The Dynamic Processes of Sea Ice on the East Coast of Antarctica—A Case Study Based on Spaceborne Synthetic Aperture Radar Data from TerraSAR-X

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Abstract—In early January 2014, the Chinese icebreaker XueLong was stopped by thick ice on its passage to rescue the trapped Russian vessel Akademik Shokalskiy along the east coast of Antarctica, between Commonwealth Bay and the Mertz Glacier. During the event, X-band spaceborne synthetic aperture radar (SAR) data were continuously acquired from the TerraSAR-X (TS-X) satellite to monitor the state of the sea ice to assist both vessels. The emphasis of this case study is not to understand how the vessels escaped danger but rather to investigate the sea ice breaks in the region, i.e., the dynamic processes of the sea ice during the event through an analysis of the TS-X data, sea ice classification, and the reanalysis of surface wind and ocean current modeling results. Therefore, we present six images of TS-X ScanSAR and newly operational wide ScanSAR imaging modes; these images provide abundant information about the state of the sea ice. Both the ScanSAR and wide ScanSAR images in the HH-polarization are used for classifying sea ice in the region; the resulting classification illustrates how the sea ice varied and finally broke during the event. A further analysis of the sea ice drift derived from the sequential TS-X images and surface wind and ocean current model data partially explains why the sea ice broke under such weather conditions. This case study contributes to a better understanding of the sea ice dynamics on both regional and local scales.

Index Terms—Classification, dynamic process, sea ice, synthetic aperture radar (SAR), X-band.

I. INTRODUCTION

Sea ice in the polar regions plays a crucial role in the ocean–atmosphere interaction by modulating heat exchange, affecting deep-water convection and thermohaline circulation, and moderating global warming. In particular, the role of sea ice in global climate change has attracted extensive attention. The sea ice in Antarctica responds differently to global warming than does that in the Arctic. Whereas the ice cover in the Arctic is experiencing a persistent decline, in 2014, the Antarctic sea ice cover attained the greatest value since 1979, 20 million square kilometers. Although clear scientific explanations of this phenomenon have not yet been published, some scientists have suggested that a change in the wind patterns in Antarctica plays a major role in the sea ice state. As a consequence, the roles of the wind [1] and sea state [2] in the sea ice shift and breakup in Antarctica are receiving more attention. Compared with comprehensive studies of Arctic sea ice, there is a need for a better understanding of sea ice state in Antarctica, especially its dynamic processes under external forces, from large to regional scales.

Because of the difficulties of approaching the polar regions for field research, spaceborne remote sensing techniques are particularly important for monitoring sea ice. Among remote sensing sensors, spaceborne synthetic aperture radar (SAR) has a unique advantage: it can monitor sea ice independently from sunlight conditions and cloud coverage, both of which have significant effects on optical remote sensing sensors in polar regions. Recent spaceborne SAR systems can operate flexibly at swath widths between 30 and 500 km and spatial resolutions between 1 and 1000 m, which makes SAR particularly suitable for observing the sea ice state on different scales. The capability of SAR to monitor sea ice has been demonstrated using the first civil spaceborne SAR sensor onboard the Seasat satellite [3]. For more than two decades, sea ice monitoring using SAR has primarily focused on 1) monitoring sea ice drift and deformation [4], [5]; 2) retrieval of sea ice parameters [6], [7]; and 3) classification of sea ice type [8]–[13].

Based on pairs of SAR data, sea ice drift can be tracked or retrieved using the widely used area correlation method [4]. Monitoring of sea ice drift using spaceborne SAR data is in a mature stage and is being effectively employed by weather services (e.g., [5]).

Classification of the sea ice type is crucial for sea ice monitoring and is used to extract the extent and concentration of the ice. Commonly used classification methods include neural networks [8], Markov random fields (MRF) [9], and support vector machine (SVM) [10]. Because the radar backscatter of different types of sea ice depends on the polarization combinations, polarimetric SAR data are exploited in sea ice classification; the advantages of polarimetric data have been previously demonstrated [11]–[13]. Additionally, the characteristics of sea ice in SAR images are related to the radar frequency. The combination of SAR data acquired at different microwave frequencies—generally within the C-, X-, and L-bands—also offers improved capabilities for ice type
classification [14]–[16]. The backscattered signal of sea ice in X-band SAR images is somewhat similar to that of C-band images, whereas that of the L-band is dissimilar because of differences in the capabilities of penetration depth and sensitivity to surface roughness.

