Measuring Deformed Sea Ice in Seasonal Ice Zones Using L-Band SAR Images

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Abstract—In order to improve the understanding of the dynamical deformation processes of sea ice in the seasonal ice zone (SIZ), measures to detect deformed ice were developed and validated using satellite L-band synthetic aperture radar (ScanSAR) images for the southern Sea of Okhotsk.

To approach, sea ice was categorized into three ice types, typical of the sea ice in this region: nilas (thin level), pancake ice (thick rough), and deformed ice (thick rough), and then the measures to classify into these categories were developed using ALOS/Phased Array type L-band Synthetic Aperture Radar (PALSAR) as a function of backscatter coefficients at HH polarization ($\sigma_{HH}$) and incidence angle ($\theta_i$), based on the field observations. Comparative analysis confirmed that PALSAR can detect deformed ice more efficiently than RADARSAT-2 (C-band SAR).

The temporal evolution of the area, judged as deformed ice from these measures, shows significant variability with both time and space, and deformed ice regions appear in relatively linear alignments with a width of a few tens of kilometers in the inner ice pack region, consistent with ice drift convergence. To confirm the results, PALSAR-2 images at HH and HV polarizations were examined as a function of $\theta_i$, based on the four-year field observations in the same area. The results revealed that $\sigma_{HH}$ and $\sigma_{HV}$ are both subject to floe sizes as well as deformed ice, and $\sigma_{HH}$ is more sensitive. This indicates that care should be taken when applying these measures to the ice areas where significantly small floes are dominant like the marginal ice zone.

Index Terms—Cryosphere, deformed sea ice, dynamics, remote sensing, sea ice, synthetic aperture radar (SAR).

I. INTRODUCTION

SEA ice plays an important role in shaping the polar climate. Associated with the significant reduction in sea ice extent in the Arctic Ocean for several decades, the Arctic-wide warming trend is twice as fast as the surrounding regions [1]. Therefore, it is quite important to reproduce the sea ice extent and thickness in the climate models to predict the future climate in the Arctic region. However, it was reported that none of the Intergovernmental Panel on Climate Change (IPCC) climate models could reproduce the observed rapid thinning trend of mean ice thickness in the Arctic Ocean [2], [3]. They stressed the need to improve the dynamic part in the model. Since the fraction of the seasonal ice zone (SIZ) in the Arctic Ocean is increasing in association with the recent rapid reduction of summer sea ice extent (see [4]–[6]), it will become more and more important in the future to understand the dynamical processes of sea ice in the SIZ. Considering the essential effect of deformation processes on the dynamical behavior and thickness distribution of sea ice especially in the SIZ (see [7]–[9]), developing the measures to detect deformed ice from satellite images and examining its temporal evolution is expected to contribute significantly to the improvement of numerical sea ice models.

To monitor deformed ice, which usually occurs on a scale less than 1 km in width, in a relatively wide region ($\geq$100 km), the space-borne synthetic aperture radar (SAR) is expected to be a useful tool because of its high spatial resolution ($\leq$100 m), wide coverage ($\geq$100 km), and high sensitivity to surface roughness. SAR data have been proven to be efficient for the study of sea ice since the launch of Seasat in 1978 [10].

While C-band SAR (4–8 GHz, wavelength = 3.8 − 7.5 cm) has been used most frequently for the polar sea ice research and attempts to estimate ice surface roughness have been made (see [11], [12]), it was pointed out that L-band SAR (1–2 GHz, 15–30 cm) is more suitable for discriminating ridged ice from level ice than C-band SAR from the comparative analysis of airborne SAR images targeted for the Arctic sea ice [13], [14] and satellite SAR images for the Baltic Sea [15] and for the saline ice of Lake Saroma, Hokkaido, Japan [16], and also than X-band SAR (8−12 GHz, 3 cm) from field measurements off Alaskan coast coordinated with satellite SAR images [17]. This is because the backscatter coefficient of SAR is sensitive to the surface roughness larger than the wavelength [18] and the wavelength of L-band SAR is close to the surface roughness of deformed ice in the SIZ. The capability of L-band SAR for detecting ice features compared with C-band SAR was confirmed not limited to the midwinter season, but also during the melt season [19], [20]. In fact, the capability of L-band SAR for extracting ridged ice had already been shown for the Beaufort Sea ice at the very early stage of the SAR history [21]. However, to the authors’ knowledge, measures for classification into ridged ice with L-band SAR, which is applicable to wide areas, has not been developed yet except for lookup tables made up by several studies (see [14], [22]). Although fine polarimetric L-band SAR images were used to develop measures to classify ice types (see [23], [24]), the analysis area is relatively limited, and further study is...
In order to develop measures to discriminate ice types, we focused on the sea ice in the southern Sea of Okhotsk as a typical SIZ [Fig. 1(a)]. The sea ice area becomes maximum at the end of February and the level ice thickness is mostly less than 1 m with the mean being 0.3–0.5 m [25] although ridged ice of more than a few meters thick occasionally appears [26]. This region has several advantages over other polar regions. First, since in situ observations have been conducted using PV “Soya” every winter in collaboration with Japan Coast Guard (JCG) since 1996 to survey the sea ice and oceanographic conditions and to tackle ad hoc topics related to sea ice [Fig. 1(b)], there are available field data for validation to some extent. Second, this region does not contain multi-year ice unlike the polar oceans, which makes it simpler to classify sea ice types. Third, all the Phased Array type L-band Synthetic Aperture Radar (PALSAR) images that overpassed the southern Sea of Okhotsk in winter were preferentially acquired via the contract between JCG and Japan Aerospace Exploration Agency (JAXA), which facilitates the monitoring of deformed ice. Since deformed ice in this region is produced mainly by dynamical thickening processes [9], [25], [27], the monitoring of deformed ice is expected to contribute to clarifying the dynamical behavior. Hence, we attempted to develop measures to classify sea ice types using PALSAR, based on our field experiments. In 2014, ALOS-2/PALSAR-2 succeeded PALSAR, adding the functions of wider coverage with wider incidence angles ($\theta = 8^\circ$–$70^\circ$) and dual polarizations (HH, HV). These additional functions provide us with an opportunity to examine the applicability of L-band SAR for detecting deformed ice and the properties of HH and HV polarizations more specifically. Thus, the purposes of this study are as follows:

1) to confirm the usability of L-band SAR (PALSAR) for detecting deformed ice by comparing with a C-band SAR image in the southern Sea of Okhotsk;
2) to develop measures to detect deformed ice using PALSAR imagery at a ScanSAR mode, and validate the measures based on field experiments;
3) to examine the properties of dual polarizations (HH and HV) with ScanSAR mode (PALSAR-2) and the capability of them for detecting deformed ice;
4) to investigate factors that can affect the capability of L-band SAR for detecting deformed ice quantitatively.

This article is organized by data description in Section II, development of the measures to classify sea ice into three ice types using PALSAR, and validation of our measures and investigation of dual polarizations using PALSAR-2 in Section III, and discussion of the results in Section IV.

II. DATA

In the analysis, we attempted to establish measures to detect deformed ice, using three different satellite SAR sensors. To validate it, we used the data obtained from the field measurements. Besides, the meteorological reanalysis data set is also used as supplementary data for analysis. Here, we briefly explain these data sets.

