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Mapping and Assessing Variability in the Antarctic Marginal Ice Zone, the Pack Ice and Coastal Polynyas

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Abstract

Sea ice variability within the marginal ice zone (MIZ) and polynyas plays an important role for phytoplankton productivity and krill abundance. Therefore mapping their spatial extent, seasonal and interannual variability is essential for understanding how current and future changes in these biological active regions may impact the Antarctic marine ecosystem. Knowledge of the distribution of different ice types to the total Antarctic sea ice cover may also help to shed light on the factors contributing towards recent expansion of the Antarctic ice cover in some regions and contraction in others. The long-term passive microwave satellite data record provides the longest and most consistent data record for assessing different ice types. However, estimates of the amount of MIZ, consolidated pack ice and polynyas depends strongly on what sea ice algorithm is used. This study uses two popular passive microwave sea ice algorithms, the NASA Team and Bootstrap to evaluate the distribution and variability in the MIZ, the consolidated pack ice and coastal polynyas. Results reveal the NASA Team algorithm has on average twice the MIZ and half the consolidated pack ice area as the Bootstrap algorithm. Polynya area is also larger in the NASA Team algorithm, and the timing of maximum polynya area may differ by as much as 5 months between algorithms. These differences lead to different relationships between sea ice characteristics and biological processes, as illustrated here with the breeding success of an Antarctic seabird.

1. Introduction

Changes in the amount of the ocean surface covered by sea ice play an important role in the global climate system. For one, sea ice and its snow cover have a high surface reflectivity, or albedo, reflecting the majority of the sun's energy back to space. This helps to keep the polar regions cool and moderates global climate. When sea ice melts or retreats, the darker (lower albedo) ocean is exposed, allowing the ocean to absorb solar energy and warm, which in turn melts more ice, creating a positive feedback loop. During winter, sea ice helps to insulate the ocean from the cold atmosphere, influencing the exchange of heat and moisture to the atmosphere with impacts on cloud cover, pressure distribution and precipitation. These in turn

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can lead to large-scale atmospheric changes, affecting global weather patterns [e.g. *Jaiser et al.*, 2012]. Sea ice also has important implications for the entire polar marine ecosystem, including sea ice algae, phytoplankton, crustaceans, fish, seabirds, and marine mammals, all of which depend on the seasonal cycle of ice formation in winter and ice melt in summer. For example, sea ice melt stratifies the water column, producing optimal light conditions for stimulating bloom conditions that Antarctic sea birds rely upon for their breeding success and survival [e.g. *Park et al.*, 1999].

In stark contrast to the Arctic, which is undergoing a period of accelerated ice loss in the last several decades [e.g. *Stroeve et al.*, 2012; *Serreze and Stroeve*, 2015], the Antarctic is witnessing a modest increase in total sea ice extent [*Parkinson and Cavalieri*, 2012]. Sea ice around Antarctica reached another record high extent in September 2014, recording a maximum extent of more than 20 million km^2 for the first time since the modern passive microwave satellite data record began in October 1978. This follows previous record maxima in 2012 and 2013, resulting in an overall increase in Antarctic September sea ice extent of 1.1% per decade since 1979. While the observed increase is statistically significant, Antarctic's sea ice extent (SIE) is also highly variable from year to year and region to region [e.g. *Maksym et al.*, 2012; *Parkinson et al.*, 2012; *Stammerjohn et al.*, 2012]. The temporal variability is underscored by sea ice conditions in 2015 when the winter ice cover returned back to the 1981-2010 long-term mean. Also, recent sea ice assessments from early satellite images from the Nimbus program of the late 1960s indicate similarly high but variable SIE as observed over 2012-2014 [*Meier et al.,* 2013; *Gallaher et al.,* 2014]. Mapping of the September 1964 ice edge indicates that ice extent likely exceeded both the 2012 and 2013 record monthly-average maximums, at 19.7±0.3 million km^2. This was followed in August 1966 by an extent estimated at 15.9±0.3 million km^2, considerably smaller than the record low maximum extent of the modern satellite record (set in 1986). The circumpolar average also hides contrasting regional variability, with some regions showing either strong positive or negative trends with magnitudes equivalent to those observed in the Arctic [*Stammerjohn et al.*, 2012]. In short, interannual and regional variability in Antarctic sea ice is considerable, and while the current positive trend in circumpolar averaged Antarctic sea ice extent is important, it is not unprecedented compared to observations from the 1960s and it is not regionally distributed.

Several explanations have been put forward to explain the positive Antarctic sea ice trends. Studies point to anomalous short-term wind patterns that both grow and spread out the ice, related to the strength of the Amundsen Sea low pressure [e.g. *Turner et al.,* 2013; *Reid et al.*, 2015]. Other studies suggest melt water from the underside of floating ice surrounding the continent has risen to the surface and contributed to a slight freshening of the surface ocean [e.g. *Bintanja et al.*, 2012]. While these studies have helped to better understand how the ice, ocean and atmosphere interact, 2012 to 2014 showed different regions and seasons contributing to the net positive sea ice extent, which has made it difficult to establish clear links and suggests that no one mechanism can explain the overall increase.

While the reasons for the increases in total extent remain poorly understood, it is likely that these changes are not just impacting total sea ice extent but also the distribution of pack ice, the marginal ice zone and polynyas. The marginal ice zone (MIZ) is a highly dynamic region of the ice cover defined by the transition between the open ocean and the consolidated pack ice. In the Antarctic, wave action penetrates hundreds of kilometers into the ice pack, resulting in small rounded ice floes from wave-induced fracture [*Kohout et al.,* 2014]. Thus, in contrast to the Arctic, ocean waves primarily define the dynamic MIZ region, though in the Arctic this may be changing as the Arctic continues to experience longer and larger ice-free summers with increased fetch on the later-timed ice edge advance [*Wang et al.,* 2015]. This in turn makes the MIZ region particularly sensitive to both atmospheric and oceanic forcing, such that during quiescent conditions, it may consist of a diffuse thin ice cover, with isolated thicker ice floes distributed over a large (hundreds of kilometers) area. In contrast, during high on-ice wind and wave events, the MIZ region contracts to a compact ice edge with rafted ice pressed together in front of the solid ice pack. In general, ocean waves define the dynamic MIZ region, where ice floes are relatively small due to wave-induced fracture. The smaller the ice floes, the more mobile they are and large variability in ice conditions can be found in response to changing wind and ocean conditions. Polynyas on the other hand are open water areas near the continental margins that often remain open as a result of strong katabatic winds flowing down the Antarctic plateau. The winds continually push the newly formed sea ice away from the continent, which influences the outer ice edge as well, thus contributing to the overall increase in total ice extent in specific regions around the Antarctic continent where katabatic winds are persistent.

Both polynyas and the MIZ are biologically important regions of the sea ice cover that have important implications for the entire trophic web, from primary productivity [*Yun et al*., submitted], to top predator species, such as seabirds. Near the ice edge and in the MIZ, the stable upper layer of the water column is optimal for phytoplankton production [e.g. *Park et al*. 1999]. This phytoplankton bloom is subsequently exploited by zooplankton, with effects that cascade up to fish, seabirds and marine mammals. Similarly, within polynyas there is a narrow opportunity for phytoplankton growth, the timing of which plays an important role in both biogeochemical cycles [*Smith and Barber*, 2007] and biological production [*Arrigo and van Dijken*, 2003; *Ainley et al*., 2010]. However, while studies have suggested that the timing of sea ice retreat is synchronized with the timing of the phytoplankton bloom, other factors such as wind forcing [*Chiswell*, 2011], thermal convection [*Ferrari,* 2014] and iron availability [*Boyd et al*, 2007, and references therein] play important roles as well.

In this study we use the long-term passive microwave sea ice concentration data record to evaluate variability and trends in the marginal ice zone, the pack ice and polynyas from 1979 to 2014. A complication arises however as to which sea ice algorithm to use. There are at least a dozen algorithms available, spanning different time-periods, which give sea ice concentrations that are not necessarily consistent with each other [*see Ivanova et a*l., 2015; 2014 for more information]. To complicate mattes, different studies have used different sea ice algorithms to examine sea ice variability and attribution. For example, *Hobbs and Raphael* [2010] used the Had1SST1 sea ice concentration data set [*Rayner et al.,* 2003], which is based on the NASA Team algorithm [*Cavalieri et al*., 1999], whereas *Raphael and Hobbs* [2014] relied on the Bootstrap algorithm [*Comiso and Nishio*, 2008]. To examine the influence in the choice of sea ice algorithm on the results, we use both the Bootstrap and NASA Team sea ice algorithms. Results are evaluated hemispheric-wide and also for different regions. We then discuss the different implications resulting from the two different satellite estimates for biological impact

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studies. We focus on the breeding success of snow petrels because seabirds have been identified as useful indicators of the health and status of marine ecosystems [*Piatt and Sydeman*, 2007].

2. Data and Methods

To map different ice types, the long-term passive microwave data record is used, which spans several satellite missions, including the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite (October 1978 to August 1987), the Special Sensor Microwave/Imager (SSM/I) sensors -F8 (July 1987 to December 1991), -F11 (December 1991 to September 1995), -F13 (May 1995 to December 2007) and the Special Sensor Microwave Imager/Sounder (SSMIS) sensor –F17 (January 2007- to present), both on the Defense Meteorological Satellite Program's (DMSP) satellites. Derived sea ice concentrations (SICs) from both the Bootstrap (BT) [*Comiso and Nishio*, 2008] and the NASA Team (NT) sea ice algorithms [*Gloersen et al.,* 1992; *Cavalieri et al.,* 1999] are available from the National Snow and Ice Data Center (NSIDC) and provide daily fields from October 1978 to present, gridded to a 25 km polar stereographic grid. While a large variety of sea ice concentration algorithms are available, the lack of good validation has made it difficult to determine which algorithm provides the most accurate results during all times of the year and for all regions. Using two algorithms provides a consistency check on variability and trends.

Using these SIC fields, we define six binary categories of sea ice based on different SIC thresholds [**Table 1**]. Because the marginal ice zone is highly dynamic in time and space, it is difficult to precisely define this region of the ice cover. *Wadhams* [1986] defined the MIZ as that part of the ice cover close enough to the open ocean boundary to be impacted by its presence, e.g. by waves. Thus the MIZ is typically defined as the part of the sea ice that is close enough to the open ocean to be heavily influenced by waves, and it extends from the open ocean to the dense pack ice. In this study, we define the MIZ as extending from the outer sea ice/open ocean boundary (defined by SIC $\geq$ 0.15 ice fraction) to the boundary of the consolidated pack ice (defined by SIC = 0.80). This definition was previously used by *Strong and Rigor* [2013] to assess MIZ changes in the Arctic and matches the upper sea ice concentration limit used by the National Ice Center in mapping the Arctic MIZ. The consolidated ice pack is then defined as the area south of the MIZ with ice fractions between 0.80 $\leq$ SIC $\leq$ 1.0. Coastal polynyas are defined as regions near the coast that have SIC < 0.80.

