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# Geophysical constraints on the Antarctic sea ice cover

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# ABSTRACT

The contrast between the slight increase of Antarctic sea ice and the drastic reduction of Arctic sea ice since the 1970s has been a conundrum to be resolved. Sea ice trajectory tracking with satellite scatterometer data in 2008 shows that ice around Antarctica is pushed offshore by katabatic winds influenced by the continental topography. The ice trajectories reveal that sea ice, grown earlier in the ice season, drifts northward away from the Antarctic continent forming a circumpolar frontal ice zone (FIZ) behind the ice edge. The FIZ thereby consists of sea ice that becomes rougher due to a longer exposure to wind and wave actions, and thicker over time by more ice growth and greater snow accumulation.

In the Antarctic circumpolar sea ice zone adjacent to the sea ice edge, satellite data in 1999–2009 exhibit a band of strong radar backscatter, which is consistent with the signature of older, thicker, and rougher sea ice with more snow in the FIZ. This sea ice band, as wide as 1000 km, serves as a 'Great Shield,' encapsulating and protecting younger and thinner ice in the internal ice pack. In the young and thin ice region behind the FIZ, ice can grow rapidly as winds continue opening interior areas thereby creating effective "ice factories." In addition, ridging can enhance ice thickness by convergence toward the circumpolar FIZ that is recirculated by westerly winds and currents. During the ice growth season, the FIZ advances until reaching lower-latitude warm waters at a boundary determined by the southern Antarctic Circumpolar Current front that is constrained by seafloor features. These persistent topographical and bathymetric geological factors help sustain the Antarctic sea ice cover. As such, the behavior of Antarctic sea ice is not a paradox as some have suggested, but instead is consistent with the geophysical characteristics in the southern polar region that starkly contrast to those in the Arctic.

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# 1. Introduction

The extent of Antarctic sea ice has increased slightly while Arctic sea ice has diminished drastically in recent decades (IPCC, 2013). This has been cited as a challenging paradox (Walsh, 2009) for which a number of explanations have been suggested, and the inconsistency between simulated and observed changes in Antarctic sea ice remains to be explained (Gagné et al., 2015). Stratospheric ozone depletion may affect atmospheric circulation patterns such as the Southern Annular Mode (SAM), limiting sea surface temperature (SST) change and sustaining the Antarctic sea ice cover (Gillett & Thompson, 2003; Marshall, 2003; Son et al., 2010). However, Sigmond and Fyfe (2010) question the efficacy of ozone depletion on sea ice change and strongly suggest that processes not linked to stratospheric ozone depletion must be invoked to explain the observation of the small increase in the Antarctic sea ice extent.

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Meltwater from Antarctic ice shelves (Rignot et al., 2013) accumulates in a cool and fresh surface layer that cushions the surface ocean from warmer deeper waters leading to an expansion of Antarctic sea ice (Bintania et al., 2013). The reduction of salinity and density in this near-surface layer may weaken the convective mixing of cold surface water with the underlying warmer water, and thus sustain Antarctic sea ice (Manabe et al., 1991). Moreover, a decrease in sea ice growth may reduce salt rejection and upper-ocean density to enhance thermohaline stratification which suppresses convective overturning, decreases upward heat transport, and thus maintains Antarctic sea ice production (Zhang, 2007). Winds also affect Antarctic sea ice trends (Holland, 2014), and model simulations indicate wind intensification may increase ice production by ridging (Zhang, 2013). As a frozen continent, Antarctica lacks heat sources such as warm river waters, breaking through landfast sea ice held by the regional bathymetry to effectively melt sea ice in the Arctic (Nghiem et al., 2014).

In contrast to past studies, this paper presents satellite observations that reveal the formation of a circumpolar frontal ice zone consisting of older, rougher, and thicker sea ice, referred here as a 'Great Shield' zone (GSZ) that in turn protects the Antarctic interior sea ice pack. Also examined are persistent factors that sustain effective ice growth while

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maintaining the Antarctic sea ice cover (i.e., decadal trend with a low rate of change of the seasonal maximum extent of the overall Antarctic sea ice cover, typically in late September). The focus here is on the growth season of Antarctic sea ice until its extent reaches the seasonal maximum in September, when the sea ice surface is under freezing conditions without significant melt to obscure satellite signatures of sea ice.

## 2. Antarctic sea ice change

Antarctic sea ice extent (SIE) retreats to a minimum of  $3.1 \times 10^6$  km<sup>2</sup> in February, which is just 16.8% of the maximum extent of  $18.5 \times 10^{6}$  km<sup>2</sup> in September as observed from multi-decadal satellite data (1979-2013) (Parkinson, 2014). Overall, the Antarctic SIE has a relatively low rate of change since the late 1970s with a slight increase that has not been nearly as large as the decreasing trend of the SIE in the Arctic and not as widespread geographically (Parkinson, 2014). There are also regional differences such as the decrease of sea ice with a shortened ice season in the Bellingshausen Sea region (see Fig. 1 for geographical names of seas and locations around Antarctica) as opposed to the late retreat and early advance in the western Ross Sea region (Stammerjohn et al., 2012). Successive Antarctic SIE maximum records in 2012, 2013, and 2014 from satellite observations (Parkinson, 2014; Reid & Massom, 2015), in contrast to record low values of Arctic SIE in March to early June 2015 (SPIN, 2015), have further accentuated the polar sea ice differences.

