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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

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wave period reduced to approximately 8 s with amplitudes up to 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). 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).

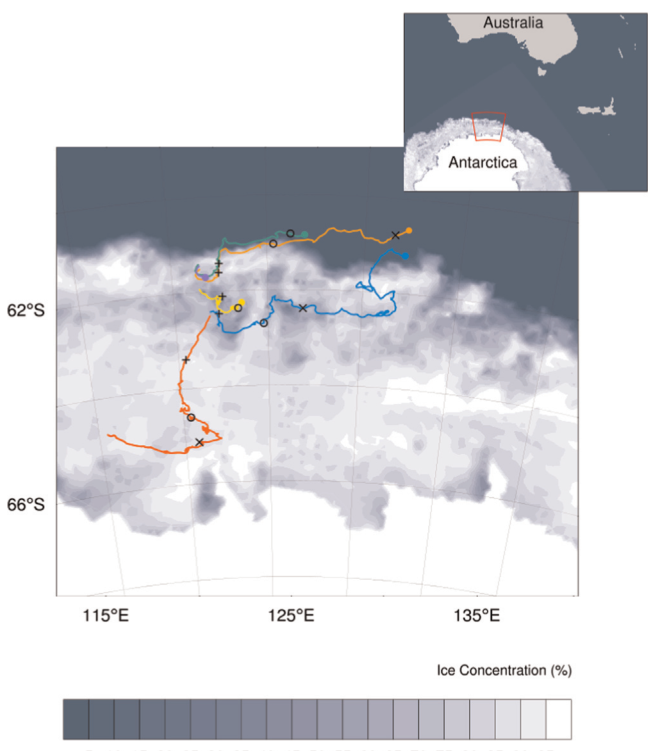

Fig. 1. The track of each waves-in-ice observing system (WIIOS) (green, orange, purple, yellow, blue) and the ship track (red). The colored round filled markers show where the WIIOS stopped transmitting. The plus, circle and cross show the locations of the WIIOS and ship during the first, second and 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.)

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

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	

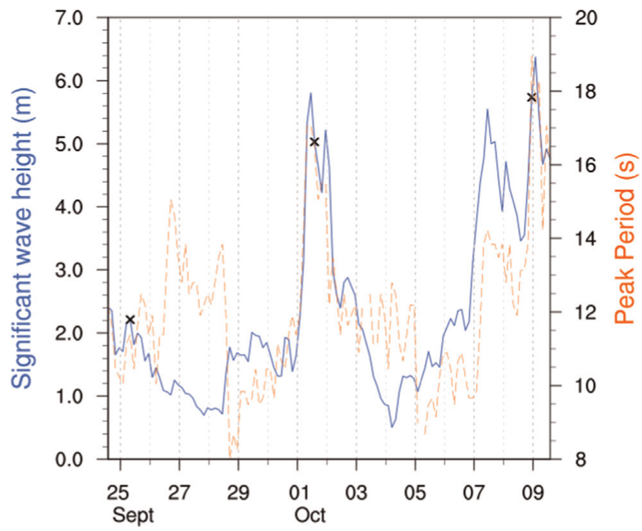

Fig. 2. An overview of the wave sensor closest to the ice edge during the three floe breakup events. The significant wave height (solid) is shown on the left axis and the peak wave period (dashed) on the right axis. The crosses indicate when the breakup events occurred.

Fig. 3. An image taken prior to the second floe breakup event (01 October 2012). (Photo Credit: *Aurora Australis* webcam, Australian Antarctic Division).

Fig. 4. An image taken after the second floe breakup event (02 October 2012). (Photo Credit: Jennifer Hutchings).

significant wave height and 10.4 s peak wave period at 02:00. By 08:00 the buoy was now 25 km from the ice edge and the waves had increased to 2.2 m and lengthened to 11.9 s.

The second event occurred on 1 October 2012 (UTC). At 12:10 a Northwest swell, visually estimated to have an amplitude of 10 cm and an approximately 15 s period was observed from the bridge. By 13:00, heavy floes readily broke and cracks opened along ridges and weaknesses. The swell continued to gradually build and by 14:00, cracks in the ice were extensive. At the time of this event we had four buoys roughly 4° east of the *Aurora Australis* (Fig. 7). The wave buoy closest to the edge (37 km) reached its peak significant wave height of 5.3 m, with a peak wave period of 16.5 s at 08:00. By 14:00, the significant wave height was still as high as 5 m and the peak wave period 15.5 s. By 17:00, the significant wave height had fallen to 4.2 m.

