Review of "Aerial observations of sea ice break-up by ship waves" by Dumas-Lefebvre & Dumont (2021)

Comment

This paper is quite a good one and is one of the first to capture a break-up event in the field that is solely caused by waves. I'd recommend minor revisions. I have some specific comments below. Regards, Timothy Williams

Answer

Thank you for your consideration of our manuscript. We are pleased that someone who has a lot of experience in the specific field of wave-induced sea ice breakup reviews our article. Your comments helped us clarify a certain aspects of the paper, and brought our understanding of the problem further. Please see below for the answers to your specific comments.

Specific comments

Comment

p2 "Floe size is also important for constraining wave propagation and attenuation..." I would make it clearer the differences between parametrisations depending on FSD and physics which is still largely unknown.

Answer

Right. We modified the sentence to "Floe size is also important for constraining some parameterisations of wave propagation and attenuation, although it is still unclear whether and how is it significant in reality."

Comment

P3 "By assuming that ice breaks up where the deformation is maximal, Roach et al. (2018) obtained that the fracture of sea ice by waves leads to a preferential size. This means that wave-induced break-up leads to a bell-shaped FSD, a result that indicates that the morphology of floes resulting from breakup might not be well represented by a power law". The bell shape in this case probably corresponds to peaks in the wavelength spectrum since there are no hydrodynamics in their model (they create a surface profile from the open water spectrum)

Answer

I understand your point but we wanted to highlight the fact that by considering the breakup idealization of (Dumont et al., 2011), i.e. sea ice conforms to wave profile and break at strain extrema, they obtain a FSD which is different than a power law truncated at $\lambda/2$.

Comment

p3. Mokus & Montiel (2021) could be worth discussing – they produced log-normal FSD from hydrodynamical simulations.

We have added the following text between lines 76 and 77 of the manuscript: "More recently, Mokus & Montiel (2021) created a 2-D hydrodynamic model for wave-induced sea ice breakup which combines linear wave theory and viscoelastic sea ice rheology in order to compute the scattering of wave by sea ice floes. Using an empirical strain threshold to define the floe size resulting from breakup, they obtained that the FSD follows a lognormal distribution under realistic wave forcings thus demonstrating that a preferential size is indeed generated by the process. They also show that the median floe size evolves with both wave period and ice thickness, result that partly contrasts with the findings of Fox & Squire (1991) and Herman (2017) in which the FSD is independent of the sea state."

Answer

p4. "Indeed it is possible to study wave-ice interactions in laboratories as Herman et al. (2018) did, but it is not clear if the results directly apply to the natural environment due to the difference of scale and properties between laboratory-grown ice and sea ice." It should be clarified that the current experiment is not completely full-scale as the waves from the ship were very short compared to "natural" waves.

Comment

The text will be modified to better reflect the fact that ship generated waves are indeed different from wind-generated waves. "Indeed it is possible to study wave-ice interactions in the laboratory, as Herman et al. (2018) did, but it is not clear if the results directly apply to the natural environment owing mostly to the complex life history of naturally-grown sea ice compared to the more homogeneous growth conditions of the laboratory. Even though ship-generated waves are different from wind-generated waves, their period and amplitude are nonetheless representative of natural waves generated in short fetch seas that impacting ice conditions."

Answer

figs 8-10: captions don't say which expt is which

Comment

Corrected

Answer

p13: the area-weighted PDF does indeed seem more representative and also has a convenient correspondance to FSD formulations in models like in Roach et al (2018)

Comment

Glad to hear your approval about the method we propose.

Answer

p15: it was useful to have this information about the origin of x* here. There was a mixture of beam and thin plate here though – moment of inertia for a beam is width$*h^3/12$ and no Poisson's ratio; for a plate EI is swapped for the flexural rigidity $Eh^3/(12(1-\nu^2))$.

Comment

Thank you for pointing out this inconsistency. We found important to present again the derivation of Mellor (1983) and Hetenyi (1946) in order to explicitly clarify and error pointed out and corrected by Boutin et al. (2018). As Boutin et al. (2018), we want to use the flexural rigidity of a plate, instead of a beam. We changed the presentation of the derivation and made it clear when we stop considering a beam and consider a plate instead. Here is the proposed text:
"This implies that the location of the maximum bending moment, and therefore of maximal deformation, is $x^* = \frac{\pi}{4}\left(\frac{4EI}{k_f}\right)^{1/4}$ where $k_f = \rho_w g$. Even though it is derived for a beam, the same logic applies to a plate, which is a better representation of an ice floe. For a plate, $EI = \frac{Yh^3}{12(1-\nu^2)}$, with Y the Young's modulus for sea ice, h the plate thickness, $\nu = 0.3$ the Poisson ratio, $\rho_w \simeq 1025$ kg m^{-3} the sea water density and g the gravitational acceleration."

