STUDIES ON FORMATION OF THE COASTAL POLYNYA AND SEA ICE THICKNESS ALGORITHM USING THE ALOS PALSAR AND PASSIVE MICROWAVE DATA

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ABSTRACT

Based on the ALOS PALSAR data and other satellite data, we have clarified the formation mechanism of the Cape Darnley Polynya, which is suggested to be the second highest sea ice production area in the Antarctic Ocean. The PALSAR images suggest that the grounded iceberg tongue is formed east of the polynya from the coast to offshore for about 100 km length. Blocking of sea ice by this tongue is responsible for this huge coastal polynya formation. We have developed the algorithms of sea ice thickness and fast ice detection for microwave radiometer data with use of the PALSAR data as the validation data. AMSR-E algorithm is made for the Antarctic Ocean, and SSM/I algorithm is made for the Arctic Ocean. The relationship between the PALSAR data and sea ice thickness is also discussed.

1. INTRODUCTION

It is widely recognized that dense water formation caused by brine rejection due to high ice production in Antarctic coastal polynyas is responsible for the formation of Antarctic Bottom Water (AABW), which is the densest water mass in the world ocean. As AABW formation sites, Weddell and Ross Seas and the region off Adelie Land are well known. Antarctic coastal polynyas are formed by divergent ice motion due to prevailing winds and/or oceanic currents, and most of the area is covered with thin ice. During winter, heat loss over thin ice is one or two orders of magnitude larger than that over thick ice, and thus coastal polynyas are regarded as the ice production factories. Active and passive satellite microwave data are very strong tools to detect polynya areas as thin ice regions (Markus and Burns, 1995[1]; Drucker et al.,

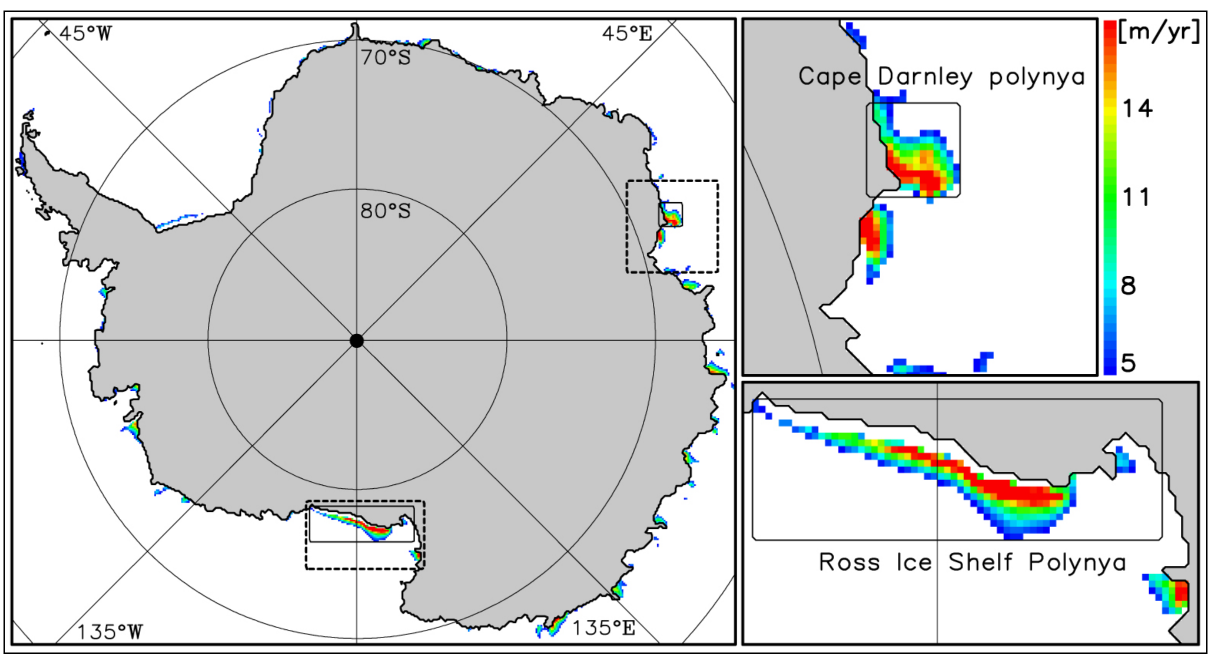

Fig. 1: Spatial distribution of annual cumulative sea-ice production (in meter) averaged over 1992-2001 with enlargements along the coasts of the Cape Darnley and Ross Sea (modified from Tamura et al. (2008)[4]).