A. Satellite SAR Images

In this study, we focused on the sea ice in the southern Sea of Okhotsk ($43^\circ$ to $50^\circ$ N, $142^\circ$ to $148^\circ$ E, Fig. 1), using three satellites SARs: PALSAR, RADARSAT-2, and PALSAR-2,
the average with the surrounding 3 pixels for each pixel. To further reduce the speckle noise, we took products, where multilook processing is performed (process- are described in Table I. For each image, we used the data obtained in January to March from 2009 to 2011. To compare the ability of detecting deformed ice between L-band and C-band SARs, one RADARSAT-2 image, which was selected during February 8–13 in 2009, February 6–12 in 2019 for the examination with PALSAR-2 images. The cruise tracks were shown in Fig. 1(b). Among the data obtained during these cruises, photos taken hourly from the upper deck of the ship, aero-photos taken from the helicopter, ice thickness data measured by means of a shipborne video system [25], and hourly visual observations according to the Antarctic Sea Ice Processes & Climate (ASPeCt) protocol (http://aspect.antarctica.gov.au/) were mainly used for analysis. Although the ASPeCt protocol was originally designed for Antarctic sea ice zone research [28], it can be applied to the Sea of Okhotsk because it was found that the ice properties there especially in the ice growth season are quite similar to those of Antarctic sea ice [9].

Here, it should be noted that ice thickness measurement by a video system is intended rather for relatively flat ice than for significantly ridged ice. However, since the ice thickening processes are closely related to deformation processes (rafting and ridging) in this region [9], ice thickness data can be an indicator of the degree of surface roughness to some extent. Visual observations include an estimate of the areal coverage, thickness, floe size, topography, and snow cover of the three dominant ice types within a radius of approximately 1 km from the ship [28]. At the same time, three photographs (left, front, and right-side of the ship) were taken from the upper deck of the ship, which were also used for validation of ice conditions. Based on these photographs, sea ice was categorized into three ice types: nilas (thin level ice), pancake (thin rough ice), and deformed ice (thick rough ice), as shown in Fig. 2. For the polar ice regions, probably we need an additional category, stable (level) thick ice. However, this category was shown to be usually deformed [9]. Therefore, we consider that three categories are enough in this area. A photographic view was taken from the helicopter at an interval of 5 min during the flight to show the ice conditions in a wide range.

Besides, to verify the temporal evolution of deformed ice regions, daily ice drift data were used. The ice drift data set was constructed on a 37.5-km grid from the image of satellite microwave sensor, The Advanced Microwave Scanning Radiometer for EOS (AMSR-E), images using the maximum correlation method [29]. The sea ice extents on individual days were determined with the AMSR-E-derived ice concentration data (https://seaice.unibremen.de/start/). When we need more detailed ice conditions, Moderate Resolution Imaging Spectroradiometer (MODIS) images with a spatial resolution of 250 and 500 m (https://worldview.earthdata.nasa.gov/) were referred to. When we need to examine the meteorological conditions at the time of the SAR observations, the meteorological reanalysis data sets (ERA-Interim) with a grid spacing of 0.125° were used, focusing mainly on 10-m wind data (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype%3Df10m/).

### Table I

| Purpose | Developing algorithm | Comparison between C- & L-bands | Validation |
|---------|----------------------|-------------------------------|------------|
| Simulations | PALSAR | PALSAR | RADARSAT-2 | RADARSAT-2 |
| Observation time (JST) | Jan to Mar in 2009 - 2011 | 2010/02/22 10:15 | 2010/02/22 10:36 | Feb in 2016 - 2019 |
| Number of images | 55 | 7 | 1 | 8 |
| Frequency | L-band | L-band | C-band | L-band |
| Wavelength (cm) | 24 | 24 | 56 | 24 |
| Polarity | HH | HH | HH | HH, HV |
| Incidence angle (deg) | 40-45 | 40-45 | 20-46 | 8-70 |
| Grid spacing (m) | 100 | 100 | 50 | 10 |
| swath (km) | -350 | -350 | -450 | -350 |

### Table II

| Year | Date | Video ice thickness | Rinded ice fraction (ASPeCt) | PALSAR-2 image acquisition dates |
|------|------|---------------------|------------------------------|----------------------------------|
| 2016 | Feb 5-11 | 1445 | 0.160±0.12 | 33 | 10 | 48 | Feb 10 & 11 |
| 2017 | Feb 10-16 | 1592 | 0.38±0.17 | 47 | 21 | 65 | Feb 13 & 14 |
| 2018 | Feb 8-14 | 3770 | 0.46±0.23 | 35 | 52 | 88 | Feb 12 & 13 |
| 2019 | Feb 6-12 | 2272 | 0.17±0.10 | 41 | 11 | 46 | Feb 7 & 11 |
| Ave. | | 0.38±0.11 | 37 | 22 | 63 |

(*) "Area" denote the areal fraction of ridged ice to the total sea ice area, while "Volume" is the volumetric fraction of ridged ice area to the total ice volume. *Number* denotes the number of observations. *Ave* means the average for 20 years from 2000 to 2019.

all of which were observed with ScanSAR mode to cover a wide area. The main specifications of each SAR image are described in Table I. For each image, we used the data products, where multilook processing is performed (processing level: 1.5 for PALSAR and PALSAR-2, and SGF for RADARSAT-2). To further reduce the speckle noise, we took the average with the surrounding 3 × 3 pixels for each pixel. The nominal resolutions are 71–157 m for PALSAR, 48–95 m for PALSAR-2, and 73–163 m for RADARSAT-2, depending on the range and azimuth directions. PALSAR images were used to develop measures to classify sea ice types. For this purpose, the backscatter coefficients at HH polarization ($\sigma^0_{HH}$) were analyzed with 35 images in total, which were obtained in January to March from 2009 to 2011. To compare the ability of detecting deformed ice between L-band and C-band SARs, one RADARSAT-2 image, which was selected so that the observation time was the closest to one of PALSAR images, was analyzed with the PALSAR image. Only 4.6-h time difference between these two images enabled direct comparison. PALSAR-2 images were used to validate the measures developed with PALSAR images, and to examine the capability of backscatter coefficients at HV polarization ($\sigma^0_{HV}$), compared with $\sigma^0_{HH}$. The dates of the images are February 10 and 11 in 2016, February 13 and 14 in 2017, February 12 and 13 in 2018, February 7 and 11 in 2019 (Table II), which were selected to overlap the “Soya” cruise period (Table II). The selection of two successive days for each year except for 2019 served to investigate the dependence of $\sigma^0_{HH}$ and $\sigma^0_{HV}$, which were calibrated, on a wide range of $\theta_i$ because the ice conditions would remain nearly the same during the two days, while the range of $\theta_i$ shifted significantly.