A reliable estimate of the Antarctic snow and sea ice thickness is still elusive (Giles et al., 2008), while there have been some seasonal estimates from Ice, Cloud, and land Elevation Satellite (ICESat) data collected along lines on sea ice surface in different regions at different times in different years (Kurtz & Markus, 2012) with a large range of uncertainty between 20% and 80% (Kern & Spreen, 2015). Such fundamental information is crucial for predictive models to attribute observed changes and to assess various impacts (Maksym et al., 2012). Antarctic sea ice properties and growth processes can be quite different from those in the Arctic. With strong wind and wave interactions, Antarctic sea ice is not necessarily limited to thermodynamic growth under quiescent conditions as its thickness can be significantly increased from rafting and ridging (Lewis et al., 2011; Massom et al., 2008) and from heavy snow loading, flooding, and freezing at the top (Ackley & Sullivan, 1994; Jeffries et al., 1997; Massom et al., 2001). During the ice-growing season, besides the thermodynamic growth, the older sea ice becomes thicker having more time for snow loading through aggregate accumulation and for greater roughness due to a prolonged exposure to high winds and large waves. Therefore, detailed measurements of snow and ice thickness and other physical properties in various regions of Antarctic sea ice are necessary to identify key dynamic and thermodynamic processes to explain Antarctic sea ice change.

As the thickness information lacks in accuracy, spatial coverage, revisit frequency, and long-term record, our approach is to utilize observations of the dynamics from sea ice trajectory tracking and from



Fig. 1. Names of places on a map of Antarctic land and ocean together with the GEBCO-2014 bathymetry (http://www.gebco.net/data\_and\_products/gridded\_bathymetry\_data/).

distribution patterns of synoptic sea ice classes using a decade of Kuband radar data, acquired in 1999–2009 by the SeaWinds scatterometer (a stable and accurate radar) aboard the QuikSCAT satellite. This approach allows an immediate examination of sea ice processes within the SIE from currently available data as a surrogate to the deficient information of Antarctic sea ice thickness distribution.

### 3. Tracking sea ice trajectories

To examine the evolution of Antarctic sea ice over the growth season (June-September), we implement an algorithm using daily QuikSCAT science data at Level 1B (L1B), accurate to 0.2 dB or 4.7% for  $3\sigma$  at ~99.7% confidence level (Tsai et al., 2000), to track the dynamics and formation of the different sea ice classes. The active microwave L1B scatterometer data in a posting of 0.25° in latitude and in longitude are provided as input to the tracking algorithm developed specifically for use with the satellite scatterometer observations. These are reprojected into polar coordinates and then interpolated to a rectangular grid with 0.1° spacing using a nearest neighbor scheme. An initial set of points in a 2° grid on sea ice for 1 June 2008 is chosen (Fig. 2a), with associated ice parcels tracked from the sequential rectangular-grid daily L1B data. Year 2008 is selected for this dynamic process study as it was one of the years of exceptional seasonal variability in Antarctic sea ice coverage, which was characterized by three distinctive phases of SIE anomalies and substantial regional variations (Massom et al., 2009), so that a large range of different conditions can be included in this study. The algorithm tracks the parcels by finding the maximum correlation of a  $5 \times 5$  window of pixels from one day to the next until September 30, 2008, or until the parcel is "melted out" as defined by its leaving the SIE.

The tracking algorithm uses ancillary SIE products derived from passive microwave data and other satellite observations. SIE datasets are readily available from the U.S. National Ice Center (NIC) and from the Integrated Climate Data Center (ICDC). The NIC SIE mask is generated from detailed manual analyses of the extent of the sea ice cover using multiple active and passive microwave, visible, and infrared satellite data sources, including observations with spatial resolution on the order of 100 m. NIC analysts pay particular attention during their sea ice cover analyses to the location of the ice edge because of the need to maintain domain awareness for safe operations near the ice edge. The use of multisensory and high-resolution data provides for a more accurate delineation of SIE than what could be generated alone from automated satellite algorithms. The NIC sea ice edge position analyses have been validated with a good agreement found by a comparison with ship observations (Ozsoy-Cicek et al., 2009). Antarctic SIE data for this study are available from NIC for 2006-2009.

To supplement NIC SIE data product before 2006, the ICDC sea ice concentration (SIC) > 0 is used to determine a SIE consistent with the conservative SIE definition by NIC. ICDC SIC values have been computed at the French Research Institute for Exploitation of the Sea with the Arctic Radiation and Turbulence Interaction Study (ARTIST) Sea Ice algorithm (Kaleschke et al., 2001; Kern et al., 2010; Spreen et al., 2008) applied to brightness temperatures measured with the 85-GHz Special Sensor Microwave/Imager (SSM/I) and/or Special Sensor Microwave Imager/Sounder (SSMIS) channels with a grid resolution of 12.5 km. The results have compared fairly well with ship observations and with satellite products from other algorithms (Beitsch et al., 2015). The combination of the NIC and ICDC SIE is used together with QuikSCAT data to obtain results over the decadal period of 1999–2009.