The third event occurred on 8 October 2012 (UTC) just before midnight. Although no waves were evident, an ice floe cracked at approximately 14:00 whilst scientists were working on the ice. At midnight, another crack appeared. At the time of this event, we had 2 buoys, one 4° and one 8° east of the *Aurora Australis* (Fig. 8). On this occasion, the wave buoy closest to the edge (31 km) had a significant wave height of 3.5 m and a peak wave period of 13.1 s at 14:00. By 23:00, the significant wave height had increased to 5.7 m and the waves had lengthened to 19 s (although now the buoy was only 18 km from the ice edge). The peak wave height (6.4 m) was reached at 02:00 on 9 October.

For each wave break up event we also investigated the v-component of the 10-m surface wind from ERA-Interim (Dee et al., 2011). This is the wind component aligned with the direction of wave propagation within the ice and could drive wave amplification in the sea ice zone that could contribute to each breakup event. However, only weak northerly winds ($\sim 5\ \mathrm{m\,s^{-1}}$) were present in all three events, suggesting that the waves responsible for the breakup events were not locally generated.

4. Floe breakup model

Validation of ice floe breakup models is restricted by a limited amount of quantitative data, and as such, there is no consensus on the best practice to model ice floe fracture. Stress and strain are thought to play a key role (Dumont et al., 2011), but as discussed in Williams et al. (2013), the stress component leads to an unrealistic breaking limit that results in waves with long wave lengths breaking floes too easily. Williams et al. (2013) solve this by deriving a critical strain incorporating a critical probability and a breaking strain. They set the breaking strain according to the limit for monochromatic waves and also include a parametrisation for the amount of energy lost during ice breakage.

Here we consider floe breakup due to strain within the floe induced by the peak wave period and significant wave height. If we consider that the strain is related to the ice thickness and wave displacement by

$$S = \frac{h}{2}\frac{\partial^2 \eta}{\partial x^2} \tag{1}$$

where h is the ice thickness, x is the propagating distance and η is the displacement (Kohout and Meylan, 2008) and assume that

$$\eta(x,t) = He^{i(kx-\omega t)}/2 \tag{2}$$

where H is the wave height at a single frequency with wavenumber k and frequency ω, we find that

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$$|S| = \frac{1}{4}k^2hH = \frac{(2\pi)^4hH}{4T^4g^2} \tag{3}$$

where T is the wave period and g is the acceleration due to gravity. Given Eq. (3), if we know the strain failure, the peak wave period and floe thickness, we can approximate the significant wave height at which the floes will break due to strain. Unfortunately, very few measurements describing the strain failure of sea ice exist, but the breaking strain for a beam of sea ice can be expressed as a function of flexural strength by following the one-dimensional Hookes's law (Williams et al., 2013),

$$S_b = \frac{\sigma}{Y},$$

where S_b is the breaking strain, σ is the flexural strength and Y is the effective Young's modulus (MPa). Following Marchenko et al. (2014) and Karulina et al. (2013), the flexural strength can be approximated by

$$\sigma \approx 0.53\ e^{-3.34\sqrt{\nu_b}},$$

where ν_b is the liquid brine content. Therefore, using Williams et al. (2013)'s estimate for the effective Young's modulus, $Y \approx 10000(1 - 3.51\nu_b) - 1000$, and given a liquid brine content of 0.1, we can approximate the breaking strain as 3.36×10^{-5} (no units for strain). Note, this is only marginally larger than Kohout and Meylan (2008)'s approximation of 3×10^{-5} to quantify an infinite resistance to floe failure. Using a breaking strain of 3.36×10^{-5} and given, $H \approx H_s/\sqrt{2}$, Eq. (3) can be rearranged to approximate the significant wave height required to break ice floes (assuming a thickness of 0.75 m thick) for a given wave period (Fig. 5).

Using the empirical approximation for the decay of the significant wave height (H_s) as a function of distance (x) found by Kohout et al. (2014),

$$\frac{dH_s}{dx} = \begin{cases} -5.35 \times 10^{-6}H_s & H_s \le 3 \\ -16.05 \times 10^{-6} & H_s \ge 3 \end{cases} \tag{4}$$

and given a wave height at the ice edge, we can approximate the wave height as a function of distance (Figs. 6–8). We assume

