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# Size distribution and shape properties of relatively small sea-ice floes in the Antarctic marginal ice zone in late winter

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ABSTRACT

In the marginal sea ice zone (MIZ), where relatively small ice floes are dominant, the floe size distribution is an important parameter affecting melt processes given the larger cumulative perimeter of multiple small floes compared with a single ice floe of the same area. Smaller ice floes are therefore subject to increased lateral melt. However, the available data have been very limited so far. Analysis of sea ice in the Sea of Okhotsk revealed that while floe size distribution is basically scale invariant, a regime shift occurs at a size of about 40 m. In order to extend this preliminary result to the Antarctic MIZ and further examine the controlling factors, the first concurrent ice floe size and ice thickness measurements were conducted in the northwestern Weddell Sea and off Wilkes Land (around 64°S, 117°E) with a heli-borne digital video camera in the late winter of 2006 and 2007, respectively. The floe sizes ranged from 2 to 100 m. Our analysis shows: 1) the scale invariance and regime shift are confirmed in both regions; 2) the floe size at which regime shift occurs slightly increases from 20 to 40 m, with ice thickness, consistent with the theory of the flexural failure of sea ice; and 3) the aspect ratio is 1.6-1.9 on average, close to the previous results. Based on these results, the processes affecting the floe size distribution and the subsequent implications on melt processes are discussed. By applying a renormalization group method to interpret the scale invariance in floe size distribution, the fractal dimension is related to the fragility of sea ice. These results indicate the importance of wave-ice interaction in determining the floe size distribution.


## 1. Introduction

The marginal sea-ice zone (MIZ), located between open ocean and the interior ice pack, is characterized by vigorous interaction with ocean waves. When ocean waves penetrate an ice cover, the wave energy is significantly attenuated by sea ice particularly for shorter wave periods, and in turn sea ice is fractured by the flexural force from penetrating waves (Squire and Moore, 1980; Wadhams et al., 1988; Squire et al., 1995). Thus relatively small ice floes, mostly less than 100 m in diameter, are dominant in the MIZ. As discussed by Steele et al. (1989), ice velocity significantly decreases for ice floes smaller than about 100 m due to the form drag effect. Additionally, Steele (1992) shows the melt rate of ice floes to significantly increase for floe sizes smaller than about 30 m because lateral melting becomes more important. Therefore, the floe size distribution is an important physical parameter in the MIZ to understand ice motion and melting. However, the available data have been very limited so far. Sea ice in the MIZ is subject to a complex interplay of thermodynamic and dynamic processes that affect the freeze and melt processes as well as the spread and retreat of the ice at a large scale. It is therefore critical to examine the general properties of floe size distribution in the MIZ and to include them in the numerical sea-ice models for climate prediction. At a small scale, floe size distribution can be used as a diagnostic tool of wave-ice interaction because it determines ocean wave activity and vice versa, as Lu et al. (2008) pointed out.

In the interior pack ice regions, the properties of sea-ice floe size distribution have been investigated by several researchers. For the Arctic and sub-polar regions, mainly ice floes larger than 100 m were analyzed with airborne radar, satellite images and aerial photographs (e.g., Weeks et al., 1980; Rothrock and Thorndike, 1984; Matsushita, 1985; Holt and Martin, 2001; Toyota and Enomoto, 2002). Their results showed that the cumulative number distribution, *N(d)*, the number of floes per unit area with diameters no smaller than *d*, follows the power law, i.e. $N(d) \propto d^{-\alpha}$, $1.7 < \alpha < 2.9$, indicating that floe size distribution is basically scale invariant. Yet at the same time these results raised the problem that the exponent $\alpha$ often exceeds 2. Mathematically, $\alpha$ corresponds to a fractal dimension, which describes the degree of complication of self-similar objects (Mandelbrot, 1967), and must be less than 2 for small ice floes, otherwise the ice area would be infinite (Rothrock and Thorndike, 1984). To solve this problem, Toyota et al. (2006) investigated the floe size distribution for floes ranging between

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1 m and 1.5 km in diameter, by combining Landsat-7/ETM+ images and ship- and helicopter-borne video images in the southern Sea of Okhotsk. As a result, they found that a regime shift occurs at a size of 20-50 m and $\alpha$ for smaller floes become reduced to 1.15. They hypothesized that the regime shift is induced by the effects of swell on floes of different sizes and thicknesses. Recently, Steer et al. (2008) and Lu et al. (2008) investigated the size distribution of ice floes smaller than 100 m with aerial photographs in the Antarctic during the melt season. In both cases changes in slope of $N(d)$ were detected at a few tens of meters. While Lu et al. (2008) attributed it to the effect of upper truncation of a power law function (Burroughs and Tebbens, 2001), Steer et al. (2008) interpreted it as a change in the regime and estimated $\alpha$ for smaller ice floes as about 1.9. This is significantly larger than the result of Toyota et al. (2006). Thus the knowledge of ice floes less than 100 m is still limited and the results obtained so far are variable depending on region and season. Due to a lack of ice thickness data, the mechanism for the floe size distribution has been unknown. From theoretical studies based on a solution for wave propagation under floating elastic plates, it is shown that ice thickness is by far the most important factor for determining the scattering and break-up of ice (Meylan, 2002; Kohout and Meylan, 2008).

