Sea ice production variability in Antarctic coastal polynyas

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Abstract Enhanced sea ice production (SIP) in Antarctic coastal polynyas forms dense shelf water (DSW), leading to Antarctic Bottom Water (AABW) formation that ultimately drives the lower limb of the meridional overturning circulation. Some studies suggest that the variability of SIP in Antarctic coastal polynyas is driven by the influence of atmospheric forcing, i.e., surface winds and air temperature. Our previous mapping of SIP in 13 major Antarctic coastal polynyas from 1992 to 2007, using a heat flux calculation with ice thickness data derived from satellite data, is extended here to examine the interannual and seasonal variability of SIP from 1992 to 2013. The interannual variability of total ice production correlates more strongly with polynya extent than with atmospheric forcing, with the exception of the Shackleton Polynya, which correlates well with wind. There is no coherent signal in the interannual variability between the major Antarctic polynyas. We find that stochastic changes to the coastal “icescape,” i.e., ice shelves, floating glaciers, fast ice, together with offshore first-year ice, are also important factors driving SIP variability on multiyear time scales. Both the Ross Ice Shelf Polynya and Mertz Glacier Polynya experienced a significant reduction in SIP due to calving events and the repositioning of icebergs and fast ice. Our results also show opposing trends between polynya-based SIP and sea ice extent in key regions of Antarctic sea ice change. Close monitoring of coastal icescape dynamics and change is essential to better understand the long-term impact of coastal polynya variability and its influence on regional AABW production.

1. Introduction

The sinking of cold, dense Antarctic Bottom Water (AABW) drives the lower limb of the global thermohaline circulation, leading to heat and material exchange between the atmosphere and deep ocean basins [Jacobs, 2004]. Enhanced sea ice production (SIP) in Antarctic coastal polynyas, and the subsequent rejection of brine into the underlying shelf waters, is responsible for the formation of dense shelf water (DSW), the precursor to AABW production [Rintoul, 1998, 2007; Williams et al., 2008, 2010; Ohshima et al., 2013]. Antarctic coastal polynyas form in regions of divergent ice motion due to prevailing winds, oceanic currents, and/or dynamical barriers blocking the passage of pack ice, thus promoting the formation of new sea ice from the heat lost from the ocean to the atmosphere [Morales Maqueda et al., 2004; Barber and Massom, 2007]. While the sea ice remains thin (<0.2 m) and is removed from the area by winds, polynya activity is sustained in these “ice factories” because the heat loss through thin sea ice (defined as < ~0.2–0.3 m) remains relatively high [Maykut, 1978]. Studying the variability of ice production in Antarctic coastal polynyas is critical to understanding past, present, and future variability in DSW formation, a precursor of AABW production.

There is growing evidence for significant decadal trends in AABW formation around Antarctica, and SIP associated with coastal polynya variability is a key mechanism to investigate. The freshening of dense water and corresponding bottom water has been reported recently in the Ross Sea and the Australian Antarctic Basin [Jacobs et al., 2002; Whitworth, 2002; Bergamasco et al., 2004; Aoki et al., 2005, 2013; Rintoul, 2007]. Further, active DSW formation at the front of ice shelves can suppress the inflow of relatively warm Circumpolar Deep Water (CDW) into the bottom of ice shelves, leading to the restraint of the basal melt of ice shelves [Timmermann and Hellmer, 2013; Kusahara and Hasumi, 2013], a key factor in global sea level change. It is the aim of the present study to examine the variability of polynya SIP in the context of these associated impacts both on and off the continental shelf.
While most observational studies have focused on regional SIP [Markus et al., 1998; Lytle et al., 2001; Renfrew et al., 2002; Williams and Bindoff, 2003; Martin et al., 2007; Williams et al., 2011; Ohshima et al., 2013], satellite detection of coastal polynyas and surface heat flux analysis has proven to be an effective way to estimate SIP in all Antarctic coastal polynyas [Tamura et al., 2007, 2008, 2011]. These studies developed a thin ice thickness algorithm using Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) brightness temperature data and estimated SIP from a heat budget analysis with the assumption that all the heat loss is used for ice formation. Higher spatial resolution estimates by Nihashi and Ohshima [2015] used the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) data, however, their study was limited to 2003–2011. This study uses the SSM/I data for the discussion of longer interannual variability of SIP from 1992 to present.

