The Antarctic Circumpolar Frontal Ice Zone

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***Abstract*—Antarctic and Arctic sea ice characteristics are starkly contrasted. Antarctic sea ice is encapsulated by a frontal ice zone (FIZ), which is a circumpolar band of sea ice consisting of older and thicker ice adjacent to the ice edge, while Arctic sea ice contains younger and thinner ice in the marginal ice zone along the ice edge. Here we examine the distribution and properties of the FIZ using NASA remote sensing data from a satellite scatterometer and from Operation IceBridge. Results show that the FIZ is a persistent feature, where sea ice is continually built up by a supply of younger sea ice effectively produced and transported from the internal ice pack. During the ice growth season, the FIZ becomes rougher, due to ice deformation and ridging, and thereby thicker. Also sustained by westerly winds and currents, the FIZ supports the maintenance of the ice cover. Future coordinated campaigns with surface and aircraft observations, together with high-resolution multi-dimensional measurements by the TanDEM-X satellite polarimetric and interferometric radar, are crucial to characterize, understand, and predict Antarctic sea ice change.**

Keywords-Antarctic sea ice; frontal ice zone; remote sensing; satellite scatterometer; Operation IceBridge; TanDEM-X SAR.

I. INTRODUCTION

The total extent of Antarctic sea ice has been preserved and even slightly increased in contrast to the drastic decrease of Arctic sea ice in recent decades. The opposite behavior in the interdecadal change of Antarctic and Arctic sea ice is considered by scientists as a paradox [1]-[4], which the cryospheric science research community has been struggling to explain. The stratospheric ozone depletion was suggested to cause atmospheric change that would maintain Antarctic sea ice [5][6]; however, this explanation was challenged by Sigmond and Fyfe [7]. Others relied on fresh meltwater and salinity reduction [8][9] and on wind effects [10][11] to address the paradox while leaving several issues unresolved.

For an explanation of the polar sea ice paradox to be plausible, it requires self-consistent answers simultaneously to all of these science questions about Antarctic sea ice: (1) What are the most effective processes for sea ice production pertaining to Antarctic conditions? (2) What are the factors protecting the sea ice cover? (3) What are the factors sustaining sea ice? (4) What are the factors causing regional variability? (5) Is there any discord among these factors? (6) Why do opposite effects occur in Antarctic and Arctic sea ice while both have to obey the same physics?

In a recent publication [12] using satellite and surface observations to address the above science questions, Nghiem et al. have presented an original research that ‘gives a plausible explanation for the difference in the Arctic and Antarctic sea ice response to the climate change of recent decades’ as noted by the peer review. A key finding is the formation of a formidable circumpolar FIZ that shields and thereby protects the internal younger and thinner sea ice.

Here we further examine the characteristics of the FIZ in the Southern Ocean encircling Antarctica. Remote sensing data used in this study include both satellite and aircraft data. In Section II, we present results from radar backscatter data, collected by the SeaWinds scatterometer aboard the QuikSCAT satellite (QS) in 1999-2009. Section III shows observations from aircraft acquired during the NASA’s Operation IceBridge (OiB) in 2009 together with the satellite results. Section IV highlights the characteristics of the FIZ in sustaining Antarctic sea ice, and presents a concept for future Antarctic field campaigns with coordinated surface, aircraft, and satellite observations, including TanDEM-X synthetic aperture radar (SAR), to advance sea ice science. The last section provides the summary and conclusion.

II. SATELLITE OBSERVATIONS

The immense extent of Antarctic sea ice requires satellite observations such as QS to identify and map different sea ice classes with different physical characteristics. QS was launched from the space complex at Vandenberg Air Force Base, California, in June 1999. QS radar backscatter data were acquired globally across orbit swaths as wide as 1800 km with a resolution of ~25 km and an accuracy of 0.2 dB for 3σ [13]. To observe the FIZ, QS satellite data were used in the sea ice classification algorithm developed by Nghiem et al. [12]. Their results revealed a band of circumpolar FIZ containing older and rougher sea ice in the zone adjacent to the sea ice edge, surrounding the internal sea ice pack consisting of younger and smoother sea ice. QS results in 2008 and on 22 September for each year in 1999-2009 identified the persistent existence of the FIZ [12].