Presented in Fig. 2 are the tracking points at the start on 1 June 2008 (Fig. 2a) and the trajectories as these points are traced from their initial places in the austral autumn to their locations on the equinox of 22 September 2008 (Fig. 2b) when the season transitioned from the austral winter to the austral spring. From the trajectories, several general characteristics of Antarctic sea ice dynamics are observed. There was an advection of sea ice outward and away from the coast of Antarctica, especially in the Weddell, Lazarev, Riiser-Larsen, and Cosmonauts Seas. Sea ice was also pushed away outward from the Ross Ice Shelf in the Ross Sea, where a split in the ice drift eastward and westward could be identified (6 o'clock area on sea ice in Fig. 2b). In the sea ice zone behind the ice edge, the trajectories reveal a westward recirculation of sea ice. Overall, the trajectories show that sea ice, which formed earlier around Antarctica in June was forced toward lower latitudes in later months, thereby forming an outer zone of older sea ice while vacating and thus diverging the internal sea ice where newer ice could grow effectively.

A number of tracking points near the coast around Antarctica remained stationary, consistently with their locations on landfast ice (multiple white areas next to the coast in Fig. 2b, also see Movie 1 at http://urban.jpl.nasa.gov/images/NghiemEtAl-Movie1.avi). The capability to track complex ice trajectories was verified with the existence of several icebergs that were closely followed by the trajectories as found in the Cooperation Sea, where one of the icebergs moved in an  $\Omega$  loop (3 o'clock area in Movie 1). Specific details of the sea ice dynamics will be presented together with the seasonal evolution of synoptic sea ice classes later in Section 6.



**Fig. 2.** Tracking of trajectories of sea ice parcels over different synoptic sea ice classes (see definitions in Section 4 and color code in Fig. 4). The left panel (a) represents the initial set of points in a 2° grid on sea ice for 1 June 2008 to track the sea ice parcels associated with this set of points to trace their trajectories while no new points are introduced or inserted throughout the tracking process. The right panel (b) shows the trajectories of the sea ice parcels at the end of the tracking on the equinox of 22 September 2008, tracing the entire history of the trajectory of each sea ice parcel from where it started, moved around, reached its final position. Red dots are the current positions of the trajectories on the given date with the orange trails indicating the drift of the tracks during the past 30 days and the trails consisting of small black dots completing all tracking points along the sea ice trajectories is presented in Movie 1 at http://urba.njpl.nasa.gov/images/NghiemEtAl-Moviel.avi.

# 4. Synoptic patterns of sea ice backscatter signatures

As indicated by the sea ice trajectory tracking, the early sea ice cover grown around the Antarctic continent was forced outward toward lower latitudes to form an outer zone of sea ice containing older and thus thicker and rougher sea ice with more snow accumulation, while the internal ice is younger and thus thinner. From electromagnetic scattering physics based on the first principle of Maxwell's equations for the snow-covered sea ice (Barber & Nghiem, 1999; Golden et al., 1998; Nghiem et al., 1990, 1993, 1995), the older, thicker, and rougher ice with more snow must have backscatter higher than that of the younger ice.

From Antarctic field observations, QuikSCAT backscatter of sea ice has been shown by Markus et al. (2011) to correlate with ICESat variability, which in turn correlates with the standard deviation of the overall snow depth and ice thickness from in-situ snow and ice measurements. Toyota et al. (2011) find that the mean ice thickness of Antarctic sea ice has a correlation with surface roughness that is even higher than that with the mean freeboard. Thus, sea ice backscatter must be higher across the outer sea ice zone around the front of the SIE behind the ice edge to be consistent with the physical characteristics of the older sea ice in that frontal ice zone (FIZ). This needs to be investigated to verify the consistency between the patterns of sea ice age from the ice tracking results and spatial patterns of sea ice backscatter from observations with QuikSCAT satellite data.

To identify different backscatter patterns of Antarctic snow-covered sea ice, we examine its radar backscatter signatures over the Southern Ocean. Fig. 3 presents QuikSCAT backscatter synoptic images, together with multi-temporal plots along five different transects from the Antarctic coast to the ice edge as sea ice grew from June to its peak extent in September of 2008. These transects are selected to be in different regions of the Southern Ocean along these longitudes: (a) 3.38°E in the Lazarev Sea crossing Bouvet Island at 54.43°S, (b) 45.0°E in the Cosmonauts Sea, (c) 176.62°W in the Ross Sea meridionally conjugated to the Bouvet transect, (d) 135.0°W in the Amundsen Sea, and (e) 30.0°W in the Weddell Sea. Refer to Fig. 1 for geographical names.

Over the synoptic sea ice patterns and in all transects (Fig. 3), QuikSCAT satellite observations reveal a special feature of Antarctic sea ice backscatter signatures with high values (>-15 dB) forming a circumpolar band along the sea ice edge that encapsulates the internal



Fig. 3. Radar backscatter patterns and transect plots of Antarctic sea ice observations in 2008 by the QuikSCAT satellite scatterometer operated at the Ku-band frequency of 13.4 GHz. The top left insets are for QuikSCAT backscatter of sea ice on 22 June and 22 September 2008, where the color scale is for backscatter values, blue for open-water ocean, grey for permanent ice, and brown for land. The backscatter plots are for (a) Transect a along 3.38°E, (b) Transect b along 45.0°E, (c) Transect c along 176.62°W, (d) Transect d along 135.0°W, and (e) Transect e along 30.0°W. The plot colors are green for June, magenta for July, blue for August, and black for September.

ice pack characterized by low backscatter. Such feature is consistent with the results from ice trajectory tracking, and thereby supports the existence of the FIZ containing older sea ice that is thicker and rougher with more snow accumulation. The FIZ surrounds the internal younger sea ice with a backscatter signature as much as 3–6 dB (equivalent to 2–4 times, converged into the linear domain from the logarithmic dB values) less than that of the sea ice in the FIZ (Fig. 3).