Although full polarimetric SAR offers a significant advantage for classifying sea ice types, its narrow swath width, generally narrower than 30 km, is a major limitation for monitoring the state of sea ice. Therefore, spaceborne SAR images taken in the ScanSAR mode are preferred for operational sea ice monitoring because of the wider swath widths (greater than 100 km). However, the wide swath is acquired at the cost of single polarization. Single (HH or VV) or dual (HH/HV or VV/VH) polarization dominates this mode, but these polarization types contain less information for ice type recognition than do quad-polarization data. In addition, the interference of noise floor stripes [17], along with the beam jointing, is also challenges for sea ice classification using ScanSAR data.

Nevertheless, because of the mature development of sea ice classification based on single-polari-zation SAR data, SAR imagery in a wide swath is an effective tool to monitor the state of sea ice over large areas. In early January 2014, the Chinese icebreaker XueLong was stopped by thick ice on its passage to rescue the trapped Russian vessel Akademik Shokalskiy along the coast of East Antarctica, between Commonwealth Bay and the Mertz Glacier. During the event, the German Aerospace Center (DLR) provided TerraSAR-X (TS-X) ScanSAR and Wide ScanSAR data in real time, along with some general analysis of the sea ice state, to the rescue centre in Australia.1

Various external and internal forces drive the dynamic processes of sea ice [18]. The external forces of surface winds, sea currents, and sea surface waves can contribute to variations in the sea ice extent, concentration, and thickness. Whereas most of the reported studies of sea ice focus on deriving geophysical parameters from spaceborne SAR data, this study aims to analyze the dynamic processes of sea ice, i.e., the mesoscale responses of sea ice to external forces during the abovementioned event, based on TS-X data, sea ice classification results, and reanalysis model data. The sea ice types are classified using the TS-X ScanSAR and Wide ScanSAR data in HH single polarization; the results illustrate how the sea ice broke during the event. Furthermore, an analysis of surface wind and sea current model data answers the question of why sea ice breaks.

This paper is organized as follows. The TS-X and reanalysis model data are briefly described in Section II. An analysis of the TS-X images to quantify variations in the sea ice state during the event is presented in Section III. In Section IV, based on the analysis of the radar signature of the sea ice from X-band SAR data, we conduct a sea ice classification of the TS-X images and consequently interpret how the sea ice broke. In Section V, we analyze the surface wind and sea current model results to understand the roles of external forces in the breaking of sea ice during the event. A summary and our conclusion are presented in Section VI.


### II. Description of the Dataset

The study area is located on the east coast of Antarctica, between Commonwealth Bay and the Mertz Glacier. X-band spaceborne TS-X data are used for sea ice classification and drift derivation. Together with the TS-X data, the reanalysis surface wind and sea current model data are used to understand the sea ice dynamics.

#### A. TS-X Dataset

Six TS-X images from the ScanSAR and Wide ScanSAR modes were acquired on first, second, fourth, fifth, seventh, and ninth days of January 2014 during the event. All of the images were acquired in horizontal–horizontal (HH) polarization and processed into the multilook ground range detected (MGD) products. The new TS-X imaging mode Wide ScanSAR has been operationally available since autumn 2013 [19]; it was designed primarily for ship detection [20] and sea ice monitoring. The Wide ScanSAR images are formed by six beams with a swath width of up to 270 km. The nominal azimuth resolution of the Wide ScanSAR data is 40 m. Technical details regarding the TS-X data are presented in Table I.

#### B. Reanalysis Model Data

The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis wind data [21], which have a spatial resolution of $0.75^\circ \times 0.75^\circ$, are used for the analysis of the weather conditions during the event. The ERA-Interim reanalysis wind data are available every 6 h at synoptic times. From the sea ice classification results (which are presented below), it is found that the sea ice in the region did not rapidly change (i.e., within several hours); therefore, daily averaged wind data are used for the analysis.