We now use QS data in 2009 to observe how the FIZ evolves during the sea ice growth season from May through the peak sea ice extent in September (Figure 1). The ice classes include rough older sea ice (RI), older sea ice (OI), younger sea ice (YI), melt on sea ice, and permanent ice as defined in the published literature [12]. Results in Figure 1 confirmed that the circumpolar FIZ, composed of RI and OI, had already formed by May in 2009. Encapsulating YI in the internal sea ice pack around Antarctica, the presence of the FIZ was persistent throughout the sea ice growth season as the ice cover expanded and reached its largest extent in September 2009. In particular along the longitude of 3.38^{o},

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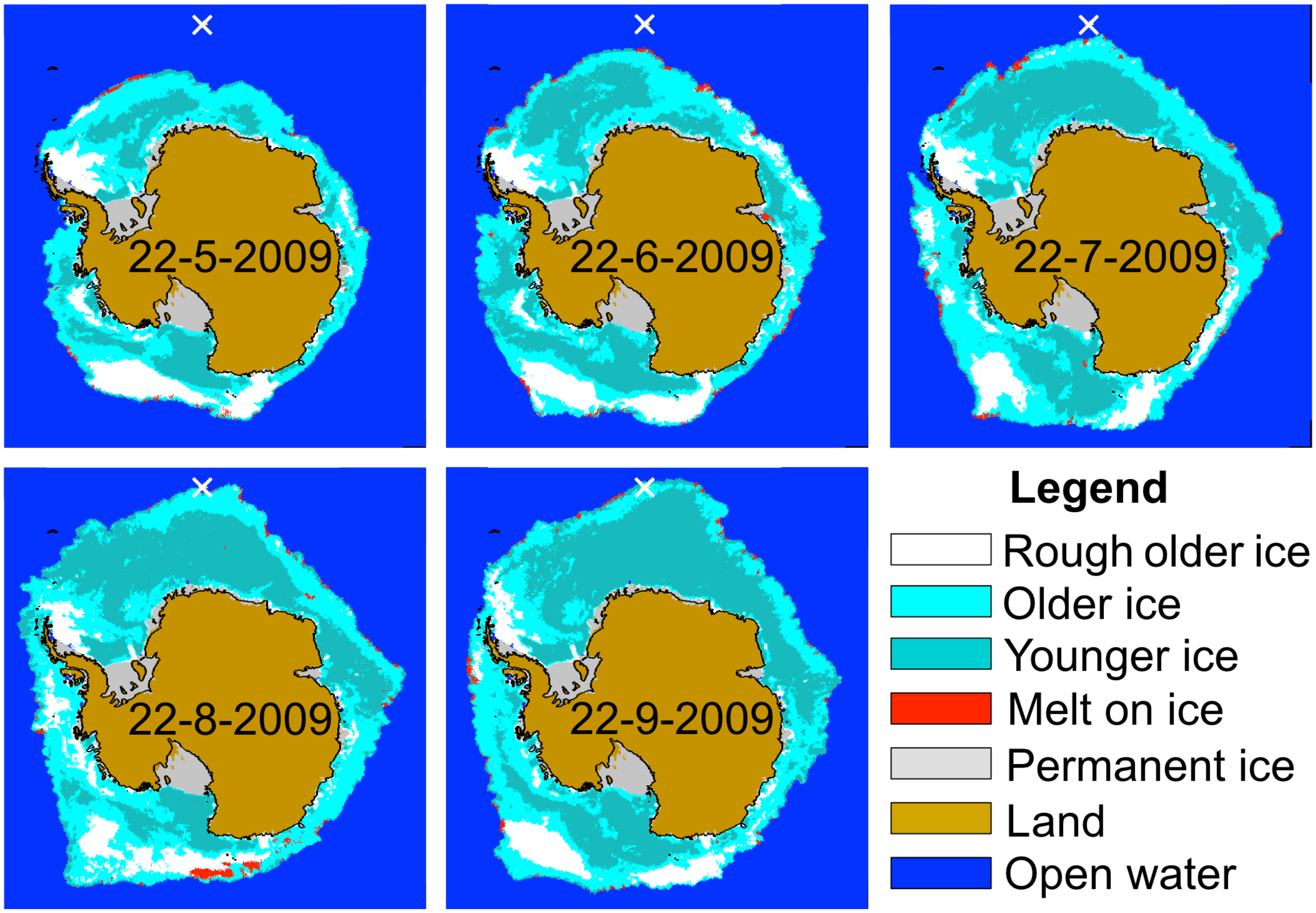

Figure 1. Antarctic synoptic sea ice classes throughout the ice growth season in 2009 observed by QS satellite data. Bouvet Island is marked by white cross.

sea ice advanced northward away from Antarctica to reach around Bouvet Island in August and could not extend much farther north in September 2009. The constraint of the sea ice edge near Bouvet Island is a recurrent feature also found in other years in 1999-2008 [12].