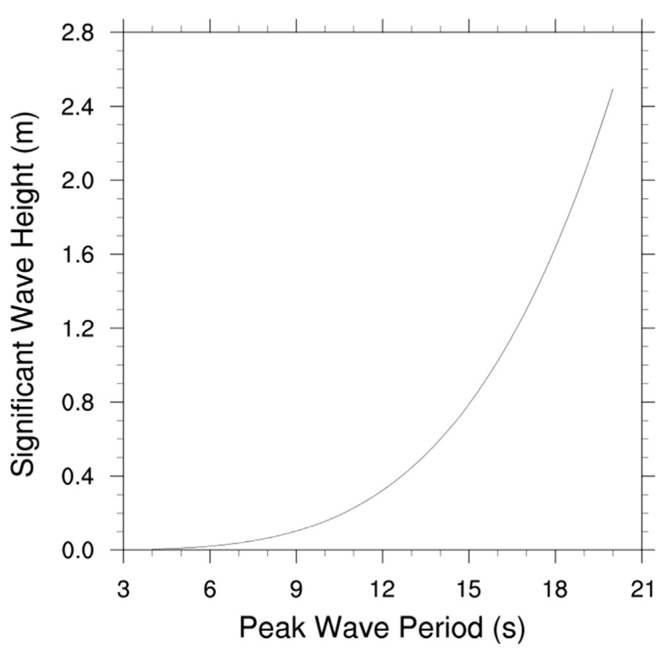

Fig. 5. An approximation of the significant wave height required to break 0.75 m thick ice floes for a given peak wave period and a breaking strain of 3.36×10^{-5}.

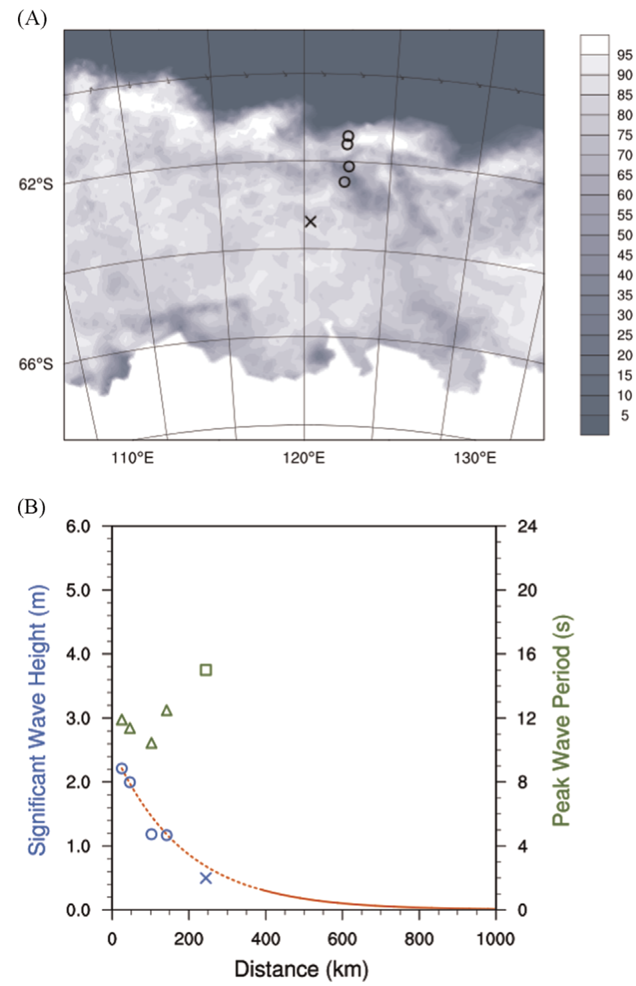

Fig. 6. Floe breakup event at 08:00 on 25 September 2012 (UTC). (a) The position of the buoys (circles) and the position of the *Aurora Australis* (cross). The sea ice concentration is represented by 100% concentration (white) and open water (blue) (Kaleschke et al., 2001; Spreen et al., 2008). (b) The significant wave heights (blue circles) and the peak wave periods (green triangles) of each sensor during this event. The approximated wave height and peak wave period at the location of the *Aurora Australis* is given by the blue cross and green square, respectively. The line shows the significant waves heights as predicted by the Kohout empirical model (Kohout et al., 2014). Using the breakup strain model, the line is divided into two sections: the distance from the ice edge where floes are likely to break (dotted), and where floes are unlikely to break (solid). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the observed wave heights at the WIIOS buoys closest to the ice edge are representative of the heights at the ice edge of the waves observed at the three breakup locations. Figs. 6–8 show there is a reasonable fit to the buoy data. It, however, gives higher wave heights at the ship location than those estimated from the ship (Table 2). Note that Eq. (4) is only applicable to the MIZ, since it was formed empirically from sensors within the MIZ. Attenuation in continuous ice, i.e. at the location of the ship during events 2 and 3, would be more rapid and thus could explain the difference between predicted and observed wave heights. Using Eqs. (3) and (4), we can also approximate the distance into the ice edge where the wave height is likely to break floes ($|S| > 3.36 \times 10^{-5}$). This is shown in Figs. 6–8 by the dashed curve, while the solid curves represents where we predict there would be insufficient energy to break the floes. During the first event (Fig. 6), the breakup event occurred within the region where floes are predicted to break. During the second event (Fig. 7) theory over-predicts the wave height and underestimates how far the waves can break ice floes. For the third event (Fig. 8), the model