We consider four mechanisms as candidates that could impact the long-term variability of SIP in Antarctic coastal polynyas. The first is atmospheric forcing, i.e., surface air temperature and wind speed is considered to have a strong influence on polynya activity as discussed in Nihashi and Ohshima [2015]. The second is decadal-to-multidecadal icescape dynamics, i.e., the calving and breakout of ice shelves, glaciers, and grounding of large icebergs around coastal polynyas, as discussed in Tamura et al. [2008, 2012] and Shadwick et al. [2013]. The third is changes to the fast ice distribution around coastal polynyas, as introduced by Fraser et al. [2012]. Though strongly related to the long-term icescape changes, we treat fast ice independently because it often changes over shorter time scales. The fourth mechanism is the extent and compactness of first-year ice in the offshore side of coastal polynyas, as introduced by Tamura and Ohshima [2011]. Our study will assess all four and discuss the relative impact each mechanism has on the long-term variability of SIP in Antarctic coastal polynyas.

2. Data

The estimation of SIP in this study follows Tamura et al. [2011]. First, thin ice thickness is estimated with the Tamura et al. [2007] algorithm, using 85 and 37 GHz brightness temperature data retrieved from the SSM/I. Next, we estimate SIP by the heat flux calculation using the thin ice thickness data and surface atmospheric data. The air-sea ice surface heat flux is obtained by assuming that the sum of radiative and turbulent fluxes at the ice surface is balanced by the conductive heat flux in the ice. The European Centre for Medium-Range Weather Forecasts Re-Analysis data (ERA-40: 1992–2001, ERA-interim: 1992–2013) and the National Centers for Environmental Prediction/Department of Energy Re-Analysis data (NCEP2: 1992–2013) are used for this calculation. The calculation is performed twice a day over the entire Southern Ocean on the SSM/I Equal Area Scalable Earth-Grid (12.5 km × 12.5 km) from 1992 to 2013.

Ice production is estimated from heat flux calculation during the freezing period (March–October) by assuming that all of the heat loss at the surface is used for ice formation. The oceanic heat flux from below is expected to be small in major Antarctic coastal polynyas because the whole water column is close to the freezing point during winter across most of the continental shelf [Muench and Gordon, 1995; Jacobs and Giulivi, 1998; Williams and Bindoff, 2003]. SIP is assumed to occur only in the grid cells assigned as areas of thin ice by the thin ice thickness algorithm. In this calculation, SIP in the thick ice area (not detected as thin ice) is assumed to be zero because ice production in the thick ice region is found to be very small from in situ observations [Lytle and Ackley, 1996; Lytle et al., 2001]. Calculation of the latent heat of fusion of sea ice and sea ice density follows Tamura et al. [2011].

One of the enduring challenges for remote sensing and modeling efforts around Antarctica is the paucity of suitable observations for validation. This is only exacerbated in the case of polynya-based SIP during the extreme wintertime conditions in coastal regions that are very difficult for ships to access. The in situ evaluation of the satellite-derived SIP estimates in our previous works has been limited to seasonal means of sea ice growth rates from the Mertz Polynya experiment in 1999 [Lytle et al., 2001; Roberts et al., 2001; Williams and Bindoff, 2003]. Available model outputs [Marsland et al., 2004, 2007; Kusahara et al., 2010] have also been used for evaluating our SIP estimates. We now have a much larger and more seasonally variable set of observations to use. Here we utilize time series of sea ice growth rates derived from instrumented Elephant seals (Mirounga Leonina) acting as biological moorings in several key polynya regions to extend this evaluation. Data were extracted from the Marine Mammals Exploring the Ocean Pole to Pole (MEOP) data portal
with details on the data processing given by Roquet et al. [2014]. We follow a simple salinity budget estimation of SIP from Charrassin et al. [2008],

$$q_0 V_0 S_0 = q_i V_i S_i + q_f V_f S_f$$  \(1\)

where \(q_0\) is the sea water density \(1027 \text{ kg m}^{-3}\); \(V_0\) is the initial volume of water, with initial salinity \(S_0\); \(V_i\) is the volume of ice formed with density \(q_i = 920 \text{ kg m}^{-3}\) and salinity \(10\); \(V_f = V_0 - V_i\) is the final volume of the seawater with salinity \(S_f\). This was successfully applied to the summer-autumn transition of the Mertz Glacier Polynya by Williams et al. [2011], and we extend it here to recent deployments of Elephant seal instruments from Australian bases at Davis station and Casey Station from 2011 to 2013.