2003[2]; Martin et al., 2004[3]).

Tamura et al.(2008) [4] provided the first mapping of sea ice production in the Southern Ocean, based on heat-flux calculation with thin ice thickness algorithm of passive microwave (Special Sensor Microwave Imager: SSM/I) developed by Tamura et al.(2007)[5]. Their mapping (Fig. 1) shows that the highest ice production occurs in the Ross Ice Shelf Polynya region. What we found from the mapping is that the Cape Darnley polynya, located west of the Amery Ice Shelf, is the second highest production area, suggesting a possible AABW formation area. We choose the Cape Darnley polynya as the test site for investigation of the Antarctic coastal polynyas and the development of sea ice thickness algorithm from the combination of the ALOS PALSAR data and other satellite data. The first purpose of this study is to clarify the formation process of the coastal polynya and its variability based on the ALOS PALSAR data. Particularly we focus on why such a huge polynya is formed. Second, we also develop the algorithms of ice thickness and fast ice detection for microwave radiometer data with use of the PALSAR data as the validation data.

2. DETAILED STRUCTURE OF THE CAPE DARNLEY POLYNYA DERIVED FROM PALSAR DATA

Figure 2 is an example of a ScanSAR mode image of ALOS PALSAR in winter off Cape Darnley. White (black) indicates high (low) backscatter. The PALSAR backscatter images can discriminate between icebergs, fast ice, first-year ice, and new ice around this area and clearly visualize the series of streamlines of new ice (Langmuir-like circulation), represented by white in the image, within the polynya. The streamlines of new ice are directed offshore-ward in the area close to the coast, while shifted westward in the offshore area, which is probably due to the effect of westward Antarctic Coastal Current. The image demonstrates that the polynya is a huge one whose size is more than 100 km x 100 km.

Since a shallow bank with 50-200 m depths exists east of this polynya, icebergs drifting from the Amery Ice Shelf via the Antarctic Coastal Current are apt to be grounded on this bank, indicated by small white patches. The image suggests that the first-year ice is accumulated around the

