 times per day along the East Antarctic coast and Ross Ice Shelf, respectively. We calculated \( R_a \) and \( R_s \) in each grid cell from the classification result of ice type during each day. Since the number of observations per day from ascending orbits does not necessarily equal that from descending orbits, instead of simple averaging, weighted averaging with the same weight for ascending and descending orbits, is used for the calculation of the \( R_a \) and \( R_s \).

The \( V_a \) and \( V_s \) are obtained by an assumption that all heat loss to the atmosphere goes toward freezing, as given by the following:

\[
V_{a,s} = \frac{Q_{a,s}}{\rho_i L_f},
\]

where \( Q_a \) (W m\(^{-2}\)) and \( Q_s \) (W m\(^{-2}\)) are heat fluxes required for sea-ice production for the active-frazil and thin solid ice area, respectively; \( \rho_i \) (=920 kg m\(^{-3}\)) is the density of sea ice; and \( L_f \) (=0.334 MJ kg\(^{-1}\)) is the latent heat of fusion for sea ice (Martin, 1981). In order to obtain the daily averaged heat fluxes \( Q_a \) and \( Q_s \), we first calculated heat flux for each AMSR-E L2A scene using the derived ice thickness data and near-surface atmospheric data. We then calculated the \( Q_a \) and \( Q_s \) by the weighted averaging with the same weight for ascending and descending orbits. The heat flux is obtained based on the assumption that the sum of radiative and turbulent fluxes at the ice surface is balanced by the conductive heat flux through the ice (see Text S2 for further details). As the near-surface atmospheric input data, we used daily averaged air temperature at 2 m, dewpoint temperature at 2 m, wind at 10 m, total cloud cover, and surface sea level pressure from a 1-h ECMWF ERA5 reanalysis data with a spatial resolution of 0.25° × 0.25°.

### 3. Results

First, we show the climatology of occurrence rate of active-frazil area \( R_a \) (Figure 1). This analysis is the first circumpolar mapping of active frazil for Antarctic coastal polynyas. For reference, the occurrence rate of total thin ice (active frazil plus thin solid ice) area is shown in Figure S2. Regions with a high rate of active frazil appear in the major coastal polynyas, particularly along the east Antarctic coast and the Amundsen Sea coast. Enlarged views of the 13 major polynyas (lower panel) demonstrate that an active-frazil region frequently occurs in the region very close to the coast for the east Antarctic coastal polynyas, Amundsen polynya (AP), and TNBP, where the occurrence rate is around 0.4–0.7 with a large gradient in regions <25 km from the coast.
For the Ross Ice Shelf polynya (RISP), the active-frazil region has an occurrence rate of only <0.35 and rarely expands offshore. The RISP has a high occurrence rate of total thin ice, comparable to that of east Antarctic polynyas (Figure S2), which means that thin solid ice is more predominant than active frazil in the RISP, compared with other polynyas.

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Since the sea-ice production rate in the active-frazil region is calculated to be typically about twice as high as that in the thin solid ice region, the occurrence rate of active frazil considerably affects the sea-ice production rate. Therefore, the Cape Darnley polynya (CDP), Mackenzie Bay polynya, Vincennes Bay polynya (VBP), Mertz polynya (MP), and TNBP, with a high rate of active frazil, have relatively high sea-ice production rate, typically over 20 m/yr close to the coast (Figures 1 and 2). The high sea-ice production rate in these polynyas is consistent with these polynyas providing the source water of AABW (e.g., Kitade et al., 2014; Narayanan et al., 2019; Ohshima et al., 2013; Williams et al., 2008).
Table 1 lists the area and sea-ice production of active frazil, thin solid ice, and total thin ice for the major 15 polynyas. Sea-ice production in the active-frazil region is larger than that in the thin solid ice region in many polynyas, despite the active-frazil region being much smaller than the thin solid ice region. As such, the higher sea-ice production rate in the active-frazil region, with its small thermal ice thickness, makes a large contribution to the sea-ice production in all categories of thin ice.