During the 2009 seasonal evolution of the Antarctic sea ice cover, the FIZ advanced outward in the circumpolar zone adjacent to the sea ice edge while the areal extent of the internal YI enlarged (Figure 1). This was due to persistent winds shaped by the Antarctic continental topography [12], forcing the transport of the internally produced YI outward to supply sea ice that continually built up and reinforced the FIZ along its south side. Some minor zonal areas of transient melt occurred on the surface of sea ice at different times in various locations near the sea ice edge (Figure 1).

III. Operation IceBridge Measurements

Measurements from the OiB can provide relevant data to characterize the FIZ in more detail. The OiB is a NASA mission using aircraft to survey the Earth's polar ice to obtain three-dimensional view of Arctic and Antarctic ice sheets, ice shelves, and sea ice [14]. OiB flights have been conducted in September-November over various Antarctic locations in multiple years. We use OiB data acquired along the 3600-km Seelye Loop over the Weddell Sea in 2009 by the Airborne Topographic Mapper (ATM) and by the Digital Mapping System (DMS). ATM is a scanning laser altimeter developed at the NASA Wallops Flight Facility in Virginia, and DMS is an airborne digital high-resolution camera maintained and operated by the Airborne Sensor Facility at the NASA Ames Research Center in California.

ATM measurements include surface elevation, slope, and roughness [15] with a sample width of 80 m and a pacing of 40 m on the surface along the flight track. Figure 2 presents ATM roughness along the OiB Seelye Loop flight on 24 October 2009, overlaid on a QS map of synoptic sea ice classes on the same day for comparison. The ATM roughness data have been averaged in each bin of $0.25^{o} \times 0.25^{o}$ in latitude and longitude along the OiB flight line. Overall, ATM observations show the largest roughness on RI, medium roughness on OI, and smaller roughness on YI. This is consistent with the general characteristics of the synoptic sea ice classes [12]. However, there is some discrepancy due to a mismatch in the spatial resolution of ATM and QS data to be cautioned in the comparison.

DMS data are processed to obtain geolocated and orthorectified images that represent the surface topography or digital elevation model (DEM). DMS DEM has a relative accuracy of ~0.2 m and a resolution of 10 cm × 10 cm [16] over a swath width of several hundred meters depending on