### B. Field Data for Validation

The sea ice observations aboard the PV “Soya” were conducted during February 8–13 in 2009, February 4–10 in 2010, February 13–17 in 2011 for developing the measures with PALSAR images, and February 5–11 in 2016, February 10–16 in 2017, February 8–14 in 2018, February 6–12 in 2019 for the examination with PALSAR-2 images. The cruise tracks are shown in Fig. 1(b). Among the data obtained during these cruises, photos taken hourly from the upper deck of the ship, aero-photos taken from the helicopter, ice thickness data measured by means of a shipborne video system [25], and hourly visual observations according to the Antarctic Sea Ice Processes & Climate (ASPeCt) protocol (http://aspect.antarctica.gov.au/) were mainly used for analysis. Although the ASPeCt protocol was originally designed for Antarctic sea ice zone research [28], it can be applied to the Sea of Okhotsk because it was found that the ice properties there especially in the ice growth season are quite similar to those of Antarctic sea ice [9].
wavelength (0.24 m) \cite{18}, \( \sigma_{HH}^0 \) of L-band SAR is expected to discriminate deformed ice from pancake ice and nilas. Since \( \sigma_{HH}^0 \) depends significantly on \( \theta_i \) \cite{31}, we attempt to develop measures to classify sea ice into these three categories as a function of \( \sigma_{HH}^0 \) and \( \theta_i \). So far, there have been several attempts which relate \( \sigma_{HH}^0 \) to ice types as a function of \( \theta_i \) for the polar regions from surface-based, airborne, and satellite SAR (see \cite{22,32,33}). However, the discrimination of ice types is not necessarily an easy problem because generally the polar regions contain various types of sea ice, including multiyear ice, first-year ice, nilas, pressure ridges, and whatever at a small scale. Besides, there has been a difficulty in establishing measures to discriminate sea ice types due to the limited number of observations.

To develop the measures, we used the photos taken hourly at the ASPeCt observations during the cruise. We identified the position of each photo on the PALSAR images, using the GPS records, and estimated \( \sigma_{HH}^0 \) around the observation area with an accuracy of 2 dB. Since \( \sigma_{HH}^0 \) usually varies on a small scale (<1 km), we first determined the lower and higher limits of \( \sigma_{HH}^0 \) within a few km range of the position, and then the representative \( \sigma_{HH}^0 \) was obtained by taking the average of the two limits. \( \theta_i \) was calculated geometrically from the relative position of the image. The air temperature range was from \(-10^\circ \text{C} \) to \(-2^\circ \text{C} \). If we confined the data to the observation time of PALSAR, the number of data would be much reduced. Therefore, we included the data taken within one day of the PALSAR observation, if available. The difference in observation time between PALSAR and photographs was corrected using reanalysis wind data on the assumption that sea ice drifts at a rate of 2% of wind \cite{34}, and the position on the PALSAR image was estimated. Then we made scatter plots between \( \sigma_{HH}^0 \) and \( \theta_i \) in Fig. 3, where ice types are discriminated by different colors. The error bars in Fig. 3 denote the upper and lower limits of \( \sigma_{HH}^0 \) around the observation points, and the solid circles show the representative value of \( \sigma_{HH}^0 \). Fig. 3 sheds light on the possibility to approximately classify three ice types by setting two threshold lines. The observation sites of individual plots are shown in Fig. 1(a). It is found that the data for deformed ice come mainly from inner ice area, whereas the data for pancake ice and nilas from the marginal ice zone (MIZ) and the near-shore region, respectively.

The two threshold lines were derived in the following way: for the threshold between deformed ice and pancake ice, first the regression line was obtained in the form of \( \sigma_{HH}^0 = a\theta_i + b \) for the lower limits of individual deformed ice data in Fig. 3 with the least-squares method. The linear regression was selected here based on Fig. 3, although \cite{33} suggested that the sensitivity of \( \theta_i \) becomes higher for smaller \( \theta_i \). Next, another regression line was obtained in the same way for the upper limits of individual pancake ice data. By taking the average of these two regression lines, the threshold line was derived. The same procedure was applied for the threshold line between pancake ice and nilas. The threshold lines obtained are expressed in the following equation:

\[
\sigma_{HH, pd}^0 = -0.197\theta_i - 7.55 \text{ (dB) for pan. – def.} \quad (1)
\]

\[
\sigma_{HH, np}^0 = -0.194\theta_i - 11.51 \text{ (dB) for nil. – pan.} \quad (2)
\]
It is noted that the incidence angle dependencies of these equations (−0.19 to −0.20 dB per degree) is close to the past result [35] (−0.21 dB per degree) for Arctic first-year sea ice. Here, it should be kept in mind that these measures were derived from the data obtained for 20° ≤ θi ≤ 42°. It should also be noticed that these measures are applicable to sea ice with L-band SAR because the incidence angle dependence on seawater is much steeper, as shown later, and the brightness at L-band correlates more directly to deformation than that at C- or X-band. To apply them to other sea ice regions, further study is required. Considering that σ0HH becomes higher with the increase of the ice surface roughness and thickness at a given θi [12], [36]–[38]), the upward deviation from (1) is expected to be an indicator of the degree of deformation. Hereafter, we use (1) and (2) to classify ice types.

2) Comparison Between PALSAR and RADARSAT-2: To examine the effectiveness of L-band SAR for detecting deformed ice to C-band SAR, which has been shown previously in polar regions (see [14]), a comparative analysis was done between a set of PALSAR and RADARSAT-2 images, covering the same area almost concurrently. Fig. 4 shows the distributions of σ0HH for both satellite images. In the analysis, we focused on how the RADARSAT-2 image represents the ice types judged from PALSAR-derived measures as expressed by (1) and (2). To address it, we set a line for cross section (L1) and two characteristic areas (A1 and A2) for statistics within sea ice area (Fig. 4) and examined the properties individually.

Fig. 5(a) shows the cross sections of σ0HH along L1 for PALSAR and RADARSAT-2, drawn as a function of distance from the right-side end. L1 was selected so as to contain as many ice types as possible, covering a wide area in the direction perpendicular to the satellite orbit. Considering the slight shift of the ice area during the observation time interval between the two images, which is estimated to be about 1 km for the representative ice drift speed (~0.1 m · s⁻¹), the averages were taken within the circle of 1 km radius at each pixel on L1. To focus on sea ice, only the range indicated by an arrow in Fig. 4, corresponding to 25° ≤ θi ≤ 34° on a PALSAR image, is drawn. The characteristics of Fig. 5(a) are summarized as follows.

1) Within sea ice area, whereas one peak which appears at about 240 km in the deformed ice region is prominent for PALSAR, several comparable peaks are found not only in the deformed ice region (about 250 km) but also in the pancake ice area (about 300 km, 320 km) for RADARSAT-2.
2) The difference in σ0HH between nilas and deformed ice is somewhat larger for PALSAR (~9 dB) than for RADARSAT-2 (~6 dB).
3) The contrast of σ0HH between open water and sea ice area is stronger for RADARSAT-2 than for PALSAR.