To automate the detection of different ice types, radial transects from 50 to 90S are individually selected to construct one-dimensional profiles [**Figure 1**]. The algorithm first steps from the outer edge until the 0.15 SIC is detected, providing the latitude of the outer MIZ edge. Next, the algorithm steps from the outer MIZ edge until either the 0.80 SIC is encountered, or the continent is reached. Data points along the transect between these SIC thresholds are flagged as the MIZ. In this way, the MIZ includes an outer band of low sea ice concentrations that surrounds a band of inner consolidated pack ice, *but* sometimes the MIZ also extends all the way to the Antarctic coastline (as sometimes observed in summer). South of the MIZ, the consolidated ice pack (0.80 $\leq$ SIC $\leq$ 1.0) is encountered; however, low sea ice concentrations can appear near the coast inside the pack ice region as well. These are areas of potential

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coastal polynyas. While it is difficult to measure the fine scale location of a polynya at 25km spatial resolution, the lower sea ice concentrations provide an indication of some open water near the coast, which for sea birds provides a source of open water for foraging. Using our method of radial transects, the algorithm then steps from the coast northward and flags pixels with < 0.80 SIC until a 0.80 SIC pixel appears and defines that region as a potential coastal polynya. Within the consolidated pack ice (and away from the coast), it is also possible to encounter instances where 0.15 < SIC < 0.80 or SIC < 0.15. These are flagged as open pack ice and open water areas within the consolidated pack ice, respectively. Finally, an ocean mask derived from climatology and distributed by NSIDC was applied to remove spurious ice concentrations at the ice edge as a result of weather effects.

Figure 2 shows sample images of the classification scheme as applied to the NASA Team and Bootstrap algorithms on days 70 and 273, respectively, in 2013. During the fall and winter months when the ice cover is expanding there is a well-established consolidated pack ice region, surrounded by the outer MIZ. Coastal polynyas are also found surrounding the continent in both algorithms. As will be discussed in more detail in the results section, the BT algorithm tends to show a larger consolidated ice pack than NT, particularly during the timing of maximum extent. During the melt season there is mixing of low and high ice concentrations, leading to mixtures of different categories, which is still seen to some extent in the March images. However, during March areas of polynyas (green), open water (pink) and open pack ice (orange) appear to extend from the coastline in some areas (e.g. southern Weddell and Ross seas). While any pixel with SIC < 0.8 adjacent to the coastal boundary is flagged as potential polynya when stepping northwards, if a pixel is already flagged as MIZ or consolidated pack ice when stepping southwards, it remains flagged as MIZ or pack ice. After that analysis, a check for pixels with SICs less than 0.8 is done to flag for broken ice or open water. Thus, during these months (e.g. December to February or March), the physical interpretation of the different ice classes may be less useful.

Using the binary classification scheme, gridded fields and regional averages are computed. We show results for the entire Antarctic sea ice cover, as well as for six different regions as defined previously by *Parkinson and Cavalieri* [2012]. These regions are shown in **Figure 3** for reference. Climatological mean daily and monthly time-series spanning 1981 to 2010 are computed for each region and for each ice classification together with the +/- one standard deviation (1σ). Monthly trends over the entire time-series are computed by first averaging the daily fields into monthly values and then using a standard linear least squares, with statistical significance evaluated at the 90th, 95th and 99th percentiles using a student t-test.

3. Results

3.1 Seasonal Cycle

3.1.1 Circumpolar Extent

We begin with an assessment of the consistency of the outer ice edge between both sea ice algorithms [**Figure 4**]. As a result of the large emissivity difference between open water and sea ice, estimates of the outer ice edge location has high consistency between the two algorithms

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despite having large differences in sea ice concentration [e.g. *Ivanova et al.*, 2014; 2015]. This therefore results in similar total sea ice extents between both algorithms during all calendar months, and similar long-term trends. This is where the similarities end however.

Figure 5 summarizes the climatological mean seasonal cycle in the extent of the different ice categories listed in Table 1 for both sea ice algorithms, averaged for the total hemispheric-wide Antarctic sea ice cover. The one standard deviation is given by the colored shading. The first notable result is that the BT algorithm has a larger consolidated ice pack than the NT algorithm, which comes at the expense of a smaller MIZ. Averaged over the entire year, the NASA Team MIZ area is twice as large as that in the Bootstrap algorithm [see also **Table 2**]. The BT algorithm additionally has a smaller spatial extent of potential coastal polynyas and little to no broken ice or open water within the consolidated pack ice. Another important result is that the BT algorithm exhibits less interannual variability in the different ice types, as illustrated by the smaller standard deviations from the long-term mean (e.g. the shading). Thus, while the total extents are not dissimilar between the algorithms, how that ice is distributed among the different ice categories differs quite substantially as well as their year-to-year variability.

The timing of the ice edge advance and retreat are generally similar in both algorithms, reflecting the fact that both algorithms do well in distinguishing open water from sea ice. In regards to the consolidated pack ice, it advances in March, with the BT algorithm showing a distinct peak in September, reaching a maximum extent of 14.89 10^6 km^2. The NT algorithm shows a somewhat broader peak, extending from July to October, with the peak extent also reached in September. In September the NT pack ice extent is a little more than twice the spatial extent of the MIZ; 11.31 10^6 km^2 vs. 5.41 10^6 km^2 [Table 2]. BT on the other hand has a much smaller fraction (41% less) of ice classified as MIZ (3.19 10^6 km^2). In both algorithms the MIZ also begins to expand in March, and continues to expand until November or December, after which it rapidly declines. However, in the NT algorithm, an initial peak in MIZ coverage is also reached around September, coinciding with the peak in the consolidated pack ice extent and stays nearly constant until the end of November. The further increase in the MIZ coverage after the consolidated ice pack begins to retreat implies that as the pack ice begins to retreat, it does so in part by first converting to MIZ over a wider area. This is consistent with the idea that in spring, the pack ice on average undergoes divergence first (in relation to the circumpolar trough being poleward and south of the ice edge, as reflected by the Semi-Annual Oscillation, SAO, of the trough). This in turn facilitates increased solar heating of open water areas, which in turn facilitates increased melt back, thus creating, eventually, a more rapid ice edge retreat (in Nov-Dec) as compared to the slow ice edge advance in autumn [see *Watkins and Simmonds*, 1999].

Open pack ice is negligible in the Bootstrap algorithm except for a slight peak in November/December. With the NASA Team algorithm however there is a clear increase in open pack ice during the ice expansion phase, which continues to increase further as the pack ice begins to retreat, also peaking in November. Open pack ice in September contributes another 1.28 10^6 km^2 to the total Antarctic sea ice extent in the NT algorithm, compared to only 0.36 10^6 km^2 in the BT algorithm. As with the open pack ice, the fraction of potential coastal polynyas also increases during the ice expansion phase, and then continues to increase as the sea ice retreats, peaking around November in the NT algorithm, with a total area of 1.02 10^6 km^2, and in December in BT (0.81 10^6 km^2). Inner open water within the pack is generally only found between November and March in both algorithms as the total ice cover retreats and reaches its seasonal minimum.

3.2.2 Regional Analysis

Analysis of the Antarctic-wide sea ice cover however is of limited value given that the sea ice variability and trends are spatially heterogeneous [*Makysm et al*., 2012]. For example, while the ice cover is increasing in the Ross Sea, it has at the same time decreased in the Bellingshausen/ Amundsen Sea region. Thus, we may anticipate significant regional variability in the amount, seasonal cycle and trends of the different ice classes (trends discussed in section 3.3). The Ross Sea for example [**Figure 6, top**] consists of a large fraction of consolidated ice throughout most of the year (April through November) in both algorithms, with considerably less MIZ. In the Bellingshausen/Amundsen Sea on the other hand [**Figure 6, 2nd row**], the NT algorithm has a MIZ extent that exceeds that of the consolidated pack ice until May, after which the spread (+/- 1σ) in MIZ and consolidated pack ice overlaps. The reverse is true in the BT algorithm, which consistently indicates a more consolidated ice pack, with only 0.51 10^6 km^2 flagged as MIZ during the maximum extent in September, compared to 0.84 10^6 km^2 in the NT algorithm. On an annual basis, the NT algorithm shows about equal proportion of MIZ and consolidated pack ice in the Bellingshausen/Amundsen Sea whereas, the BT algorithm indicates a little more than a third of the total ice cover is MIZ. In the Ross Sea there is also a very broad peak in the maximum extent of the consolidated pack ice, stretching between July and October in the NT algorithm, and a peak in MIZ extent in late August/early September with a secondary peak in December as the pack ice continues to retreat. The BT algorithm shows a similar broad peak in the pack ice extent, but with less interannual variability, and a nearly constant fraction of MIZ throughout the advance and retreat of the pack ice. Annually the NT algorithm shows about 56% more MIZ in the Ross Sea than the BT algorithm. Note that in both algorithms, the pack ice retreats rapidly after the maximum extent is reached.

In the Weddell Sea, the pack ice extent advances in March in both algorithms and peaks in August in the NT algorithm, September in BT. The MIZ also begins its expansion in March and continues to increase until September in NT, and then again until December (both algorithms) as the pack ice quickly retreats [**Figure 6 (middle)**]. In this region, the sea ice expands northwards until it reaches a region with strong winds and currents. The open pack ice north of the pack ice continues to expand either by further freezing or breaking of the pack ice by the winds and currents. Overall, the Weddell Sea has the largest spatial extent in the MIZ in both algorithms, as well as the largest distribution of pack ice. In the NT algorithm however, the MIZ extent within the Weddell Sea is again considerably larger than in the BT algorithm. For example, in September the NASA Team algorithm gives a climatological mean MIZ extent of 1.61 10^6 km^2, twice as large as that in the Bootstrap algorithm (0.83 10^6 km^2).

Finally, in the Indian and Pacific Ocean sectors [**Figure 6, 4th row**] the MIZ extent increases from March until November in both algorithms, retreating about a month after the peak extent in the pack ice is reached. However, in the Pacific Ocean sector [**Figure 6, bottom**], the MIZ comprises a larger percentage of the overall ice cover, being nearly equal in spatial extent in the

NASA Team algorithm, and even exceeding that of the pack ice in September (0.93 (MIZ) vs. 0.76 10^6 km^2 (pack ice)). This results in an annual mean extent of MIZ that exceeds that of the consolidated pack ice. This is the only region of Antarctica where this occurs. In the BT algorithm, the reverse is true, with again a larger annual extent of pack ice than MIZ.

While the above discussion focused on regional differences in the MIZ and the consolidated pack ice, the spatial extent and timing of coastal polynyas also varies between the algorithms. For example, in the Bellingshausen/Amundsen sea region, the maximum polynya area occurs in July in NT (0.17 10^6 km^2) and in December in the BT algorithm (0.11 10^6 km^2). Thus, while the overall maximum spatial extent in polynya area is not all that different in the two algorithms, the timing of when the maximum is reached differs by 5 months. This is also the case in the Pacific Ocean where the NASA Team algorithm reaches its largest spatial extent in polynya area in August (0.14 10^6 km^2) whereas the Bootstrap shows the maximum polynya area occurring in November (0.11 10^6 km^2). In other regions, such as the Indian Ocean, the Ross Sea and the Weddell Sea, the timing of the maximum polynya area occurs similarly in both algorithms, during November for the Indian Ocean and December in the Ross and Weddell Seas. The Ross and Weddell seas have the largest climatological polynya areas, 0.32 (NT)/0.26 (BT) 10^6 km^2 and 0.33 (NT)/0.30 (BT) 10^6 km^2, respectively.

3.2 Trends

3.2.1 Spatial Expansion/Contraction during September

As mentioned earlier, estimates of the outer ice edge location are similar between both algorithms. This is also true in terms of the locations where the outer edge is expanding or contracting. A way to illustrate this is shown in **Figure 7 (top)**, which shows a spatial map of the trend in the outer edge of the entire ice pack (defined as the 15% SIC contour, equivalent to the total sea ice extent) for both algorithms during the month of September, the month at which the ice pack generally reaches its maximum extent. Locations of northward expansion (red areas) and contraction (blue areas) are remarkably consistent between algorithms as well as the spatial extent of the expansion and contraction. In both algorithms the ice edge shows trends towards expansion within the Ross Sea, the Amundsen Sea and the Pacific and Indian Ocean sectors, except for the Davis Sea, where there is a trend towards contraction of the outer ice edge. The Bellingshausen and Weddell seas also show trends towards contraction of the outer ice edge.