3. Results

In our past studies [Tamura et al., 2008, 2011], we have discussed uncertainties in the absolute value of ice production. First, therefore, we compare our satellite-derived SIP results with the best available in situ observations, i.e., the seal-derived SIP results (Figure 1). While the accuracy of seal-derived data is lower than ship-based measurements, it is the relative change in data values across the winter months that forms the basis of the SIP estimates. In addition, the seal data measurements are not directly coincident with the grid cells of the satellite estimates, both spatially and temporally. Nonetheless, we find good agreement in the broad magnitude (e.g., the mean difference between Sssmi and Sseal is within \(\sim 20-25\%\) of each other) and intramonthly variability of these two independent measurements (Figure 1). Seal-derived SIP (m/d) is calculated as 8 day running mean of daily accumulated ice production. Satellite-derived ice production is calculated as mean value in the total nine grid cells of the SSM/I grid cell including the seal position in each day and its surrounding eight grid cells.

Figure 1. Time series of daily sea-ice production (m) calculated using satellite and ERA-Interim data (solid line) and available instrumented seal data (dashed line). Mean sea-ice production (m) of the solid line and dashed line (Sssmi and Sseal) are also shown. Seal-derived ice production is calculated as 8 day running mean of daily accumulated ice production. Satellite-derived ice production is calculated as mean value in the total nine grid cells of the SSM/I grid cell including the seal position in each day and its surrounding eight grid cells.
rare comparisons with the seal observations are invaluable as independent validation of the satellite-derived SIP estimation. Furthermore, such a comparison is a first for remote sensing studies.

Annual cumulative ice production around the continental shelf of Antarctica (i.e., the entire Southern Ocean), averaged over 1992–2013, is shown in Figure 2. The highest ice production is in the major Antarctic coastal polynya regions, as shown in past studies [Tamura et al., 2008; Nihashi and Ohshima, 2015]. The SIP results of the present study are the same as those of Tamura et al. [2011], and these results differ slightly from those of Tamura et al. [2008] due to a change in the parameters for the latent heat of fusion of sea ice and sea ice density, as described in Tamura et al. [2011]. For the discussion of the variability of ice production in Antarctic coastal polynyas, it is necessary to define the area of each coastal polynya, because the SIP estimate strongly depends on the polynya extent. We define the area of 13 major coastal polynyas (the polynya name follows Massom et al. [1998]) as the ocean area within 100 km from the coastline (to minimize the SIP uncertainty caused by the effect of warm oceanic heat from offshore deep water) with a subjective border in latitude and longitude (shown by thick black lines in Figure 2) and show these, together with total ice production and mean thin ice area during winter (March–October) in Table 1. Total ice production of the 13 coastal polynyas amounts to 1779 km$^3$, and shows the trend of $+0.06%/yr$. In the Ross Ice Shelf Polynya and Weddell Sea coastal polynyas, the total ice production is high (382 and 271 km$^3$, respectively) because we integrate ice production along a very broad stretch of coastline. In Weddell Sea coastal polynyas, however, the ice production per grid cell (Figure 2) is small. There is also high ice production shown in the Cape Darnley Polynya and Mertz Glacier Polynya (182 and 172 km$^3$, respectively), as shown in past studies [Tamura et al., 2008; Nihashi and Ohshima, 2015]. The ice production trends for each polynya region, together with the thin ice area trends, are also presented in Table 1. We find a large decreasing trend for SIP in the Ross Ice Shelf Polynya ($-1.1%/yr$) and Cape Darnley Polynya ($-0.98%/yr$), and these results are consistent with our past results [see Tamura et al., 2008, Table 1]. By contrast, there are significant increases (at the 5% level) in SIP for the Amundsen Polynya, Bellingshausen Polynya, and Barrier Polynya ($+2.7%/yr$, $+2.6%/yr$, and $+2.4%/yr$, respectively).

The interannual variability of the total ice production is shown in Figure 3. There is no coherent signal in the interannual variability across the 13 major Antarctic coastal polynyas. In the Weddell Sea coastal polynyas, the pattern of interannual variability is similar to that presented in Renfrew et al. [2002], although their
Table 1. Mean Values of Annual Cumulative Sea-Ice Production (km$^3$) and Thin Ice Area (km$^2$) (Thickness < 0.2 m) for the 13 Major Antarctic Coastal Polynyas With Their Standard Deviations and Trends (% yr$^{-1}$)