First two points indicate that PALSAR is more useful to discriminate deformed ice from both thin rough ice (pancake ice) and thin level ice (nilas) than C-band SAR. This feature is consistent with the past studies [14], [16]. Although the third point is opposite to the result of [14], we infer that the result depends on the sea surface conditions because C-band SAR signal is sensitive to relatively small roughness [16]. It is noted in Fig. 5(a) that the ice edge is shifted eastward by a few km in a PALSAR image relative to a RADARSAT-2 image. Considering the persistent southerly winds of ~10 m · s⁻¹ during the observation time interval, and the sharp angle between the ice edges and L1, the discrepancy of ice edges is attributed to the slight northward movement of sea ice area rather than the properties of radar signals.
To minimize such discrepancy caused by the slight movement (~1 km) of sea ice area, it would be better to compare the statistics of areal distribution of $\sigma_{HH}^0$ between the two images. To do so, we selected two characteristic circular areas (A1 and A2) with a radius of 15 km within sea ice area. According to Fig. 4(a) and MODIS images, whereas mixture of pancake ice and nilas is the dominant category in A1, A2 is mainly composed of deformed ice. The histograms of $\sigma_{HH}^0$ within A1 and A2 are shown in Fig. 5(b) for individual images. According to (1), the threshold values of $\sigma_{HH}^0$ for PALSAR between deformed ice and pancake ice are $-14.2 \text{ dB}$ at A1 ($\theta_i = 33.5^\circ$) and $-12.0 \text{ dB}$ at A2 ($\theta_i = 22.6^\circ$). Therefore, Fig. 5(b) shows that A2 is occupied almost completely with deformed ice, while A1 is covered largely with nilas and pancake ice but only slightly (3.6%) with deformed ice. Fig. 5(b) shows that whereas the ranges of $\sigma_{HH}^0$ for PALSAR are clearly separated between A1 and A2, those for RADARSAT-2 are significantly overlapped. Considering the effect of $\theta_i$ for RADARSAT-2, the overlapped range would increase further. Besides, the peak in the histogram of A2 is much higher and sharper for PALSAR than for RADARSAT-2. This indicates that L-band SAR is much more useful to discriminate deformed ice from thin level ice or thin rough ice, compared with C-band SAR, which is consistent with Fig. 5(a) and past studies (see [14], [16]).

3) Mapping of Deformed Ice: As a next step, we attempt to find out the features of temporal evolution of deformed ice regions by mapping them from January to March in 2010. To minimize the speckle noises which often appear at a pixel scale, we took the following method: first, we categorized each pixel into deformed ice, pancake ice, and nilas, using (1) and (2). Then, we set windows composed of $9 \times 9$ pixels (about 1 km square) and calculated the fractions of each ice type ($F_d$, $F_p$, and $F_n$) by

$$F_d = \frac{N_d}{9 \times 9}, \quad F_p = \frac{N_p}{9 \times 9}, \quad F_n = \frac{N_n}{9 \times 9}$$

where $N_d$, $N_p$, and $N_n$ denote the number of pixels categorized into deformed ice, pancake ice, and nilas, respectively. By mapping $F_d$ for each PALSAR image, we obtained the temporal evolution of deformed ice regions in the southern Sea of Okhotsk. Since it is difficult to distinguish between sea ice and open water just from PALSAR, we determined sea ice extent by the area where ice concentration is greater than 15% in the AMSR-E-derived ice concentration maps.

The results show that sea ice area started to extend around the Gulf of Patience off Sakhalin [Fig. 1(a)] with deformed ice occupying about half of the total ice area on January 7, and spread rapidly to cover the wide area off Sakhalin with a decrease in deformed ice regions by January 31, probably because deformed ice was disintegrated by the divergent motion caused by prevailing easterly winds. In February, sea ice area further spread southward to cover the area around Hokkaido, with large temporal variability of deformed ice regions. In March, sea ice area began to retreat northward until the end of March. In these figures, deformed ice regions are characterized by: 1) large temporal variability of them and 2) rather aligned distribution with about a few tens of km in width and about a few hundreds of km in length.

To verify these characteristics from a physical viewpoint, two successive maps on February 17 [Fig. 6(a)] and 22 [Fig. 6(b)] are shown as an example. It is noticeable that the deformed ice region increased significantly in a wide area off east Sakhalin during this period. For comparison, we mapped the mean divergence/convergence pattern of sea
Fig. 5. Comparative analysis between PALSAR and RADARSAT-2 (a) Cross sections of $\sigma_0^{HH}$ along L1 in Fig. 4 for PALSAR (red) and RADARSAT-2 (black) with a focus on the range pointed by the arrow in Fig. 4. Ice types described in the figure were derived from the threshold curves of (1) and (2). Open water area was determined from the AMSR-E-derived ice concentration map and MODIS images on February 22, 2010. (b) Histograms of $\sigma_0^{HH}$ within A1 and A2 in Fig. 4 for (Left) PALSAR and (Right) RADARSAT-2. Two vertical broken lines denote the thresholds between nilas and pancake ice and between pancake ice and deformed ice at A1 ($\theta_i = 33.5^\circ$) and A2 ($\theta_i = 22.6^\circ$), determined by (1) and (2). Note that whereas A2 is covered almost completely with deformed ice, A1 mostly with nilas and pancake ice.
ice drift during this period, using AMSR-E-derived ice drift data [Fig. 6(c)]. This figure shows that ice drift convergence is prominent especially off east Sakhalin, where deformed ice regions increased. This applies in most cases and therefore supports the validity of our measures to some extent. At the same time, it is also noticed that in most of the maps, the area, judged as deformed ice from our measures, appears commonly in the MIZ along the ice edges, as shown in Fig. 6(a) and (b), irrespective of ice drift conditions. Although it might be possible that deformation processes become more active due to wave–ice interaction in the MIZ, there is a possibility that other factors affected the radar signal significantly.
Thus, our measures need further examination from field observations.

**B. Further Examination With ALOS-2/PALSAR-2 Images**

Here, our measures are tested for PALSAR-2, which has the additional functions of dual polarization at ScanSAR mode (Swath width: 350–490 km) and a wider range of $\theta_i$ ($8^\circ$–$70^\circ$), to examine to what extent they are available and how they can benefit from dual polarization data, based on the field observations conducted onboard the PV “Soya” in Februaries for four years (2016–2019).

1) Ice Conditions in 2016–2019: The ice conditions during the observation periods were significantly different, as shown in MODIS images (Fig. 7). Whereas newly formed ice covered a wide area in this region in 2016 and 2019, developed ice was prominent in 2017 and especially in 2018. This is elucidated by the statistics of ice thickness data monitored by the video system and visual observations based on the ASPeCt protocol. For comparison, all ice thickness data are plotted as a function of latitude in Fig. 8 for the individual years. Mean thickness with a standard deviation in each year is listed in Table II. It is clearly shown that as a whole ice thickness was significantly thicker in 2018 (mean ice thickness: 0.46 m) than in 2016 (0.19 m) and 2019 (0.17 m). As a whole, the order of years for mean ice thickness is $2016 \approx 2019 < 2017 < 2018$. The major difference between 2016 and 2019 is dominant ice type: pancake ice in 2016 and nilas in 2019, reflecting the difference in ice thickness variation between these two years in Fig. 8. The ice thickness in 2017 is rather close to the normal, averaged for 20 years (Table II).

The characteristic of the ridge statistics in each year is coincident with ice thickness in Table II, where the fractions of ridged ice area and volume were calculated, based on the ASPeCt observations, in the same way that [39] did for Antarctic sea ice. According to Table II, deformed ice contributed about half of the total area and about 90% of the total ice volume in 2018, significantly higher compared with other years. Again, the statistics of deformed ice in 2017 is close to the normal. The order of years for degree of deformed ice is $2016 \approx 2019 \ll 2017 < 2018$, which is the same as for ice thickness. This result confirms that ice thickness
distribution can be a good proxy for the degree of surface roughness in this region. Another different ice feature between the four years is dominant floe size: pancake ice in 2016, 2–20 m in 2017, 20–100 m in 2018, and nilas in 2019. Such a significantly different ice conditions among these four years will serve to interpret the properties of PALSAR-2 images.