The time-series plots in Fig. 3 present the evolution of sea ice in different Antarctic regions as a function of latitude. Along Transect a (Fig. 3a) from June to July 2008, the FIZ became widened as its outer edge advanced toward Bouvet Island. In August, the FIZ inner edge was pushed outward and its width contracted. The FIZ continued extending farther north as it reached Bouvet Island in September. As an example at latitude 63°S on Transect a (vertical black line in Fig. 3a), backscatter was decreasing from June to September, indicating the northward passage of the FIZ while the space behind remained opened and even expanded for more ice divergence, thus creating new spaces where sea ice can effectively grow to form younger and thus thinner ice consistently associated with lower backscatter. If the seasonal evolution of sea ice formation were dominated only by thermodynamic ice growth in place, then the backscatter should have been increasing along with the sea ice growth at that location. This example highlights the interplay of dynamics and thermodynamics in the seasonal evolution of Antarctic sea ice.

The FIZ along Transect b (Fig. 3b), characterized by the high backscatter signature, gradually migrated northward between June and September. In the Ross Sea, it was already established by June and consistently maintained there during June-September as seen in Transect c (Fig. 3c). In the Amundsen Sea along Transect d (Fig. 3d), the FIZ moved to northward with a slight decrease in the peak magnitude between June and July then became significantly pronounced in August and September. Along Transect e (Fig. 3e) in the Weddell Sea, the FIZ had the widest with the sea ice edge persisting between 57°S and 58°S. Although showing variable characteristics over different oceanic regions, these transect profiles capture the presence of the FIZ around Antarctica constituting a circumpolar band of sea ice (GSZ), which will be quantitatively defined with synoptic sea ice classes in Section 5.

#### 5. Synoptic classes of sea ice

Here, the objective is to capture the synoptic patterns of Antarctic sea ice pertaining to different classes of sea ice having different backscatter signatures corresponding to older and younger sea ice with different ice thickness, roughness, and snow accumulation as presented earlier in Section 4. This necessitates the development of a method for a synoptic classification of Antarctic sea ice. Hence, we carry out a statistical analysis of Antarctic sea ice backscatter during the sea ice growth period from June to September over the entire Southern Ocean. We find that the backscatter histograms have a typical shape similar to that of the Gaussian distribution with a single peak. This is in contrast to the bimodal distribution of Arctic sea ice backscatter, having separate and distinctive peaks for seasonal and perennial sea ice in freezing seasons, which was used in the algorithm development for Arctic sea ice classification (Nghiem & Neumann, 2007; Nghiem et al., 2006). This is because Antarctic sea ice is dominated primarily by first-year sea ice, rather than the coexistence of two major distinctive classes of firstyear (seasonal) and multi-year (perennial) ice in the Arctic (Nghiem et al., 2007).

Since the Antarctic sea ice backscatter ( $\sigma_0$ ) statistics are similar to the Gaussian distribution, the probability density function of  $\sigma_0$  is determined by two independent parameters: The mean value ( $\sigma_M$ ) and the standard deviation (*STD*), which are used here as the basis to define synoptic sea ice classes. First, we identify the high backscatter range with values larger than  $\sigma_M$  as corresponding to older, rougher, and thicker sea ice with more snow in the FIZ, and the low backscatter range with values smaller than  $\sigma_M$  as pertaining to younger and thus thinner sea ice with less snow. Then, an additional synoptic sea ice class with backscatter larger than one *STD* above  $\sigma_M$  is identified as corresponding to the most-deformed older ice and thus likely the thickest sea ice. Based on these backscatter ranges, the following synoptic sea ice classes are defined: Rough older ice (RI) for  $\sigma_0 > \sigma_M + STD$ , older ice (OI) for  $\sigma_M + STD \ge \sigma_0 > \sigma_M$ , and younger ice (YI) for  $\sigma_M \ge \sigma_0$ . Coincidentally, these thresholds are found to be within 0.3 dB of those used to identify different Arctic sea ice classes (Nghiem et al., 2006, 2007). In addition, a limited amount of 'permanent' ice, including ice shelves and persistent landfast ice, is routinely identified and mapped around Antarctica by the NIC (NIC, 2015).

Per the above definition, the synoptic sea ice classes are mapped from QuikSCAT backscatter data within the ancillary SIE products from NIC and ICDC that are described earlier in Section 3. Patterns of the distribution of sea ice classes are presented in Fig. 4 around the September equinox in 1999–2009. This is the seasonal transition time from the austral winter into the spring when the Antarctic SIE is generally at or near its maximum extent in each year. In all years, the Antarctic sea ice cover was encapsulated all around the ice pack by a FIZ, which is now defined as the sea ice zone consisting of RI and OI classified quantitatively with  $\sigma_M$  and *STD* pertaining to the Gaussian statistics of sea ice  $\sigma_0$ . The outer ice edge of the FIZ can be found close to the coast in regions such as in the Somov Sea, D'Urville Sea, and Mawson Sea, or very far away from the coast particularly in the Lazarev Sea where the FIZ may extend all the way to Bouvet Island (white cross in Fig. 4).

