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Formation processes of sea ice floe size distribution in the interior pack and its relationship to the marginal ice zone off East Antarctica

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ABSTRACT

To understand the behavior of the Seasonal Ice Zone (SIZ), which is composed of sea-ice floes of various sizes, knowledge of the floe size distribution (FSD) is important. In particular, FSD in the Marginal Ice Zone (MIZ), controlled by wave–ice interaction, plays an important role in determining the retreating rates of sea-ice extent on a global scale because the cumulative perimeter of floes enhances melting. To improve the understanding of wave–ice interaction and subsequent effects on FSD in the MIZ, FSD measurements were conducted off East Antarctica during the second Sea Ice Physics and Ecosystems eXperiment (SIPEX-2) in late winter 2012. Since logistical reasons limited helicopter operations to two interior ice regions, FSD in the interior ice region was determined using a combination of heli-photos and MODIS satellite visible images. The possible effect of wave–ice interaction in the MIZ was examined by comparison with past results obtained in the same MIZ, with our analysis showing: (1) FSD in the interior ice region is basically scale invariant for both small- (<100 m) and large- (>1 km) scale regimes; (2) although fractal dimensions are quite different between these two regimes, they are both rather close to that in the MIZ; and (3) for floes <100 m in diameter, a regime shift which appeared at 20–40 m in the MIZ is absent. These results indicate that one role of wave–ice interaction is to modulate the FSD that already exists in the interior ice region, rather than directly determine it. The possibilities of floe–floe collisions and storm-induced lead formation are considered as possible formation processes of FSD in the interior pack.

1. Introduction

Sea ice plays an important role in the polar climate system, due largely to its reduction of heat transfer from ocean to atmosphere and its high reflectance of solar radiation. Therefore the behavior of the sea ice extent particularly in the SIZ has a significant impact on the climate variability in the surrounding regions. Since the SIZ is composed of numerous ice floes with various sizes, FSD is an important parameter which controls the behavior of the SIZ. From a dynamical standpoint it is closely related to the deformation process of the ice cover, while thermodynamically it affects the melting rates of sea ice because smaller floes absorbs heat more efficiently from the surrounding seawater than larger floes (Rothrock and Thorndike, 1984). As for melting effects, it is suggested that FSD also contributes to the rapid decreasing trend in the Arctic summer sea ice extent (Asplin et al., 2012). According to their results, large expanses of open water introduce long fetch in the Arctic Ocean, leading to the storm-induced ice breakup, which accelerates the melting process. The effect of FSD on melting rate was shown to be significant for ice floes smaller than about 30 m (Steele, 1992).

To predict the retreat rates of the extent of the SIZ on a global scale, it is important to understand the melting processes in the MIZ, which is an outer fringe of the interior ice pack area. The MIZ is characterized by individual ice floes at typically lower ice concentration and vigorous wave–ice interaction that plays an important role in determining the FSD due to wave-induced flexural failure of ice (Squire, 2007; Squire and Moore, 1980; Wadhams et al., 1988). As a storm can induce wave–ice interaction even in the interior ice pack region in the Antarctic seas (Kohout et al., 2014), in this study we refer to the MIZ and the interior ice region as regions with comparatively lower and higher ice concentration, respectively (Fig. 4). Since relatively small ice floes are dominant in the MIZ, FSD is a controlling factor of the melting processes. Given that FSD in the MIZ is determined by the interplay of penetrating waves with the pre-existing sea ice, it is an important issue to clarify the FSD in the

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interior ice region and the effect of wave–ice interaction on the formation processes of FSD in the MIZ.

Recent studies revealed that FSD in the MIZ has a different regime for floes smaller than a few tens of meters (d_t m) compared with larger floes (Lu et al., 2008; Toyota et al., 2006, 2011). The cumulative number distribution, $N(d)$, defined as the number of floes per unit area with diameters no smaller than d, was found in both regimes to follow the power law, $N(d) \propto d^{-\alpha}$, indicating that FSD for both regimes is basically scale invariant. Yet the exponent α was shown to be quite different between these regimes. Whereas for $d > d_t$ α often exceeded 2, for $d < d_t$ α took significantly lower values ranging from 0.7 to 1.5 depending on the distance from the ice edge (Lu et al., 2008; Matsushita, 1985; Toyota and Enomoto, 2002; Toyota et al., 2006, 2011). This indicates that wave–ice interaction plays an important role in determining the FSD in the MIZ. It follows that understanding wave–ice interaction is requisite for the prediction of the retreating rate of sea ice extent on a global scale.

On the other hand, it was shown in earlier studies focusing on FSD in the interior ice region that $N(d)$ follows a power law for floes larger than about 100 m and α often exceeds 2, similar to the case of $d > d_t$ in the MIZ (e.g., Holt and Martin, 2001; Rothrock and Thorndike, 1984; Weeks et al., 1980). However, since measurements of FSD for floes smaller than about 100 m are sparse, the properties of FSD covering a wide range of floe sizes in the interior ice region is not yet fully understood. Although Steer et al. (2008) showed for floes in the interior ice region of the Weddell Sea in the melting season that FSD for $d < 20$ m had a different regime from that for $d > 20$ m, it is likely that FSD for smaller floes was much more affected by melting than by dynamical processes. Besides, field observations of wave activities in the MIZ have been very limited (Liu et al., 1991; Squire and Moore, 1980; Wadhams et al., 1988), with no concurrent observation of FSD made so far. Therefore, it still remains unclear how waves produce FSD in the MIZ, and how this differs from that in the interior ice region through wave–ice interaction, which may be one of the possible factors that has hampered the accurate prediction of sea ice extent retreat in numerical sea ice models (Holland et al., 2006).