2) Validation From Field Measurements: To validate our measures based on field data, we obtained $\sigma_{\text{HH}}^0$ and $\theta_i$ at the ship position at the observation time and compared the ice category predicted by the measures with the real ice conditions around the ship. Considering its high spatial variability, $\sigma_{\text{HH}}^0$ is given by (mean) ± (a standard deviation) within the area of
TABLE III
VALIDATION OF OUR ALGORITHM WITH ALOS-2/PALSAR-2

| Date       | \(\theta_i\) (deg) | \(\sigma_{HH}^0\) (dB) | Prediction | Reality               |
|------------|---------------------|------------------------|------------|-----------------------|
| 2016-02-10 | 55.7                | -28.3/7.9              | nilas      | nilas with small flat ice floes |
| 2016-02-11 | -                   | -                      | -          | open water             |
| 2017-02-13 | 43.4                | -13.1/1.8              | deformed   | deformed ice with relatively small floes |
| 2017-02-14 | 18.7                | -12.0/7.1              | pancake    | large pancake ice area near shore |
| 2018-02-12 | -                   | -                      | -          | open water             |
| 2018-02-13 | 25.8                | -12.9/4.1              | pancake    | vast pancake ice area with swells |
| 2019-02-07 | 30.7                | -18.2/5.8              | nilas      | nilas with patches of open water area |
| 2019-02-11 | -                   | -                      | -          | open water             |

(*) In the table, \(\theta_i\) is the incidence angle at the ship position in the image.
\(\sigma_{HH}^0\) is the mean ± standard deviation within the area of 2 × 2 km around the ship.

2 km × 2 km around the ship. Since the measures were derived from PALSAR for \(20^\circ < \theta_i < 42^\circ\) (Fig. 3), it would be ideal that validation be done within this range. However, due to the limited number of observations we extrapolated the measures somewhat for \(\theta_i\) less than 20\(^\circ\) or larger than 42\(^\circ\). The results are shown in Table III.

Focusing on the cases where our ship was in the ice area, five points were available for validation. According to Table III, the measures represent the real conditions well. As an example, three sets of the \(\sigma_{HH}^0\) maps and photos are shown in Fig. 9. Especially for the case of February 13, 2018 [Fig. 9(c) and (d)], our ship was surrounded by a vast pancake ice area near the ice edge, which was well predicted by our measures. For the case of February 13, 2017 [Fig. 9(a) and (b)], deformed ice floes can certainly be found in the photo. In Fig. 9(e) and (f), new ice sheet (nilas) is well represented. Thus, it can be said that our measures work well to some extent to classify sea ice into three categories. If we can assume that \(\sigma_{HH}^0\) is most sensitive to surface roughness at a given \(\theta_i\), the upward deviation from the threshold line (1) is considered to represent the degree of ice deformation. Therefore, hereafter the deviation from (1) is referred to as HH anomaly, expressed as

\[
\text{(HH anomaly)} = \sigma_{HH}^0 - \sigma_{HH, pd}^0 \quad (\text{dB})
\]

and will be used to examine the validity for detecting significantly deformed ice.

3) Properties of Dual Polarization: To examine and compare the general properties of HH and HV polarizations, one set of images obtained on February 12, 2018 are exemplified in Fig. 10. The features found in Fig. 10 are listed as follows.

1) As a whole \(\sigma_{HV}^0\) is about 10 dB lower than \(\sigma_{HH}^0\).
2) A strong dependence on \(\theta_i\) for both polarizations, with \(\sigma_{HV}^0\) being less affected by \(\theta_i\) within the sea ice area.
3) \(\sigma_{HV}^0\) has some advantage in detecting sea ice area for smaller \(\theta_i\).
4) The contrast between sea and land is much greater at \(\sigma_{HV}^0\) than at \(\sigma_{HH}^0\).

In general, \(\sigma_{HV}^0\) at L-band is less sensitive to internal volume scattering from bubbles and brine pockets and is enhanced mainly by multiple bouncing produced by surface roughness or topography, and thereby is expected to be more sensitive to vertical structure and less sensitive to \(\theta_i\) [10]. Hence, they state that cross-polarization SAR (\(\sigma_{HH}^0\)) is more suitable for mapping ice deformation features such as ridges and rubble areas especially for first-year ice which is less affected by air bubbles. The second, third, and fourth points are well explained by this property.

To show the difference between \(\sigma_{HH}^0\) and \(\sigma_{HV}^0\) more clearly, their cross sections along L1 [in Fig. 10(a)] are drawn in Fig. 11. The data on February 12 and 13 are superimposed to see the dependence on a wide range of \(\theta_i\), assuming that the ice conditions did not change much during these two days. Since the ice conditions are usually quite different between the MIZ and inner ice pack area, inner ice pack area is marked in Fig. 11. Fig. 11 elucidates the features (Points 1–4) found in Fig. 10. Especially, Points 2 is clearly shown at \(30^\circ \leq \theta_i \leq 45^\circ\) on February 12 and \(7^\circ \leq \theta_i \leq 17^\circ\) on February 13, where \(\sigma_{HH}^0\) decreases with the increase of \(\theta_i\) more rapidly than \(\sigma_{HV}^0\). This result is comparable to [13] (compare with their Fig. 7). Besides, it is noticeable that for both \(\sigma_{HH}^0\) and \(\sigma_{HV}^0\) at \(30^\circ \leq \theta_i \leq 45^\circ\), the decreasing rate with the increase of \(\theta_i\) is more rapid in the open water on February 13 compared with sea ice area on February 12, indicating that in sea ice area both radar signals are less sensitive to \(\theta_i\) compared with open water. This property is coincident with the past results for C-band \(\sigma_{HH}^0\) [33].

In Fig. 11, extremely low values of \(\sigma_{HH}^0\) and \(\sigma_{HV}^0\) appear at \(\theta_i \approx 51^\circ\) near the western ice edge on February 12. Considering the on-ice winds (i.e., westerly) of 5–15 m·s\(^{-1}\) and cold air temperature \((-9^\circ\text{C} \text{to} -7^\circ\text{C})\) on this day, it is likely that significantly flat sea surface produced due to wave attenuation in the presence of grease ice is most responsible for this. This speculation is supported by the in situ observation conducted in the similar situation in the same area during the cruise in 2016. The on-site ice sampling observation revealed that the observation area was covered with grease ice of 8 cm thick, and both \(\sigma_{HH}^0\) and \(\sigma_{HV}^0\) showed about 8-dB lower values, compared with the surrounding area. This result is similar to that of [40], which found a frazil slick near the ice edge appears dark on Seasat SAR (L-band) images. Considering that seawater surface within inner sea ice area tends to be considerably flat due to wave attenuation, this justifies the assumption that basically the SAR signals in inner sea ice area represent the properties of sea ice, much less affected by seawater.