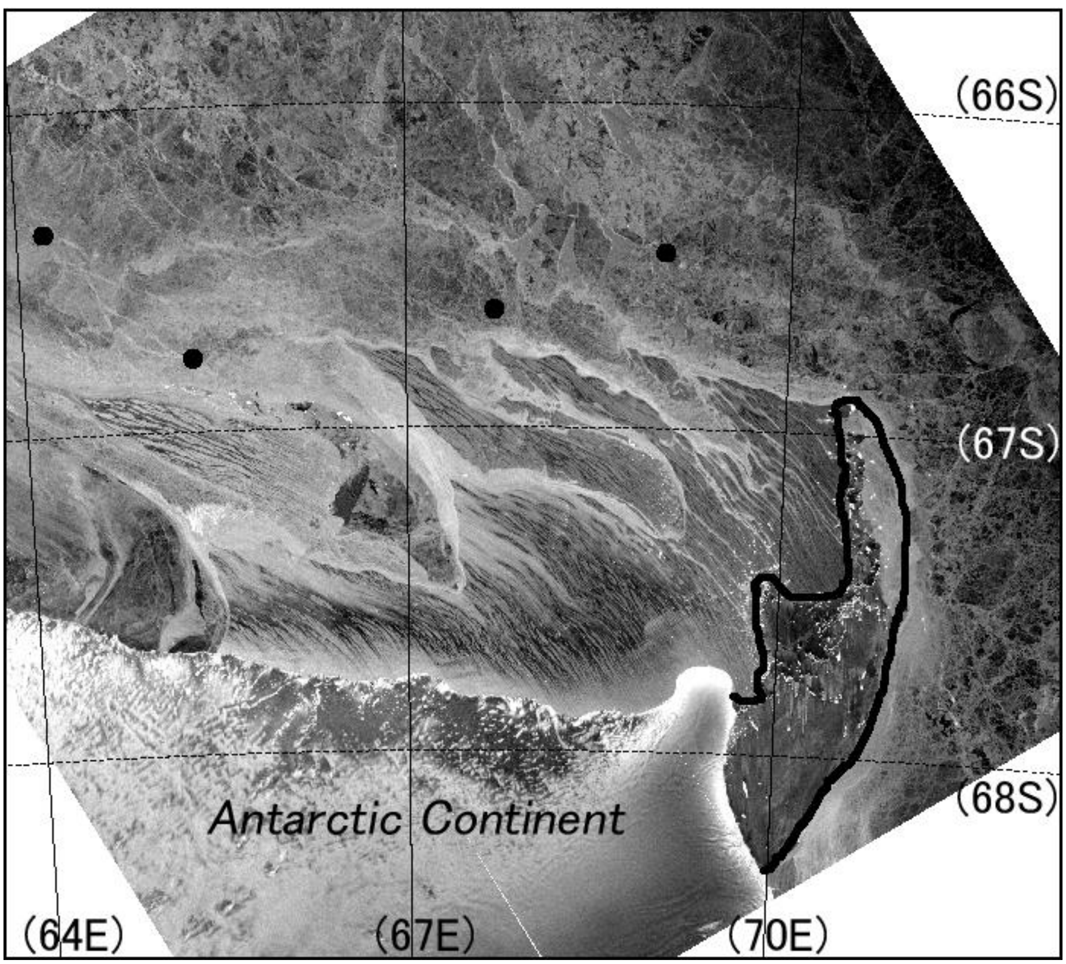

Fig. 2: ALOS PALSAR ScanSAR mode image off Cape Darnley, East Antarctica on 31 July 2007. Solid circles indicate mooring sites.

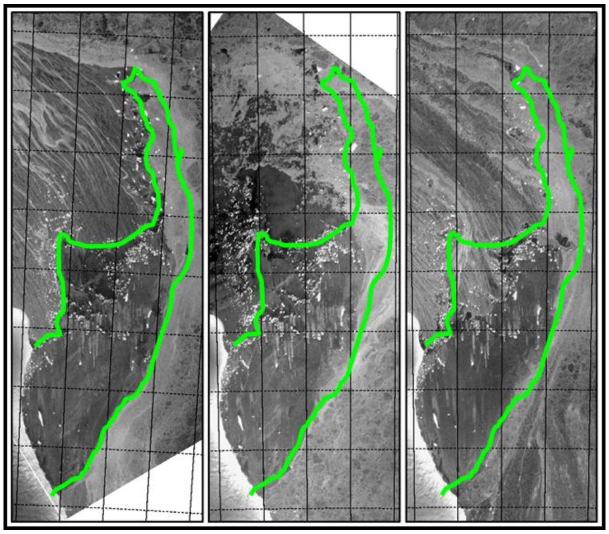

Fig. 3: Time series of PALSAR ScanSAR mode images off Cape Darnley (left: 31 July 2007; center: 26 December 2007; right: 10 May 2008).

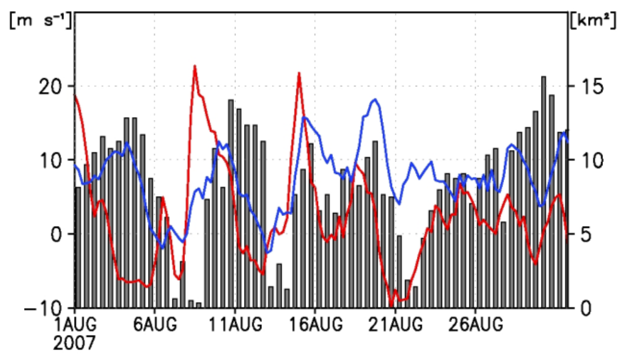

Fig. 4: Time series of the areal extent of the Cape Darnley polynya (bar) derived from SSM/I data, offshore-ward wind component (blue lines), and alongshore/westward wind component (red lines) from NCEP2 data.

grounded icebergs, and then the iceberg tongue (fast ice) is formed from the coast (south) to offshore (north) for about 100 km length, indicated by thick contours in Fig. 2. Figure 3 shows time series of PALSAR ScanSAR mode images throughout the year. It is found that positions of most of the icebergs and the shape and location of the grounded iceberg tongue have not been changed (indicated by green lines) at least for our analysis period of one year.