The total thin ice area in our study differs only slightly from that of NO2015, since the threshold value of PR discriminating between thin ice and thick ice is almost the same. On the other hand, the sea-ice production is considerably higher than that of NO2015 (see Figure S3 for a map of the difference in sea-ice production rate between the two). The estimates from ECMWF Interim Re-Analysis (ERA-Interim) data, compared to the here used ERA5 data, give almost the same results (Table S1). For all thin ice pixels, NO2015 uses a single equation for PR-thickness, close to that for thin solid ice in Nakata et al. (2019). Therefore, NO2015 regards an active-frazil area with very small ice thickness as thin solid ice with larger thickness, causing the sea-ice production by NO2015 to be significantly underestimated. For example, in the CDP, where the
### Table 1

**The Area and Sea-Ice Production of Active Frazil, Thin Solid Ice, and their Sum, With the Correlation Coefficient With Surface Wind, for 15 Major Coastal Polynyas**

| Polynya name | Active frazil | Thin solid ice | Total thin ice | NO2015 |
|--------------|---------------|----------------|----------------|--------|
|              | $S_a \ (10^3 \text{ km}^2)$ | $S_s \ (10^3 \text{ km}^2)$ | $S_t \ (10^3 \text{ km}^2)$ | $\text{Ratio}$ | $S_a \ (10^3 \text{ km}^2)$ |
| CDP          | 4.2 ± 4.3     | 7.3 ± 5.0      | 11.6 ± 4.6     | 0.25   | 11.5 ± 4.6 |
| MBP          | 1.9 ± 1.4     | 2.8 ± 2.4      | 4.7 ± 2.6      | 0.19   | 4.6 ± 2.7  |
| BaP          | 2.4 ± 2.4     | 3.9 ± 3.2      | 6.3 ± 3.1      | 0.27   | 5.4 ± 3.2  |
| SP           | 3.7 ± 3.3     | 5.5 ± 4.6      | 9.2 ± 4.4      | 0.20   | 9.2 ± 4.5  |
| VBP          | 2.9 ± 2.4     | 4.0 ± 2.6      | 6.9 ± 2.5      | 0.28   | 6.8 ± 2.5  |
| CPP          | 2.5 ± 2.4     | 2.3 ± 1.9      | 4.8 ± 2.2      | 0.23   | 4.7 ± 2.2  |
| DaP          | 2.0 ± 2.0     | 2.4 ± 2.2      | 4.3 ± 2.3      | 0.23   | 4.3 ± 2.4  |
| DiP          | 2.8 ± 3.0     | 4.2 ± 3.4      | 7.0 ± 3.3      | 0.12   | 7.1 ± 3.2  |
| MP           | 4.1 ± 4.1     | 8.8 ± 5.4      | 12.9 ± 4.8     | 0.01   | 12.6 ± 5.1 |
| TNBP         | 0.9 ± 1.0     | 3.3 ± 2.1      | 4.3 ± 2.3      | 0.09   | 4.2 ± 2.4  |
| RISP         | 3.3 ± 4.0     | 14.1 ± 8.8     | 17.4 ± 9.5     | 0.03   | 17.0 ± 9.7 |
| AP           | 4.6 ± 3.6     | 5.2 ± 4.2      | 9.8 ± 4.4      | 0.21   | 9.8 ± 4.7  |
| BeP          | 2.6 ± 2.6     | 4.0 ± 3.1      | 6.6 ± 3.7      | 0.45   | 6.0 ± 3.4  |
| RONP         | 0.9 ± 1.0     | 18.2 ± 1.8     | 27.2 ± 2.6     | 0.36   | 24.2 ± 2.7 |
| ELSP         | 1.4 ± 1.7     | 2.5 ± 2.1      | 3.9 ± 2.2      | 0.14   | 3.9 ± 2.2  |
| Total        | 40 ± 18       | 72 ± 19        | 112 ± 26       | 0.36   | 110 ± 25   |