While there is general consistency between the algorithms in both the location and changes of the outer ice edge over time, there are differences as to how the MIZ and pack ice widths are changing [**Figure 7, middle and bottom**]. In the BT algorithm, the MIZ width is a relatively constant ring around the edge of the consolidated pack ice, with little change over time. Thus, in the BT algorithm, the spatial pattern of expansion/contraction of the total ice cover in September is largely a result of the changes happening in the pack ice [Figure 7, bottom]. The NT algorithm on the other hand shows more pronounced changes in the MIZ, such that both the MIZ and the pack ice contribute to the observed spatial patterns and changes in the total ice cover. However, expansion/contraction of the MIZ and pack ice in the NT algorithm sometimes counter act each other. For example the contraction of the total ice edge the Bellingshausen Sea is a result of contraction of the consolidated ice pack while the MIZ width is generally increasing as a result of the MIZ moving further towards the continent. This is also true in the Weddell Sea and the Indian Ocean.

Somewhat surprisingly, the spatial pattern of expansion/contraction of the MIZ is broadly similar between both algorithms, despite overall smaller changes in the BT algorithm. This highlights the fact that the spatial trends in SIC are similar to the spatial trends in SIE as well as to the timing of advance/retreat/duration, so that the spatial trends in the MIZ and pack ice will show the same overall pattern because they rely on SIC. This also highlights the fact that the spatial pattern persists throughout the regional ice covered area, i.e. from the edge to the coastal area, which may imply that climate-related regional wind-driven changes at the ice edge are felt all the way to the coast. Alternatively it may imply that the ocean is also responding to the same climate-related wind changes, thus communicating the change all the way to the coast.

3.2.2 Circumpolar and Regional Daily Trends

Figure 8 summarizes daily circumpolar Antarctic trends in the pack ice, MIZ and polynyas for both algorithms, with monthly mean trends listed in **Table 3**. Both algorithms are broadly similar during the ice expansion phase, indicating positive trends in the consolidated ice pack and mostly negative trends in the MIZ until the pack ice reaches its peak extent. Thus, during these months, the positive trends in total SIE are a result of expansion of the consolidated pack ice. However, during retreat of the pack ice, trends in the MIZ switch to positive in the NASA Team algorithm while remaining mostly negative in the Bootstrap algorithm. At the same time, daily trends in the pack ice become noisy in the NT algorithm, alternating between positive and negative trends while trends remain positive in the BT algorithm. Table 3 indicates that the positive trends in the consolidated pack during the ice expansion/retreat phase (March through November) are statistically significant ($p<0.01$) for the BT algorithm, and from March to July in the NT algorithm ($p<0.05$). Trends in the MIZ are not statistically significant, except during September and October at the 90% confidence level in the NT algorithm. Trends in the pack ice are larger in the BT algorithm, particularly in August through November, in part reflecting a shrinking MIZ whereas the NT algorithm shows positive trends in the MIZ during those months. Trends in possible polynyas near the continent are negative throughout most of the year in both algorithms, except for December and January. However, none of the polynya trends are statistically significant.

Regionally, there are larger differences between the two algorithms, in particular with regards to the MIZ as already alluded to in Figure 7. To highlight the regional differences Figure 9 shows daily trends as a function longitude (x-axis) and month (y-axis) for the pack ice (top), the MIZ (middle) and coastal polynyas (bottom). Monthly trends averaged for each of the 5 sectors are also listed in Table 3. Focusing first on the pack ice trends, we find the spatial patterns of positive and negative trends are generally consistent between both algorithms, though the magnitudes of the trends tend to be larger in the Bootstrap algorithm, which in turn impacts the statistical significance of the trends (see also Table 3). For example, in the Ross Sea, the largest regional positive trends in total SIE are found at a rate of 119,000 km^2 per decade [e.g. *Turner et al.*, 2015], accounting for about 60% of the circumpolar ice extent increase. In the BT algorithm this is entirely a result of large positive trends in the pack ice from

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March to November ($p<0.01$). While the Ross Sea sector trends from the NT algorithm are spatially consistent with the pack ice trends shown in the BT algorithm, trends are only statistically from April to June ($p<0.05$). Instead, statistically significant positive trends in the MIZ dominate August to October in the NT algorithm, which is also the season with the largest overall trends in the SIE in this region (e.g. Spring). This would suggest perhaps different interpretation of processes impacting the overall ice expansion in the Ross Sea depending on which algorithm is used. Several studies have suggested a link between sea ice anomalies in the Ross Sea and the wind-field associated with the Amundsen Sea Low (ASL) [e.g. *Fogt et al*., 2012; *Hosking et al*., 2013; *Turner et al*., 2012]. The strengthened southerly winds over the Ross Sea cause a more compacted and growing consolidated ice cover in the BT algorithm at the expense of a shrinking MIZ, whereas in the NT algorithm the area of the MIZ is increasing more than the pack ice during autumn, which may additionally suggest an oceanic influence. While this is true as averaged over the entire Ross Sea sector, Figure 9 highlights that the area-averaged trends hide spatial variability, with positive trends in the MIZ in the eastern part of the Ross Sea and negative trends in the western part.

While the magnitude of pack ice trends are generally larger in the Bootstrap algorithm, there are some exceptions. For example, in the Weddell Sea, the NT algorithm exhibits larger negative trends in the pack ice between June and November whereas the BT algorithm shows mixed positive and negative trends of smaller magnitude. This is also true with regards to MIZ trends during these months. However, none of the trends are statistically significant. In the Weddell Sea, expansion of the overall ice cover is only statistically significant during the autumn months (MAM) [e.g. *Turner et al*., 2015]. During this time-period, both algorithms agree on statistically significant positive trends in the pack ice area, that extend through May for the NT algorithm ($p<0.05$) and through June for the BT algorithm ($p<0.05$). Statistically significant trends are also seen during March in the MIZ and polynya area ($p<0.05$), with larger trends in the NT algorithm ($p<0.01$). Thus, overall expansion of sea ice in the Weddell during autumn is in part driven by expansion of the MIZ early in the season, after which it is controlled by further expansion of the consolidated pack.

In contrast, the Bellingshausen/Amundsen Sea is a region undergoing declines in the overall ice cover [e.g. *Parkinson and Cavalieri*, 2012; *Stammerjohn et al*., 2012]. Separating out trends for both the pack ice and the MIZ reveals negative trends in the consolidated pack ice during the start of ice expansion in March and April and also during initial retreat (September and October) in both algorithms, though none of the trends are statistically significant [Table 3]. This is the only region where the BT algorithm does not show statistically significant trends in the pack ice. Negative trends are also found in the MIZ during the initial ice advance phase in both algorithms though again none of them are statistically significant. Interestingly, during June and July, the NT algorithm shows large positive trends in the pack ice ($p<0.01$) at the expense of negative trends in the MIZ, though the MIZ trends are not statistically significant and are smaller than the positive trends in the pack ice. While the MIZ trends are not statistically significant, these results are consistent with the observation that the SIE trends in the Bellingshausen/Amundsen Sea are largely wind-driven, so it would be expected that the wind-driven compaction would lead to decreased MIZ and increased pack ice. Finally, both algorithms indicate statistically significant positive trends in coastal polynyas during November for this region (with larger trends in the NT algorithm, +1,000 km^2a^{-1} ($p<0.05$) and +600 km^2a^{-1} ($p<0.10$), respectively).

Finally, in the Pacific and Indian Oceans we again see spatial consistency in pack ice and MIZ trends for both algorithms, with generally larger (smaller) pack ice (MIZ) trends for the BT algorithm, though trends are closer in magnitude in the Pacific sector from March to July. The BT algorithm indicates statistically significant trends in the pack ice from March to November in both sectors ($p<0.05$), while trends in overall SIE are only statistically significant in the Indian Ocean during MAM and JJA. The inconsistency in statistical significance between total SIE and pack ice trends is likely a result of corresponding negative trends in the MIZ, particularly in the Pacific sector, though the negative BT MIZ trends are not statistically significant. The NT algorithm mostly has statistically significant trends in the pack ice during the initial expansion phase only ($p<0.05$). In the Indian Ocean, there are also significant positive trends in MIZ during March ($p<0.05$) and April ($p<0.10$) and also June and July ($p<0.10$) that would contribute towards overall positive SIE trends. Both algorithms suggest an increase in polynya area from March to May ($p<0.05$) in the Pacific sector, and the NT for the Indian sector in March ($p<0.05$).

In summary, while the magnitude of trends differs between both algorithms, there is general spatial consistency in the patterns of positive and negative trends in the consolidated pack ice and the MIZ. Results suggest that positive trends in total SIE are generally a result of statistically significant positive trends in the consolidated pack ice in the BT algorithm in all sectors of the Antarctic, except for the Bellingshausen/Amundsen Sea sector and the Weddell Sea during ice retreat. The NT algorithm on the other hand suggests more instances of statistically significant positive trends in the MIZ, though this is highly regionally dependent. Finally, the largest expansion of polynya area is found in the Bellingshausen/Amundsen Sea during November, whereas small increases in polynya area are found in both the Indian and Pacific sector during the ice expansion phase. Outside of these regions/months, no significant changes in coastal polynya area are observed.

3.2.3 Seasonal Trends in MIZ and Pack Ice Width

Finally we compute the overall width of the MIZ and pack ice following *Strong and Rigor* [2013] and produce seasonal means. Time-series of seasonal means of the circumpolar MIZ width and pack ice width are shown in **Figure 10** for all seasons except summer when the results are noisy. As we may expect following the previous results, the NASA Team algorithm consistently shows greater MIZ width and smaller pack ice width than the Bootstrap algorithm. During autumn (MAM) however, the differences between the algorithms are reduced, both for the MIZ and pack ice widths. In addition, during this season, trends in the MIZ and pack ice are largely consistent, with no trend in the MIZ and increases in the pack ice on the order of 21.2 km dec^{-1} and 20.0 km dec^{-1} ($p<0.01$) for the BT and NT algorithms, respectively.

During winter (JJA) and spring (SON) however, the NT and BT algorithms exhibit opposing trends in the MIZ with the NT algorithm indicating an increase and the BT a decrease. The largest positive trend in the MIZ width occurs during spring at a rate of +10.3 km dec^{-1} ($p<0.01$) in the NT algorithm, indicating a 6% widening over the satellite record. This widening is a result of the MIZ moving slightly equatorward rather than expanding southwards. However, despite a statistically significant trend, there remains substantial interannual variability in the SON MIZ width, with the maximum width recorded in 2003 (310 km) and the minimum in 1985 (217 km), with a mean SON MIZ width of 248 km. The trend during winter is considerably smaller at +2.7 km dec^{-1}, as a result of expansion equatorward and southwards, yet it is not statistically significant.

For the pack ice, both algorithms show statistically significant positive trends towards increased width of the pack ice, which are also nearly identical during winter at +18.7 and +18.1 km dec^{-1} ($p<0.01$) for the BT and NT algorithms, respectively. This represents a widening of the pack ice of approximately 11% from 1979 to 2014 during winter. As one may expect, differences in the pack ice width between the algorithms are largely found in spring as a result of the MIZ expanding in the NT algorithm. During SON the trends in the width of the pack ice are slightly smaller than during winter, with trends of +16.7 (BT, $p<0.01$) and +10.0 (NT, $p<0.05$) km dec^{-1}.

Interestingly, the interannual variability in the pack ice is similar between both data sets, showing correlations between the two algorithms of 0.92 (JJA), 0.77 (SON) and 0.96 (MAM). For the MIZ, interannual variability is generally about twice as large in the NASA Team algorithm and the two data sets are not highly correlated except for autumn, with correlations of 0.39 (JJA), 0.43 (SON), and 0.67 (MAM).