<table>
<thead>
<tr>
<th>Polyna</th>
<th>Ice Production (km$^3$)</th>
<th>Trend of Ice Production (% yr$^{-1}$)</th>
<th>Mean Thin Ice Area (10$^3$ km$^2$)</th>
<th>Trend of Thin Ice Area (% yr$^{-1}$)</th>
<th>Correlation Coefficients of Ice Production With</th>
<th>Correlation Coefficients of Thin Ice Area With</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Thin Ice Area</td>
<td>Air Temp.</td>
</tr>
<tr>
<td>Ross</td>
<td>382 ± 63</td>
<td>−1.1</td>
<td>22 ± 3.0</td>
<td>−0.46</td>
<td>0.89</td>
<td>−0.24</td>
</tr>
<tr>
<td>Weddell</td>
<td>271 ± 50</td>
<td>+0.76</td>
<td>27 ± 5.2</td>
<td>+0.83</td>
<td>0.92</td>
<td>0.49</td>
</tr>
<tr>
<td>Darnley</td>
<td>182 ± 23</td>
<td>−0.98</td>
<td>13 ± 1.6</td>
<td>−0.72</td>
<td>0.80</td>
<td>−0.22</td>
</tr>
<tr>
<td>Mertz</td>
<td>172 ± 30</td>
<td>−0.29</td>
<td>15 ± 2.2</td>
<td>−0.51</td>
<td>0.95</td>
<td>0.23</td>
</tr>
<tr>
<td>Amundsen</td>
<td>123 ± 24</td>
<td>±2.7</td>
<td>12 ± 2.1</td>
<td>±2.3</td>
<td>0.82</td>
<td>−0.26</td>
</tr>
<tr>
<td>Shackleton</td>
<td>123 ± 12</td>
<td>+0.59</td>
<td>11 ± 1.2</td>
<td>+0.75</td>
<td>0.59</td>
<td>0.21</td>
</tr>
<tr>
<td>Barrier</td>
<td>101 ± 20</td>
<td>+2.4</td>
<td>9.4 ± 1.9</td>
<td>+2.0</td>
<td>0.94</td>
<td>0.61</td>
</tr>
<tr>
<td>Vincennes</td>
<td>90 ± 13</td>
<td>+0.71</td>
<td>8.6 ± 1.2</td>
<td>+0.86</td>
<td>0.84</td>
<td>0.12</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>89 ± 9.3</td>
<td>+0.14</td>
<td>5.1 ± 0.6</td>
<td>+0.69</td>
<td>0.76</td>
<td>−0.22</td>
</tr>
<tr>
<td>Dibble</td>
<td>80 ± 10</td>
<td>−0.02</td>
<td>8.3 ± 1.0</td>
<td>−0.52</td>
<td>0.63</td>
<td>0.38</td>
</tr>
<tr>
<td>Bellinghausen</td>
<td>59 ± 14</td>
<td>±2.6</td>
<td>7.7 ± 1.3</td>
<td>±1.8</td>
<td>0.83</td>
<td>0.03</td>
</tr>
<tr>
<td>Terra Nova</td>
<td>56 ± 8.7</td>
<td>+0.34</td>
<td>3.6 ± 0.6</td>
<td>+0.06</td>
<td>0.96</td>
<td>0.27</td>
</tr>
<tr>
<td>Dalton</td>
<td>51 ± 10</td>
<td>+0.17</td>
<td>6.5 ± 0.9</td>
<td>−0.24</td>
<td>0.88</td>
<td>0.21</td>
</tr>
<tr>
<td>Total</td>
<td>1779 ± 88</td>
<td>+0.06</td>
<td>148 ± 10</td>
<td>+0.34</td>
<td>0.69</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*The ice production calculation was performed for 1992–2013 using ERA-interim data. Correlation coefficients of sea-ice production with thin ice area (thickness < 0.2 m), mean ERA-interim surface air temperature, mean ERA-interim offshore component of wind speed, onshore wind period during winter (March–October), SAM, SOI, and mean sea ice concentration of the offshore surrounding area of each polynya are also shown. Correlation coefficients of thin ice area (thickness < 0.2 m) with mean ERA-interim offshore component of wind speed and onshore wind period during March–October are also shown. The thick line in Figure 2 indicates the locations of the polynyas. When the ice production trend or correlation coefficients are statistically significant at the 5% and 1% level is shown with underline and bold underline, respectively. The Mann–Kendall rank statistics are used for the trend detection and the calculation of its significance level. The t test is used for the calculation of significance level of correlation coefficients.

The monthly ice production in Antarctic coastal polynyas is shown in Figure 4. Although we use only the ice production from March to October for the discussion of interannual variability in this study, we also show the ice production in summer (November to February) in this figure. As expected, the summer ice production over these months is generally smaller than the ice production in any other month. The ice production is the largest in the early stage of the freezing period (March or April). This reflects the ease with which offshore thin ice can grow at the very onset of the freezing period. Also, the offshoredward expansion of the polynyas is relatively uninhibited at this time because there is less consolidated pack ice. This is consistent for all Antarctic coastal polynyas in early winter compared to mid-winter, though more significant in the higher-latitude coastal polynyas of the Weddell and Ross Seas, and is also true for Arctic polynyas [Tamura and Ohshima, 2011]. There is no clear seasonality in the range of variability in monthly ice production in the 13 coastal polynyas. The range of variability each month is relatively large in the Barrier Polynya, Amundsen Polynya, and Bellinghausen Polynya, whose trends of annual cumulative SIP are statistically significant.