| Polynya name | Ice production | Area | Ice production | Area |
|--------------|----------------|------|----------------|------|
|              | $V_a \ (10^3 \text{ m}^3)$ | $V_s \ (10^3 \text{ m}^3)$ | $V_t \ (10^3 \text{ m}^3)$ | $V_a \ (10^3 \text{ m}^3)$ |
| CDP          | 10.7 ± 1.2     | 3.9 ± 0.6 | 4.7 ± 0.5 | 16.4 ± 2.2 |
| MBP          | 5.8 ± 1.1      | 3.4 ± 0.4 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| BaP          | 3.6 ± 0.9      | 3.4 ± 0.4 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| SP           | 5.5 ± 0.7      | 3.1 ± 0.3 | 4.7 ± 0.5 | 3.4 ± 0.4  |
| VBP          | 4.5 ± 0.6      | 3.7 ± 0.2 | 4.7 ± 0.5 | 3.4 ± 0.4  |
| CPP          | 3.3 ± 0.5      | 1.7 ± 0.2 | 4.7 ± 0.5 | 3.4 ± 0.4  |
| DaP          | 2.4 ± 0.4      | 1.8 ± 0.2 | 4.7 ± 0.5 | 3.4 ± 0.4  |
| DiP          | 4.6 ± 0.9      | 3.9 ± 0.5 | 4.7 ± 0.5 | 3.4 ± 0.4  |
| MP           | 7.6 ± 0.7      | 9.0 ± 1.6 | 4.7 ± 0.5 | 16.4 ± 2.2 |
| TNBP         | 2.7 ± 0.8      | 3.9 ± 0.5 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| RISP         | 10.8 ± 2.7     | 21.4 ± 1.8 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| AP           | 7.0 ± 0.8      | 4.7 ± 0.9 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| BeP          | 4.7 ± 1.4      | 3.5 ± 0.7 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| RONP         | 3.0 ± 1.0      | 2.8 ± 1.2 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| ELSP         | 2.5 ± 0.6      | 2.4 ± 0.5 | 4.7 ± 0.5 | 9.8 ± 0.7  |
| Total        | 79 ± 4         | 78 ± 4     | 157 ± 6       | 50.0 ± 25  |

**Note.** $S_a$ in Area (upper) panel is the average area with daily standard deviation. $V_a$ in Ice-production (lower) panel is the average annual sea-ice production with yearly standard deviation. Corr. is the correlation coefficient with the wind component that best correlates with (upper panel) active-frazil area and (lower panel) ice production of active frazil. The critical value of correlation coefficients at the 99% significance level is about ±0.06. Ratios in Area and Ice-production panels show the ratios of active frazil to total thin ice. NO2015 indicates the statistics of thin ice area and ice production derived from the algorithm of NO2015. For the calculations, the daily data during March–October (April–October for the correlation calculation) from 2003 to 2010 were used. Analysis areas are designated by yellow lines in Figure S4. In addition to the 13 polynyas treated in NO2015, statistics of another two polynyas (indicated by CPP and ELSP) are shown. BeP, Bellingshausen polynya; CDP, Cape Darnley polynya; MP, Mertz polynya; RISP, Ross Ice Shelf polynya; RONP, Ronne Ice Shelf polynya; TNBP, Terra Nova Bay polynya; VBP, Vincennes Bay polynya.
active frazil is predominant, sea-ice production increases by ~36% (Table 1). This higher value of the CDP is consistent with the sea-ice production used as the salt flux condition in the simulation of DSW formation off Cape Darnley by Nakayama et al. (2014), which reproduces realistic DSW and AABW formation observed by Ohshima et al. (2013).

Next, we examine the relationship between the active-frazil area and surface wind. The active-frazil area has a high positive correlation with surface wind in all the major coastal polynyas (Table 1). By contrast, the thin solid ice area has a negative correlation with surface wind in many polynyas such as the CDP, VBP, and MP. The total thin ice area is positively correlated with surface wind, but its correlation coefficient is <0.3 for all the polynyas except the Bellingshausen polynya and Ronne Ice Shelf polynya. The low correlation of total thin ice area is a result of compensation of the positive correlation of active frazil by the negative correlation of thin solid ice with the surface wind. This low positive correlation is consistent with previous studies (e.g., NO2015). The coefficient of variation, defined as [standard deviation]/[mean value], for total thin ice area is calculated to be about 0.5, averaged for all the major polynyas. The coefficients of variation for active frazil and thin solid ice areas are calculated to be about 1.0 and 0.7, respectively. These values are larger than that of total thin ice area. This result implies that, while total thin ice area is stably maintained, a transition between ice types frequently occurs in that thin ice area, depending upon surface wind speed. Specifically, active frazil induced by strong winds is transformed into thin solid ice under the weak wind conditions. When the polynya ice production is defined as the production in the active-frazil area, ice production for all the polynyas has a much higher correlation with surface wind than in NO2015 (Table 1).