On the other hand, in less concentrated ice area like the MIZ, seawater surface may become rough forced by winds and waves. In such a case, the radar signals from sea surface may become comparable to those from sea ice. To extract sea ice properties, we need to know how the radar signals from sea surface depend on surface conditions and \(\theta_i\). To this end, we selected open water area along L1 in each PALSAR-2 image carefully, referring to MODIS images, and then plotted \(\sigma_{HH}^0\) and \(\sigma_{HV}^0\) all together as a function of \(\theta_i\) in Fig. 12. It is found that whereas the variation range of \(\sigma_{HH}^0\) exceeds 7 dB at a given \(\theta_i\), caused by Bragg-scattering under various wind speeds, ranging from 2 to 13 m·s\(^{-1}\) [41], [42], that of \(\sigma_{HV}^0\) is much reduced to mostly less than 5 dB. This...
means that $\sigma_{0}^{\text{HV}}$ is not so sensitive to sea surface conditions as $\sigma_{0}^{\text{HH}}$ especially for $26^\circ \leq \theta_i \leq 46^\circ$. This is probably because in most cases, sea surface slope is not steep enough to generate the cross-polarization component significantly, as pointed out by Dierking [31]. Based on almost linear relationship between $\sigma_{0}^{\text{HV}}$ and $\theta_i$ for $26^\circ \leq \theta_i \leq 46^\circ$ in Fig. 12, it can be assumed that this slope represents the dependence of $\sigma_{0}^{\text{HV}}$ on $\theta_i$ for flat surface to some extent within this range of $\theta_i$. Hence a regression line, as expressed by (5), was derived with the least-squares method as a reference for flat surface

$$\sigma_{\text{HV,ow}}^{0} = -0.636\theta_i - 5.78 \text{ (dB)},$$

The regression line is drawn in Fig. 12 with the root mean square error (1.03 dB). Since the deviation of $\sigma_{0}^{\text{HV}}$ from (5) is considered to be caused mainly by steep surface produced on ice, we refer to it as HV anomaly to represent the degree of ice surface roughness hereafter. HV anomaly is expressed as follows:

$$(\text{HV anomaly}) = \sigma_{0}^{\text{HV}} - \sigma_{\text{HV,ow}}^{0}. \tag{6}$$

Here, it should be noted that the dependence of $\sigma_{0}^{\text{HV}}$ on $\theta_i$ is somewhat weaker for sea ice than for open water, as mentioned earlier. Therefore, HV anomaly may be somewhat affected by $\theta_i$. Even so, it would be possible to use this parameter as an indicator of ice surface roughness when the variation of $\theta_i$
is small. Ideally, it would be desirable to define HV anomaly by the deviation from $\sigma_{HV}$ at level sea ice like nilas. However, we took this method here because our data were too limited to derive a formula for level sea ice.

4) Properties of HH and HV Anomalies: In this section, we verify to what extent HH anomaly and HV anomaly, introduced in the previous section, can represent the degree of ice deformation. For this purpose, we took the cross sections of $\sigma_{HH}$ and $\sigma_{HV}$ along L2 of 150 km length in Fig. 10(a) and compared the results among the four years. Line L2 was selected so that it lies within the ice-covered area in all the years and its direction is parallel to the satellite orbit, i.e., $\theta_i$ is kept constant on the cross section line, to minimize the effects of open water area and $\theta_i$. It is expected that the significantly different ice conditions among the four years facilitate to interpret the results. HH and HV anomalies are plotted as a function of latitude in Fig. 13(a) and (b), respectively. To apply (4) and (6), the image where $\theta_i$ along L2 is within the range of $26^\circ \leq \theta_i \leq 46^\circ$ was selected in each year.

In both Fig. 13(a) and (b), the values in each year are clearly distinguished, reflecting the individual ice conditions. Unexpectedly, it is remarkable that as a whole the order of HH anomaly is $2019 < 2016 \approx 2018 < 2017$ in Fig. 13(a) and that of HV anomaly is $2019 < 2016 < 2018 < 2017$ in Fig. 13(b), both of which do not coincide with the order of mean ice thickness in Table II ($2016 \approx 2019 < 2017 < 2018$). To confirm this discrepancy, we recalculated mean ice
thickness for the limited areas around L2. The result was 0.23 ± 0.13 m for 2016, 0.39 ± 0.17 m for 2017, 0.46 ± 0.23 m for 2018, and 0.20 ± 0.11 m for 2019, which is almost the same as the total average.

Among the above results, coincident with ice thickness distribution are significantly lower values of HH and HV anomalies in 2019. It is prominent especially to the south of 44.9° N. In this year nilas was dominant, occupying 35% of the total sea ice area in the observation area (Fig. 14). Although mean ice thickness is almost the same between 2016 and 2019, it is reasonable that HH and HV anomalies in 2016 are much higher than in 2019, considering that the dominant ice type is pancake ice in 2016. On the other hand, given the significant difference in ice thickness conditions between 2016 and 2018 (Fig. 8), it is noticeable that HH anomaly is almost the same between these two years. As for HV anomaly, the difference in $\theta_i$ between these two years might affect the result. However, it should be noted that HV anomaly in 2017 is constantly higher than in 2018 even for the same $\theta_i$ (= 45.6°).

Thus, our results indicate that only the effect of ice surface roughness, i.e., the degree of ice deformation, cannot
explain Fig. 13 and another effect should be considered to explain the observed $\sigma_{HH}^0$ and $\sigma_{HV}^0$. This will be discussed in Section IV.

IV. DISCUSSION

A. Possible Effects of Floe Size on $\sigma_{HH}^0$ and $\sigma_{HV}^0$

Here we discuss the possible factors other than ice surface roughness, which can affect the radar signals, to explain the discrepancy discussed in the previous section. Since seawater in the sea ice area and grease ice usually have a smooth surface due to wave attenuation, it is unlikely that they affected $\sigma_{HH}^0$ and $\sigma_{HV}^0$ significantly because the smooth surfaces are so much weaker/darker that their variation cannot explain the large variations observed. Therefore, the plausible factors should come from the sea ice properties. As mentioned in Section III-B1, another different ice feature between four years is dominant floe size. Fig. 14 shows the histograms of each floe size category for individual years, compiled from ASPeCt observations. As a whole, the order of floe sizes is 2016 < 2017 < 2018. In 2016 pancake ice, occupying 34% of total sea ice area, is dominant and the largest floe category is 20–100 m with only 3%, whereas in 2018 the dominant category is 20–100 m with 29% and even floes larger than 2 km occupied 10%. In 2017, floe size conditions are intermediate between these years with the category of 2–20 m being dominant with 44%. On the other hand, ice floe in 2019 is characterized by the dominance of nilas, occupying 35%. These features were confirmed from aero photos taken near L2 from the helicopter (not shown). Whereas tiny floes less than a few meters are dominant even in the midst of sea ice area in 2016, relatively small floes (∼a few tens of meters) in 2017 and large floes (∼a few hundreds of meters) in 2018 are prominent.