4. Implications for a Seabird

Here we use data on the MIZ and the consolidated ice pack from both algorithms to understand the role of sea ice habitat on breeding success of a seabird, the snow petrel *Pagodroma nivea*. As mentioned in the introduction, the MIZ is a biologically important region because it is an area of high productivity and provides access to food resources needed by seabirds [*Ainley et al*., 1992]. During winter, productivity is reduced at the surface in open water, while it is concentrated within the ice habitat, especially within the ice floes [*Ainley et al.,* 1986]. This patchy distribution of food availability within the MIZ and pack ice provides feeding opportunities for seabirds such as the snow petrel. Observations suggest that the snow petrel forages more successfully in areas close to the ice edge and within the MIZ than in consolidated ice conditions [*Ainley et al.,* 1984, 1992].

Breeding success of snow petrels depends on sufficient body condition of the females, which in part reflects favorable environmental and foraging conditions prior to the breeding season. Indeed, female snow petrels in poor early body condition are not able to build up the necessary body reserves for successful breeding [*Barbraud and Chastel*, 1999]. Breeding success was found to be higher during years with extensive sea ice cover during the preceding winter [*Barbraud and Weimerskirch*, 2001]. This is in part because winters with extensive sea ice are associated with higher krill abundance the following summer [*Flores et al*., 2012; *Loeb et al.,* 1993; *Atkinson et al.,* 2004], thereby increasing the resource availability during the breeding season. However, extensive winter sea ice may protect the under ice community from predation and thus reduce food availability, in turn affecting breeding success [*Olivier et al.,* 2005]. By distinguishing between the areas of MIZ and pack ice, we can expect a better understanding of the role of sea ice on food availability and hence breeding success of snow petrels.

In the following, we expect that an extensive pack ice may reduce breeding success by protecting the under ice community from predation, while an extensive MIZ may increase breeding success by providing easier access to foraging. With the classifications as defined by both algorithms we calculated the MIZ and pack ice area in a wide rectangular sector defined by the migration route of the snow petrel [*Delord et al.,* 2013] from April to September [see **Table 4** for latitude and longitude limits]. We then averaged the MIZ and pack ice extents over the entire winter from April to September. We next employed a logistic regression approach to study the effects of MIZ and pack ice area within this sector and evaluate the impacts on breeding success the following summer. The response variable was the number of chicks C_t in a breeding season *t*, from 1979 to 2014 collected at Terre Adélie, Dumont D'Urville [*Barbraud and Weimerskirch*, 2001, *Jenouvrier et al*., 2005].

Effects of MIZ and pack ice area were analyzed using Generalized Linear Models (GLM) with logit-link functions and binomial errors fitted in R using the package glm. We selected the best model according to the information criteria AIC, the chosen model being the one that minimizes the AIC, and the ability of two models to describe the data was assumed to be "not different" if the difference in their AIC was < 2 [*Burnham and Anderson*, 2002]. While non-linear models may be more appropriate as ecological system relationships are likely more complex than linear relationships, without *a priori* knowledge of the mechanisms that could lead to such non-linear relationships, it is extremely difficult to interpret the results.

Table 5 summarizes model selection. The model with the lowest AIC suggests an effect of the consolidated pack ice area on breeding success as derived from the Bootstrap algorithm. The MIZ and pack ice areas calculated from the NT algorithm are not supported (AIC difference>2). As expected we found that the effect of consolidated pack ice on breeding success was negative [**Figure 11**]. In other words, more extensive consolidated pack ice during winter tends to reduce breeding success the following summer by limiting foraging opportunities. The effect of the MIZ however was uncertain, contrary to what one may expect given the increased opportunities for foraging within the MIZ. However, if we had only used ice classifications based on the NASA Team algorithm, the model with the lowest AIC would have suggested an importance of the MIZ. We would have then concluded a negative effect of the MIZ on the breeding success of snow petrels, contrary to what one may expect given that the MIZ is the main feeding habitat of the species. By using both algorithms, we instead conclude that the breeding success of snow petrels is negatively affected by the pack ice area as calculated with the Bootstrap algorithm.

5. Discussion

The positive trends in Antarctic sea ice extent are currently poorly understood and are at odds with climate model forecasts that suggest the sea ice should be declining in response to increasing greenhouse gases and stratospheric ozone depletion [e.g. *Turner et al*., 2013; *Bitz and Polvani*, 2012; *Sigmond and Fyfe*, 2010]. However, several modeling studies, such as those used in the phase 5 Coupled Model Intercomparison Project (CMIP5), have suggested that the sea ice increase over the last 36 years remains within the range of intrinsic of internal variability [e.g. *Bitz and Polvani*, 2012; *Turner et al*., 2013; *Mahlstein et al*., 2013; *Polvani and Smith,* 2013; *Swart and Fyfe*, 2013]. Earlier satellite from the 1960s and 1970s and from ship observations suggest periods of high and low sea ice extent, and thus high natural variability [*Meier et al*., 2013; *Gallaher et al*., 2014]. Further evidence comes from ice core climate records, which suggest that the climate variability observed in the Antarctic during the last 50 years remains within the range of natural variability seen over the last several hundred to thousands of years [*Thomas et al*., 2013; *Steig et al*., 2013]. Thus, we may require much longer records to properly assess Antarctic sea ice trends in contrast to the Arctic, where negative trends are outside the range of natural variability and are consistent with those simulated from climate models.

While many assessments of how Antarctic sea ice trends and variability compare with climate models have focused on the net circumpolar sea ice extent, it is the regional variability that becomes more important. For example, *Hobbs et al*. [2015] argue that when viewing trends on a regional basis, the observed summer and autumn trends fall outside of the range of natural variability as simulated by present-day climate models, with the signal dominated by opposing trends in the Ross Sea and the Bellingshausen/Amundsen seas. These results have questioned the ability of climate models to correctly simulate processes at the regional level and within the southern ocean-atmosphere-sea ice coupled system.

The net take-away point from these studies is that the net circumpolar changes in sea ice extent do not enhance our understanding of how the Antarctic sea ice is changing. Instead our focus should be on what drives regional and seasonal sea ice changes, including feedbacks and competing mechanisms. This study aims to better understand regional and total changes in Antarctic sea ice by focusing not only on the total ice area, but also on how the consolidated pack ice, the marginal ice zone and coastal polynyas are changing. Differences in climatologies and trends of the different ice classes may suggest different processes are likely contributing to their seasonal and interannual variability. In addition, the different contributions of ice types towards the overall expansion of the Antarctic sea ice cover between algorithms may in turn influence attribution of the observed increase in SIE. For example, within the highly dynamic MIZ region, intense atmosphere-ice-ocean interactions take place [e.g. *Lubin and Massom*, 2006] and thus an expanding or shrinking MIZ may help to shed light on the relative importance of atmospheric or oceanic processes impacting the observed trends in total SIE. Another issue is whether or not new ice is forming along the outer edge of the pack ice or if it is all being dynamically transported from the interior.

However, a complication exists, what sea ice algorithm should be used for such assessments? In this study we focused on using passive microwave satellite data for defining the different ice types as it is the longest time-series available and is not limited by polar darkness or clouds. However, results may be highly dependent on which sea ice algorithm is used to look at the variability in these ice classes, which will also be important in assessing processes contributing to these changes as well as implications of these changes to the polar marine ecosystem. In this study, the positive trends in circumpolar sea ice extent over the satellite data record are primarily driven by statistically significant trends ($p<0.05$) in expansion of the consolidated pack ice in both sea ice algorithms. However, an exception occurs in the NASA Team sea ice algorithm after the ice pack reaches its seasonal maximum extent when the positive trends in the pack ice are no longer as large, nor statistically significant. Instead, positive trends in the MIZ dominate during September and October ($p<0.10$). This is in stark contrast to the Bootstrap algorithm, which shows a declining MIZ area from March through November.

The algorithms also give different proportions of how much the total ice cover consists of consolidated ice, MIZ or polynya area. In some regions, such as the Pacific Ocean sector, the NT algorithm suggests the MIZ is the dominant ice type whereas in the BT algorithm, the pack ice is dominant, which is true for all sectors analyzed in the Bootstrap algorithm. Considering the circumpolar ice cover, the MIZ in the NASA Team algorithm is on average twice as large as in the Bootstrap algorithm. In the Arctic, *Strong and Rigor* [2013] found the NASA Team algorithm gave about three times wider MIZ than the Bootstrap algorithm. In this case, the Bootstrap results agreed more with MIZ widths obtained from the National Ice Center (NIC).

Differences between the algorithms are not entirely surprising as the two algorithms use different channel combinations with different sensitivities to changes in physical temperature. In addition, the NT uses previously defined tie points for passive microwave radiances over known ice-free ocean, and ice types, defined as type A and B in the Antarctic, as the radiometric signature between first-year and multiyear ice in the Antarctic is lost. The ice is assumed to be snow-covered when selecting the tie points, which can result in an underestimation of sea ice concentration if the ice is not snow covered. In addition, seasonal variations in sea ice emissivity can be very large, leading to seasonal biases in either algorithm. The advantage of the Bootstrap algorithm is that the ice concentration can be derived without an *a priori* assumption about ice type, though consolidated ice data points are sometimes difficult to distinguish from mixtures of ice and open ocean due to the presence of snow cover, flooding or roughness effects.

While one may expect the Bootstrap algorithm to provide more accurate results than the NASA Team algorithm, near the coast the BT algorithm has been shown to have difficulties when temperatures are very cold. Because the NT algorithm uses brightness temperature ratios it is largely temperature independent. However, during summer or for warmer temperatures, the NT algorithm may indeed be biased towards lower sea ice concentrations whereas the BT algorithm may be biased towards higher ice concentrations [e.g. *Comiso et al.,* 1997]. In the Arctic, the MIZ is not only driven by wave mechanics and flow breaking (dynamic origin), but also by melt pond processes in summer (thermodynamic origin) [*Arnsten et al*., 2015]. Thus, larger sensitivity of the NT algorithm to melt processes may be one reason for the large discrepancy observed in the Arctic. Interestingly, the BT algorithm shows less interannual variability in the ice types compared to NT (as shown by the smaller standard deviations). This would in turn influence assessments of atmospheric or oceanic conditions driving observed changes in the ice cover. What is clear is that more validation is needed to assess the accuracy of these data products, especially for discriminating the consolidated pack ice from the MIZ. Errors likely are larger in the MIZ because of the coarse spatial resolution of the satellite sensors. Another concern is that mapping of the consolidated ice pack does not always mean a compact ice cover. The algorithms may indicate 100% sea ice concentration (e.g. a consolidated pack ice), when in reality the ice consists of mostly brash ice and small ice floes more representative of the MIZ. Future work will focus on validation with visible imagery.

Conclusions

Total Antarctic sea ice cover is expanding in response to atmospheric and oceanic variability that remains to be fully understood. One may expect that these increases would also be manifested in either equatorward progression of the MIZ or the consolidated pack ice or both. In this study we identified several different ice categories using two different sets of passive microwave sea ice concentration data sets. The algorithms are in agreement as to the location of the northern edge of the total sea ice cover, but differ in regards to how much of the ice cover consists of the marginal ice zone, the consolidated ice pack, the size of potential polynyas as well as the amount of broken ice and open water within the consolidated ice pack. Here we use sea ice concentration thresholds of $0.15 \leq SIC < 0.80$ to define the width of the MIZ and $0.80 \leq SIC \leq 1.0$ to define the consolidated pack ice. Yet applying the same thresholds for both sea ice algorithms results in a MIZ from the NASA Team algorithm that is on average twice as large as in the Bootstrap algorithm and considerably more broken ice within the consolidated pack ice. Total potential coastal polynya areas ($SIC \leq 0.80$) also differ between the algorithms, though differences are generally smaller than for the other ice types analyzed.