To improve the understanding of floe size distribution in the MIZ, concurrent floe size and ice thickness measurements were conducted for the first time with a heli-borne digital video camera in the Weddell Sea and off the Wilkes Land in late winter. These measurements covered floe sizes ranging from 2 m to 100 m. Ice thickness measurements were conducted using a heli-borne EM in the Weddell Sea and a video system off Wilkes Land. The major purpose of this study is to extend the preliminary result of the Okhotsk sea ice to the Antarctic MIZ, determine the general properties of the size distribution for relatively small ice floes, and to examine the processes affecting the floe size distribution and the subsequent impacts on melt process. This will, in turn, inform the parameterization of these processes in numerical sea-ice models. In the analysis special attention is paid to the scale invariant property, and to interpret this a simple renormalization group method (Turcotte, 1992) is applied. Based on the results, some possible melting processes are proposed.

## 2. Measurements

Floe size measurements were conducted in the northwestern Weddell Sea during the expedition of the Winter Weddell Outflow Study (WWOS) and off Wilkes Land during the expedition of the Sea Ice Physics and Ecosystem Experiment (SIPEX).

### 2.1. Weddell Sea

The WWOS expedition was performed with the German ice-breaker R/V "Polarstern" for the period from August 25 to October 29, 2006 in the northwestern part of the Weddell Sea. This corresponds to the outflow region of the Weddell Gyre (Fig. 1). The expedition was an interdisciplinary project, including physical and chemical oceanography, sea-ice physics and chemistry, biology, and bathymetry. The details are described in Lemke (2009) and the ice concentration in the study region from AMSR-E is shown in Fig. 2. During this expedition, floe size observations were conducted with a heli-borne digital video camera (SONY, DCR-TRV30) on September 19 (60.1°S 50.8°W), October 17 (60.4°S 43.8°W) and October 18 (60.5°S 42.1°W), when the ship was crossing the MIZ. The heli-tracks were selected in a direction normal to the ice edge as shown in Fig. 3. Pictures of the ice conditions in each region are also shown in Fig. 4. These figures show that all the observation areas between the open water and interior ice pack contained small ice floes, which is typical of the MIZ. During the observations, the weather was clear and there was only a small amount of cloud.

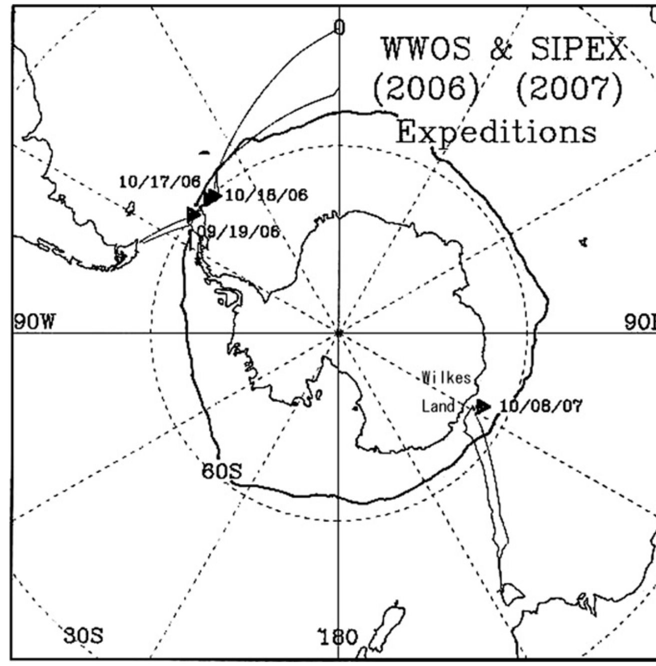


**Fig. 1.** Map showing cruise tracks and observation area for the WWOS and SIPEX expeditions with the ice edge on Sep. 30 (1971-2000) (Japan Meteorological Agency, 2001).

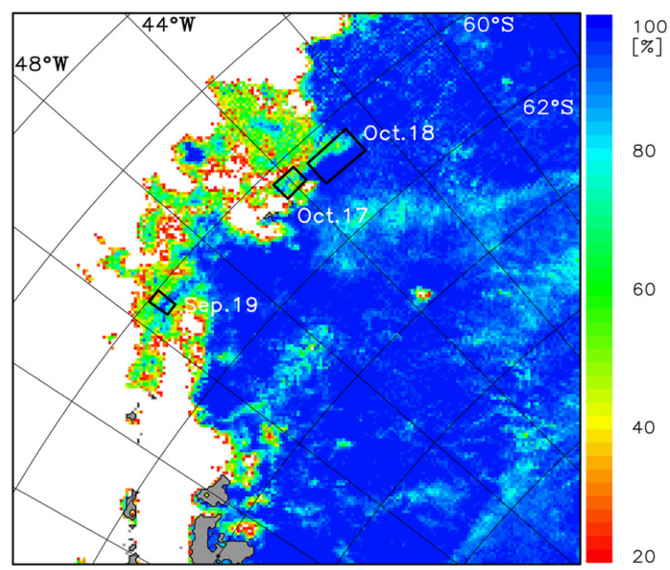


**Fig. 2.** Ice concentration map by AMSR-E in the Weddell Sea, as of Oct. 17, 2006. The approximate areas of Fig. 3 are shown with thick black lines.

A heli-borne video camera, installed on the step of the helicopter with a tripod, recorded the ice conditions along each flight track. During the flights, the position and altitude were recorded every 10 seconds with GPS (Garmin, GPSMAP76) with a nominal accuracy of $< 15$ m. The helicopter flew at several fixed altitudes, ranging from 90 to 1125 m, where the higher altitude was set for large floes and the lower for smaller floes (Table 1). To determine the scale of each image, the ship's hull was embedded into an image at each representative altitude. Small fluctuations in altitude were also taken into account when calculating the scale. After the observation, the video tapes were downloaded to a personal computer and then image files with $640 \times 480$ pixels were created every minute at each altitude in JPEG