The sea surface current data are derived from the hybrid coordinate ocean model (HYCOM) GLBu0.08 global analysis data [22]. The Navy Coupled Ocean Data Assimilation (NCOA) [23] system incorporates the available radar altimeter observations and in situ sea surface temperatures—along with the vertical profiles of water temperature and salinity from Argos floats, XBTs, and buoys—into the HYCOM forecast. The HYCOM GLBu0.08 sea current data have a uniform resolution of 1/12° in both longitude and latitude between the latitudes of 80.48°S and 80.48°N.

### Table I

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<td>230</td>
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<tr>
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III. ANALYSIS OF THE TS-X IMAGES

In this section, the acquired TS-X images are presented along with a general description of the sea ice variation during the event.

All six TS-X images are shown in Fig. 1. On the SAR images, part of the Antarctic coast can be identified on the bottom or at a corner of the images. Two identifiable locations from the west to the east are Cape De La Motte and the Mertz Glacier, respectively.

A clear presentation of the significant changes in the ice state in the Antarctica observed in these TS-X images is that the protruding tongue of the Mertz Glacier has broken away. These positions can be used as geographic references. To the north of the coast is sea ice, the majority of which is attached to the coast; a small portion is scattered off the coast. On January 1, the approximate position of the R/V XueLong was 144°25′E/66°39′S, where the pack ice surrounded it, and the MV Akademik Shokalskiy was at 144°15′E/66°50′S. The
positions of both vessels are marked by blue dots on the TS-X image acquired on January 1, as shown in Fig. 1. From January 1 to 5, a large area of sea ice seems to have a constant distribution. This sea ice clung to the Antarctic coast, thus making it appear to be continuous land. However, on January 7, inside of this large area of sea ice, a wide lead can be identified clearly from this TS-X image. This large lead extended in a north–south direction and had some narrow leads that extended off of it similarly to the branches of a tree. This large lead stretched from the north to the coast in the south and was approximately 7000 m wide. The small leads, which were approximately 1000 m wide, stretched eastward from the main lead.

Because of the absence of a TS-X image on January 6, we use the moderate resolution imaging spectroradiometer (MODIS) Terra image acquired on January 6 at 23:30 UTC, which is shown in Fig. 2, as a supplement to analyze the state of the sea ice. In this image, an initial crack with a width of approximately 1000 m can be observed. Compared with the TS-X image on January 7 at 18:36 UTC, we can infer a significant enlargement of the main lead, as much as 6000 m over approximately 19 h.

Although the continuously acquired TS-X images and the MODIS image clearly reveal the temporal and spatial variation of the sea ice state during the event, a more detailed analysis of sea ice classification is necessary to determine which types of sea ice broke during the event.

IV. SEA ICE CLASSIFICATION OF THE TS-X IMAGES

In this section, we first present the radar signature of the sea ice in the X-band TS-X HH polarization data, followed by a detailed description of sea ice classification using the TS-X data.

A. Radar Signatures of Sea Ice in the TS-X HH Polarization Data

The classification of sea ice types from the TS-X images is based on a report released by the Antarctic Climate and Ecosystems Cooperative Research Centre [24]. However, the report only approximates the types of the sea ice in the TS-X images. The detailed classification of sea ice types is based on our previous experience, as well as on the information obtained from TS-X and RADARSAT-2 images acquired in the previous years. Off the coastline, fast ice, multiyear (MY) pack ice, first-year (FY) pack ice, brash ice, and open water are presented from the west to the east in the TS-X images. The fast ice clings to the coast. The MY ice is next to the fast ice, in which large ice floes are embedded. To its east is the FY ice, which is further classified into level FY ice and deformed FY ice. The brash ice lies in the easternmost location among these ice types and is scattered in the open water. Four enlarged subimages extracted from the TS-X image acquired on January 1 that present the different sea ice types are shown in Fig. 3.