While the spatial extents of the different ice classes may differ, the seasonal cycle is generally consistent between both algorithms. Climatologically, the advance of the consolidated ice pack happens over a much longer period (~7-8 months) than the retreat (~4-5 months), while the MIZ exhibits a longer advance period (~8-10 months). This seasonal cycle in expansion/contraction of the ice cover is in general agreement with results by *Stammerjohn et al*. [2008] who showed sea ice retreat generally begins in September at the outer most edge of the sea ice and continues poleward over the next several months. However, what these results show is that while the pack ice starts to retreat around September, this in turn results in a further expansion of the MIZ, the amount of which is highly dependent on which algorithm is used. The timing of when the maximum polynya extent is reached however can differ by several months between the algorithms in regions such as the Bellingshausen/Amundsen Sea and the Pacific Ocean.

Since the MIZ is an important region for phytoplankton biomass and productivity [e.g. *Park et al.,* 1999], mapping seasonal and interannual changes in the MIZ is important for understanding changes in top predator populations and distributions. However, as mentioned above, results are highly dependent on which sea ice algorithm is used for delineating the MIZ. Furthermore, accurately mapping the extent of the MIZ from coarse resolution satellite data such as that from passive microwave sensors remains problematic. The MIZ is very dynamic in space and time, making it challenging to provide precise delimitations using sea ice concentrations that are in turn sensitive to melt processes and surface conditions. Nevertheless we examined the impact the winter MIZ and consolidated pack ice area as derived from both algorithms would have on the breeding success of snow petrels the following summer. The different proportions of MIZ and consolidated pack ice between algorithms affected the inferences made from models tested even if trends were of the same sign. Given the sensitivity of the relationships between ice types and breeding success of this species, caution is warranted when doing this type of analysis as different relationships may emerge as a function of which sea ice data set is used in the analysis. Further work is needed to validate the accuracy of the ice types from passive microwave.

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Tables

Table 1. Sea ice categories defined in this study.

Region	Definition	Binary Classification Value
Outer MIZ	Outer region of sea ice with ice concentration between 15% and 80%	16
Inner Polynya	Region near the coast with concentration < 80% south of 80% concentration	32
Distant ice	Scattered sea ice regions north of MIZ, possibly islands or atmospheric storms	48
Pack Ice	Ice concentration > 80%	80
Inner open water	Concentration < 15% south of MIZ	112
Open pack ice	Concentration > 15% and < 80% within consolidated ice region	128

835 **Table 2.** Monthly mean extents of the different ice classes. Values are only listed for the consolidated
836 pack ice, the marginal ice zone and the potential coastal polynya area. Values are listed in 10^6 km^2.

	NASA Team			Bootstrap		
Total Antarctic						
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	2.44	0.31	1.94	2.06	0.36	2.27
February	1.51	0.20	1.18	1.25	0.22	1.49
March	2.03	0.25	1.42	1.65	0.24	2.08
April	2.71	0.42	3.27	1.84	0.31	4.62
May	3.07	0.62	5.85	1.97	0.37	7.79
June	3.63	0.69	8.22	2.31	0.37	10.65
July	4.03	0.66	10.31	2.53	0.35	13.00
August	4.75	0.62	11.29	2.88	0.34	14.49
September	5.41	0.63	11.31	3.19	0.35	14.89
October	5.41	0.74	10.83	3.39	0.38	14.16
November	5.62	1.02	7.92	3.69	0.63	11.10
December	5.05	0.88	3.81	3.56	0.81	5.43
Annual	3.83	0.59	6.49	2.54	0.39	8.53
Ross Sea						
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	0.83	0.10	0.28	0.68	0.13	0.40
February	0.47	0.05	0.11	0.40	0.07	0.19
March	0.62	0.10	0.34	0.45	0.09	0.57
April	0.60	0.15	1.22	0.37	0.09	1.63
May	0.60	0.15	1.93	0.36	0.08	2.43
June	0.67	0.15	2.29	0.40	0.08	2.91
July	0.75	0.14	2.63	0.44	0.07	3.27
August	0.91	0.12	2.67	0.50	0.07	3.43
September	0.98	0.13	2.64	0.54	0.08	3.46
October	0.86	0.17	2.73	0.55	0.09	3.39
November	0.89	0.30	2.19	0.59	0.17	2.87
December	1.17	0.32	0.92	0.76	0.26	1.45
Annual	0.78	0.16	1.67	0.50	0.11	2.18
Bellinghausen/Amundsen Sea						
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	0.35	0.07	0.32	0.29	0.08	0.38
February	0.28	0.05	0.16	0.22	0.06	0.21
March	0.37	0.06	0.10	0.27	0.07	0.21
April	0.50	0.07	0.20	0.29	0.06	0.48
May	0.54	0.12	0.42	0.31	0.06	0.83
June	0.63	0.16	0.66	0.37	0.05	1.17
July	0.68	0.17	0.89	0.43	0.05	1.45
August	0.79	0.15	1.01	0.51	0.05	1.60
September	0.84	0.14	1.00	0.51	0.05	1.62
October	0.73	0.14	0.97	0.46	0.06	1.50
November	0.69	0.13	0.86	0.45	0.08	1.25
December	0.57	0.11	0.55	0.42	0.11	0.72
Annual	0.58	0.12	0.60	0.38	0.06	0.96
Weddell Sea						
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	0.72	0.12	0.93	0.60	0.11	1.07
February	0.37	0.08	0.70	0.30	0.06	0.84
March	0.47	0.06	0.87	0.38	0.04	1.07
April	0.69	0.07	1.49	0.46	0.05	1.87
May	0.82	0.10	2.53	0.54	0.06	3.04
June	0.96	0.10	3.62	0.64	0.06	4.21
July	1.08	0.08	4.51	0.65	0.05	5.16

August	1.39	0.08	4.73	0.75	0.06	5.62
September	1.62	0.09	4.67	0.83	0.06	5.78
October	1.51	0.13	4.42	0.84	0.07	5.48
November	1.53	0.31	3.34	0.86	0.14	4.56
December	1.87	0.33	1.65	1.24	0.30	2.33
Annual	1.09	0.13	2.80	0.67	0.09	3.43
			Indian Ocean			
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	0.26	0.01	0.16	0.23	0.02	0.18
February	0.15	0.01	0.06	0.14	0.01	0.08
March	0.24	0.01	0.03	0.24	0.02	0.06
April	0.43	0.01	0.16	0.35	0.05	0.30
May	0.57	0.13	0.55	0.43	0.08	0.80
June	0.75	0.14	1.04	0.53	0.08	1.40
July	0.82	0.13	0.59	0.54	0.07	2.05
August	0.87	0.11	2.09	0.57	0.06	2.59
September	1.03	0.12	2.24	0.67	0.07	2.81
October	1.33	0.15	2.02	0.87	0.08	2.71
November	1.62	0.18	1.10	1.13	0.13	1.75
December	0.94	0.07	0.37	0.74	0.09	0.55
Annual	0.75	0.10	0.96	0.54	0.06	1.29
			Pacific Ocean			
Month	**MIZ**	**Polynya**	**Pack Ice**	**MIZ**	**Polynya**	**Pack Ice**
January	0.28	0.01	0.24	0.25	0.02	0.26
February	0.23	0.01	0.14	0.19	0.02	0.17
March	0.34	0.02	0.10	0.31	0.03	0.15
April	0.51	0.05	0.20	0.38	0.06	0.34
May	0.54	0.11	0.43	0.35	0.10	0.67
June	0.61	0.14	0.62	0.38	0.11	0.93
July	0.70	0.14	0.73	0.45	0.10	1.10
August	0.81	0.14	0.79	0.54	0.09	1.19
September	0.93	0.14	0.76	0.63	0.10	1.17
October	0.96	0.14	0.71	0.68	0.09	1.08
November	0.88	0.10	0.44	0.66	0.11	0.70
December	0.49	0.05	0.30	0.41	0.06	0.38
Annual	0.61	0.09	0.46	0.44	0.07	0.69

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Table 3. Comparison of trends in the marginal ice zone, polynyas and the consolidated pack ice for March through November (1979 to 2013) for both the NASA Team and Bootstrap sea ice algorithms. Trends are computed in km^2 per year. Statistical significance at the 90th, 95th and 99th percentiles are denoted by $^{+}$, $^{++}$ and $^{+++}$, respectively. Results are only shown for March through November.

	NASA Team			Bootstrap		
			Total Antarctic			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	+2,900	+700	+14,300^{+++}	+4,900	-300	+18,000^{+++}
April	-8,200	-500	+29,600^{+++}	-10,400	-1000	+38,000^{+++}
May	-9,400	-2,400	+35,000^{+++}	-8,500	-2,200	+41,300^{+++}
June	-10,100	-5,100	+32,900^{+++}	-9,200	-2,400	+52,400^{+++}
July	-3,400	-5,700	+22,600^{++}	-6,600	-2,300	+25,200^{+++}
August	+3,700	-3,600	+11,900	-6,200	-1,500	+31,800^{+++}
September	+10,900^{+}	-3,300	+3,700	-4,200	-1,400	+39,400^{+++}
October	+9,600^{+}	-4,900	+7,300	-4,300	-2,900	+25,200^{+++}
November	+2,600	-4,000	+6,000	-9,800	-3,700	+29,400^{+++}
			Ross Sea			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	+2,800	+300	+4,100	+1,500	-100	+7,700^{++}
April	-1,400	-1,500	+12,400^{++}	-2,700	-1,400	+14,600^{+++}
May	+2,600^{+}	-2,200	+11,100^{++}	-700	-1,100	+16,400^{+++}
June	0	-1,200	+12,700^{++}	-2,000	-800	+18,600^{+++}
July	+700	-700	+8,200^{+}	-700	-600	+14,200^{+++}
August	+6,900^{+++}	-1,600	+3,400	+500	-900	+12.700^{+++}
September	+4,800^{++}	-1,200	+1,800	-700	-700	+15,100^{+++}
October	+5,400^{+++}	-2,300	+7,300^{+}	+1,100	-1,300	+17,600^{+++}
November	+3,700^{+}	-1,200	+4,400	-700	-1,600	+13,700^{+++}
			Bellinghausen/Amundsen Sea			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	-7,500	-1,500	-2,800	-2,400	-1,700	-7,500
April	-8,600	-800	-3,100	-3,100	-900	-7,700
May	-8,600	-1,200	+2,800	-2,100	-800	-4,600
June	-6,800	-2,600	+8,500^{+++}	-2,100	-500	+1,300
July	-3,500	-2,500	+10,100^{+++}	-700	-700	+4,000
August	-1,200	-700	+7,000^{+}	+500	-200	+2,700
September	+2,600	-500	-300	+1,500^{+}	-200	-100
October	-800	-200	-1,100	-300	-200	-1,800
November	+2,600	+1,000^{++}	-1,400	+1,600	+600^{+}	+300
			Weddell Sea			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	+4,100^{++}	+1,300^{++}	+9,500^{++}	+2,600^{++}	+600^{+}	+13,600^{+++}
April	+1,700	+400	+12,000^{++}	-2,000	+200	+19,200^{+++}
May	-100	-400	+9,400^{++}	-1,500	-600	+14,400^{+++}
June	-2,300	-900	+100	-4,800	-600	+8,800^{++}
July	-2,900	-1,100	-4,800	-4,200	-400	-100
August	-1,700	-700	-5,100	-3,500	-100	+600
September	-200	-600	-100	-2,900	-200	+4,900
October	+4,300	-1,400	-8,800	-3,700	-700	+3,400
November	-2,100	-3,500	-4,700	-6,300	-2,200	+700
			Indian Ocean			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	+2,500^{++}	+300^{+}	+9,500^{++}	+2,100^{++}	+300^{+}	+1,500^{++}
April	+1,500^{+}	+600^{+}	+12,000^{++}	-500	+300	+5,200^{+++}
May	-200	+600^{+}	+9,400^{++}	-1,400	+100	+7,700^{+++}
June	+2,600^{+}	-500	+100	+900	-300	+7,600^{++}
July	+3,500^{+}	-700	-4,800	+100	-100	+7,600^{++}
August	+1,300	-300	-5,100	-1,500	0	+9,900^{+++}