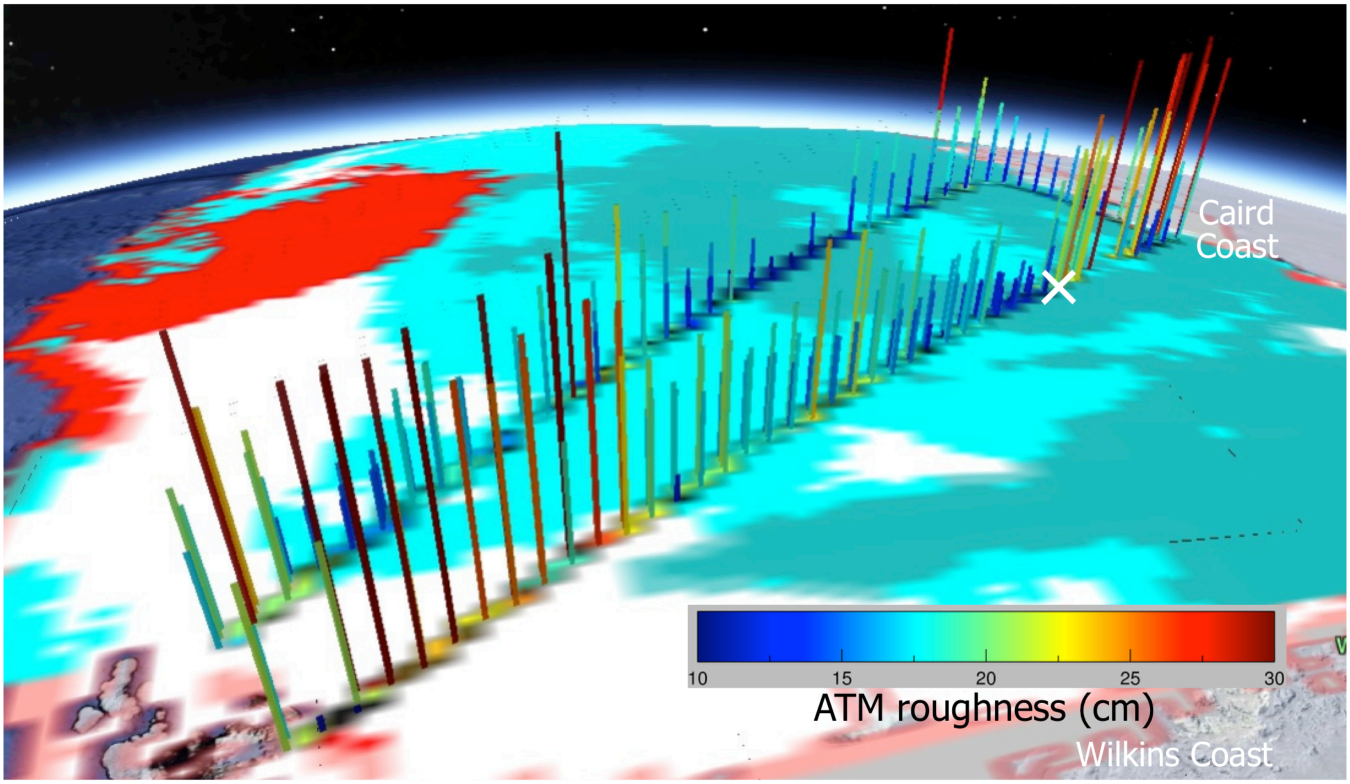

Figure 2. ATM measurement of sea ice surface roughness along the 3600-km Seelye Loop flight on 24 October 2009 during the NASA Operation IceBridge campaign over the Weddell Sea, together with QS sea ice classes on the same day. The white cross marks the location of the DMS DEM strip in Figure 3.

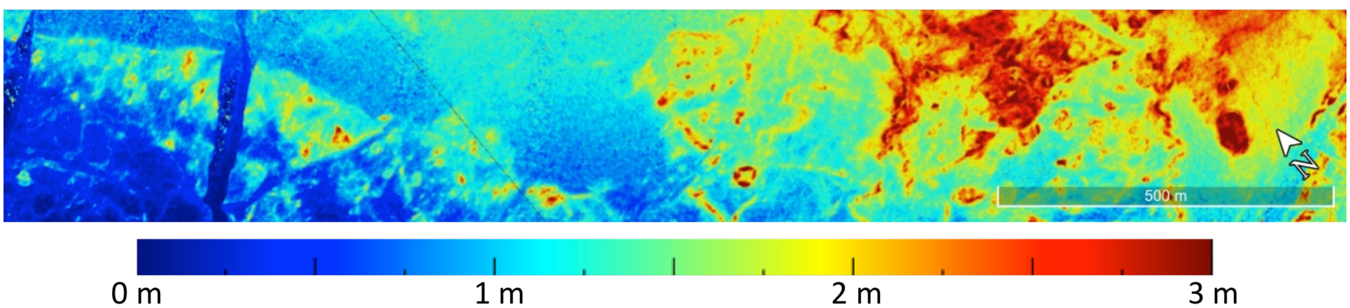

Figure 3. DMS measurement of snow-covered sea ice surface DEM in the Weddell Sea on 24 October 2009 during the Operation IceBridge campaign at the location marked by the white cross in Figure 2. The gray inset bar is a 500-m scale. This DEM is referenced to the minimum level of 0 meter.

the flight altitude. Within the DMS DEM accuracy limit, areas with pronounced features on sea ice surface such as deformed sea ice, ruble ice, pressure ridges, and other large-scale roughness [17] can be identified and statistically categorized over various sea ice classes. A 2-km segment of DMS DEM reveals a complicated surface of snow-covered sea ice varying over a range of more than 3 m (Figure 3).

