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# In situ observations of wave-induced sea ice breakup

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ABSTRACT

Ocean waves can propagate hundreds of kilometers into sea ice, leaving behind a wake of broken ice floes. Three floe breakup events were observed during the second Sea Ice Physics and Ecosystem Experiment (SIPEX-2). We show that the three breakup events were likely influenced by ocean waves. We compare the observations to a wave induced floe breakup model which includes an empirical wave attenuation model, and show that the model underestimates the extent of floe breaking for long period waves.

## 1. Introduction

Antarctic sea ice, a critical component of the climate system, is highly influenced by the dynamic nature of the Southern Ocean. Since the beginning of polar exploration, observations of Southern Ocean waves inducing ice floe breakup have been reported. Heroic-era polar explorer, Shackleton, was forced to evacuate a comparatively safe ice floe (home for the previous past six months), when swell caused it to break apart (Shackleton, 1982). More recently, Kohout et al. (2014) found ocean waves propagating into the sea ice field were capable of playing a greater role in ice breakup than previously thought. They also found trends in significant wave height in the Southern Ocean correlate closely with trends in Antarctic sea ice extent, however, this relationship is yet to be fully understood. Evidence suggests that it is likely that decadal-scale changes in the atmospheric circulation are closely associated with trends in heat flux, ocean wave activity and ice motion, and hence with trends in sea ice extent. With wave heights in the Southern Ocean predicted to increase in the future (Dobrynin et al., 2012), there is an even greater need to understand the role of waves within this system. One vital aspect of wave–ice interaction is ice floe breakup due to waves.

Although obtaining observations of wave breakup of sea ice is logistically extremely difficult and consequently quantitative in situ observations are rare, they have been observed in both Polar Regions. Physically the processes are similar, although large waves are more common in the Antarctic due to the large fetch that the Southern Ocean provides. However, the limitations on wave fetch in the Arctic are predicted to decrease as Arctic sea ice retreats under climate change leaving more open water.

A breakup event was observed during a 1986 winter cruise to the Weddell Sea, and inspired the description and analysis presented in Liu and Mollo-Christensen (1988). During that cruise, the R/V *Polarstern* was 560 km from the ice edge when an approximately 1 m amplitude wave with 18 s wave period (estimated via ship based radar) resulted in the breakup of the surrounding ice pack. The ice was reported to be highly deformed and above 0.9 concentration with a mean thickness of 0.8 m. Anomalously low spatial wavelengths initially characteristic of the event were observed to lengthen with progressive breakup and deformation, eventually approaching values normally associated with waves of the observed frequency in a deep, ice-free ocean or in a floating uniform ice cover of moderate thickness.

Prinsenberg and Peterson (2011) report a breakup event during the summer of 2009 in the Canadian Beaufort Sea pack ice. Wave period and amplitude were measured via the ships high frequency sonar data and helicopter-borne laser sensors. Initially, while approximately 150 km from the ice edge, the peak wave period was estimated at 13.5 s with an amplitude of 0.4 m. The following day, after sailing 150 km NW (and closer to the ice edge), the peak wave period reduced to approximately 8 s with amplitudes up to

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0.8 m. They reported that large 2–3 km wide and 2–3 m thick multi-year ice floes were broken into smaller floes less than 100 m wide.

Fortuitously, during a campaign to improve our understanding of how large waves decay in sea ice (Kohout et al., 2014), we observed three floe breakup events. Here we report the details of these breakup events and show how they coincide with wave events, and thus provide further insight into the wave conditions required to induce floe breakup.

## 2. Deployment

We deployed a series of waves-in-ice observation systems (WIIOS) on Antarctic sea ice in Spring 2012 during the second Sea Ice Physics and Ecosystem Experiment (SIPEX-2) (Kohout et al., 2014, 2015). On 23 September 2012 (UTC), three WIIOS were deployed from a hovering helicopter close to the ice edge and approximately 5 km apart. Before the remaining two WIIOS were deployed, a low front arrived, bringing snowstorms and winds averaging 45 knots. The remaining WIIOS were therefore deployed using the aft crane on the RSV *Aurora Australis*. The WIIOS furthest from the edge was deployed in large swell approximately 160 km south of the ice edge. Each of the WIIOS generally drifted in an easterly direction with the outermost WIIOS drifting faster than the inner most sensors. During the six week recording period, the area covered by the WIIOS was bounded by 60°30′S–63°0′S and 121°0′E–130°0′E (Fig. 1). The WIIOS were deployed on first-year ice on floes 10–25 m wide with a freeboard of 0.1–1 m (Table 1).