Answer

P16. Good point about the half-wavelength and x* lengths corresponding to maxima in deformation. Here could be a good point to mention Asplin (2012), who noticed breaking into strips of half-wavelength in a place far from the ice edge. As in the Mellor quote, it seems like the presence of the ice edge is quite important, that the break-up occurs so fast (after very few cycles) that the fracture always seems to occur at the closest maxima to the edge which you and Herman et al (2018) found to be correlated to the x* length. Another paper which could be relevant is Williams and Squire (2014) who looked at results from a hydrodynamic model to see that maxima in long floes were separated by half a wavelength (more like the Asplin case), but they didn't look at the distance from the ice edge to the first maximum.

Comment

This is a very good remark. In our opinion, the event that [Asplin et al., 2012] describe does not provide sufficiently detailed information about the floe size (only a few visual observations are mentioned), and wavelength (they use the deep open water dispersion relation) that would allow a solid relationship to be found between the two. Moreover, they infer that the FSD follows a power law instead of measuring it. However, you are right about how we should interpret $x^\star$ and $\lambda/2$ and we will modify our discussion accordingly, adopting the following general line of thought. If an observed FSD is bounded by $x^\star$, this would highlight that the fracture is tied to the ice edge, while if it's bounded by $\lambda/2$, it would mean that waves have had the chance to propagate further into the ice sheet before breaking it up, in other words that break-up happened more slowly with respect to the waves. What our results seem to suggest is that break-up occurred as soon as the strain reached the critical value, at a location that is a certain distance from the ice edge where the strain is zero.

Answer

P17. Not totally convinced of the importance of fatigue since it sounds like the break-up front is advancing very fast. Maybe it is important at the end of the MIZ – perhaps there is more spread in floe size there?

Comment

You are right. What we wanted to discuss here is that the location where the ice breaks is smaller than x^*, which might not be related to fatigue but instead to the fact that the maximum strain is larger than the critical strain. Fatigue, as you say, will play a role if an unbroken ice plate has been deformed by the passing of many waves. There is evidence of this in our observations. The discussion will be modified accordingly.

Answer

P18-19: "which is close to $\frac{1}{2}$, the ratio ... in deep water" should maybe change to "for deep water without any ice cover" The thing to look at would be the change in wavelength going from open water to choose the dispersion relation and then calculate the group velocity, rather than assuming the break-up front advances at the group velocity. The work of Sakai & Hanai (2002) would be relevant too, who showed a transition from elastic plate to mass loading behaviour as floe length decreased (with artificial floes in a laboratory) so fragmented ice behaving in a mass loading way is consistent with this. It would be an interesting result though if c_b and c_g were about the same, and would make some sense as well.

Comment

This will be corrected. However, here we do not assume that the break-up front advances at the group speed. We measure the speed of the break-up front, named c_b, and then compare this value with the wave group speed c_g, which is estimated the observed in-ice wavelength and period, before the ice breaks into smaller floes. We were not able to reliably measure the period and wavelength in fragmented sea ice. c_g is then compared to the theoretical values assuming mass loading and flexural dispersion relation, from which we conclude that the former applies better to our problem. This will be clarified in the manuscript.

Answer

Eqn (16): maybe a transmission coefficient should be multiplied by a_0 to get the amplitude in the ice? This would be smaller for thicker ice, making the 2nd attenuation coefficient even smaller compared to the 1st. The difference is indeed marked between the 2 cases. Another counterintuitive thing is that the thin ice is broken into smaller floes which would scatter less and would be expected to have lower attenuation than the longer floes. Other FSD-dependent parameterisations like creep also attenuate waves less when the floe size is lower. Perhaps there is more friction between floes or something like that (bigger perimeter), but like you say that is a bit out-of-scope.

Comment

We are delighted by the discussion triggered by the counterintuitiveness of our results. We adopted a point of view where we do not assume any underlying attenuation mechanism. Assuming a transmission coefficient would mean that scattering happens, which is probably the case. However, we want to let the door fully opened as to whether other mechanisms (known or unknown) are at play, only to conclude that, like Boutin et al. (2018) says, there are multiple possible attenuation mechanisms and they still need to be further investigated.

Answer

Comment

p22: "The modal shape of the FSDs informs us that sea ice breaks up systematically at strains lower than the extrema such that material fatigue is of important when considering breakup (Langhorne et al., 1998)". I don't follow this argument – it shows that there is a preferential length scale doesn't it? The spread around the mode could come from many sources (as you say in the next sentence a bit) – ice heterogeneity (as you mention), an irregular ice edge, waves from a spread of angles. Ship waves are curved also – this could maybe have an effect over a longer distance into the ice.

Answer

The modal shape of the FSD indeed tells us that there is a preferential size, so would have done a linearly increasing distribution bounded by x^*. In the the latter case, where the floe size would have primarily been of x^* with decreasing probability towards small floes, x^* would have been the preferential size and thus the ice would have mainly broke where strain is maximal. On the contrary, observing a preferential size at a value lower than x^* indicates that the ice breaks at a critical strain that is lower than the maximal strain.

Typos

Comment Fig 4 caption: maltab → matlab

Answer Corrected

References

[Asplin et al., 2012] Asplin, M. G., Galley, R., Barber, D. G., and Prinsenberg, S. (2012). Fracture of summer perennial sea ice by ocean swell as a result of Arctic storms. *Journal of Geophysical Research: Oceans*, 117(C6).