Because the TS-X images were acquired continuously in a short period, the characteristics of the sea ice did not change significantly within the acquisitions. Furthermore, the TS-X images were acquired in different orbits and at different incidence angles, which provides an opportunity to study the relationship between the radar backscatter coefficients of different sea ice types and the incidence angles to better understand the X-band radar signatures of the sea ice. Fig. 4 shows the dependence of the radar backscatter coefficients of the fast ice, MY ice, and FY ice on the incidence angles derived from the six TS-X images. The colored squares in the figure represent the mean radar backscatter coefficients of sea ice derived from the pixels within a one-degree bin of the incidence angle.

The diagram indicates that the radar backscatter coefficients of the fast ice, in this case, varied between $-18.07$ and $-10.88$ dB for incidence angles between $17^\circ$ and $46^\circ$. For incidence angles less than $43^\circ$, the radar backscatter coefficients decreased with increasing incidence angle with a slope of $-0.24$ dB/°. We notice that the outliers at incidence angles of greater than $44^\circ$ are from the TS-X image acquired on
January 2. However, understanding the origin of these outliers in the fast ice and MY ice from the same image requires further investigation.

The MY pack ice, which constitutes a narrow zone that extends from the northwest to the southeast, is positioned next to the fast ice. The radar backscatter coefficients of the MY ice are greater than those of the fast ice in the vicinity by an overall value of 2.0 dB and exhibit a decreasing trend with a slope that is greater than those of the fast ice in the vicinity by an overall value of 2.0 dB and exhibit a decreasing trend with a slope that is greater than those of the fast ice. Therefore, the MY ice zone is nearly parallel to the fast ice boundary. According to our collection of SAR images acquired in 2013, the sea ice in this MY ice zone is pack ice that existed there for at least a summer. During this period, the ice was repeatedly broken and accumulated.

The FY ice is to the east of the MY ice and can be further divided into two subtypes, deformed FY ice and level FY ice. The variations in the two subtypes of FY ice radar backscatter coefficients are represented by the yellow and green symbols in Fig. 4. The deformed FY ice has a rough surface and therefore has greater radar backscatter coefficients than do the other three types of sea ice shown in Fig. 4. The mean radar backscatter coefficients of the deformed FY ice are generally greater than −12.5 dB for incidence angles between 20° and 45°. The radar backscatter coefficients of level FY ice are less than those of both deformed FY ice and MY ice, but they are very similar to the values of the fast ice.

Brash ice refers to ice fragments that are less than 2 m across. In the east portion of the region, such fragments accumulated and covered a large area. Because of their thinness and collisions driven by sea surface waves, brash ice becomes easily deformed, thus giving it a rough surface. Therefore, for each ice fragment, the backscatter coefficient is high. When small fragments of brash ice are accumulated into patches, the space between these patches is filled with seawater. This bright and dark tonal variation of brash ice is similar to that of FY ice. However, the difference is that the gaps among the brash ice patches are irregular in size and shape, whereas most of the level FY ice patches have nearly equal sizes and round shapes.

Some backscatter characteristics of ice types are summarized in Table II.

The relation between the radar backscatter coefficients of the X-band SAR and sea surface water is much more complex than for sea ice, which depends on both the incidence angle and sea surface wind speed and direction. The geophysical model function (GMF) XMOD2 [25] describes this relationship in detail. In the presented TS-X data, the radar backscatter coefficients of open water exhibit a variation of greater than 15 dB from 22° to 48°. Therefore, the backscatter coefficients of open water overlap with that of certain sea ice types, and we found that the overlapping is particularly obvious for incidence angles between 30° and 35°.

Although the radar backscatter signatures of different sea ice types and open water in the X-band TS-X image have some discrepancies, there are also quite obvious overlaps among them. Therefore, other parameters of sea ice derived from the TS-X data, in addition to the radar backscatter coefficients, were used for the classification.

B. Sea Ice Classification Approach and Results

The SVM method is used in this study for performing sea ice classification based on the TS-X single-polarization data. The classification basis includes the TS-X radar backscatter coefficients, texture features, and incidence angle values. This method was implemented in a previous study using the RADARSAT-2 dual-polarization (HH/HV) data [26]. This approach includes two general steps: extraction of the texture features from the SAR data and implementation of the SVM classification.