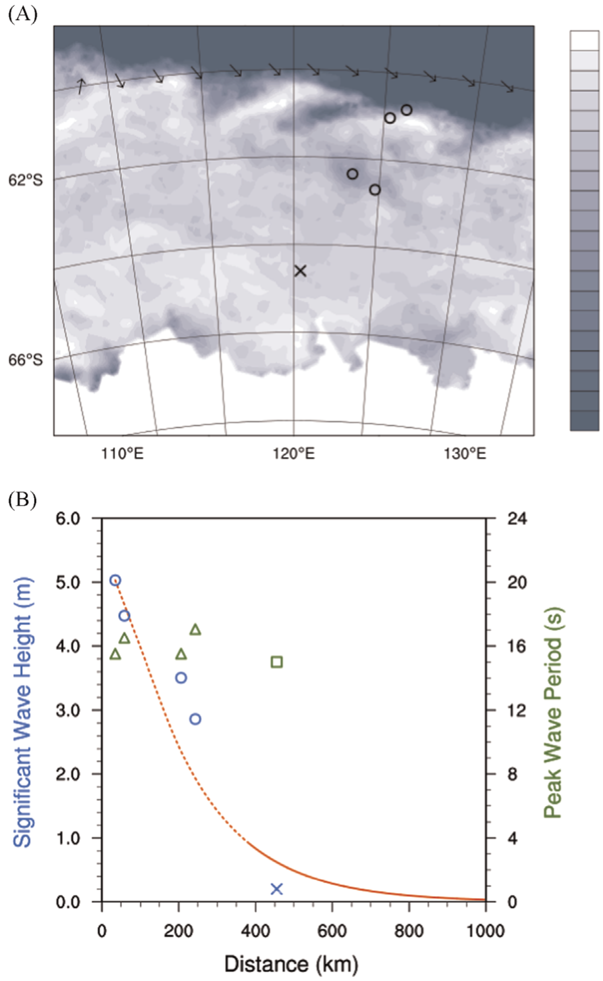

Fig. 7. Floe breakup event at 14:00 on 01 October 2012 (UTC). (a) The position of the buoys (circles) and the position of the *Aurora Australis* (cross). The sea ice concentration is represented by 100% concentration (white) and open water (blue) (Kaleschke et al., 2001; Spreen et al., 2008). (b) The significant wave heights (blue circles) and the peak wave periods (green triangles) of each sensor during this event. The approximated wave height and peak wave period at the location of the *Aurora Australis* is given by the blue cross and green square, respectively. The line shows the significant waves heights as predicted by the Kohout empirical model (Kohout et al., 2014). Using the breakup strain model, the line is divided into two sections: the distance from the ice edge where floes are likely to break (dotted), and where floes are unlikely to break (solid). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