3. VARIABILITY AND FORMATION MECHANISM OF THE CAPE DARNLEY POLYNYA

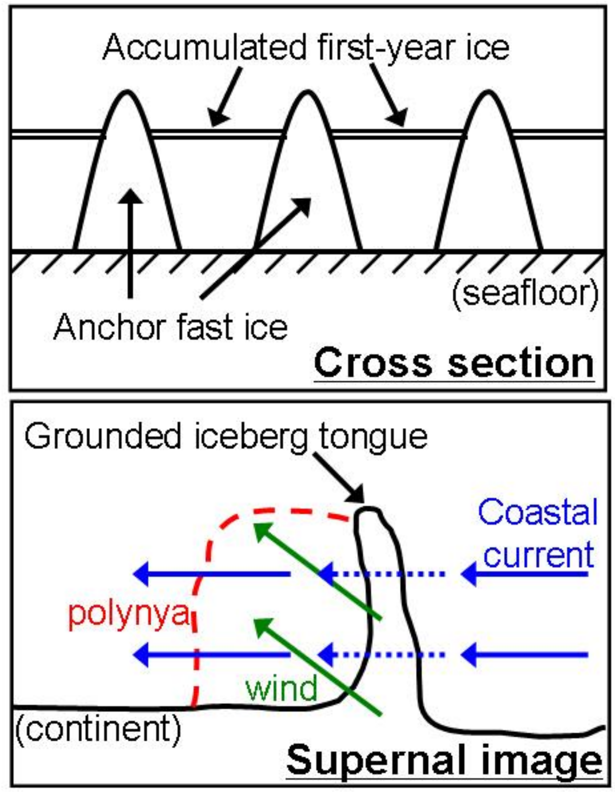

Fig. 5: Schematics of the formation mechanism of the Cape Darnley polynya.

Figure 4 shows time series of the polynya areal extent (bar) derived from SSM/I, offshore-ward wind component (blue lines), and alongshore/westward wind component (red lines) from NCEP2 data. It is found that the polynya area is significantly correlated with the offshore wind with 0.5-1 day lag, suggesting that the polynya is formed by the offshore-ward wind. It is noted that the polynya area is also correlated with the alongshore/westward wind with 1-3 day lag. The coastal current is considered to be driven partly by the alongshore wind. This result, along with the westward-shift of the streamlines in Fig.2, suggests the importance of the westward coastal current on the polynya formation.

Figure 5 shows the schematics of the proposed formation mechanism of the Cape Darnley polynya. Because a part of the westward coastal current can pass through the iceberg tongue, sea ice is carried away in the west side of the tongue while accumulated in the east side of the tongue. This filtering effect of the tongue is considered to be very important on the polynya formation. Similar mechanism can be also applied to other coastal polynyas in East Antarctica (Massom et al., 1998 [6]).

4. RELATIONSHIP BETWEEN PALSAR DATA AND SEA ICE THICKNESS

We discuss the relationship between the PALSAR backscatter and ice thickness derived from MODerate resolution Imaging Spectroradiometer (MODIS) infrared data and heat flux calculation by the method of Tamura et al.(2006)[7]. Figure 6 shows scatterplot of PALSAR HH backscattering coefficient and the ice thickness. Only for thin ice regime of less than 0.1 m, a linear-like relationship between HH backscattering coefficient and ice thickness is found. For ice thickness of more than 0.1 m, there seems no relationship between them.

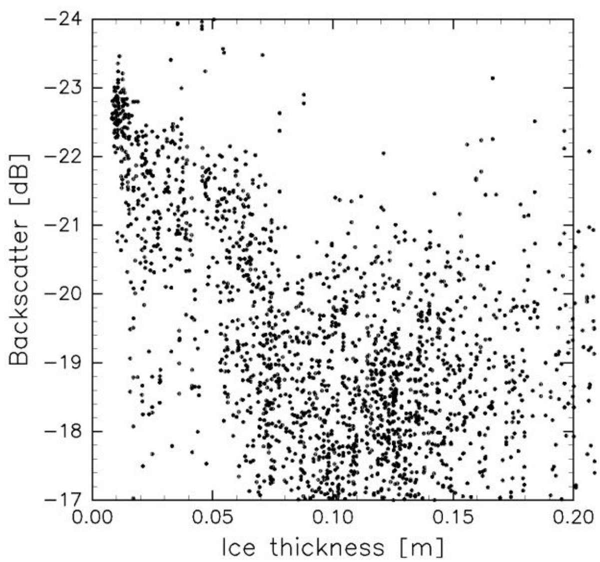

Fig. 6: Scatterplot of PALSAR HH backscattering coefficient on the vertical axis and MODIS ice thickness on the horizontal axis on 20 June 2006.