Sea ice texture features are extracted from the TS-X data using a gray level co-occurrence matrix (GLCM). Eight frequently used features (mean, variance, homogeneity, contrast, dissimilarity, entropy, angular second moment, and correlation) are used for the sea ice classification. One important step of the GLCM calculation is to optimize its parameters, which are the window size, displacement, quantization levels, and orientation, to extract the values of the features. To set the appropriate parameters, a number of tests are performed. To demonstrate this process, we use the example of optimizing the window size parameter. Fig. 5 shows the normalized texture values calculated using different window sizes of 9 × 9, 19 × 19, 29 × 29, and 39 × 39 pixels. The numbers along the x-axis correspond to the eight texture features (mean, variance, homogeneity, contrast, dissimilarity, entropy, angular second moment, and correlation), whereas the y-axis indicates the normalized values of those features. The different colored lines refer to different sea ice types. The larger the variance between the different

![Fig. 4. Dependence of the sea ice radar backscatter coefficients on the incidence angles derived from all six images.](image-url)
types of sea ice, the more likely it is that there is separation between them. Therefore, we can see that the window size of 39 × 39 pixels performed better than the others.

Similarly, experiments are also performed to determine another parameter, the displacement. It is set at 4. The quantization level is set to 32, which is sufficient according to a previous study [27]. The orientation is set to 0°, 45°, 90°, and 135°, such that each TS-X image generates four GLCMs. The final GLCM is generated based on the average of these four GLCMs, which is reasonable because sea ice can grow in all directions.

The SVM [28, 29] is an effective machine learning method that can model complex nonlinear boundaries through the use of adapted kernel functions. The one-versus-one SVM classifier is used in this study.

To implement the SVM classification, the following steps are needed:
1) building a training dataset;
2) training and modeling of an SVM classifier; and
3) applying the constructed SVM classifier to a SAR image.

The training dataset is built with samples from all six TS-X images, and these samples are derived using a window size of 5 × 5 pixels and a step size of 0.5° for the incidence angle. The classification basis includes the TS-X radar backscatter coefficients for the HH-polarization, eight GLCM texture features, the incidence angles, and zone maps. These zone maps are maps of four coarse categories, which are the fast ice zone, MY ice zone, FY ice zone, and open water zone. They are obtained by an initial classification, the bases of which include the TS-X subimages in a previous study [30]. In the second step, a radial basis function (RBF) is used to construct the classifier. Through training, we obtained its optimized parameters (the penalty parameter is 16384 and the kernel parameter is 256). Next, we used these optimized parameters to construct the SVM classifier, and we then used this classifier to classify the sea ice types for each TS-X image.

We select the TS-X images acquired on January 1, 4, 5, and 7 to illustrate the classification results shown in Fig. 6. From January 1 to 5, the distribution of the sea ice is generally consistent. To quantitatively evaluate the consistency of these classifications from day to day, four submaps are clipped from the classification maps to the same geographic extent (the white rectangle in Fig. 7), where the distribution of fast ice, MY ice, and large ice floes seldom change from January 1 to 5. Comparing the four submaps, a total consistency of 81.5% is obtained. This partially proves that the classification results among multiple days are generally consistent. However, there are still some inconsistencies among the four maps. In this study, the training samples are selected randomly based on visual interpretation. Analysis of the radar backscatter signatures of different sea ice types also indicates that there are many overlaps among the different sea ice types. The misinterpretation of ice types during sampling may result in inconsistency in classification among the four maps.

The other issue arising from the sea ice classification is the selection of training samples. Analysis of the radar backscatter coefficients of sea ice presented in the previous part indicates that they depend on the incidence angles. Therefore, the training samples are selected from all six images to cover the various incidence angles for each sea ice type. This raises the issue of whether the classification is a real “classification” or simply recognition, which can be explained from two sides. On the one hand, the training dataset consists of only some samples; some pixels are selected as representative, but the classification is implemented for all pixels. On the other hand, an additional experiment described below further proves this point. Samples of the training dataset are only from the TS-X subimages in gray shown in Fig. 8, whereas the testing dataset comes from the leftover parts. The calculated confusion matrices of sea ice classification implemented in the test dataset in the 4 days are listed in Table III. The results indicate that the sea ice classification works fairly well for the independent test dataset, with an overall accuracy of 93.22%, 90.82%, 93.39%, and 89.71% for the 4 days, respectively.