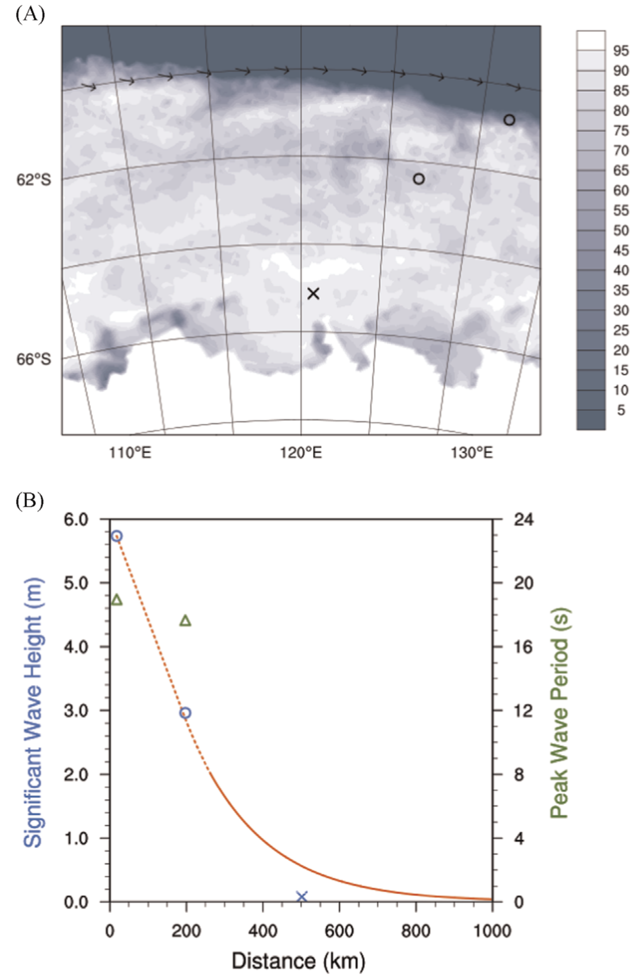

Fig. 8. Floe breakup event at 23:00 on 08 October 2012 (UTC). a) The position of the buoys (circles) and the position of the *Aurora Australis* (cross). The sea ice concentration is represented by 100% concentration (white) and open water (blue) (Kaleschke et al., 2001; Spreen et al., 2008). (b) The significant wave heights (blue circles) and the peak wave periods (green triangles) of each sensor during this event. The approximated wave height at the location of the *Aurora Australis* is given by the blue cross. The line shows the significant waves heights as predicted by the Kohout empirical model (Kohout et al., 2014). Using the breakup strain model, the line is divided into two sections: the distance from the ice edge where floes are likely to break (dotted), and where floes are unlikely to break (solid). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

significantly underpredicts the breaking zone length (by almost 300 km) and again overpredicts the wave height. A comparison of the model skill during each event shows that for longer peak wave periods, the strain model underestimates the extent of floe breakup, a consequence of the dominance of T^{-4} in $|S|$ (Eq. 3). A more detailed data set showing the full extent of floe breakup is required to determine the skill of the strain model for shorter periods.

Using Eqs. (3) and (4), we also predict the strain induced by the event reported in Prinsenberg and Peterson (2011). To induce a strain of 27×10^{-5} at the breakup point 150 km from the ice edge would require a wave height of 1.8 m at the ice edge, a height that is not unreasonable in the present day Arctic. Using a similar approach to predict the strain induced during the Weddell Sea winter cruise event (Liu and Mollo-Christensen 1988) of 195×10^{-5} at 560 km from the ice edge and the observed 1 m significant wave height (rather than 1 m amplitude) would require a 20 m wave at the ice edge. This seems unlikely, but is consistent in that the empirical model overestimates significant wave height to get an appropriate amount of strain.

The comparison of the SIPEX-2 floe breakup observations to the breakup theory presented here suggests that a simple model defining breakup in terms of strain is insufficient. Mellor (1986) considers that there is a minimum length of sea ice which can bend and then break the ice floe, indicating the importance of floe size and wavelength. Another likely important factor to consider is fatigue in sea ice (Langhorne et al., 1998).

5. Summary

The results presented here provide unique measurements of waves-in-ice during observed floe breakup events. We show that three ice floe breakup events coincide with three wave events. Although the wave height at the ice edge was only just over 2 m during the first event, the *Aurora Australis* was relatively close to the ice edge. The ice station was chosen during a temporary minimum in wave height. The waves gradually grew over the next few hours, eventually growing to a height large enough to induce floe breakup. The second floe breakup event occurred just after a large wave event occurred near the ice edge. During this event, waves were observed from the ship (the location of the breakup event) and extensive horizontal cracks perpendicular to the wave direction were seen (Fig. 4), providing convincing evidence that the floe breakup event was wave induced. The cause of the third breakup event is more ambiguous as although a large wave event occurred near the ice edge during the breakup event, no waves were evident from the ship (the location of floe breakup).

Of further interest is the similarly sized broken floe lengths in Fig. 4. This motivates further investigation into the relationship between floe size distribution and wave propagation through sea ice.

We compare a floe breakup model, incorporating an empirical wave attenuation model, with the floe breakup observations, and show that the model underestimates the extent of the breakup during long period events. The consequence of this is that long wave period events are breaking ice floes further into sea ice than the theory predicts. Due to the singular location of observed floe breakup events, we cannot identify whether the model overestimates the extent of the breakup during the first event. An enhanced model that includes physical processes such as fatigue, along with further experiments, is required to improve our understanding and then our modeling capability in this field. We suggest a wave experiment combined with high definition aerial imagery over the marginal ice zone before and after the breakup events would provide ideal data for providing deeper understanding of the floe breakup process and improved validation of floe breakup models.

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