4. Factors Controlling Variability of Active Frazil

In many coastal polynya models originating from Pease (1987), the active-frazil area is regarded as the polynya area, as follows: An active-frazil area is formed by offshore sea-ice drift. Frazil ice produced in the active-frazil area is moved faster than offshore pack ice, and it thus accumulates at the edge of the active-frazil area and is finally transformed into consolidated ice. Therefore, the width of the active-frazil area is determined by a balance between offshore sea-ice drift and frazil ice production. Sea-ice drift and ice production mainly depend on offshore wind and air temperature. Based on this concept, we comprehensively examine how active-frazil extent and sea-ice production are related to such atmospheric factors for all the 15 major polynyas.

For this analysis, we define one-dimensional quantities, active-frazil extent $A/L$ (km) and one-dimensional (1-D) ice production $V/L$ (m km day$^{-1}$), where $A$ is the daily active-frazil area (km$^2$), $V$ is the daily ice production (m km$^2$ day$^{-1}$), and $L$ is the coastline length (km), for each polynya. For determination of $L$, we derived the boundary lines between ocean and land/landfast sea-ice in each polynya domain, using land and landfast sea-ice grid mask developed by NO2015 with a grid resolution of 6.25 km. The boundaries of grid cells were smoothed to minimize the coastline's distance and the sum of the smoothed coastline segments ($l$) was regarded as $L$. We also define daily effective offshore wind ($W$) as $\Sigma(w_i l_i)/L$, where $w_i$ is an offshore wind component relative to the coastline segment ($l_i$), represented by

$$w_i = \begin{cases} u_i \cdot n_i, & u_i \cdot n_i > 0 \\ 0, & \text{otherwise} \end{cases}$$

where $u_i$ and $n_i$ are the wind velocity and unit vector normal to the coastline segment, respectively. We also used daily air temperature ($T$) in each polynya, obtained from the 1-h ERA5 reanalysis data.

We first discuss the relationships between active frazil and atmospheric factors, using daily data for all the major polynyas during 8 years. Figures 3a and 3b show scatterplots of offshore wind versus air temperature with active-frazil extent and 1-D ice production shown by the color scale, respectively. The active-frazil extent is significantly correlated with both the offshore wind and air temperature, with partial correlation coefficients of 0.59 and 0.55, respectively, in the multiple regression analysis. By contrast, 1-D ice production is strongly correlated with offshore wind but not with air temperature, with partial correlation coefficients of 0.72 and 0.16, respectively, in the multiple regression analysis. Although the ice production should depend on offshore wind and air temperature through calculation of the turbulent heat flux, the correlation is high with the wind while very low with the air temperature.
When air temperature increases, the ice production rate decreases, which causes a decrease in the volume of frazil ice that accumulates at the polynya edge. Thus, the polynya extent increases with increasing air temperature. However, 1-D ice production is not changed by air temperature because of the decrease in sea-ice production rate. Under the condition of lower temperature (typically <-10°C) and higher wind speed (typically >5 m/s), which is prone to approach a steady state, 1-D ice production is controlled solely by the wind (see the isoline contours in Figure 3b), while active frazil extent is determined both by the air temperature and wind (Figure 3a). These dependencies of active-frazil extent and 1-D ice production on air temperature and offshore wind are consistent with the previous polynya models (e.g., Biggs et al., 2000).

Finally, we represent the characteristics of the 15 major polynyas from the viewpoint of active frazil. Based on the averaged data for 8 years, both the active-frazil extent and 1-D sea-ice production are found to strongly depend on the offshore wind speed (Figures 3c and 3d). The large active-frazil extent and high 1-D sea-ice production in the east Antarctic polynyas can be explained by the stronger offshore wind.