C. Sea Ice State Derived From the Classification Results

The analysis presented above proves that the approach and methodology used in this study are effective for sea ice classification. Thus, we now further identify the sea ice state based on the classification maps.

The pack ice, including the MY pack ice and the FY pack ice, clung to the fast ice. There were ice floes scattered in the both pack ice zones. The distribution and position of these three sea ice types seldom changed, even for the large ice embedded in them. From January 1 to 4, one small change that was identified is that the edge of the pack ice moved gradually westward. Its edge moved westward approximately 5000 m from January 1 [Fig. 6(a)] to January 4 [Fig. 6(b)]. We use a parameter named the compact ratio to quantify the area change of the same ice type in the same geographical extent between two scenes. The
Fig. 6. Sea ice classification of the TS-X data acquired on (a) January 1, (b) January 4, (c) January 5, and (d) January 7, in 2014.

Fig. 7. White rectangle in the left sea ice classification map shows the location of the right images which are clipped from January 1, 2, 4, and 5.

Fig. 8. Additional experiment to verify the efficiency of the classification. Samples in the training dataset are selected from the gray parts of the TS-X images, while the sea ice classification is implemented on the leftover parts for testing.
area of MY and FY pack ice on January 4 becomes less than that on January 1, which results in a compaction ratio of 0.8931, indicating that the pack ice was under a continuous external force and thus horizontally packed more closely on January 4 than on January 1. Moreover, significant variations in the distribution of the brash ice indicate a change in the surface wind and the subsequently developed sea surface waves in this region, which we analyze in detail in Section V.

On January 7, the main lead (which was north–south oriented) separated the MY ice from the fast ice. The majority of the MY ice broke away from the fast ice in the south, whereas a small portion of the MY ice remained fastened to the northern fast ice. In this position, the FY ice broke away from the MY ice, thereby resulting in a wide lead. Compared with the MODIS image acquired on January 6 at 23:30 UTC, this lead widened 6 km more within 19 h, and the pack ice in the east moved further eastward. Branched from the main lead, several narrow leads opened and extended eastward in the region of the FY ice. In the north, the FY ice broke into patches, and several small leads extended along the edges of the small FY ice floes.

### V. Interpretation of Sea Ice Breaking

In Section IV-C, the sea ice classification indicates how the sea ice broke in this case. In the following section, the sea ice drift is quantitatively derived from sequential TS-X data. Through comparison with the analysis of the weather conditions, we verify that external forces contributed to the breaking of the sea ice during this event.

#### A. Derivation of the Sea Ice Drift

Sequential TS-X images were acquired before and after the sea ice break; thus, we could extract the sea ice drift using the maximum cross-correlation (MCC) method [17]. Two sub-scenes, shown in Fig. 9(a) and (b), which are extracted from the TS-X images taken on January 4 and 7, respectively, are selected as data pairs to derive the sea ice drift [Fig. 9(c)].

The derived sea ice drift suggests that the sea ice moved to the east in the direction of $84^\circ$ relative to the north. We further divide the vectors into three categories according to their orientation: $76^\circ$–$85^\circ$ (red), $85^\circ$–$90^\circ$ (green), and $90^\circ$–$97^\circ$ (blue). The average displacement values in the three regions are 6705, 7104, and 7423 m, respectively, and these values increase gradually from the blue category to the red category. Comparing the sea ice drift map with the classification maps, we observe that FY ice dominated the red region, while MY ice dominated the green region. The larger displacement and greater deviation from the east in the red region might indicate that the FY ice was not as packed as the MY ice; thus, the FY ice was more easily broken and dispersed by external forces in this case.

#### TABLE III

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<th>CASE ON January 1</th>
<th>Class</th>
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<th>LFY1</th>
<th>OW</th>
<th>DFY1</th>
<th>IFS</th>
<th>MYI</th>
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FI, fast ice; LFY1, level FY ice; OW, open water; DFY1, deformed FY ice; IFS, ice floes; MYI, MY ice.
Fig. 10. Daily averaged surface wind maps at a height of 10 m derived from the ERA-Interim reanalysis wind data from January 1 to 7, 2014. The dashed rectangle indicates the geographic coverage in which the TS-X images and sea ice classification are presented.

