



HOKKAIDO UNIVERSITY

Title	Studies on formation and variability of Antarctic coastal polynyas taking account of ice type [an abstract of entire text]
Author(s)	中田, 和輝
Description	この博士論文全文の閲覧方法については、以下のサイトをご参照ください。 https://www.lib.hokudai.ac.jp/dissertations/copy-guides/
Degree Grantor	北海道大学
Degree Name	博士(環境科学)
Dissertation Number	甲第12489号
Issue Date	2016-12-26
Doc URL	https://hdl.handle.net/2115/64736
Type	doctoral thesis
File Information	Kazuki_Nakata_summary.pdf



Studies on formation and variability of Antarctic coastal polynyas taking account of ice type

(海氷タイプに着目した南極沿岸ポリニヤの形成・変動に関する研究)

要約

A feature of sea-ice cover over coastal areas is the appearance of coastal polynyas, which is formed by the offshore wind and/or ocean current. In Antarctic coastal polynyas, high production of sea ice occurs due to huge heat loss to atmosphere, resulting in the formation of dense water, precursor of Antarctic Bottom Water. Therefore, Antarctic coastal polynyas have important roles in ocean thermohaline circulation and biogeochemical cycles such as the CO₂ exchange between the atmosphere and deep ocean.

Sea-ice production within polynyas is directly related to polynya extent and thin-ice thickness within the polynya. Thus, it is important to estimate thin ice thickness accurately and examine the factor determining the polynya extent and variability. Several studies have developed algorithms for estimation of the thin ice thickness from brightness temperature (TB) of satellite passive microwave sensor. In these algorithms, ice thickness of less than 20 cm is empirically estimated by utilizing the negative correlation between the ice thickness and a ratio of the horizontally to vertically polarized TBs (PR). The empirical equation has been obtained from a direct comparison of PR and ice thickness derived from thermal infrared satellite data. The thickness is commonly referred to as, thermal ice thickness, as it is estimated from heat flux calculations using ice surface temperature. Thermal ice thickness is the one which correspond to heat flux assuming uniform ice thickness in the footprint, and is useful quantity for the estimation of sea-ice production. Several studies also have extended these algorithms to mapping of sea-ice production for Antarctic coastal polynyas, and the factor determining the polynya extent has been investigated using sea-ice data obtained from these

algorithms.

However, there are the following two problems in these thin ice thickness algorithms. One is that the PR-thickness relationship differs depending on the study area. The difference in ice thickness reaches nearly 10 cm for the same PR value of 0.07 between the algorithms by Martin et al. [2005] and Nihashi and Ohshima [2015], which results in large differences in the sea ice production estimates. The other is that the PR-thickness relationship has relatively large dispersion even in the same study area (ocean).

Thin ice (polynya) areas are classified roughly into two types. One is active frazil type: frazil/grease ice area where open water appears under turbulent conditions due to strong wind. The other is thin solid ice type: nearly uniform thin ice area such as nilas formed under relatively calm condition. Regarding active microwave sensors, specifically in the case of synthetic aperture radar (SAR) systems, the active frazil region is represented as a region with high backscatter streaks of frazil/grease ice, and thin solid ice region is represented as a uniform low backscatter region without the streaks. It has been speculated that the difference in these ice types causes the reduction in accuracy of the ice thickness algorithm. In addition, the information of ice type is necessary to examine the polynya mechanism because each ice type likely has different formation and variability process. In this study, we developed a high accurate thin ice algorithm with discrimination of ice type, and examined the formation and variability of Antarctic coastal polynyas using data obtained from the algorithm. In addition, based on the findings derived from the satellite data, we developed a more realistic numerical polynya model than previous one, and discussed the polynya formation and variability through idealized experiments using the model.

In the algorithm study, we used 36 GHz and 89 GHz TBs data of Advanced Microwave Scanning Radiometer for EOS (AMSR-E, the resolution of 12.5 and 6.25 km, respectively), MODerate resolution Imaging Spectroradiometer (MODIS, the resolution of 1 km) data and the Advanced Synthetic Aperture Radar (ASAR, the resolution of 150 m) data, obtained from the major three polynyas around the Antarctica (Ross Ice Shelf polynya (RISP), Ronne Ice Shelf polynya (RONP) and Cape Darnley polynya (CDP)). We estimated thermal ice thickness for the

AMSR-E footprint using MODIS and ERA-Interim atmospheric data. After thin ice areas are divided into the two types from the ASAR data, we examined the AMSR-E PR-MODIS ice thickness relationship for each type.

The result shows the clear difference of PR-thickness relationship between the two ice types. Fitted into scatterplot of PR versus thermal ice thickness using exponential curve as with previous studies, the derived curves for active frazil and solid ice types are similar to those of Martin et al. [2005] and Nihashi and Ohshima [2015], respectively. These results indicate that it is not appropriate for polynya with both ice types to apply the algorithm by the single PR-thickness relationship.