The interannual variability of mean thin ice area and air temperature in the 13 major coastal polynyas is shown in Figure 5. Correlation analysis of SIP with thin ice area and air temperature is shown in Table 1. Positive correlation coefficients indicate an increase in SIP in conjunction with increasing thin ice area and increasing air temperature. In the majority of polynyas, the interannual variability of total ice production correlates more strongly with polynya extent than with atmospheric conditions such as air temperature. For all polynyas, the correlation coefficients of ice production with polynya extent are statistically significant at the 1% level. On the other hand, the correlation coefficients of ice production with air temperature are only statistically significant in the Weddell Sea coastal polynyas and Barrier Polynya, at the 5% and 1% level.

Tamura et al., 2007; 2008. Similar changes to the icescape occurred for the Mertz Glacier Polynya (Figure 3i), where the un grounding of iceberg B-9B led to the calving of the Mertz Glacier Tongue in 2010, changing the overall regime. The red line in Figure 3i shows the ice production calculated using MODIS fast ice data following Tamura et al. [2012]. The annual cumulative SIP in 2012 and 2013 decreased by 21% and 27%, respectively, compared to the 2000–2009 mean ice production. The ice production in the Mertz Glacier Polynya has decreased after the Mertz Glacier calving event and has been setting minimum records every year until 2013.

The monthly ice production in Antarctic coastal polynyas is shown in Figure 4. Although we use only the ice production from March to October for the discussion of interannual variability in this study, we also show the ice production in summer (November to February) in this figure. As expected, the summer ice production over these months is generally smaller than the ice production in any other month. The ice production is the largest in the early stage of the freezing period (March or April). This reflects the ease with which offshore thin ice can grow at the very onset of the freezing period. Also, the offshoredward expansion of the polynyas is relatively uninhibited at this time because there is less consolidated pack ice. This is consistent for all Antarctic coastal polynyas in early winter compared to mid-winter, though more significant in the higher-latitude coastal polynyas of the Weddell and Ross Seas, and is also true for Arctic polynyas [Tamura and Ohshima, 2011]. There is no clear seasonality in the range of variability in monthly ice production in the 13 coastal polynyas. The range of variability each month is relatively large in the Barrier Polynya, Amundsen Polynya, and Bellinghausen Polynya, whose trends of annual cumulative SIP are statistically significant.
respectively. This means high ice production is associated with warm air temperature. Under extreme cold air conditions, greater ice production occurs, leading to increased backfill of the polynya area [Pease, 1987]. Also, it should be kept in mind that the mean air temperature in these two polynyas has been cold enough to form a polynya from 1992 to 2013 (Figures 5a and 5d). Because Antarctic coastal polynyas are naturally...
situated in freezing atmospheric conditions, thin ice area, expressed through the polynya extent, is considered to be the key parameter for new ice production.

The correlation analysis of SIP and thin ice area with offshore wind speed and onshore wind period is also shown in Table 1. The definition of offshore wind direction follows that shown in Nihashi and Ohshima [2015, Table 3], i.e., the direction of the wind that shows the highest correlation with the polynya area. For all polynyas in this study, the onshore wind direction is southward, with the exception of the Terra Nova Bay polynya, for which the onshore wind direction is westward. The onshore wind period is the

Figure 4. Monthly sea-ice production (km$^3$) calculated using ERA-interim (solid line with error bars showing plus/minus one STD), and NCEP2 (dashed line), averaged over 1992–2013 for the 13 major Antarctic coastal polynyas.
accumulated onshore-wind-days during winter (March–October). The positive correlation coefficients indicate that SIP and thin ice area increase with increasing offshore wind speed and increasing onshore wind period. In the Barrier Polynya and Shackleton Polynya, the correlation of offshore wind speed with polynya extent and ice production is statistically significant at the 1% level. In the Amundsen Polynya and Bellingshausen Polynya, the correlation between ice production and offshore wind speed is statistically significant at the 1% level. However, there is no statistically significant correlation for the other polynyas. Testing the sensitivity to offshore wind angle has little impact on these correlations. In the Amundsen Polynya, the Weddell Sea coastal polynyas, the Cape Darnley Polynya, and the Mackenzie Bay Polynya, the interannual