B. Analysis of the Surface Wind

The daily surface wind maps at a height of 10 m derived from the ERA-Interim reanalysis dataset from January 1 until January 7 during the event are shown in Fig. 10. The black dashed-lined square in the figures represents the region in which the TS-X images and sea ice classifications are presented. The wind maps from January 1 until January 4 suggest that a rather strong southeasterly wind blowing from Antarctica toward the open sea, with a magnitude varying between approximately 8 and 10 m/s, was dominating the region. Although the dominant wind in the region was still a southeasterly wind on January 5, its magnitude significantly reduced to approximately 5 m/s. The wind map on January 5 suggests that a wind system from the open sea toward Antarctica arrived at the region. The wind conditions became rather complicated on January 6. The wind from the open sea and the opposite wind from Antarctica, which had similar magnitudes of less than 3 m/s, appear to be balanced in the region. The northwesterly wind from the open sea dominated the entire region on January 7, and the wind speed increased to approximately 5–6 m/s.

The spatial and temporal variations of surface wind are quite consistent with the state of the sea ice revealed in the TS-X images and the classification results. The strong and constant southeasterly wind from January 1 until January 4 played a major role in packing the sea ice. From January 5, the southeasterly wind became weak, although it still dominated the vicinity. The response of sea ice is related to the surface wind; the sea ice was more compact on January 5 than on previous days, as determined from the sea ice classification results. The change in the weather conditions on January 6 was a turning point for the dynamic processes of the sea ice in this event. The wind maps shown in Fig. 10 present the daily averaged wind speeds, in which the temporal variation of the surface wind field within 1 day is eliminated.

Fig. 11(a) and (b) shows the surface wind field on January 6 at 6:00 and 18:00 UTC, respectively; comparison of these maps reveals that the surface wind field on that day experienced a significant temporal variation within the 12-h period. The north wind in the region at 6:00 UTC had a speed of less than 0.5 m/s. However, the speed greatly increased to approximately 5 m/s within 12 h, and the wind changed to a northwesterly wind. The derived sea ice drift shown in Fig. 9 suggests that the average orientation of the sea ice break was 84° clockwise relative to the north, whereas the direction of the surface wind at 18:00 UTC on January 6 in the sea ice break region was 130° clockwise relative to the north. The motion of the sea ice is in a direction of 46° to the left relative to the wind direction. The difference between the sea ice drift and wind directions is due to the strong Coriolis force on the sea ice motion in the southern polar region. Combining these results with the appearance of the sea ice lead observed in the MODIS image acquired at 23:30 UTC on January 6, we can conclude that the change in the surface wind on January 6 played a major role in the sea ice breaking. The persistent northwesterly wind from January 6 onward further pushed the FY and MY sea ice away. Consequently, the observed lead in the TS-X image...
Fig. 12. Daily mean HYCOM sea surface current analysis data from January 1 to 7, 2014. The dashed rectangle indicates the geographic area in which the TS-X images and sea ice classification are presented.

acquired on January 7 at 18:25 UTC became larger than that observed in the MODIS images.

C. Analysis of the Sea Surface Current

In this section, the HYCOM sea surface current analysis data are presented to identify the role of sea surface currents on the breaking of the sea ice during the event. Fig. 12 shows the daily mean sea surface current field from January 1 to 7. Similar to the wind maps shown in Fig. 12, the black dashed rectangles in the maps represent the region in which we studied the breakup of the sea ice. Although the sea ice boundary setting in the HYCOM model is not consistent with the sea ice cover observed in the TS-X images, we can assume that the modeled sea surface currents are equal (or near) to the subsurface sea currents when the sea is covered by ice.