The effect of floe size on the radar backscatter was suggested by previous studies from C-band SAR. Sandven et al. [43] showed from concurrent field measurements with ERS 1 SAR near the MIZ in the Barents Sea that $\sigma_{VV}^0$ at C-band is about 5 dB higher for small floes (∼20 m) than for large floes (>500 m). If their results are applicable for $\sigma_{HH}^0$ at L-band SAR, HH anomaly in 2018 becomes larger than that in 2017, as expected. Thus, that may explain the discrepancy in 2018. However, to our knowledge, quantitative estimates about the effect of floe sizes at L-band SAR are few. Although Dierking and Busch [14] made a lookup table for ice classifications with JERS-1 ($\sigma_{HH}^0$ at L-band) separately for fractured ice and consolidated ice, their difference was not necessarily clear.

How can floe size distribution affect the radar signal? The possible mechanism is explained by the schematic picture in Fig. 15. For a given ice concentration, the total perimeter
Fig. 14. Histograms of sea ice floe size obtained from ASPeCt observations for (a) 2016, (b) 2017, (c) 2018, and (d) 2019. The notation of floe size is as follows: F: frazil ice, P: pancake ice, N: nilas, B: brash ice, R1: 2–20 m, R2: 20–100 m, R3: 100–500 m, R4: 500 m–2 km, and R5: >2 km.

of ice floes, i.e., the total length of the boundaries between sea ice and seawater, becomes longer as the floe size becomes smaller. Considering that sea ice freeboard creates more or less steep roughness at those boundaries, it is likely that the radar backscatter is enhanced at ice margins at both HH and HV polarizations as well as in the inner deformed ice region. Therefore, it seems reasonable that this mechanism works to decrease the total radar backscatter when floe sizes are significantly larger than normal like 2018, and vice versa. Although the lookup table by Dierking and Busch [14] is not necessarily clear, when looking at the bright ice floe margins in their Figs. 3 and 4 and Plates 1-3 of [44], it is obvious that this effect is significant for $\sigma^0_{\text{HH}}$ at L-band.

To be more specific, we estimate the approximate ratio of total perimeter between these four years, based on the floe size histogram in Fig. 14. In calculation, the floe size for each category is represented by 0.5 m for pancake ice, 2 m for brash ice, 10 m for 2–20 m, 50 m for 20–100 m, 300 m for 100–500 km, 1000 m for 0.5–2 km, and 2000 m for >2 km. No perimeter is assumed for grease ice and nilas. Suppose $A$ and $D$ to be the given total sea ice area and floe diameter, respectively. The number of ice floes is given by $N = 4A/(\pi D^2)$ and then the total perimeter becomes $P = N \cdot \pi D = 4A/D$. In this way, the total perimeter of sea ice including all categories for each year can be calculated by

$$P_{\text{total}} = \sum_{i=1}^{M} (4A_i)/D_i$$

where $M$, $A_i$, and $D_i$ are the number of categories, the areal fraction of category $i$, and the representative floe size of category $i$, respectively. The calculated $P_{\text{total}}$ per unit area (1 km$^2$) is $2.91 \times 10^6$ m for 2016, $1.49 \times 10^6$ m for 2017, $0.74 \times 10^6$ m for 2018, and $1.26 \times 10^6$ m for 2019. Referenced to the value in 2017 close to the normal, the ratio is estimated as 1.95 for 2016, 0.50 for 2018, and 0.85 for 2019. Therefore, roughly estimated, the total perimeter in 2016 is twice of 2017, four times of 2018, and 2.3 times of 2019.

Given the fact that the HH anomaly in 2016 with small and little deformed ice floes is comparable to that in 2018 with large and much deformed ice [Table II, Fig. 13(a)], it is inferred that the effect of four times total perimeter on HH anomaly is almost comparable to twice ice surface roughness, assuming that ice surface roughness is proportional to ice thickness. The reason why HH anomaly was the highest in 2017 is presumably because the ice thickness and floe size conditions were close to the normal and our measures worked effectively, compared with 2016 and 2018. The lowest HH anomaly in 2019 is attributed mainly to the dominance of nilas.
Considering that the mean HH anomaly along L2 is $-3.3 \pm 2.9$ dB in 2019, which is close to the threshold value between nilas-pancake ice ($-3.9$ dB) obtained from (2), it seems that our measures worked well in this year. As for HV anomaly, the effect of floe size distribution should be significant as well, in light of the fact that the values in 2017 are higher than those in 2018 when $\theta_i$ is exactly the same and ridged ice is more prominent [Fig. 13(b)].

Thus, our result indicates that the reduced (enhanced) total perimeter due to the dominance of larger (smaller) ice floes also affects the radar signal significantly at both HH and HV polarizations and should be taken into account for detecting deformed ice with L-band SAR. This explains why the MIZ along the ice edges was often judged as deformed ice from our measures, as shown in Fig. 6(a) and (b). In the MIZ, subject to ocean waves, smaller ice floes tend to be produced due to wave-induced breakup processes. Consequently, the floe size conditions in the MIZ are usually quite different from those in the inner ice pack region where most of the samples were collected for developing our measures [Fig. 1(a)]. On the other hand, it should also be kept in mind that the MIZ with lower ice concentration is more subject to open water than the inner ice pack region. As shown in Fig. 11 and also by [45], the sensitivity of backscatter to $\theta_i$ becomes much higher at low $\theta_i$ (especially $\leq 30^\circ$) for open water and $\sigma_{0HH}$ may exceed that at sea ice. Considering that $\theta_i$ is relatively low at the east side (i.e., near range side) ice edges in Fig. 6, this effect may be also significant. Therefore, it is likely that the smaller floe size conditions and lower ice concentration in the MIZ are both responsible for the enhancement of $\sigma_{0HH}$, misleading us in detecting deformed ice. This is the limitation of our measures when applying it to the MIZ.

B. Relative Importance of Deformed Ice and Floe Size

Finally, we examine the relative importance of these two factors, i.e., ice surface roughness (degree of deformation) versus total floe perimeter (floe size effect) for HH and HV polarizations. For this purpose, we introduce the following parameter:

$$\Delta = (\text{HH anomaly}) - (\text{HV anomaly}).$$  \hspace{1cm} (8)

Note that each right-hand term in (8) is expressed as the summation of the effects of degree of deformation ($R$) and floe size ($F$). The cross section of $\Delta$ along L2 is shown in Fig. 16. It is remarkable that $\Delta$ is separated between the four years in Fig. 16. Here we should keep in mind that HV anomaly somewhat contains the effect of $\theta_i$, which comes from the different sensitivity of $\sigma_{0HV}$ to $\theta_i$ between open water and sea ice. To avoid this, we compare the results between

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**Fig. 15.** Schematic pictures, showing how floe size distribution affects $\sigma_{0HH}$ and $\sigma_{0HV}$. (a) For smaller ice floes with less deformed ice like 2016 and 2017. (b) For larger ice floes with much deformed ice like 2018. Ice floes in 2019 are characterized by dominance of nilas, as shown in Fig. 14. In the figures, red and blue arrows denote backscattering at the deformed ice and ice margins, respectively.
2017 and 2018 (both $\theta_i = 45.6^\circ$) and between 2016 and 2019 (both $\theta_i = 27.2^\circ$) separately.