PALSAR polarimetric mode data provide four backscatter data of HH, VV, HV, and VH. Wakabayashi et al. (2004)[8] showed that the VV-to-HH backscattering ratio is highly correlated with ice thickness especially in thin ice region by the surface salinity, by comparing with the in-situ ice thickness data in the Sea of Okhotsk. Similar relationship is also presented in the Cape Darnley polynya (Fig. 7). The SAR backscatter usually shows the low values for thin ice regions (polynyas and leads) that consist of thin flat ice (nilas) and/or greese ice, with a higher value by the increase of the ice thickness (surface roughness of ice) (Willmes et al., 2010[9]). However, active frazil (frazil ice streaks) in the polynya shows higher values because the short waves accompanying the Langmuir-like circulation generate Bragg scattering, leading to a higher backscatter (Drucker et al., 2003[2]; Martin et al., 2005[10]). Thus, only from the HH backscatter, it is difficult to distinguish thin ice with thick ice, especially for the case between active frazil with first-year ice (Fig. 7a). On the other hand, the VV-to-HH backscattering ratio can distinguish thin ice with thick ice of fast ice and first-year ice clearly (Fig. 7b). More polarimetric mode data will be needed for the development of PALSAR sea ice thickness algorithm.

5. VALIDATION OF AMSR-E ICE THICKNESS ALGORITHM IN THE ANTARCTIC OCEAN

For examining the Antarctic coastal polynyas, the

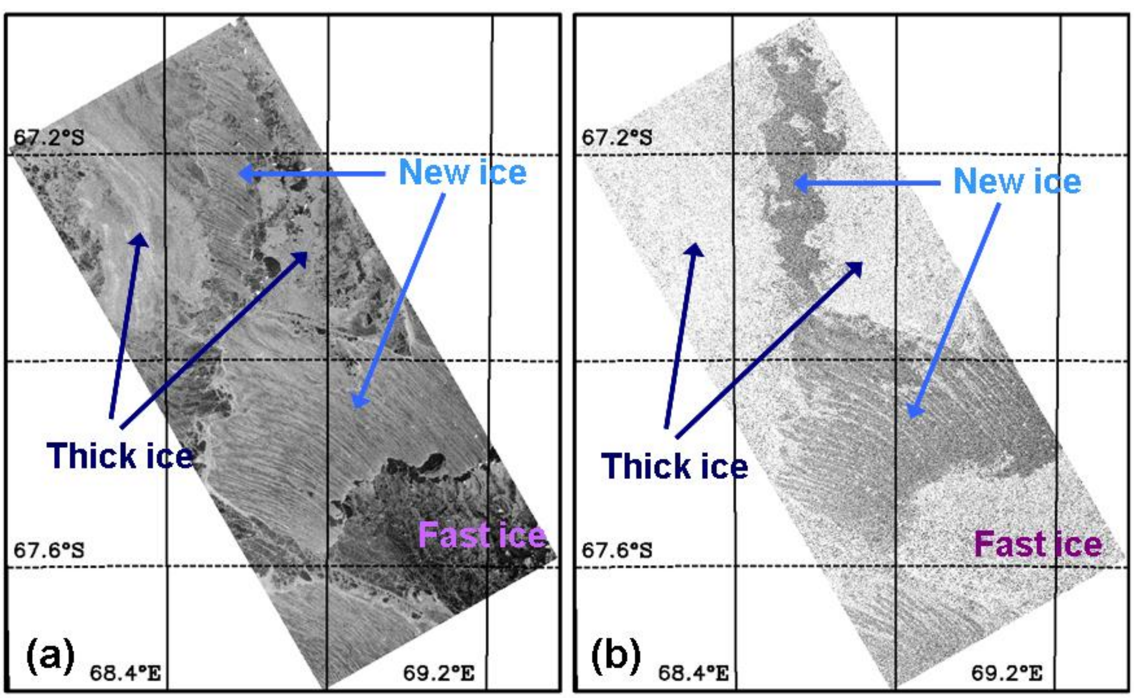

Fig. 7: (a) HH backscatter coefficient, and (b) VV-to-HH backscattering ratio from the PALSAR polarimetric mode data off Cape Darnley on 21 August, 2008.