Figure 3. Scatterplot of daily offshore wind versus air temperature with (a) active-frazil extent and (b) 1-D ice production of active frazil, shown by color scale, based on daily data from the 15 major polynyas. The mean offshore wind versus (c) mean of active-frazil extent and (d) mean annual sea-ice production for the 15 major polynyas. We used the data for air temperatures of <-5°C, during freezing period (April–October) for the period 2003–2010. The contours in (a) and (b) show the average values of active frazil extent and 1-D ice production, with the contour intervals of 5 km and 0.7 m km day\(^{-1}\), respectively.
5. Discussion and Conclusion

In this study, we presented the first mapping of active-frazil area and associated sea-ice production for Antarctic coastal polynyas, using the AMSR-E and ERA5 reanalysis data. The mapping shows that active-frazil area is predominant along East Antarctica and its occurrence rate reaches 0.4–0.7 in the areas very close to the coast. For frazil-dominant polynyas, estimated ice production is increased by \( \sim 20\%–50\% \), compared with estimates in previous studies that cannot represent active frazil.

It is difficult to perform an exact error analysis for sea-ice production because of the lack of in situ observation data. Instead, we checked the sensitivity to various settings used in our study (Table S1). One possible caveat of our study is the omission of summer-time sea-ice production (November to February), which is excluded due to relatively large uncertainties. However, the total sea-ice production in all the major polynyas during this period is estimated to be only about 4% of the sea-ice production from March to October. The total sea-ice production with the sea-ice concentration threshold of 1%, instead of 30%, is increased only by 4%. The use of different reanalysis data would give a measure of errors caused by the atmospheric input data. When the ERA-Interim data are used as atmospheric data instead of ERA5 data used in the main setting, the normalized root mean square error of the difference in annual sea-ice production for 15 samples of all the major polynyas (Table S1) is calculated to be \( \sim 9\% \). Although another reanalysis data might yield larger differences, since ERA-Interim data is not fully independent of ERA5 data, all these sensitivity analyses support the robustness of our calculated results to some extent.

We examined the variabilities of active-frazil area and the associated ice production for all the major polynyas. Active-frazil extent strongly depends on both offshore wind and air temperature. While sea-ice production is determined by offshore wind only. This is consistent with many polynya models (e.g., Pease, 1987) in which an active-frazil area is considered as the polynya area. The high predominance of active-frazil area in the East Antarctic coastal polynyas could be explained by strong offshore winds.

Our ice production data set can be used to investigate DSW that is formed by polynya ice production and could be a precursor of AABW. Active frazil seems to be a common feature for all coastal polynyas in the world. Thus, more reliable estimates of sea-ice production should be made for coastal polynyas in other ice-covered oceans by accounting for active frazil.

Recently, it has been shown that frazil ice occurs as green frazil ice in late summer in major Antarctic polynyas (DeJong et al., 2018). These frazil ice-associated algal blooms may be a major phenomenon around Antarctica that is overlooked in regional carbon and ecosystem models (Lieser et al., 2015). Further, recent observations suggest that frazil ice could incorporate resuspended sediment through suspension freezing in a coastal polynya (Ito et al., 2019). This process constitutes an important aspect of marine sediment transport and biogeochemical cycling. As such, frazil ice can also be a key player in the material cycle and biological productivity. The circumpolar mapping of active-frazil ice presented in this study provides basic information for such investigations.

Data Availability Statement

The AMSR-E brightness temperature and ice concentration data were obtained from website of the National Snow and Ice Data Center (NSIDC), University of Colorado (https://nsidc.org/data/ae_l2a/versions/4; https://nsidc.org/data/ae_si12/versions/3). The ECMWF ERA5 data were downloaded from the Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels). The ERA-Interim data were obtained from the ECMWF Research Data Server (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). The data set of land/landfast ice mask, created by Nihashi and Ohshima (2015), ice type and sea ice production, created in this study, can be obtained from the website (http://www.lowtem.hokudai.ac.jp/wwwod/polar-seaflux/).
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