Figure 5. Time series of winter-mean thin ice area (km²) with thickness <0.2 m (blue line) and ERA-interim air temperature (K) at 2 m (red line) for the 13 major Antarctic coastal polynyas from 1992 to 2013, averaged over March–October for each year. The thin black solid line indicates annual ice production (km³) (same line and y axis label as the solid line in Figure 3).
variability of polynya extent has only a weak correlation with the onshore wind period. On the other hand, total ice production in these polynyas correlates relatively well with onshore wind period ($r = -0.54$, $-0.40$, $-0.38$, and $-0.24$, respectively). The correlation coefficient between total ice production and onshore wind period in the Ross Ice Shelf Polynya is positive and statistically significant at the 5% level. Although this means that high ice production is associated with onshore wind period, this result may be meaningless, because the onshore wind period in the Ross Ice Shelf Polynya, averaged over 1992–2013, is only 2.2 days (not shown) and is the lowest value for all 13 polynyas. For most of the polynyas, the interannual variability of total ice production correlates more strongly with polynya extent than with wind parameters.

Moving beyond local meteorological effects, we now briefly investigate the influence of the Southern Annular Mode (SAM) and Southern Oscillation Index (SOI) on ice production in the 13 major coastal polynyas (Table 1). A detailed examination of the influence of large-scale modes on SIP requires a lagged correlation analysis, but such an analysis is outside of the scope of this paper. Here we present just the zero-lag values. For the majority of polynyas, ice production correlates to some extent with both SAM (negative) and SOI (positive). However, these correlation values are very small. The strongest correlations (significant at the 5% level) are between the Amundsen Polynya ice production and SOI (positive) and the Cape Darnley Polynya ice production and SOI (negative). To interpret these correlations, we refer to the ice concentration anomalies under various SOI conditions presented by Kwok and Comiso [2002]. The El Nino Southern Oscillation is known to be a strong driver of the large-scale atmospheric mode known as the Pacific South American (PSA) pattern [Yuan and Li, 2008], which shares similarities with the Amundsen Sea Low [Turner et al., 2013].

As such, it is not unexpected that one of the strongest correlations between SOI and SIP occurs in the Amundsen Polynya. This polynya experiences a negative sea ice concentration anomaly under positive SOI conditions [Kwok and Comiso, 2002], possibly reducing the polynya backfill pressure, and subsequently increasing ice production. Although ice production in the Cape Darnley Polynya shows the strongest negative correlation with SOI, most other polynyas have a positive correlation with SOI. There is no coherent signal between the interannual variability of SAM and SOI with ice production in the major Antarctic coastal polynyas (not shown). It is possible that an increase in near-coastal sea ice during times of positive SOI along the Mawson coast [Kwok and Comiso, 2002] acts as an impediment to the export of new ice in the Cape Darnley Polynya, thus reducing ice production, and manifesting as a negative correlation between SOI and ice production there. Although no discussion of the positive correlation between SOI and SIC anomalies along the Mawson coast is given, Kwok and Comiso [2002] point to the presence of a wave number 2 pattern evident at zero lag. While the strongest expressions of this pattern occur either side of the Antarctic Peninsula, a broad (but weaker) positive correlation between SOI and SIC anomalies is observed between ~0°E and 80°E.

4. Discussion

There are documented uncertainties in the absolute value of satellite-derived SIP estimates [Tamura et al., 2008, 2011]. However, the interannual and seasonal variability of ice production in each coastal polynya can be examined because the ice production estimation is performed with the same thin ice algorithm and objective analysis data over the entire Southern Ocean. Further, the present study provides the most comprehensive comparison with in situ SIP observations, calculated independently from instrumented seal data. The results of the present study provide an example of how long-term daily data could be useful for monitoring the variability of DSW formed along the Antarctic coast. Ultimately, the application of the AMSR-E data provides more reliable estimates of ice production at higher spatial resolution [Nihashi and Ohshima, 2015], and so our future target is an expansion of the analysis period by using the Advanced Microwave Scanning Radiometer-II (AMSR-II) data. However, SSM/I data are still indispensable for the discussion of longer-term variability since the 1990s.

AABW formation is directly controlled by SIP in Antarctic coastal polynyas. SIP can greatly change through ice sheet dynamics, as shown after the calving events in the Ross Ice Shelf in 2000 and the Mertz Glacier in 2010. Such ice shelf calving, with its corresponding changes to fresh water output to the coastal environment, has the capacity to strongly influence AABW production. The recent acceleration of discharge from glaciers in west Antarctica could expand to other coastal regions, such as East Antarctica [Cook et al., 2013;
Greenbaum et al., 2015], and might affect AABW variability into the future. The monitoring of SIP as well as ice sheet change is vitally important for better understanding of AABW variability.