Microwave Scanning Radiometer-EOS (AMSR-E) data would provide more accurate spatial distribution of ice thickness than the SSM/I data, because the AMSR-E has twice the resolution of the SSM/I. AMSR-E thin ice thickness algorithm has been newly developed for the Antarctic coastal polynyas using the polarization ratio (PR) values at 36.5 GHz and 89 GHz channels.. The algorithm can detect thin ice (coastal polynya) area and can estimate the thickness of ≤0.15 m. The algorithm is based on a comparison between the PR values of AMSR-E and ice thickness data estimated using the MODIS infrared data, in a similar way to Nihashi et al.(2009)[11]. We used 60 clear-sky MODIS images of the coastal polynyas in the Weddell and Ross Seas and near Cape Darnley. We also developed a fast ice detection algorithm based on a scatter plot of AMSR-E brightness temperature at 89 GHz vertically and horizontally polarized channels in a similar way to Tamura et al.(2007)[5]. For validation of thin ice and fast ice detection algorithms, ALOS PALSAR data are used since satellite SAR images can delineate polynya edges and fast ice area with a higher spatial resolution, free of cloud/water vapor effects.

Figure 8 shows a map of thin ice thickness and fast ice from AMSR-E around the Cape Darnley polynya region. The spatial resolution is about 6 km. Figure 9 shows an ALOS PALSAR image corresponding to Figure 8. The shape and location of thin ice (polynya) regions generally coincide with those from AMSR-E algorithm. In Fig.8, the area of fast ice is shown by black mask using the fast ice detection algorithm. Also the grounded iceberg tongue can be represented well. The data of other day and of other polynyas show similar result. These results suggest that the AMSR-E algorithms perform well, and that the ALOS PALSAR images are quite useful for the validation data.

We have also estimated sea ice production using AMSR ice thickness data and heat flux calculation. The area of high sea ice production has the annual cumulative ice production of 10-15m thickness, and this high ice production area well corresponds to the coastal polynya area detected from ALOS PALSAR images.

6. VALIDATION OF SSM/I ICE THICKNESS ALGORITHM IN THE ARCTIC OCEAN

As well as the Antarctic coastal polynyas, we have also developed thin ice thickness algorithm for the Arctic coastal polynyas (Tamura and Ohshima, 2011[12]). As the first step, we have developed SSM/I algorithm that can estimate sea ice thicknesses of up to 0.15 m, based on the SSM/I 85- and 37-GHz polarization ratios through a comparison with sea ice thicknesses estimated from the Advanced Very High Resolution Radiometer (AVHRR) data. ALOS PALSAR data are also used for validation of this algorithm. Here, we show four examples of the comparison using PALSAR data. Figure 10 shows examples of the spatial distribution of the HH backscatter

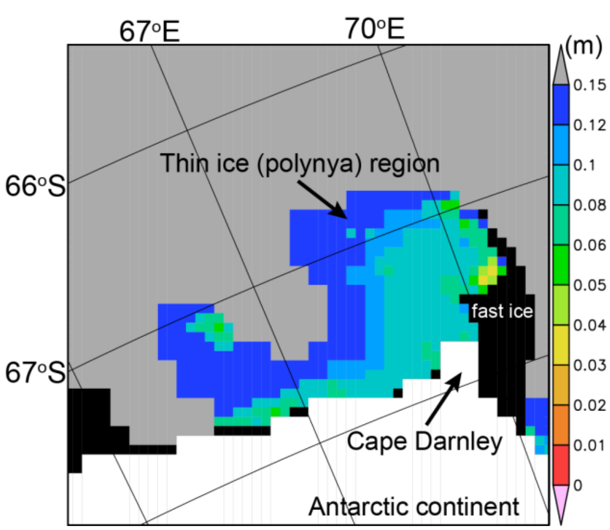

Fig. 8: Map of thin ice thickness and fast ice from AMSR-E in the Cape Darnley polynya region on 31 July 2007. White indicates the Antarctic continent (landmask from NSIDC). Black indicates fast ice detected from AMSR-E.