Regarding 2017 and 2018, Fig. 16 shows that $\Delta$ of 2018 is constantly a few dB higher than that of 2017. This is described as follows:

$$R_{\text{HH}}^{2018} + F_{\text{HH}}^{2018} - R_{\text{HV}}^{2018} - F_{\text{HV}}^{2018} > R_{\text{HH}}^{2017} + F_{\text{HH}}^{2017} - R_{\text{HV}}^{2017} - F_{\text{HV}}^{2017}.$$

Then it can be rewritten as follows:

$$\Delta R_{\text{HH}}^{2018−2017} - \Delta F_{\text{HH}}^{2018−2017} > \Delta R_{\text{HV}}^{2018−2017} - \Delta F_{\text{HV}}^{2018−2017}$$ (9)

where $\Delta R_{\text{HH}}^{2018−2017}$ stands for the difference of $R$ at HH polarization between 2018 and 2017, for example. Equation (9) means that the enhancement of radar signals by $R$ in 2018 relative to that by $F$ in 2017 is a few dB larger at HH polarization than at HV polarization. In other words, the increase of $R$ in 2018 worked more efficiently at HH polarization than at HV polarization. From the viewpoint of floe size effect, it can be said that the enhancement of radar signals due to $F$ in 2017 was more effective at HV polarization than at HH polarization.

Regarding 2016 and 2019, $\Delta$ is also constantly separated in Fig. 16. In this case, ridged ice area was commonly limited to only about 10% of total ice area (Table II). The major difference is that the dominant floe category was pancake ice in 2016, whereas nilas in 2019. Therefore, ice surface is its margin, which should work to increase both effects of $R$ and $F$ in 2016 compared with 2019. It would be difficult to separate these two effects. We infer that somewhat steep and randomly oriented roughness produced by raised rims acted to enhance the HV signals effectively.

To summarize, our results showed that while floe size affects both HH and HV signals, the HV signal is more sensitive to floe size effect for both relatively thick ice and pancake ice than the HH signal. Because of this property, $\sigma_{\text{HH}}^0$ is considered to be more sensitive to the MIZ, characterized by small ice floes and the presence of pancake ice, than $\sigma_{\text{HV}}^0$. Therefore, it is expected that our measures work more effectively to detect deformed ice by combining $\sigma_{\text{HH}}^0$ with $\sigma_{\text{HV}}^0$.

Yet, a question remains as to why our measures did not work successfully to detect deformed ice in 2018 unlike 2017. Fig. 13(a) shows that HH anomaly in 2018 is close to zero or even negative with the mean along L2 being $-0.6 \pm 1.2$ (sd) dB in contrast to $1.5 \pm 1.6$ dB in 2017, although deformed ice was more prominent in 2018 than in 2017. We infer that our measures were derived from the field measurements in 2009 to 2011, when floe size was moderate and floes larger than 500 m were absent, quite different from those in 2018. On the other hand, the ice conditions in 2017 were close to the normal, averaged for 2000–2019 (Table II). Probably that is why our measures worked well to detect deformed ice in 2017, but not so much in 2018.

Here, we roughly estimate the effect of $F$ in 2018. Since ice surface roughness due to $R$ in 2018 is about 1.2 times larger than in 2017, judging from the ratio of mean ice thickness, the mean HH anomaly along L2 in 2018 is expected to be $1.8 \times (1.5 \times 1.2)$ dB for the same floe size conditions as in 2017. This is 2.4 dB higher than the real value. Considering that the total floe perimeter in 2018 is about half of that in 2017, it is roughly estimated that twice the total floe perimeter increases $\sigma_{\text{HH}}^0$ at L-band by 2–3 dB. This cautions us to take the floe size conditions into account as well as ice deformation when developing and applying the measures with L-band SAR.

Fig. 16. Cross section of $\Delta = (\text{HH anomaly}) - (\text{HV anomaly})$ in dB along line L2 in Fig. 10(a).
V. Conclusion

For better understanding of deformation processes in the SIZ, we developed measures to detect deformed ice using ALOS/PALSAR images as a preliminary step toward monitoring the temporal evolution of deformed ice regions, based on the field measurements aboard PV “Soya” in the Sea of Okhotsk. This region has some advantage over other polar regions for this purpose in that the absence of multyear ice makes the classification of sea ice types simpler. Comparison between PALSAR and RADARSAT-2 confirmed that L-band SAR is more useful to detect deformed ice than C-band SAR, which is consistent with the past studies. Assuming that brightness correlates to deformation, at least for the three ice categories (nilas, pancake ice, and deformed ice) found in this region and for L-band, the measures were derived by plotting $\sigma_{0}^{HH}$ as a function of $\theta_{i}$ and calculating the threshold lines between different ice types with the least-squares method. Mapping deformed ice regions with these measures revealed the following properties.

1) Forced by winds and ocean waves, deformed ice regions are quite variable with both time and space. In the inner ice pack region, the temporal evolution of deformed ice regions was consistent with the convergence/divergence zone of ice drift.

2) The area, judged as deformed ice from our measures, appears in relatively linear alignments mainly along the ice edge and with a width of a few tens of kilometers in the inner ice pack region.

To confirm the above results, we examined the applicability of our measures to ALOS-2/PALSAR-2 images, based on the four-year field measurements (2016–2019) conducted aboard the PV “Soya” in the same region. The results are summarized as follows:

3) The validity of our measures was confirmed to some extent from direct comparison with the real ice conditions for $19^\circ \leq \theta_{i} \leq 56^\circ$.

4) In open water area, the variability of $\sigma_{0}^{HV}$ was much reduced compared with $\sigma_{0}^{HH}$ and the dependence of $\sigma_{0}^{HV}$ on $\theta_{i}$ is somewhat larger than that within sea ice area.

5) Both $\sigma_{0}^{HH}$ and $\sigma_{0}^{HV}$ are affected significantly not only by ice surface roughness but also by floe size distribution through the total perimeter of sea ice floes.

6) The relative contribution of floe size distribution to the radar signals is estimated to be larger at HV polarization than at HH polarization by a few dB.

Regarding Item 5, in terms of contribution to the enhancement of $\sigma_{0}^{HH}$, it is roughly estimated that four times the total perimeter (i.e., 1/4 floe size for the same sea ice area) is comparable to about twice the ice surface roughness and enhance $\sigma_{0}^{HV}$ at L-band by 4–6 dB. From these results, it is most likely that the linear alignments along the ice edge described in Item 2 are attributed not to deformed ice, but to smaller ice floes with lower ice concentration, produced by the wave-induced breakup. To distinguish deformed ice regions from the region subject to such a floe size effect like the MIZ, combining our measures with $\sigma_{0}^{HV}$ might be useful, as suggested by Items 4 and 6.

All these results indicate that we should be careful when applying our measures to the sea ice regions where floe size distribution is significantly different from the normal conditions in the southern Sea of Okhotsk. To find out a universal measure, which is applicable to all the sea ice area, we need further investigation about how ice surface roughness and floe size distribution affect the radar signal with the dependence on $\theta_{i}$ quantitatively. Especially, theoretical work on the relationship radar signals and surface roughness is required in the future. Recently, rigorous statistical methods have been introduced to study ice-type classification with the $\theta_{i}$ effect [46], [47], and further development is expected. For this purpose, the international research expedition, “Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC),” which is ongoing in the Arctic Ocean from October 2019 to October 2020, is expected to provide us with an opportunity to extend this result.

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