This study presents the interannual variability and trends in SIP for the 13 major Antarctic coastal polynyas. In the majority of polynyas, the interannual variability of total ice production correlates more strongly with polynya extent than with atmospheric forcing (e.g., surface air temperature and wind speed), with the exception of the Shackleton Polynya, which correlates better with wind. Overall, there is no coherent signal in the interannual variability across the major Antarctic coastal polynyas. Linking ice production to DSW/AABW formation, the SIP trends agree with reports that Ross Sea Bottom Water (RSBW) has recently freshened [Aoki et al., 2005; Rintoul, 2007; Jacobs and Giulivi, 2010] and the Cape Darnley Bottom Water has warmed [Couldrey et al., 2013]. Around the Amundsen Polynya and Bellingshausen Polynya, ice sheet and ice shelf melt have recently been increasing [Rignot et al., 2008; Pritchard et al., 2012]. Although our previous study [Tamura et al., 2008] shows that the ice production trends in the Amundsen Polynya and Bellingshausen Polynya in the 1990s are negative, this study shows a significant positive trend that could be caused by the aforementioned recent change in surface salinity.

Tamura et al. [2008] reported large ice production reduction events in 2000 and 2002 in the Ross Ice Shelf Polynya. The result of this study represents these events. The purple dotted lines in Figure 3k show the t test range of the 5% statistically significant level for the mean SIP averaged over 1992–2013, excluding 2000 and 2002. The 2002 SIP value is outside of this range and the 2000 SIP value is close to the 5% level line. The large SIP reductions in 2000 and 2002 in the Ross Ice Shelf Polynya are considered to be statistically significant events in the 22 years interannual variability.

Comiso et al. [2011] and Drucker et al. [2011] show an increasing SIP trend in the Ross Ice Shelf Polynya and this is inconsistent with our results. For the Ross SIP estimation, Comiso et al. [2011] and Drucker et al. [2011] use the thin ice thickness algorithm from Martin et al. [2007] which is developed for the Ross Ice Shelf Polynya and has an advantage of being able to detect moving icebergs [Comiso et al., 2011]. On the other hand, the advantage of our thin ice thickness algorithm is its circumpolar applicability for the discussion of all 13 major coastal polynyas, using the same standard. It should be kept in mind that the defined area of the Ross Ice Shelf Polynya in Comiso et al. [2011] and Drucker et al. [2011] is much larger than ours in the offshoreward direction.

Comiso et al. [2011] also mentions the secondary polynyas that can form downwind of moving icebergs. Our results show that the vast majority of the ice production area sits inside the defined polynya area (thick black lines in Figure 2) during 1992–1999 and 2001–2013 (not shown). In 2000, a part of the secondary polynya appears outside of the defined polynya area. If we include the SIP in this area, the total SIP value in the Ross Ice Shelf Polynya in 2000 increases by 34.2 km³ (+12%). Even if we include this SIP, the conclusions are not modified for SIP in the Ross Ice Shelf Polynya, i.e., the large SIP reduction in 2000, and the decreasing trend from 1992 to 2013. It is intriguing that while the 100 km offshore limit of the polynya definition contains the vast majority of observed SIP, we arrive at a different conclusion to Comiso et al. [2011].

While we cannot certify which algorithm/method is correct, we can present objective results from other studies in support of our results. As discussed in Tamura et al. [2008], the specific values of our SIP estimates are consistent with a salt budget analysis derived from in situ ship-based observations [Williams and Bindoff, 2003]. The present study confirms the validity of our SIP estimates with the additional comparison with seal-derived data. The interannual variability of our SIP results is consistent with other passive microwave SIP estimation studies [e.g., Renfrew et al., 2002].

Tamura et al. [2012] estimated SIP in the Mertz Glacier Polynya by resolving the detection of glacier, iceberg, and fast ice variability with NASA Moderate Resolution Imaging Spectroradiometer (MODIS) data. The above study showed that the annual cumulative SIP in 2010 and 2011 had decreased by 14–20% compared to the 2000–2009 mean ice production. Similar estimation using the higher spatial resolution AMSR-E data (2003–2011) shows a similar reduction [Nihashi and Ohshima, 2015]. The result of this study is consistent with these past results and also shows that this reduction has been setting minimum records every year until 2013. The purple dotted lines in Figure 3i show the t test range of the 5% statistically significant level for the mean SIP averaged over 1992–2009. The 2012 and 2013 SIP values are outside of this range. The decrease in SIP in the Mertz Glacier Polynya after the Mertz Glacier calving is considered to be a statistically significant event in the 22 years interannual variability. Campagne et al. [2015], based on a 250 year long sediment
core in this region, suggested that large and abrupt changes in local sea ice and bottom water conditions occur with a 70 year periodicity, associated with the Mertz Glacier Tongue calving and regrowth dynamics.