The FIZ characteristics around Antarctica are found to be quite variable over the years, particularly in certain seas such as the Ross Sea when comparing 2001 and 2006 observations, or the Weddell Sea when comparing 1999 and 2008 observations. The width at different locations can vary by an order of magnitude from ~100 km to ~1000 km whereas the location of the inner side of the FIZ can be very close to the Antarctic coast or more than 1000 km away. Table 1 shows quantitative examples of measurements of the FIZ widths, and the distances from its inner side to the Antarctic coast along multiple transects across various seas in the Southern Ocean at different seasonal times in 2008. Despite this large variability, the extensive circumpolar FIZ surrounds YI in the internal ice pack in all years (Fig. 4). Formed by a combination of OI and RI, it helps protect and maintain (more details later) the internal younger and thinner sea ice that likely has less snow cover due to its shorter time available for the seasonal snow accumulation. As such, the FIZ acts as a shield zone (GSZ) or a defensive barrier for the thinner and weaker internal ice pack that continues growing as the GSZ advances toward its outermost position in the austral spring as shown in the next section.

#### 6. Seasonal evolution of sea ice

To examine the seasonal evolution of sea ice, the retrieved trajectories of sea ice parcels are overlaid on maps of sea ice classes in Fig. 5 for day 22 of June, July, August, and September 2008 covering the period from around June solstice to September equinox. By 22 June 2008 (top left, Fig. 5), a sea ice cover, containing an extensive distribution of OI and RI, was observed to have formed from close to the Antarctic coast extending to the sea ice edge with areas of YI present particularly in the Weddell, Lazarev, Riiser-Larsen, Ross, and Amundsen Seas. In those seas, the older sea ice moved outward, driven by katabatic winds that created open space behind the FIZ for YI to grow (see Movie 1). However, the sea ice edge was the closest to the Antarctic coastline in the D'Urville Sea to Mawson Sea region.

By 22 July (top right, Fig. 5), the FIZ advanced farther north in the South Atlantic toward Bouvet Island with the internal YI expanding to a larger region behind a more distinctive FIZ from the Weddell Sea through the Lazarev Sea to the Riiser-Larsen Sea. Sea ice trajectories adjacent to the coast along the Lazarev and Riiser-Larsen Seas showed a westward drift driven by the polar easterlies. As sea ice moved outward in the Weddell and Lazarev Seas, the ice trajectories curved eastward as



Fig. 4. Synoptic classes of Antarctic sea ice around the September equinox in 1999–2009. The location of Bouvet Island is marked with the white cross.

driven by the westerlies. In the Ross Sea, the sea ice edge could only reach slightly northward while the region of YI in the internal ice pack was maintained by sustaining winds off the Ross Ice Shelf. In this region, sea ice trajectories revealed a split eastward and westward as sea ice moved outward away from the shoreline (Movie 1). From the D'Urville Sea to Mawson Sea, the ice edge was stable and did not extend much farther after June with some motions corresponding to the easterlies along the coast. Several small areas of transient ice surface melt occurred along the ice edge and within FIZ (top right, Fig. 5).

#### Table 1

Frontal ice zone (FIZ) distances and widths along different longitudes on 22 July, 22 August, and 22 September 2008. The FIZ distance is between the coastline (or the outer edge of Ross ice shelf) and the inner edge of FIZ. The FIZ width is between the inner and outer edges of the FIZ. The uncertainty in the FIZ distance and FIZ width is  $\pm$  25 km.

Longitude (°)	Distance (km)			Width (km)		
	22 Jul	22 Aug	22 Sep	22 Jul	22 Aug	22 Sep
3.38	885	1100	1410	720	470	495
45.0	190	465	515	550	355	360
-176.62	1050	1035	1055	530	530	510

By August (lower left panel, Fig. 5), the region of internal YI in the Weddell Sea through Lazarev Sea to Riiser-Larsen Sea had grown larger. The inner side of the FIZ was also pushed outward while the outer side had not advanced or even slightly retreated in the Weddell Sea, resulting in a smaller FIZ width. Sea ice trajectories tracked from June to August clearly show the cyclonic pattern of the Weddell Gyre formed by the Antarctic Circumpolar Current (ACC) interactions with the Antarctic Continental Shelf. The internal YI also appeared larger in Cooperation Sea behind the FIZ. In the Ross Sea, the internal YI was persistent while sea ice trajectories off the Ross Ice Shelf exhibited the westward and eastward split (also see Movie 1). The pattern of the Ross Sea gyre became well defined by the long June-August trajectories of sea ice as the outer OI and RI arched and followed along the westerlies (Movie 1). Again sea ice in the D'Urville Sea to the Mawson Sea region remained stable, although with transient melt areas occurred on the sea ice surface near the ice edge.

By September (lower right, Fig. 5), the internal YI extent became the largest as the inner side of the FIZ advanced northward across the Weddell, Lazarev, Riiser-Larsen, and Cosmonaut Seas, while the trajectories of OI and RI in the FIZ traced along consistently with the westerlies. At this time, the outer side of the FIZ reached Bouvet Island. In



Fig. 5. Antarctic sea ice trajectories overlaid on maps of synoptic sea ice classes on 22 June, July, August, and September 2008. Red dots are the current positions of the trajectories on the given date with the orange trails indicating the drift of the tracks during the past 30 days and the trails consisting of small black dots completing all tracking points along the sea ice tracks since 1 June 2008. The color code for open water and sea ice classification is the same as in Fig. 4. Dark grey represents land. The location of Bouvet Island is marked with the white cross.

the Ross Sea, the internal YI extent became larger compared to that in earlier months while the outer sea ice in the FIZ continued being entrained by the westerlies (Movie 1). The extent of the internal YI in the Cooperation and Davis Seas also widened. The sea ice edge retreated in the D'Urville Sea while it extended in the adjacent Mawson Sea. Between June and September, SIE in the Bellingshausen Sea was variable with intermittent retreats and advances while transient melt areas on the sea ice surface were observed in different months (Fig. 5). In late September, the FIZ was still persistently surrounding and protecting the internal sea ice around Antarctica while sea ice in the FIZ was consistently recirculated by the westerlies (Movie 1). In an opposite manner, winds in the Arctic can significantly contribute to sea ice loss such as the 'Polar Express' driven by the dipole pattern of atmospheric anomalies (Nghiem et al., 2007; Perovich et al., 2011), which accelerates sea ice transport directly out of Fram Strait in the Arctic.