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September	+4,600^{+}	-900	-100	+400	-100	+6,700^{++}
October	+1,900	-900	-8,800	-200	-400	+8,600^{++}
November	+2,000	-200	-4,700	-500	-400	+8,700^{++}
			Pacific Ocean			
Month	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**	**dMIZ/dt**	**dPoly/dt**	**dPack/dt**
March	+1,100	+400^{+++}	+2,800^{+++}	+1,100^{++}	+600^{+++}	+1,500^{++}
April	-1,400	+800^{+++}	+5,600^{+++}	-2,100	+700^{+++}	+5,200^{+++}
May	-3,000	+800^{++}	+6,100^{+++}	-2,800	+300^{+}	+7,700^{+++}
June	-3,600	+200	+7,000^{+++}	-1,200	-300	+7,600^{++}
July	-1,300	-700	+5,700^{++}	-100	-400	+7,600^{++}
August	-1,500	-300	+2,200	-2,200	-300	+9,900^{+++}
September	-900	-100	+1,400	-2,500	-300	+6,700^{++}
October	-1,200	0	+3,700^{++}	-1,100	-300	+8,600^{++}
November	-3,500	-500	+4,400^{++}	-4,000	-200	+8,700^{++}

Table 4. Monthly latitude/longitude corners used for assessment of sea ice conditions on snow petrel breeding success.

	April	**May**	**June**	**July**	**August**	**September**
$Latitude_1$	-65	-65	-65	-65	-65	-65
$Latitude_2$	-60	-60	-60	-60	-55	-55
$Longitude_1$	90	65	50	35	25	50
$Longitude_2$	120	120	120	120	115	140

Table 5. Results of model selection for the relationship between pack ice and MIZ on breeding success of snow petrels. Model selection is based on the lowest AIC score, highlighted in gray. The slope of the regression is also shown.

Model	**Variable**	**AIC**	**Slope**
Bootstrap	MIZ	931.86	-0.57544
NASA Team	MIZ	887.11	-1.31416
Bootstrap	Pack ice	879.17	-1.04223
NASA Team	Pack ice	927.8	-0.41916

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Figure 1. Example of a radial profile from 50 to 90S at -11.60 degrees West on 3 September 1990, showing the different sea ice classifications found along this transect.

Figure 2: Samples of ice classification on day 70 (March) and day 273 (September) 2013. Results are shown for both the NASA Team (top) and Bootstrap (bottom) sea ice algorithms. The MIZ (red) represents regions of sea ice concentration between 15 and 80% from the outer ice edge, the pack ice is shown in light purple, representing regions of greater than 80% sea ice concentration. Orange regions within the pack ice represent coherent regions of less than 80% sea ice concentration, pink areas open water and green regions of less than 80% sea ice concentration near the Antarctic coastline. Dark blue represents the ocean mask applied to remove spurious ice concentrations beyond the ice edge.

Figure 3. Southern hemisphere regions as defined by *Parkinson and Cavalieri* [2012].

Figure 4. Location of the mean 1981-2010 outer marginal ice edge for both the NASA Team and Bootstrap algorithms.

Figure 5. Long-term (1979-2013) seasonal cycle in total Antarctic extent of the consolidated pack ice, the outer marginal ice zone, polynyas, open pack ice (or broken ice within the pack ice), and inner open water. There are essentially no scattered ice floes outside of the MIZ. NASA Team results are shown on the left and the Bootstrap on the right.

Figure 6. Long-term (1979-2013) seasonal cycle in regional sea ice extent of the consolidated pack ice, the outer marginal ice zone, polynyas, open pack ice (or broken ice within the pack ice), and inner open water. Results for the NASA Team algorithm are shown on the left and Bootstrap on the right, and for the Ross, Bellingshausen/Amundsen, Weddell, Indian and Pacific Oceans.

Figure 7. Expansion (red) or contraction (blue) of the outer ice edge (top), the width of the marginal ice zone (middle) and the width of the pack ice from 1979 to 2013 during the month of September.

Figure 8. Daily trends (1979 to 2013) in the consolidated pack ice, the outer MIZ and potential coastal polynyas for the entire Antarctic sea ice cover for the NASA Team (left) and Bootstrap (right) algorithms. Trends are provided in 10^6 km^2 a^{-1}.

Figure 9. Daily (1979-2013) trends in regional sea ice extent of the consolidated pack ice (top), the outer marginal ice zone (middle) and potential coastal polynyas (bottom). Results for the NASA Team algorithm (left) and Bootstrap (right) are shown as a function of longitude. Trends are provided in 10^6 km^2 a^{-1}. Note the difference in color bar scales.

Figure 10. Time-series of seasonal mean JJA (top), SON (middle) and MAM (bottom) marginal ice zone (left) and consolidated pack ice (right) for both sea ice algorithms; NASA Team is shown in red, Bootstrap in black. Shading represents one standard deviation. Note the difference in y-axis between the pack ice and the MIZ plots.

Figure 11. Breeding success of snow petrel (top) and effect of the Bootstrap pack ice on the breeding success of snow petrels (bottom).

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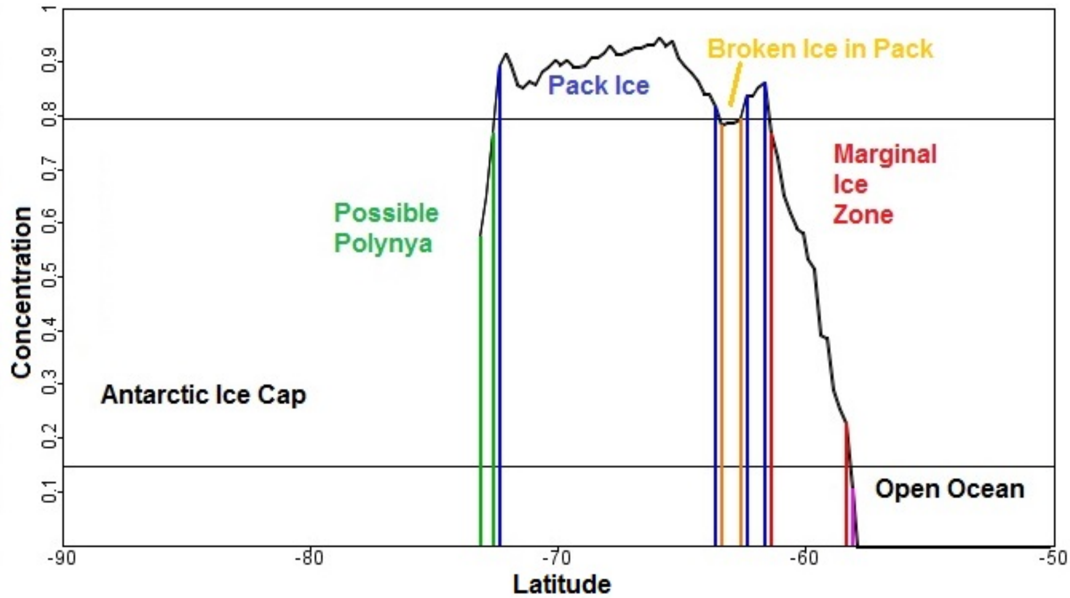

Figure 1. Example of a radial profile from 50 to 90S at -11.60 degrees West on 3 September 1990, showing the different sea ice classifications found along this transect.

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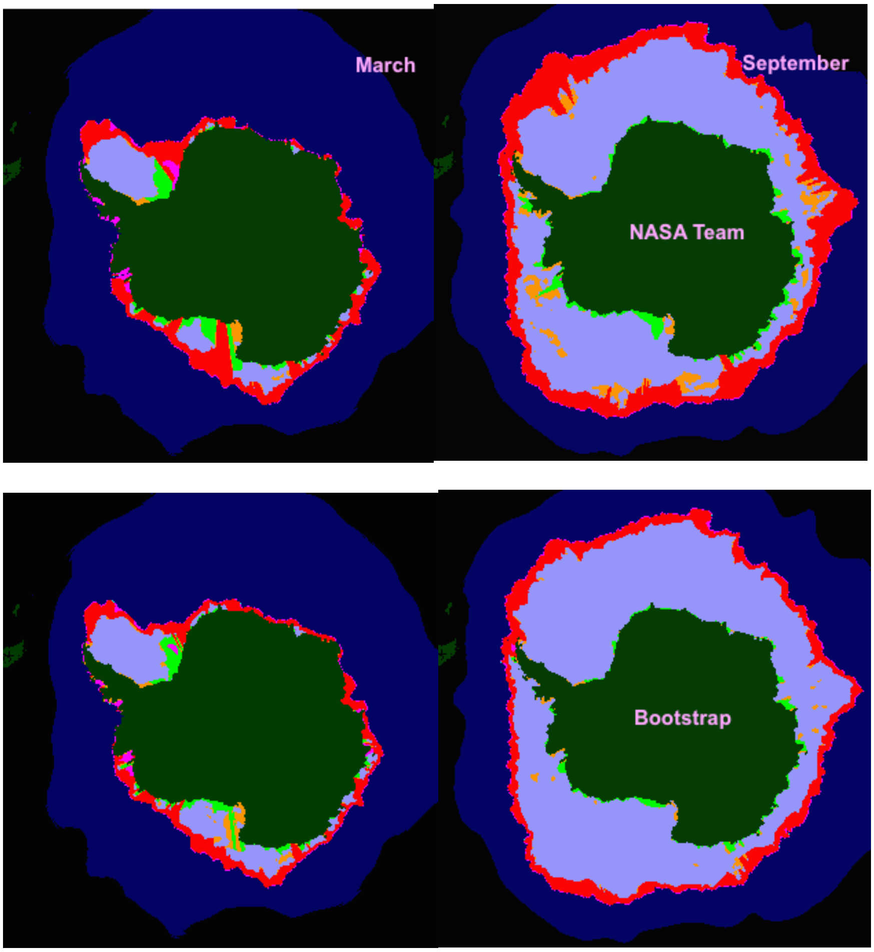

Figure 2: Samples of ice classification on day 70 (March) and day 273 (September) 2013. Results are shown for both the NASA Team (top) and Bootstrap (bottom) sea ice algorithms. The MIZ (red) represents regions of sea ice concentration between 15 and 80% south of the outer ice edge (defined by the ocean mask) and north of the pack ice. The pack ice is shown in light purple, representing regions of greater than 80% sea ice concentration. Orange regions within the pack ice (and away from the coastline) represent 'broken ice areas', coherent regions of less than 80% sea ice concentration. Pink areas are open water (SIC < 15%) areas detected south of the ocean mask but north of the coastline, and light green areas of less than 80% sea ice concentration extending from the Antarctic coastline are potential coastal polynyas. Dark blue represents the ocean mask applied to remove spurious ice concentrations at and beyond the ice edge.