As described previously in this study, we found a statistically significant trend of increasing ice production in the Amundsen Polynya and Bellingshausen Polynya, and a statistically significant positive correlation between the Amundsen Polynya ice production and SOI. The Amundsen Polynya and Bellingshausen Polynya are increasingly thought to be driven by the Amundsen Sea Low [Turner et al., 2013, 2015]. However, the extents of both polynyas have no statistically significant correlation with wind (Table 1). One common feature for both polynyas is that the onshore wind period is much longer than that of other polynyas (not shown). In these two polynyas, ice production occurs under a relatively dominant onshore wind regime, in contrast to other polynyas. We propose the following hypothesis to explain this apparent contradiction. Due to the recent reduction of sea ice extent in the Amundsen and Bellingshausen Sea, the offshore side of these two polynyas is no longer covered with compact pack ice [Stammerjohn et al., 2012]. In this situation, during an offshore wind period, the polynya area can easily expand, and we consider that this is the reason for the increase of SIP in these polynyas. Correlation coefficients of sea-ice production with mean sea ice concentration of the offshore surrounding area of each polynya (200 km outside) in the Amundsen Polynya and Bellingshausen Polynya are statistically significant and greater than that of most other polynyas (Table 1). This result is consistent with our hypothesis.

In addition, we also found a statistically significant trend of increasing ice production in the Barrier Polynya (+2.4%/yr; Table 1). The blue line in Figure 3d shows the MODIS fast ice extent inside the Barrier Polynya and its surrounding area (66°S–68.5°S, 78°E–83°E) averaged over the freezing period (March–October). These MODIS fast ice data are an improved version of the Fraser et al. [2012] data set, with a spatial and temporal resolution of 1 km and 15 days, respectively. Ice production and fast ice extent in the Barrier Polynya show a clear negative correlation (−0.61; 5% level), and this could be extended to imply decreasing fast ice extent with respect to increasing ice production. The Barrier SIP correlates well with air temperature, offshore wind speed, and sea ice concentration in the offshore area, and with the variability of fast ice extent around this polynya, especially in the regional-scale change near polynyas.

The decreasing ice production trend is shown for the Cape Darnley Polynya. The negative correlation of Cape Darnley Polynya ice production with SOI is statistically significant. The blue line in Figure 3b shows the MODIS fast ice extent around the Cape Darnley Polynya (66.5°S–68°S, 68.5°E–71°E) averaged over the freezing period (March–October). In fact, this also indicates the extent of the grounded iceberg tongue east of the Cape Darnley Polynya, responsible for the extension of the Cape Darnley Polynya [Ohshima et al., 2013]. Ice production and fast ice extent in the Cape Darnley Polynya have a positive correlation (+0.44). The varying sign of the relationship between sea ice production and fast ice extent highlights the complexity of this interaction. For example, while a large fast ice extent to the east of a polynya effectively increases polynya size and SIP, formation of fast ice within the polynya itself could decrease production. Fast ice variability is considered to influence SIP variability, however further analysis is outside of the scope of the present paper.

5. Conclusion

This study presents the variability of SIP for the 13 major Antarctic coastal polynyas. In the majority of polynyas, the interannual variability of total ice production correlates more strongly with polynya extent than with atmospheric forcing, with the exception of the Shackleton Polynya. There is no coherent signal in the interannual variability between the major Antarctic coastal polynyas. It has been considered that the variability of wind and temperature, including through large-scale climate modes like SAM and SOI, could contribute as major factors in the long-term variability of SIP in Antarctic coastal polynyas. However, this study shows that other three factors are also important, such as the configuration of ice-shelves/floating glacier-tongues, landfast ice, and offshore first-year ice. SIP has sharply decreased in regions where there have been the calving and breakout of the ice shelves and glaciers, as shown in the Ross Ice Shelf Polynya and Mertz Glacier Polynya. The expansion and reduction of fast ice close to coastal polynyas have also affected the SIP, as shown in the Barrier Polynya. SIP is also considered to have increased due to the recent reduction of sea ice extent in the offshore first-year ice zone, as shown in the Amundsen Polynya and Bellingshausen Polynya. Although the impacts of these three cases for SIP are not universally applicable to all Antarctic coastal polynyas, these icescape changes clearly impact the SIP variability at multiyear time scales. All three
mechanisms/processes are missing from objective general analysis data sets such as ERA-interim, and therefore the long-term variability of polynyas can only be effectively detected and monitored through satellite observations.

References

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