#### 7. Factors influencing the formation and evolution of sea ice

Given the new insights derived from the above observations of sea ice trajectories and synoptic classes, next we discuss factors that enhance the growth and persistently maintain the Antarctic sea ice cover. First, regarding the physical characteristics of sea ice itself, the FIZ consists of older and thicker sea ice with more snow accumulation adjacent to the sea ice edge. This constitutes an opposite condition to what is typically found in the Arctic where the peripheral marginal ice zone (MIZ) mostly consists of younger, thinner, and smoother level first-year sea ice with less snow (except in Greenland Sea) including unconsolidated pancake, nilas, and new ice like frazil and grease ice (WMO, 2014). Such sea ice in the Arctic MIZ is easily broken up by wind-wave actions and melted from surface by warm air or from beneath by warm waters (Perovich & Richter-Menge, 2015, Webster et al., 2014, 2015) and sensitive to dynamic or thermodynamic forcing that reduces sea ice in the Arctic (Perovich, 2011). Moreover, the older and thicker sea ice in the Antarctic FIZ, extending 100 km to 1000 km (Section 5) around the ice pack, can suppress sea states more effectively and thus reduce sea ice break-up induced by storms as compared to feeble ice conditions in the Arctic MIZ.

In the internal sea ice region behind the FIZ, persistent katabatic winds force the opening, production, and advection of ice. In the newly opened or ice divergence areas, protected behind the FIZ, the YI can have a large growth rate, inversely related to sea ice thickness by as much as an order of magnitude between thin and thick ice (Thorndike et al., 1975). Sea ice production is thus enhanced as winds keep refreshing the effective ice growth with fast-growing new ice (Heil et al., 1998). In leads and polynyas opened by persistent winds, ice production is so effective that these areas are considered as ice factories (Barber & Massom, 2007) that amply supply sea ice and thus contribute to sustaining the Antarctic sea ice cover. As the internal ice is forced to converge toward the inner side of the formidable FIZ, ice ridging is enhanced and ice volume can increase dynamically by ice convergence as suggested by Zhang (2013). Field observations in the Bellingshausen and Amundsen Seas indicate that rafting and ridging play important roles at different stages of sea ice floe development in the process of floe thickening (Worby et al., 1996).

The general pattern of persistent offshore winds that drive the FIZ outward (Movie 1) is also effective in promoting sea ice growth by the advection of very cold air to grow more ice, by pushing the sea ice edge outward, and by the suppression of waves due to the ice advancing and thus impeding water mixing and subsurface melt (Nghiem et al., 2012). Offshore winds blowing across the sea ice surface are also less effective in creating large waves, and thus resulting a calm sea state (Nghiem et al., 2012). When on-ice winds occur, sea ice near the edge

can become compacted (Massom et al., 2008), thereby reinforcing the FIZ. Furthermore, such compaction promotes the jet formation (Heorton et al., 2014) that sustains the recirculation of sea ice in the FIZ.

Winds such as the polar westerlies, easterlies, and offshore katabatic winds play a major role in forcing sea ice growth and dynamics as presented above. The pattern of wind fields around Antarctica is consistently controlled by the Antarctic topography, including the coastal morphology and the presence of the ice sheet and associated ice shelves. Parish and Cassano (2003) found that Antarctic surface winds display a high degree of persistence with mean directions related to the local topographic configuration of the ice sheet. In their flow simulation, the initial arbitrary circumpolar low-level winds become modified by the Antarctic terrain within 72 hours such that the direction of the wind vectors becomes tied to the underlying terrain. Results from this simulation and from later analyses (Parish et al., 2006) even hint at the westward and eastward split off the Ross Ice Shelf, which is evident in sea ice drift trajectories observed with satellite data (see the region of sea ice at 6 o'clock in Movie 1). Parish and Cassano (2003) further suggest that the establishment of the low-level wintertime Antarctic wind field is critically dependent on the role of topography in shaping the Antarctic boundary layer winds through blocking and subsequent adjustment.

During the growth season, Antarctic sea ice reaches north up to an oceanic frontal zone, where SIE cannot advance much farther and seems to be constrained to certain locations in various regions of the Southern Ocean (Movie 1). Throughout the decade of 1999-2009, the SIE attained its maxima at or near Bouvet Island around the September equinox (Fig. 4), except in 2001 and 2006 when SIE also expanded to the island but later in October. Over an extensive region in the Southern Ocean from north of Bouvet Island to the Antarctic coast, more than 11,000 conductivity-temperature-depth profiles, collected by sensors mounted on southern elephant seals in February-November 2008, showed a water mass transition from the warm ACC Regime to the Weddell Cold Regime across Bouvet Island (Biuw et al., 2010; Zhou, 2013). This oceanic frontal pattern of warm and cold waters, spanning across Bouvet Island, continues delimiting the northern extent of the Antarctic sea ice cover in the South Atlantic Ocean, as sea ice cannot survive when it reaches the warm waters. Moreover, air temperatures measured at Bouvet Island have been stable over a period of 13 years since 1994 (Fig. 6), which is another factor supporting the sea ice stability in this region.