We considered that the difference of PR-thickness relationship is caused by the presence or absence of open water. Because the ratio of open water in sea-ice region is largely reflected in gradient ratio (GR) of 36 and 89 GHz vertically polarized TBs, the two types can be clearly discriminated by the PR-GR plane. Based on these results, we have developed a new thin ice algorithm in which polynyas are classified into the two ice types by a linear discriminant method. From the algorithm, we made a data set of ice type and thin ice thickness for the entire Southern Ocean on a daily basis, during winter (April-October) for the period 2003-2010. In addition, we estimated ice production from heat flux calculation using the thickness and ERA-interim atmospheric data.

We carried out the climatological mapping of Antarctic coastal polynyas from these sea-ice data. The results show that the active frazil type is more predominant in the East Antarctica, where the prevailing offshore wind blows. Especially, the CDP has the highest occurrence frequency of active frazil region. By contrast, the RISP has highest occurrence frequency of thin solid ice, where relatively weak offshore wind blows. In the previous algorithms, ice thickness was overestimated because the PR-thickness relationship is similar to that of the thin solid ice type. Therefore, in the new algorithm, sea-ice production in the polynyas along the East Antarctica was corrected to be higher values than previous studies. Especially, sea ice production in the CDP with the highest occurrence frequency of active frazil type is calculated to be about 1.5 times as that of the previous studies.

We examined the daily variabilities of each ice type using our sea-ice data targeting the CDP, which has high occurrence frequencies of polynya, active frazil

and thin solid ice regions. For the variability of active frazil area, Pease [1987] has proposed a simplified polynya model, which has been the basis of subsequent many polynya models. The model assumes that the frazil ice accumulates at the active frazil edge and is finally transformed into solid ice, considering that frazil ice in the active frazil region moves offshore faster than solid ice. In the model, active frazil area is determined by a balance between the offshore sea-ice drift and frazil ice production, and a key parameter is the so called collection depth, defined as an assumed constant thickness of frazil ice accumulating at the polynya edge.

We investigated to what degree the simplified polynya model by Pease [1987] can explain a real active frazil area. To apply the model to our available data set, we used the modified model of Nakata et al. [2015] introducing lag time in which the frazil ice moves offshore and accumulates at the active frazil edge. In this analysis, we used daily active frazil area, ice production data derived from AMSR-E and ice drift estimated from ERA-Interim surface wind. The result shows that the model can represent about 72% of the variability of active frazil area when using lag times of 0.5-1.5 days. In this analysis, we can also estimate the collection depth of frazil ice. The collection depth is estimated to be around 7-21 cm, which is consistent with the values assumed in the previous modelling studies.

It is found that active frazil region is transformed into thin solid ice region in the case of calm condition. Correlation coefficient between temporal changes of active frazil and thin solid ice areas is around -0.8, which suggests that the transformation mainly causes the expansion of thin solid ice region. Therefore, coastal polynyas with prevailing offshore wind such as the CDP maintain largely although strength of offshore wind causes transformation of ice type.

These previous polynya models, which are idealized models considering sea-ice budget at the active frazil edge, cannot reproduce the detailed sea-ice features seen in the active frazil region. For example, they cannot reproduce the offshore-ward streaks of frazil/grease ice associated with organized circulation like Langmuir circulation. We consider that reproduction of the detailed sea-ice features is necessary for development of a more realistic polynya model. This may be possible by using a Lagrangian frazil ice model developed by Matsumura and Ohshima [2015], which

can represent the behavior of frazil ice in the ocean. In this study, we applied this frazil ice model to more realistic numerical polynya model.

The model domain is $55.5 \text{ km} \times 7.5 \text{ km} \times 90 \text{ m}$, with horizontally periodic boundaries in the alongshore direction, and the horizontal and vertical grid spacing are 150 m and 3 m, respectively. We experiment two cases with offshore wind of 10 m s^{-1} and 15 m s^{-1} , with initial air temperature of $-20 \text{ }^{\circ}\text{C}$.

For the representation of active frazil region, we introduced the behavior of solid ice in the Eulerian frame and the transformation process of frazil ice into solid ice, into the frazil ice model. The numerical polynya model performs the following procedure at each time step. From an initial condition in which solid ice covers the whole surface, solid ice is advected by offshore wind, using a relationship equation between ice drift and surface wind. In the active frazil region formed by offshore solid ice drift, frazil ice is generated and grown due to heat loss to the atmosphere. frazil ice particles reached at the active frazil edge are transformed into new solid ice with a collection depth. We used the collection depths of 10 cm and 20 cm in the case of 10 m s^{-1} and 15 m s^{-1} surface wind, respectively. Initial salinity is uniformly 32 psu and the initial potential temperature is uniformly set to the surface freezing point, over the whole domain. The model is integrated for 72 hours.

The model reproduced that frazil ice particles exist at $<80 \text{ m}$ depth and move offshoreward with forming streaks of grease ice approximately parallel to surface wind, whose width and direction are approximately consistent with those seen from SAR images. The model also reproduced thermal ice thickness of 0-5 cm within active frazil, which is consistent with that obtained from MODIS data. The thermal ice thickness is much thin compared with frazil ice thickness of 15 cm. The thinning of thermal ice thickness is caused by both the sinking of frazil ice and formation of grease ice streaks, which results in high sea-ice production within active frazil region. The new numerical polynya model incorporating the production and advection process of frazil ice can reproduce Antarctic coastal polynya extended $>30 \text{ km}$ just off coast, which is not reproducible in previous polynya models.