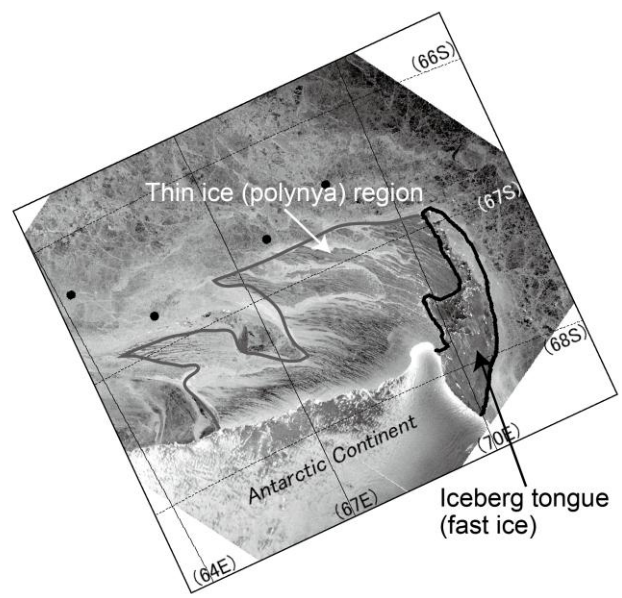

Fig. 9: ALOS PALSAR image of the Cape Darnley polynya region on 31 July 2007. Thin ice (coastal polynya) region is surrounded by gray lines. Iceberg tongue (fast ice) is surrounded by black lines.