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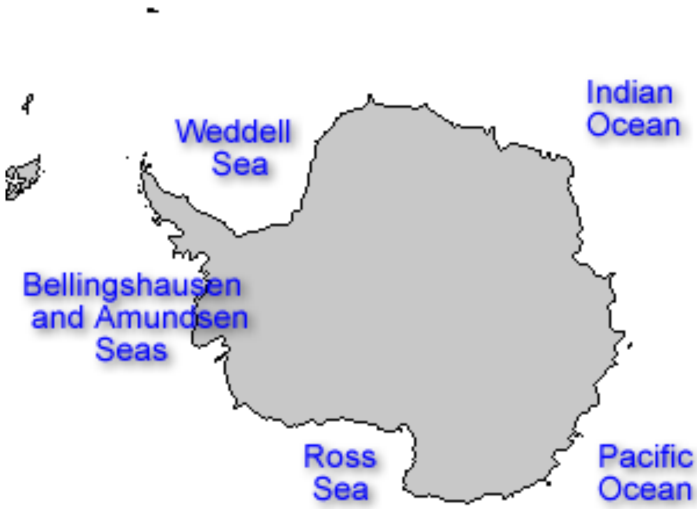

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908 **Figure 3.** Southern hemisphere regions as defined by *Parkinson and Cavalieri* [2012].

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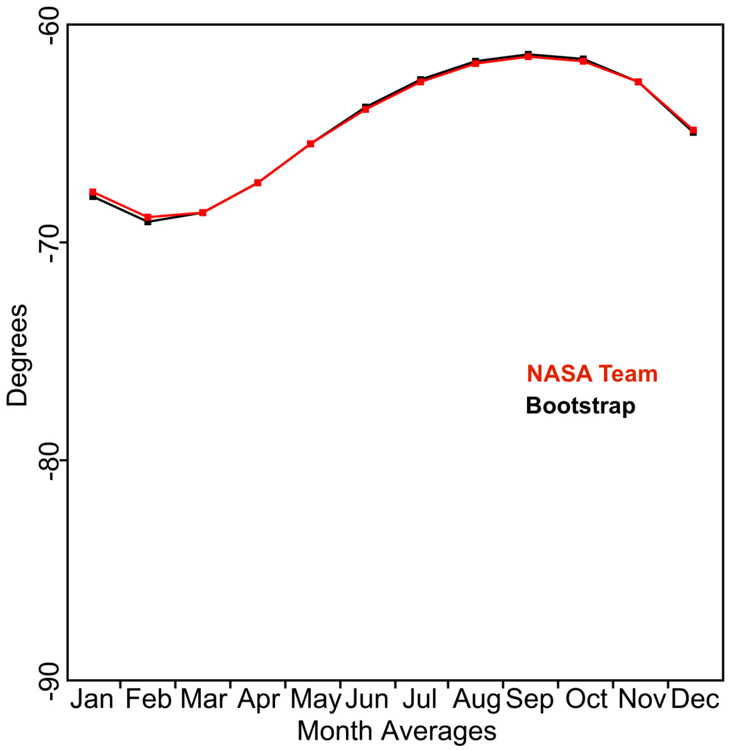

Figure 4. Location of the mean 1981-2010 outer marginal ice edge for both the NASA Team and Bootstrap algorithms.

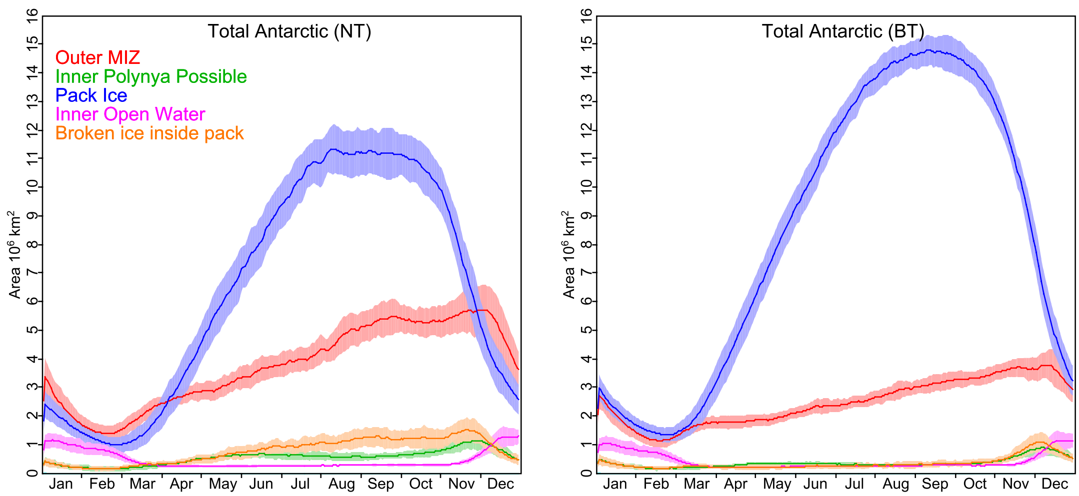

Figure 5. Long-term (1979-2013) seasonal cycle in total Antarctic extent of the consolidated pack ice, the outer marginal ice zone, polynyas, broken ice within the pack ice, and inner open water. There are essentially no scattered ice floes outside of the MIZ. NASA Team results are shown on the left and the Bootstrap on the right.

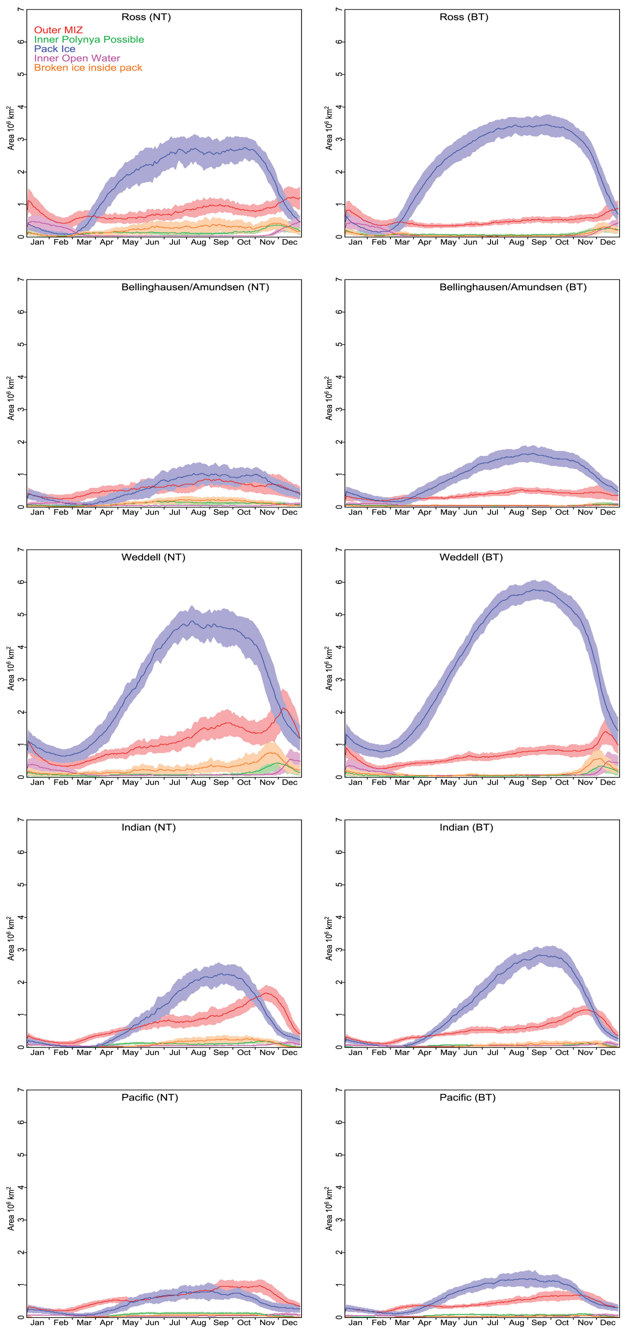

Figure 6. Long-term (1979-2013) seasonal cycle in regional sea ice extent of the consolidated pack ice, the outer marginal ice zone, polynyas, broken ice within the pack ice, and inner open water. Results for the NASA Team algorithm are shown on the left and Bootstrap on the right, and for the Ross, Bellinghausen/Amundsen, Weddell, Indian and Pacific Oceans.

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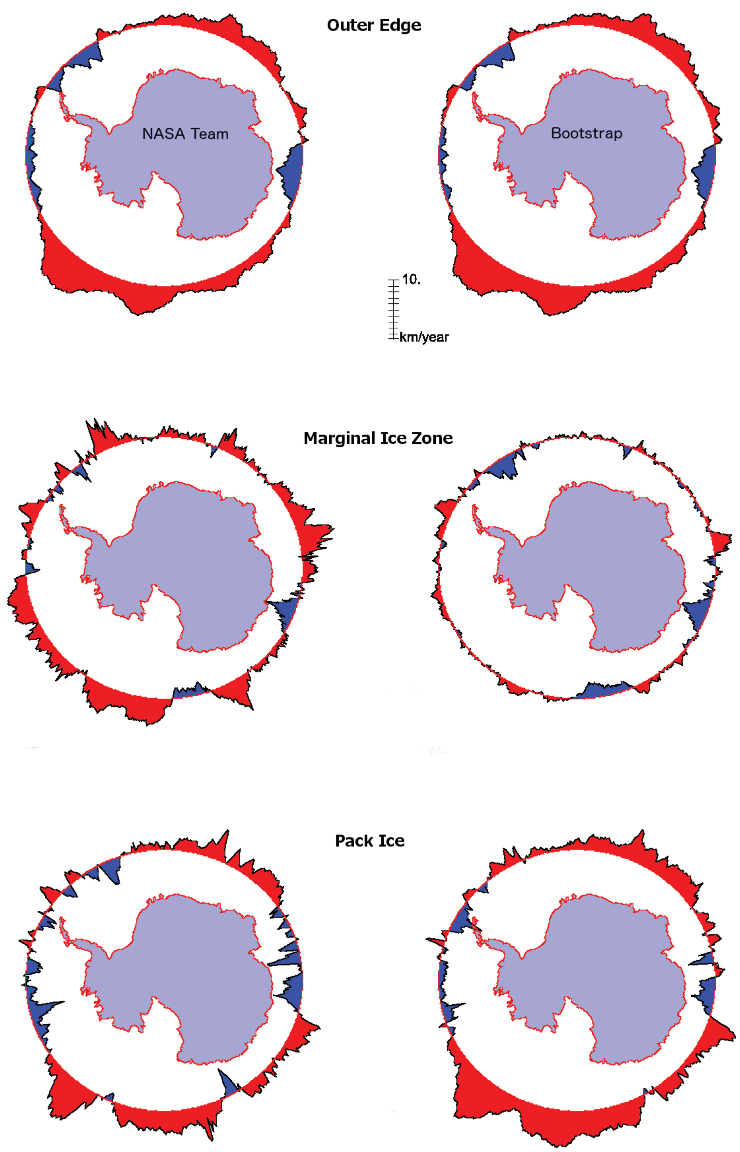

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927 **Figure 7.** Expansion (red) or contraction (blue) of the outer ice edge (top), the width of the marginal ice
928 zone (middle) and the width of the pack ice from 1979 to 2013 during the month of September.