IV. DISCUSSIONS

The characteristics of the Antarctic circumpolar FIZ consisting of formidable sea ice are directly opposite to the feeble ice conditions in the marginal ice zone (MIZ) consisting of young and thin ice along the edge of the Arctic sea ice cover. As presented, the FIZ consists of older sea ice grown earlier in the sea ice season and gradually advanced outward away from the Antarctic coast. The FIZ is continually built up by a supply of ice from the internal YI that can grow efficiently with a high growth rate, while the FIZ is furthermore sustained by a recirculation driven by persistent westerly winds and currents [12]. As observed in Figure 2, the FIZ has a larger roughness, corresponding a larger thickness as Toyota et al. [18] demonstrate that the mean ice thickness of Antarctic sea ice correlates with the surface roughness even better than with the mean freeboard. Persistently consisting of thicker ice, the circumpolar FIZ serves as a shield to protect the Antarctic sea ice cover. This is in a stark contrast to the Arctic MIZ that is easily reduced by melt and by wind and wave effects, making Arctic sea ice vulnerable to climate change. QS satellite scatterometer data acquired in 1999-2009, Oceansat-2 collected in 2009-2014, and SCATSAT-1 to be obtained in 2016-2021 together provide interdecadal observations of sea ice change.

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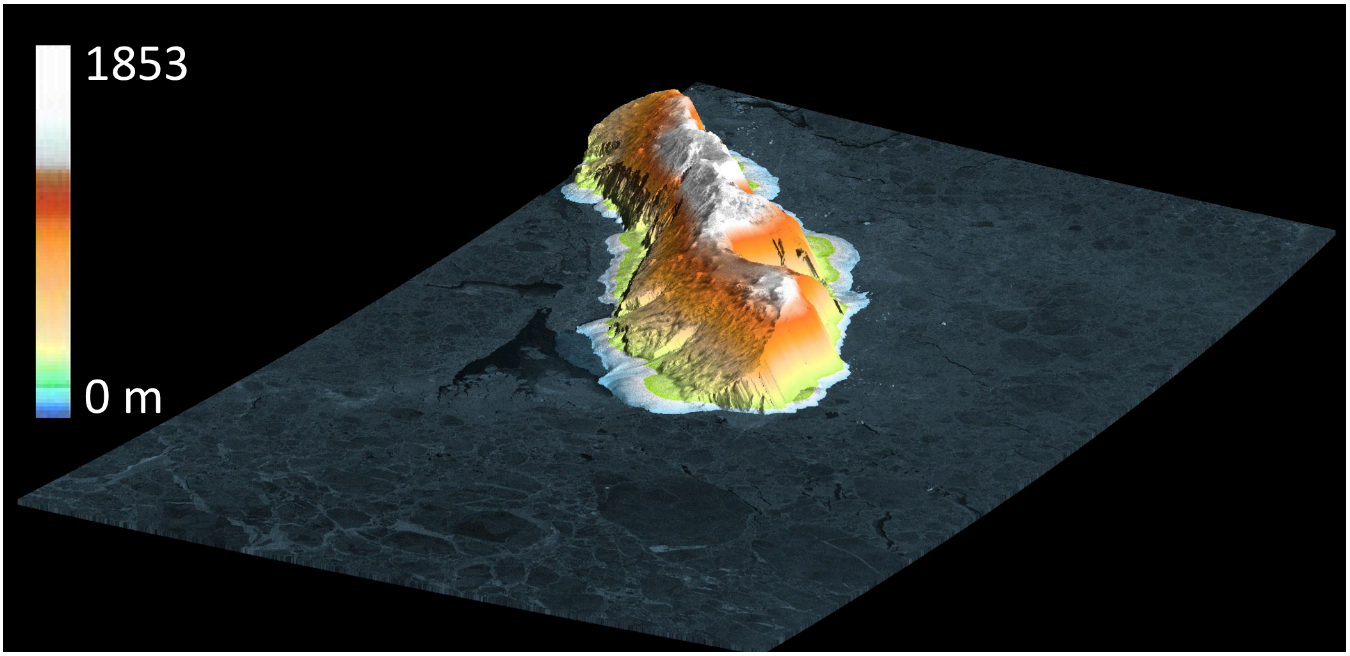

Figure 4. Example of TanDEM-X 2D backscatter pattern of Antarctic sea ice surrounding Sturge Island, located at 67.42°S and 164.73°E, where the island topography is measured in 3D by TanDEM-X interferometry.

To fully quantify the properties of the FIZ and to determine its long-term change demand extensive observations from the surface to aircraft and satellite levels at multiple scales in time and in space across the vast extent of the Southern Ocean over decades. This is particularly important to advance Antarctic science research, as there have been overwhelmingly more observations and modeling activities for the Arctic. A potential approach is to maximize the science return from the NASA's significant investment in the current OiB by developing a collaborative coordination with a future acquisition of a massive satellite SAR dataset, such as TanDEM-X [19] acquired over the Antarctic sea ice cover at its seasonal maximum extent, typically reached in the month of September or October.