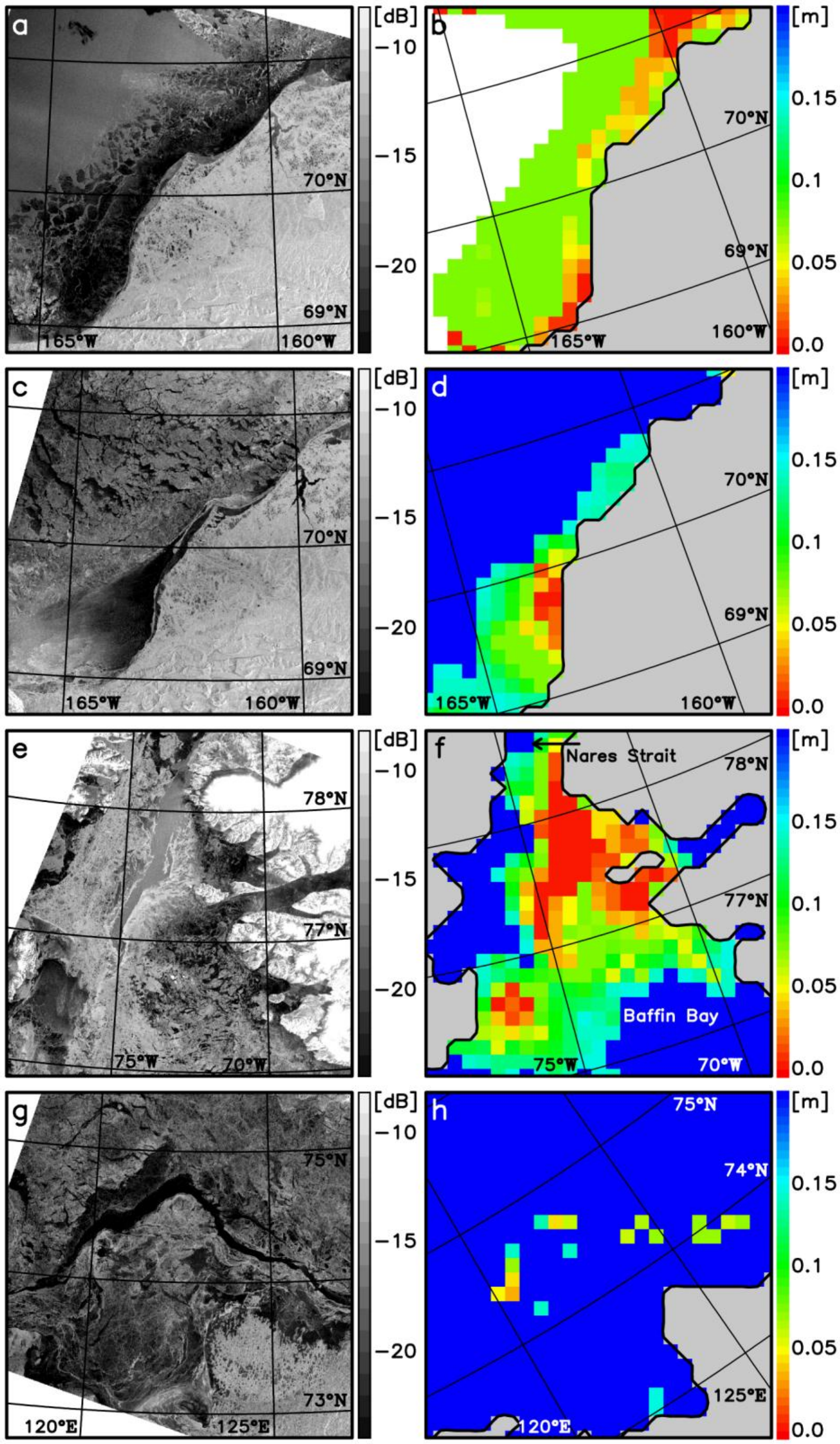

Fig. 10: (a,c,e,g) ALOS PALSAR backscatter and (b,d,f,h) SSM/I sea ice thickness for (a,b) the Chukchi polynya on 28 November 2006, for (c,d) the Chukchi polynya on 30 December 2007, for (e,f) the North Water (NOW) polynya on 17 January 2007, and for (g,h) the Laptev polynya on 16 March 2007. The solid lines and white pixels in (b,d,f,h) indicate the coastline of the SSM/I landmask and open water, respectively.

acquired from PALSAR and ice thickness estimated from the SSM/I thin ice algorithm in the NOW, Chukchi, and Laptev polynyas.

In the Chukchi polynya cases (Figs. 10a-d), the spatial pattern of offshoreward increase in the ice thickness derived from the SSM/I algorithm well corresponds to that of offshoreward backscatter increase in the PALSAR images. For both cases that the polynya is surrounded by open ocean (Figs. 10a and 10b) and by pack ice (Figs. 10c and 10d), the shapes of thin ice area derived from the SSM/I algrotithm and PALSAR images have good agreement. In the North Water (NOW) polynya case (Figs. 10e and 10f), similar agreements of the shape and offshoreward (southward) increase of the backscatter and ice thickness are shown in the thin ice areas around 76.5 N 77 W and 77 N 72 W. However, the NOW polynya case shows rather complex features, i.e. the higher backscatter regions do not always correspond to thicker ice regions. For example, the relatively dark band surrounded by bright areas (from 78.2 N 73 W to 77 N 75 W) has higher backscatter than other thin flat ice areas detected by the SSM/I algorithm. The NOW polynya is considered to be made and maintained by the ice bridge in the southern Nares Strait preventing ice drift from the Arctic Ocean to Baffin Bay, prevailing southward winds, and the southward water flow from the Arctic Ocean. Taking account of these conditions, we cannot exclude the possibility of that this southward band is actually open water. The SSM/I algorithm in this study uses the Bootstrap algorithm for the detection of open water areas. If this area is open water in actual, the Bootstrap algorithm may not be able to detect small open water area due to its spatial resolution (25 km). In the Laptev polynya case (Figs. 10g and 10h), there is a long narrow polynya shown by low backscatter between 74 N and 75 N. The area between this polynya and the coast is covered with landfast ice judging from the satellite thermal imageries. Although the SSM/I algorithm partly detects this narrow polynya, the SSM/I does not have enough resolution for the smaller scale polynya, leading to the underestimation of thin ice area. This demonstrates that SAR image is the strongest tool for detecting narrow polynyas regardless of cloudy and night conditions.

7. COMPREHENSIVE INVESTIGATIONS

To clarify the formation process of the polynya and the associated dense water formation, we are making comprehensive investigations combining mooring and hydrographic observations, and numerical modeling, in addition to the satellite data analyses. The moorings of ADCP (Acoustic Doppler Current Profiler), current meters and CT (conductivity-temperature recorders) were done at four stations (solid circles in Fig.2) off the Cape Darnley by the Japanese IPY project. The mooring data have shown that strong downslope current occurs in accordance with the arrival of cold dense bottom water shortly after the increase of sea-ice production estimated from the satellite data. These facts indicate that bottom water is indeed produced locally off the Cape Darnley due to the high sea ice production in the polynya. We have moored the two sets of IPS (Ice Profiling Sonar)/ADCP/CT moorings for continuous monitoring of ice and ocean inside the polynya during 2010-2011. This will provide ice thickness data with high temporal resolution. These data will serve as the great data set for truth and validation of PALSAR data and ice thickness algorithm from passive microwave (AMSR-E and SSM/I).

8. CONCLUSION

The ALOS PALSAR data have been used for investigation of the Antarctic coastal polynyas. In this study, the Cape Darnley polynya is chosen as the test site. Its formation mechanism has been clarified by the PALSAR data. The PALSAR data are found to be very good validation data for developing of thin sea ice and fast ice detection algorithms for microwave radiometer data (AMSR-E and SSM/I). In near future, combination study with other satellite data and in-situ sea ice data by the mooring observations will lead further understanding of the polynya process and high accuracy algorithm.

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