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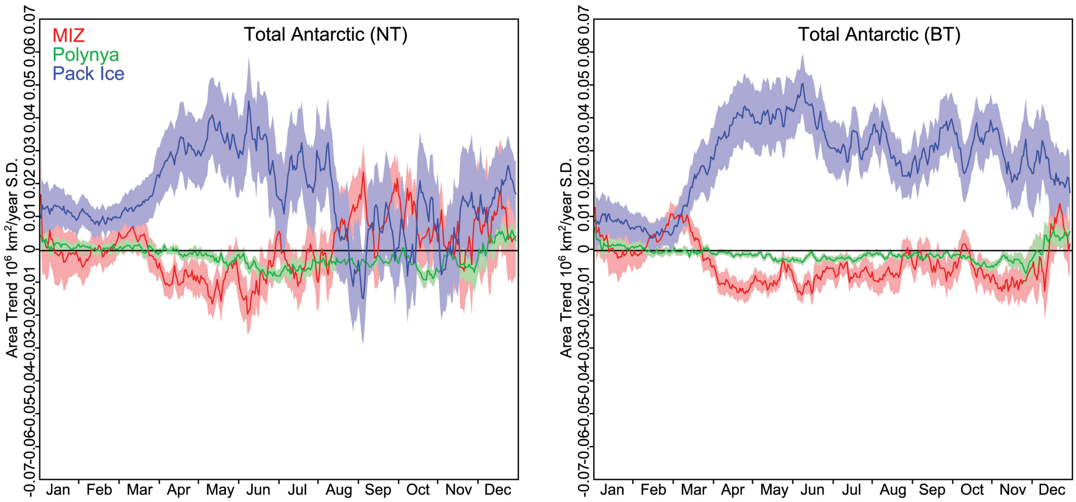

Figure 8. Daily trends (1979 to 2013) in the consolidated pack ice, the outer MIZ and potential coastal polynyas for the entire Antarctic sea ice cover for the NASA Team (left) and Bootstrap (right) algorithms. Trends are provided in 10^6 km^2 a^{-1}.

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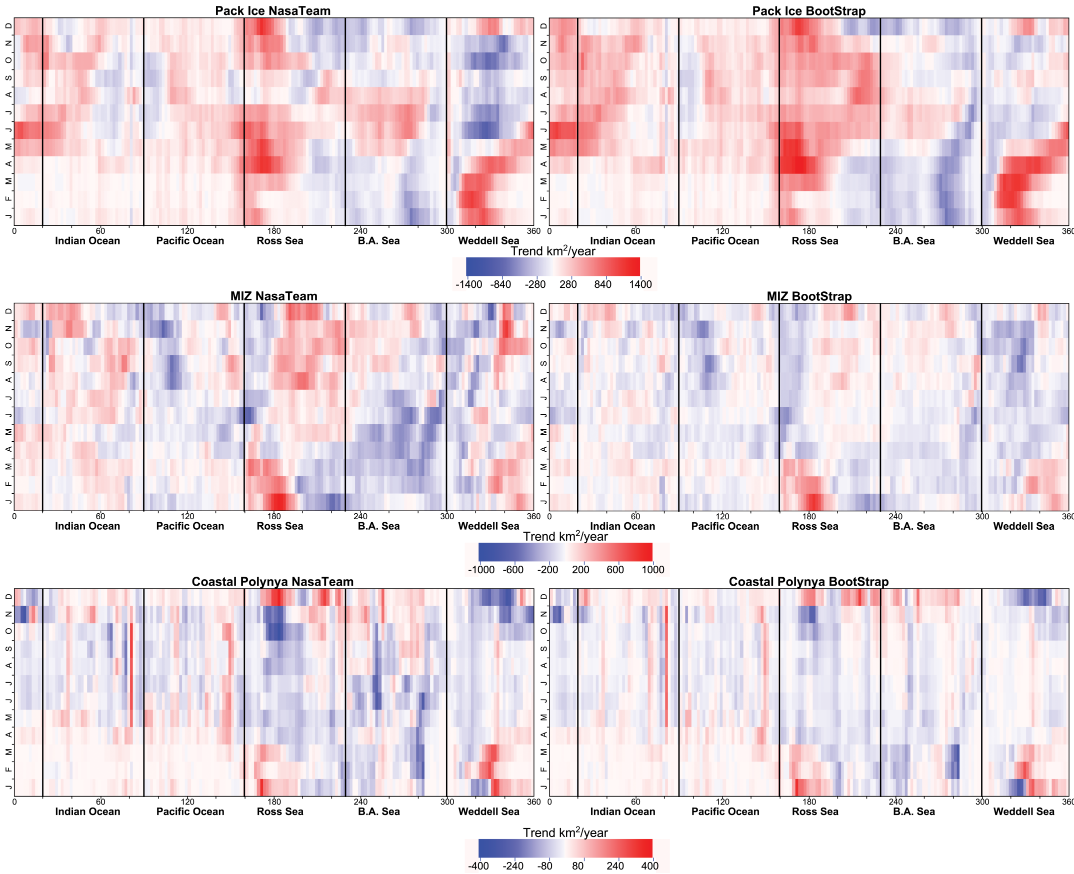

Figure 9. Daily (1979-2013) trends in regional sea ice extent of the consolidated pack ice (top), the outer marginal ice zone (middle) and potential coastal polynyas (bottom). Results for the NASA Team algorithm (left) and Bootstrap (right) are shown as a function of longitude. Trends are provided in 10^6 km^2 a^{-1}. Note the difference in color bar scales.

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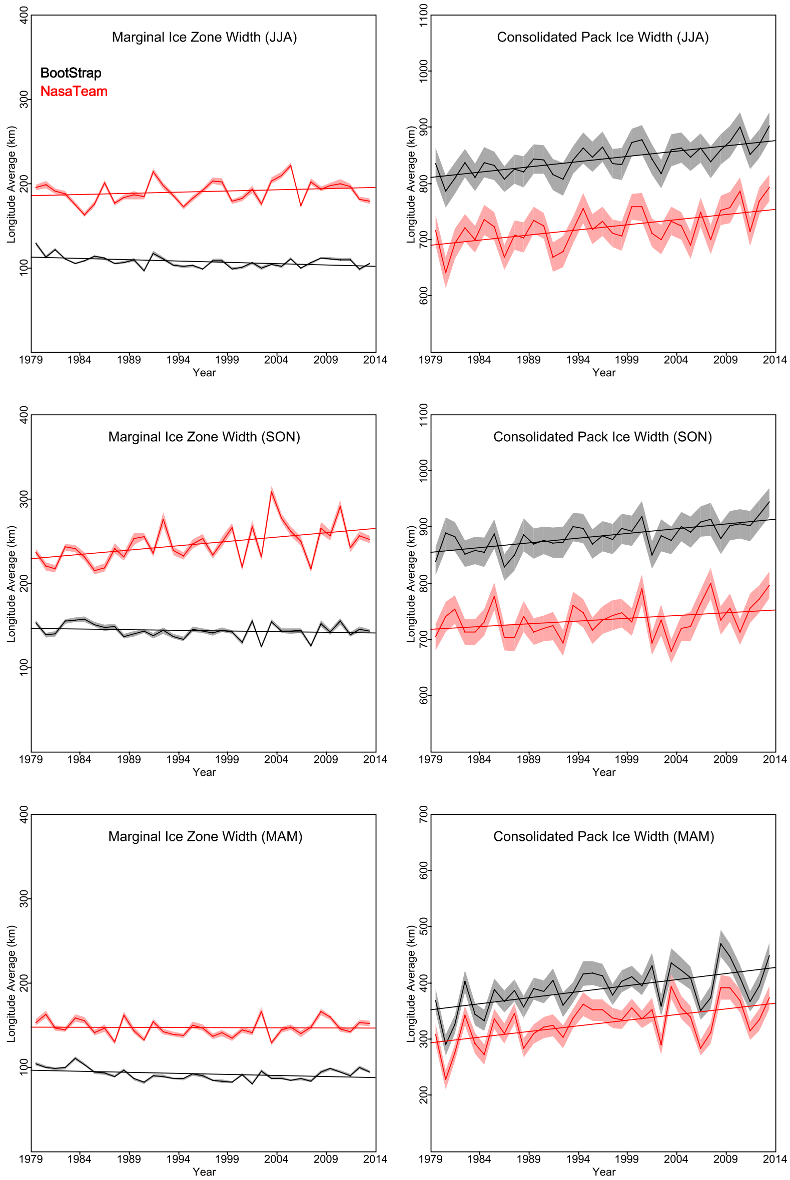

Figure 10. Time-series of seasonal mean JJA (top), SON (middle) and MAM (bottom) marginal ice zone (left) and consolidated pack ice (right) for both sea ice algorithms; NASA Team is shown in red, Bootstrap in black. Shading represents one standard deviation. Note the difference in y-axis between the pack ice and the MIZ plots.

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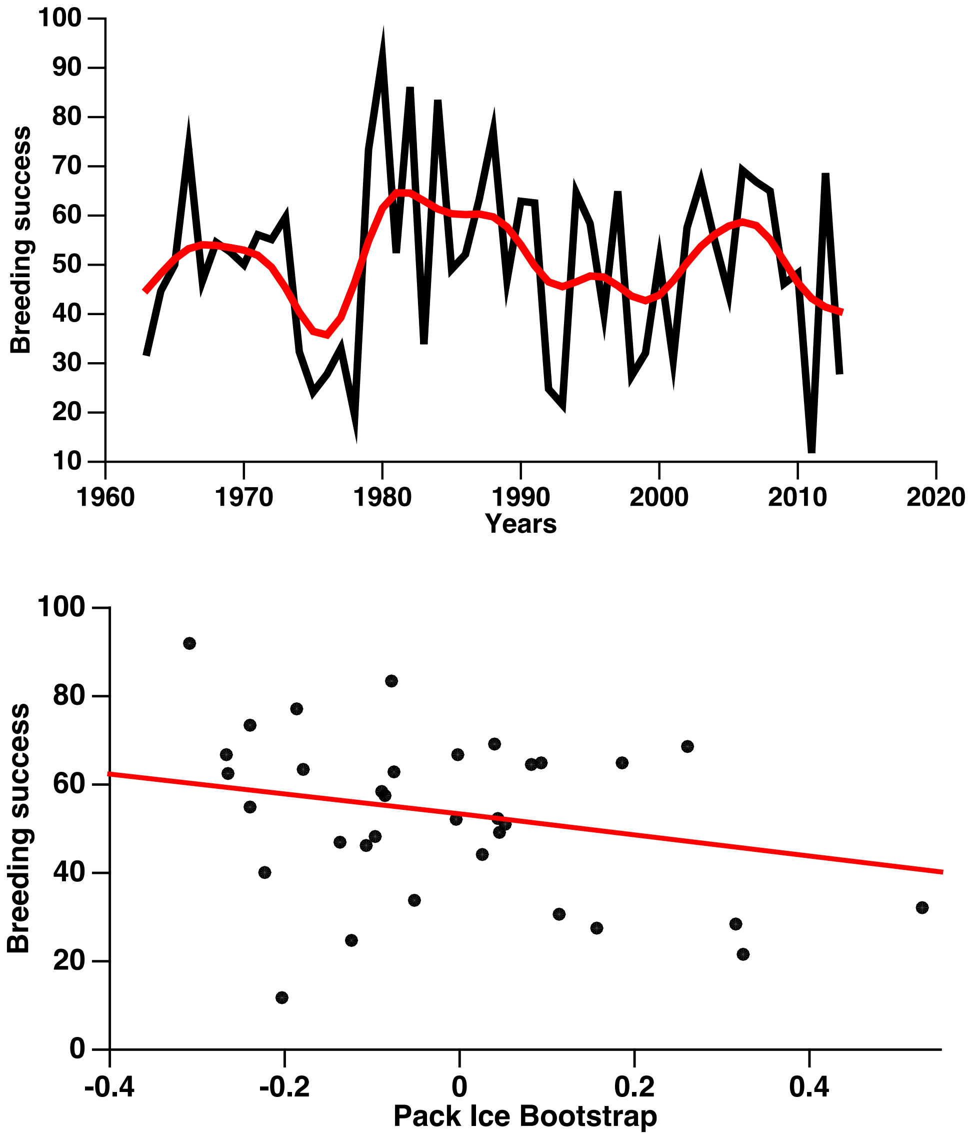

Figure 11. Breeding success of snow petrel (top) and effect of the Bootstrap pack ice on the breeding success of snow petrels (bottom).