Interestingly, the Antarctica coast current (ACoC) in the region also exhibited significant temporal and spatial variation during the week. On average, the ACoC flows westward and parallel to the Antarctic coast. The HYCOM analysis data suggest that the northeasterly sea surface current increased gradually from January 1 to 4 and reached the highest value, which was greater than 0.5 m/s, on January 4. However, the speed dramatically reduced to approximately 0.3 m/s on January 6. On January 7, the modeled sea surface current speed was less than 0.1 m/s but remained northeasterly. Comparing the sea surface current maps with the classification of sea ice in the area, we can observe that when the sea ice began to break on January 6, the sea surface current was weaker compared with the previous days when the sea ice was strongly packed, although its direction was counter to the direction of the breaking sea ice. When the magnitude of the sea surface current reduced further, the lead that had appeared became wider, as can be observed in the TS-X image from January 7.

VI. SUMMARY AND CONCLUSION

In this case study, the backscatter coefficients of different types of sea ice in the X-band SAR, the classification of sea ice using single polarization TS-X ScanSAR and Wide ScanSAR data, and the dynamic processes of Antarctic sea ice on a regional scale are investigated.

The TS-X ScanSAR and Wide ScanSAR data that were continuously acquired during the event make it possible to investigate the radar characteristics of different sea ice types using a large range of incidence angles, from the steepest angle of 15° to the shallowest angle of 45°. The backscatter coefficients of fast ice and MY ice in the X-band radar exhibit an overall decreasing trend as the incidence angle increases from 15° to 43°. Although there are overlaps among the ranges for the radar backscatter coefficients among the four classes of sea ice (fast ice, MY ice, deformed FY ice, and level FY ice), it was found that the deformed FY ice had the greatest value, varying between −15 and −9 dB. The MY ice radar backscatter coefficients were greater than those of the level FY ice but less than those of the deformed FY ice. The fast ice had the lowest X-band radar backscatter coefficients among the four types of sea ice. However, all the comparisons described above are only for incidence angles of less than 43°. For incidence angles greater than 43°, the distinct high values of the radar backscatter of the fast ice and MY ice still require further study.

The sea ice classification indicates that pack ice, whether MY ice or FY ice, is likely to be separated from fast ice under external forces, even though the pack ice might have clung to the fast ice for a while. Second, leads are more likely to develop at boundaries between ice types. Third, the ice zone that contains ice floes is easy to break, and cracks are likely to occur or extend along the edges of ice floes.

The sea ice pack, sea ice motion, and size of the sea ice leads are the three major factors regarding the sea ice state that we could determine from the TS-X images. The consistency between the sea ice state and the variation of surface wind field suggests that the surface wind stress was a major positive force on the sea ice dynamics during this event. The persistent wind that blew northwestward from the Antarctica toward the open sea from January 1 to 5 packed the MY and FY sea ice with the...
fast ice. The increasing northwesterly wind on January 6 was the turning point of this event, which caused the FY and MY sea ice to separate from the fast ice. The rather strong northwesterly wind that blew throughout the entire day of January 7 further pushed the FY and MY pack ice away from the fast ice and widened the lead to approximately 7 km.

Regardless of the magnitude of the sea surface current in the region, it remained in the southwest direction, counter to the break in the sea ice, thus representing a force that could pack the sea ice. The key finding is that the lead formation occurred when the northwesterly wind became strong, even though the easterly-northeasterly surface current remained as a force to pack the sea ice. This indicates that the surface wind should play a dominant role in the lead formation. Leppäranta [31] presents a ratio of $I_{aw} = NaU_a/U_{wg}$ to determine whether the ice motion is dominantly driven by wind ($I_{aw} < 1$) or by ocean circulation ($I_{aw} > 1$). $Na$ is the Nansen number and is set to 0.03 in this case according to [31]. $U_a$ is set to 5 m/s according to the ERA-Interim model result on January 6 at 18:00 UTC. The surface current on January 6 was approximately 0.1 m/s. Because the geostrophic current $U_{wg}$ is less than the surface current, the ratio should be greater than 1.5, which indicates that the sea ice motion in this case is dominantly driven by wind. This is consistent with our finding and deduction in this case study. Finally, the event occurred in the southern hemisphere summer; therefore, the internal force of the sea ice was small. Furthermore, a large area of open water was located to the southeast of the sea ice, which allowed the sea ice to move freely to the southeast.

**Acknowledgment**

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**References**


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