The conceptual science plan is to conduct multi-phase surveys to obtain contemporaneous and collocated OiB and TanDEM-X data in conjunction with surface measurements using buoys, stations, and field observations from Antarctic icebreaker expeditions and drone operations. OiB ATM data can be used to calibrate DMS DEM, and then to compare with and correctly interpret TanDEM-X data in two (2D) and three dimensions (3D). While OiB can provide accurate and high-resolution measurements, the aircraft data are limited to a finite number of flight lines with pointwise or narrow-strip measurements. Once verified with OiB results, TanDEM-X can provide multiple measurements of sea ice properties across the vast coverage over Antarctic sea ice at its maximum extent, which may take more than 55 days to complete the massive TanDEM-X SAR data acquisition.

A major advantage is that the TanDEM-X SAR has monostatic, bistatic, polarimetric, and single-pass interferometric capabilities for robust ice and open water identification [20], sea ice classification [21], ice drift measurement [22][23], and DEM assessment [23] at a high resolution. For instance, open water detected by TanDEM-X is a crucial reference to estimate the sea ice freeboard from collocated OiB data. Since radar backscatter is sensitive to sea ice roughness [12] that correlates with sea ice thickness [18], TanDEM-X 2D SAR backscatter patterns are an independent source of information to cross-verify 3D DEM results from remote sensing estimates. Then, the 2D SAR backscatter can be used to examine the spatial distribution of roughness and thickness of Antarctic sea ice. As DEM derived from SAR interferometry represents scattering center height, which is dependent on the penetration depth in snow-covered sea ice as a function of the electromagnetic wave frequency, DEM of the snow surface from coordinated OiB DMS optical data is necessary to understand and interpret TanDEM-X 3D observations over different sea ice classes that can be mapped in 2D by TanDEM-X data [21]. Moreover, the coordinated OiB/TanDEM-X Antarctic Science Campaign (OTASC) can be extended from sea ice into land to assess the DEM over terrestrial snow-covered ice, where the topography can shape wind patterns that exert a significant control on sea ice formation and evolution [12]. Figure 4 gives an example of TanDEM-X 2D and 3D observations of Antarctic sea ice surrounding Sturge Island to illustrate the versatility of the TanDEM-X capabilities.

Moreover, a fully polarimetric interferometry theory for bistatic radars [24], inherently reduced to the case of monostatic radars as a special case, has been derived based on the fundamental basis of the first principle of Maxwell's equations to preserve the phase information that is imperative for the interpretation of TanDEM-X polarimetric and interferometric data. This is crucial as the foundation of electromagnetic physics for 2D and 3D SAR signatures of snow-covered sea ice and land ice to develop remote sensing algorithms, considering noise effects at various resolutions specifically required by different science research objectives. Results from aircraft and satellite algorithms can then be validated by surface truth and observations collected during Antarctic field campaign expeditions coordinated with remote sensing overflights.

The international community report on Global Satellite Observation Requirements for Floating Ice – Focusing on Synthetic Aperture Radar, specifically calls for the use of TanDEM-X capabilities to observe sea ice [25] in the Strategic Plan 2015-2018 of the Polar Space Task Group operated under the auspices of the World Meteorological Organization Executive Council Panel of Experts on Polar and High Mountain Observations, Research, and Services [26]. In view of multiple satellite missions for Earth science, results from the OiB/TanDEM-X coordinated campaign can serve as a reference to compare with results from future satellite missions such as the NISAR mission [27], the ICESat-2 mission [28], and the proposed Tandem-L mission [29]. From these missions, long-term validated remote sensing observations will be crucial as input to as well as verification of models for Antarctic sea ice seasonal prediction and decadal projection.

V. SUMMARY AND CONCLUSION

The Antarctic circumpolar FIZ is examined in this paper. Observations from remote sensing data show that the FIZ forms with sea ice produced earlier in the ice-growth season. Then the FIZ becomes older, rougher, and thicker as the Antarctic sea ice extent reaches its seasonal maximum in the austral winter-spring transition. In contrast to the feeble MIZ in the Arctic, the persistent FIZ encapsulates and protects the younger and thinner ice in the internal ice cover, and thereby contributes to the maintenance of Antarctic sea ice. The future OTASC field campaign is formulated to characterize the FIZ quantitatively, and to obtain a basic reference for comparisons with observations from future satellite missions to determine interdecadal change of Antarctic sea ice.

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