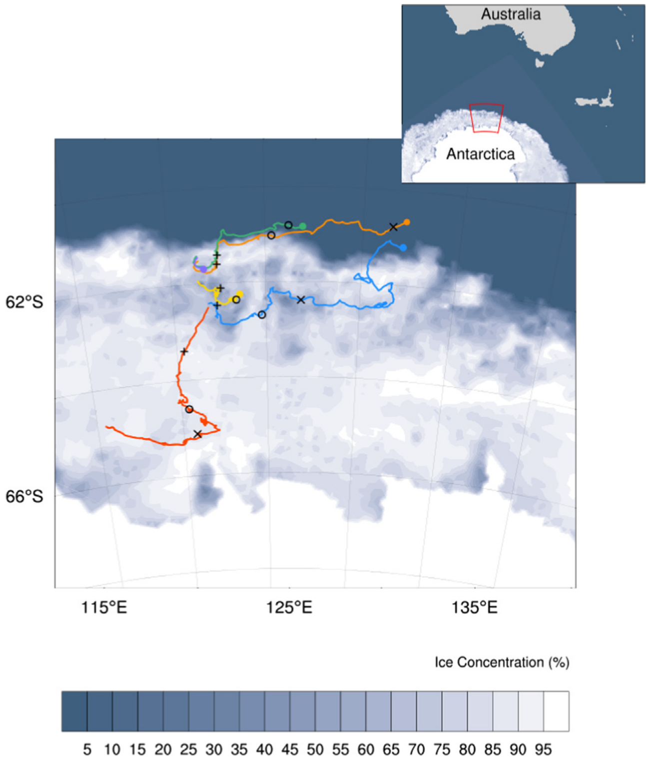

**Fig. 1.** The track of each waves-in-ice observing system (WIIOS) (green, orange, purple, yellow, blue) and the ship track (red). The colored round filled markers show where the WIIOS stopped transmitting. The plus, circle and cross show the locations of the WIIOS and ship during the first, second and third breakup events. The inset shows the location of the experiment on a larger scale, with the red box indicating the main figure. The contours show the mean sea ice concentrations between 23 September and 2 October 2012. The Antarctic continent is shown in white. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Along the deployment transect, the average ice floe diameter increased steadily from 2–3 m at the ice edge to 10–20 m approximately 200 km from the ice edge. Beyond this, there was an abrupt increase in floe diameter to hundreds of meters. Ice, estimated from manual shipboard observations, was between 0.5 and 1 m thick and was all first-year ice. For the duration of the WIIOS measurements, the rate at which sea ice concentration increased with distance from the edge was relatively high when compared to climatology for this location (Kohout et al., 2014). Every three hours, the WIIOS simultaneously woke and recorded wave accelerations for 34 min. Each WIIOS performed on-board data quality control and spectral analysis before returning the wave spectrum via satellite. A detailed description of the onboard analysis and data returned is provided in Kohout et al. (2015). The metadata and raw data are hosted at the Australian Antarctic Division Data Centre (Kohout and Williams, 2013).

## 3. Floe breakup events

Three ice floe breakup events were observed from the *Aurora Australis* during the SIPEX-2 voyage (Fig. 1, Table 2). These three events coincided with wave events (Fig. 2), suggesting that it is likely wave forcing induced the floe breakup events. Figs. 3 and 4 show images of the sea ice before and after the second wave breakup event. Prior to the wave event, the sea ice consisted of large continuous sheets (Fig. 3). After the event, elongated cracks formed in the sea ice, clearly showing the wave direction (perpendicular to the cracks). Also, the cracks formed by the waves were evenly spaced, suggesting a relationship between wave induced ice break up and floe size distribution (Fig. 4).

The first event occurred on 25 September 2012 (UTC), during the first SIPEX-2 ice station 299 km from the ice edge. At 02:00 when we arrived at the ice station no waves were evident. Throughout the morning, waves gradually built and by 07:00 waves were clearly observable. By 09:00 the ice began to break apart with cracks opening along ridges and weaknesses, e.g., sea ice bridges where previously broken floes had frozen back together. The waves were visually estimated to have a significant wave height of 0.5 m and a peak wave period of approximately 15 s. At the time of this event, we had four buoys collecting wave data approximately 2° east of the *Aurora Australis* (Fig. 6). The wave buoy closest to the ice edge (32 km) recorded waves with a 1.7 m significant wave height and 10.4 s peak wave period at 02:00. By

**Table 1**
Approximate dimensions of each floe with a wave sensor.

| Sensor | Freeboard (m) | Width (m) | Length (m) |
|---|---|---|---|
| 1 | 0.1 | 12 | 12 |
| 2 | 1 | 10 | 16.5 |
| 3 | 0.15 | 10 | 15 |
| 4 | 0.15 | 10 | 16.5 |
| 5 | 0.5 | 11.5 | 24 |

**Table 2**
An overview of the three floe breakup events, showing the ships location, the distance from the ice edge ($x$), both the estimated observed (est) and predicted (pre) significant wave heights ($H_s$), and the estimated observed peak wave period ($T_p$). No wave period was observed for the 3rd event.

| | Date and time (UTC) | Lat (°S) | Lon (°E) | $x$ (km) | $H_s$ (m) est | $H_s$ (m) pre | $T_p$ (s) |
|---|---|---|---|---|---|---|---|
| Event 1 | 25 Sep 2012 09:00 | 63.39 | 120.32 | 244 | 0.5 | 0.60 | 15 |
| Event 2 | 01 Oct 2012 13:00 | 64.60 | 120.33 | 455 | 0.1 | 0.52 | 15 |
| Event 3 | 09 Oct 2012 00:00 | 65.13 | 120.63 | 502 | 0.0 | 0.51 | |