To examine patterns of SST around SIE, the Multi-sensor Ultra-high Resolution (MUR) SST product was obtained from the Physical Oceanography Distributed Active Archive Center (MUR, 2010), which has a relative accuracy of 0.5 °C in high-latitude oceans. As examples, MUR SST for 2008 and 2009 are overlaid on SIE around September equinox (Fig. 7). The results reveal that SIE closely conforms to the isotherm at -1.4 °C, slightly above a seawater freezing point around -1.9 °C (Foldvik & Kvinge, 1974). The SST isotherm at -1.0 °C is also relatively close to the ice edge in most places, although it may have some detachment from the SIE in some cases such as in the Bellingshausen Sea in 2008 (Fig. 7). In general, the SIE is typically enclosed by the -1.0 °C SST isotherm in each year.

The overall conformance of SIE to the SST isotherms indicates that ocean temperatures exert significant control in delimiting the maximum reach of SIE. In turn, patterns of warm and cold waters associated with oceanic fronts are significantly governed by bathymetry (Kim & Orsi, 2014; Langlais et al., 2011; Moore et al., 1997; Orsi et al., 1995). In particular, Kim and Orsi used buoy, hydrographic, and altimetric data to infer ACC fronts and their variability between 1992 and 2011, which encompasses the entire period (1999–2009) considered in this study.

In the Southern Ocean, the locations of -1.0 °C SST isotherms on 22 September in 1999–2009 are closely bundled, especially around the region of Bouvet Island and the meridionally conjugate region (180° away in longitude) on the opposite side of the continent (Fig. 8). These isotherms are in the proximity of the southern ACC front, or sACCf, delineated by Kim and Orsi (2014) (Fig. 8) and by others (Orsi et al., 1995; Sokolov & Rintoul, 2002). Pronounced seafloor features can strongly guide sACCf, such as in the region around Bouvet Island, located at a triple junction of the American-Antarctic, Mid-Atlantic, and Atlantic-Indian Ridges, and in the region of Pacific-Antarctic Ridge in the Somov Sea.

Notably, the -1.0 °C SST isotherms cut across the Kerguelen Plateau (Fig. 9) through the Fawn Trough where sACCf transports in conformity



Fig. 6. Air temperature measured at Bouvet Island, obtained from the National Oceanic and Atmospheric Administration (NOAA) Global Surface Summary of the Day (GSOD) dataset (https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod). The horizontal axis is for number of days counted from 1 January 1994 (1 is for 1 January 1994, 366 is for 1 January 1995, etc.). This uninhabited island is located near a triple junction on the southern end of the Mid-Atlantic Ridge. It is the most remote island in the world with more than 1600 km away from the nearest land in any direction.



**Fig. 7.** Maps of Multi-sensor Ultra-high Resolution (MUR) Sea Surface Temperature (SST) represented by the color bar in degrees Celsius on the right with isotherms at -1.0 °C (black contour) and -1.4 °C (green contour) on National Ice Center (NIC) Sea Ice Extent (SIE) mask in maroon for: (a) 22 September 2008, and (b) 22 September 2009. The white cross marks the location of Bouvet Island.

with the bathymetry (Park et al., 2009). This is also where the seasonal maximum SIE can recurrently reach to, but cannot cross over to the warm side. While effects of Antarctic bathymetry may contribute to

the overall sustenance of Antarctic sea ice, bathymetry in the Arctic in contrast may work to reduce sea ice more effectively. For example, the landfast sea ice recurrently controlled by the seafloor across the



Fig. 8. Map of the southern Antarctic Circumpolar Current (ACC) front (sACCf) delineated by the white contour (Kim & Orsi, 2014) with MUR SST – 1.0 °C isotherms represented by the black contours on 22 September in 2002–2009 plotted together with the GEBCO-2014 bathymetry. The isotherms are closely bundled close to the sACCf over pronounced seafloor features such as ridges while they tend to spread apart across smooth abyssal plains. The white cross marks the location of Bouvet Island.

mouth of the Mackenzie River may delay the river discharge to accumulate a larger volume of warmer waters later breaking through the landfast ice to melt more sea ice (Nghiem et al., 2014). Climate-ocean models also indicate that oceanic fronts are tightly constrained by the local bathymetry (de Boer et al., 2013; Graham et al., 2012), while Coupled Model Intercomparison Project phase 5 (CMIP5) simulations report no significant relationship between the latitudinal positions of the ACC fronts and the westerlies (Meijers et al., 2012). However, the bathymetry may impose less control on the sACCf over the abyssal plains and in deep basins, thereby allowing more effects from atmospheric drivers like SAM and El Niño Southern Oscillation (Kim & Orsi, 2014). These dynamic atmospheric effects can cause more sea ice variability, particularly over the Bellingshausen Plain that is a deep basin (Fig. 8, also see Fig. 1 for the location of the Bellingshausen Plain). The different levels of bathymetry control on SST are also observed over the Kerguelen Plateau, a submerged microcontinent (Fig. 9) also called by paleogeologists and geographers as a submerged continent (Edmond, 2013; World Heritage Encyclopedia, 2016), as the MUR SST isotherms closely pinch through Fawn Trough while they tend to spread apart over the abyssal plains in the Enderby and Australian Antarctic Basins.