To improve the understanding of the formation processes of FSD in the SIZ through wave–ice interaction, we planned the concurrent observations of wave activity and FSD from the Australian R/V "Aurora Australis" off Wilkes Land, East Antarctica during SIPEX-2 in late winter 2012. In this experiment, wave activity was observed using five buoys equipped with accelerometers on stable ice floes in the MIZ (see Kohout et al., 2014 for details). Since logistical reasons limited helicopter operations to only two interior ice regions about 250 km from the ice edge due to weather conditions (Fig. 1),

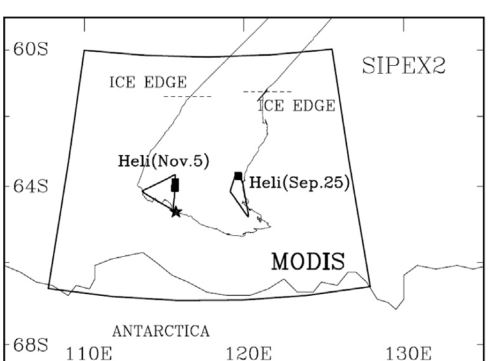

Fig. 1. Map showing cruise track (thin line) and heli tracks (thick lines) for the. SIPEX-2 expedition with the ice edge locations (broken lines) and the frame of MODIS images used for this study shown. Solid squares show the positions of heli-photos used for analysis and the star shows the position where R/V "Aurora Australis" became stuck (see Section 5.2 for details).

however, in this study we focus on FSD in the interior ice region by combining heli-photo data with MODIS channel 1 visible, 250 m resolution satellite images. Instead of direct measurements, we examine the effect of wave–ice interaction on FSD by comparing this study with previous results obtained in the MIZ off Wilkes Land in 2007 (Toyota et al., 2011) on the assumption that FSD is almost the same in the same region and in the same season. The result obtained from the buoys is used to interpret our analytical result of FSD. Ice thickness data were also obtained along the ship track with a video system (Toyota et al., 2004) to test theoretical studies that show ice thickness is by far the most important factor in determining the scattering and break-up of sea ice (Kohout and Meylan, 2008; Meylan, 2002).

The major purpose of this study is to (i) detail the properties of floe size distribution in the interior ice region, (ii) speculate on the effects of wave–ice interaction on FSD in the MIZ by comparing the results with those obtained previously in the MIZ of the same region, and (iii) improve the understanding of the formation process of FSD in the MIZ. In all analyses, the property of scale invariance will be emphasized. The formation processes of FSD in the interior ice region will also be discussed based on the data obtained and the meteorological reanalysis dataset (ERA-Interim). To support our discussion, additional observational evidence from the expedition will be documented.

2. Data

During the SIPEX-2 expedition, FSD was produced from heli-borne camera photos and MODIS satellite images for the interior ice region. Ice thickness along the ship track was also monitored with a video system. Here the heli-borne photos, ice thickness video system, and the analytical procedure to obtain FSD from the MODIS satellite images will be outlined.

2.1. Helicopter observation

The SIPEX-2 expedition was conducted from the Australian icebreaker R/V "Aurora Australis" for the period from September 15 to November 16, 2012 off East Antarctica. The expedition was an interdisciplinary project, including physical oceanography, sea ice physics, chemistry and biology (Meiners et al., this issue). The ice concentration in the study region from AMSR-E is shown in Fig. 2. During this expedition, the ship navigated within the sea ice zone from September 23 to November 10. Floe size observations were conducted with a heli-borne digital camera (GoPro) in the two interior ice regions, both located about 250 km inward from the ice edge: around 63.74°S 119.70°E on September 25 and around 63.86°S 115.69°E on November 5. The tracks of the ship and helicopter and ice concentrations on those days are shown in Figs. 1 and 2, respectively. During the observations, the weather was clear and there was only a small amount of cloud. Around these areas the dominant floe size was larger than a few km and floes smaller than 100 m were only seen between large floes. In addition to a heli-borne camera, an approximate FSD, unsuitable for quantitative analysis, was recorded every minute with a forward-looking camera installed on the upper deck of the ship. According to this measurement, the dominant floe sizes in the MIZ were about 2–3 m, 5–6 m, and 10–20 m in the zones of 0–70 km, 70–100 km, 100–190 km from the ice edge (61.0°S 122.0°E), respectively.

A heli-borne digital camera, installed on the step of the helicopter, took the photos of the ice conditions directly below the helicopter every five seconds along each flight track with a fish-eye lens (view angle: 170°) to cover a broad area. During the flights, the position and altitude were recorded every 10 s with GPS (Garmin, GPSMAP196) with a nominal accuracy of < 15 m.