In summary, the stark contrast in geophysical characteristics between the southern and northern polar regions causes different behaviors of Antarctic and Arctic sea ice. Regarding sea ice properties, the Antarctic circumpolar FIZ with older rougher and thicker sea ice acts a Great Shield to protect the younger internal ice, as opposed to the Arctic MIZ with younger and thinner sea ice that is easily broken up and melted away. Regarding atmospheric forcing, persistent Antarctic winds create ice factories, thicken ice by ridging, and recirculate ice to enhance and sustain the sea ice cover, as opposed to Arctic winds contributing to sea ice loss such as the 'Polar Express' that efficiently exports sea ice directly to warm ocean where it melts. Regarding oceanic effects, the Antarctic bathymetry guides the distribution of water masses to constrain the location of the sACCf that holds the persistence of the sea ice cover, as opposed the Arctic bathymetry responsible for mechanisms that aggravate sea ice loss (e.g., release of warm waters from the Mackenzie River).

#### 8. Conclusion and discussions

Based on daily observations acquired by the SeaWinds scatterometer aboard QuikSCAT from 1999 to 2009, we have tracked sea ice trajectories and mapped synoptic sea ice classes (RI, OI, and YI) around Antarctica. Trajectories of sea ice tracked in the 2008 growth season (June-September) illustrate the pattern of Antarctic sea ice growth and dynamics, showing the outward expansion of the FIZ where OI and RI accrues and recirculates along with the polar westerlies. Persistent offshore winds recurrently open internal space for effective ice production behind the extensive FIZ, which serves as the GSZ that in turn protects the internal YI. These mechanisms can enhance sea ice production with a high growth rate in the internal YI together with rafting and ridging behind the FIZ that protects and thus persistently preserves the seasonal sea ice pack in the Southern Ocean.

As the Antarctic sea ice cover is sustained under the influence of winds guided by topography and waters guided by bathymetry, the sustenance of Antarctic sea ice is maintained by both topographic and bathymetric characteristics as these are stable geological factors. Nevertheless, a large regional variability of the SIE can still occur such as in the Bellingshausen Sea where sea ice can advance, retreat, or melt intermittently because the deep abyssal plain does not exert a strong control on water masses and thus allows variable effects from atmospheric forcing. The thermodynamic and dynamic interplay in the Antarctic sea ice formation and evolution processes is consistent with the regional geophysical characteristics that are in a stark contrast to those in the Arctic, thus the different behaviors of sea ice observed in the polar regions should not be considered a paradox.

While the synoptic sea ice classes defined in this study use statistics of sea ice backscatter, the specific ranges of physical properties



Fig. 9. Map of MUR SST - 1.0 °C isotherms as black contours on 22 September in 2002–2009 on the GEBCO-2014 bathymetry in the region of the Kerguelen Plateau, a submerged microcontinent. The isotherms closely bundle as they pass across the Kerguelen Plateau through the Fawn Trough. However, the isotherms tend to spread apart over the deep Enderby Basin and the deep Australian Antarctic Basin where seafloor features are not pronounced.

pertaining to various sea ice classes still need to be further determined from multiple satellite active and passive remote sensors together with field observations (e.g., International Polar Year Antarctic Sea Ice Processes and Climate (ASPeCt) at http://aspect.antarctica.gov.au/ipy), and must be rigorously connected with physical-based scattering and emission physics from the first principles founded by Maxwell's equations. Patterns of sea ice classes and their characteristics and thickness are necessary to assess ice volume in the FIZ and over the ice production regions behind it, using remote sensing (e.g., interferometry and altimetry) and in-situ networks (e.g., International Programme for Antarctic Buoys at http://www.ipab.ag/). Moreover, autonomous sensors in submerged vehicles (e.g., Williams et al., 2014) or on drones can avoid thickness bias. This is because surveys by such sensors are not limited to selective thinner ice conditions, usually sought after as accessible routes during icebreaker operations.

Satellite data and field observations have been acquired at different times, in different seasons and years, and over different regions of Southern Ocean. However, a well-designed mission using aircraft and/ or satellite remote sensing in conjunction with surface networks and coordinated field campaigns is still necessary to characterize the FIZ. Such a study needs to include the internal ice production processes and their seasonal evolution in order to quantitatively capture the dynamic and thermodynamic processes at play, and thereby rigorously examine the specific regional behaviors of Antarctic sea ice. More complete and accurate datasets have also become available for key parameters such as bathymetry (Weatherall et al., 2015) and topography (Zink & Moirera, 2015). These can help advance the understanding and thus improve models that resolve inconsistencies with observations to capture the true Antarctic sea ice behavior in sea ice modeling. With these considerations, advanced research remains necessary to explain not only present behavior, but also to be able to forecast the response of the Antarctic sea ice cover to climate change given the geophysical constraints described in this paper.

#### **Data sources**

Data can be found at https://podaac.jpl.nasa.gov/ for QuikSCAT, http://dx.doi.org/10.5067/GHGMR-4FJ01 for sea surface temperature, http://www.natice.noaa.gov/Main\_Products.htm for NIC sea ice products, http://www.gebco.net/data\_and\_products/gridded\_bathymetry\_ data/ for GEBCO 2014 bathymetry, and https://data.noaa.gov/dataset/ global-surface-summary-of-the-day-gsod for air temperature data.

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.rse.2016.04.005.

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