Toward a method for downscaling sea ice pressure

The paper documents the development of an idealised sub-climate model grid cell (5kmx5km) modelling study of the sea ice internal pressures found at the tips of leads. A viscous plastic model is used to find the immediate internal stress states across the model for given internal stress states at the model domain boundaries. A single lead is placed within the sea ice of arbitrary size in the form of a rectangle of no ice and the stress states at the tips of the lead are documented. An idealised ship is placed at the end of the simulated lead and the simulated ice pressures on the ship are recorded. Model simulations are documented showing the changing ice stresses for a number of cases. First the model is tested for the case of no-ship, with the expected deformation rates related to an analytical case. Cases with leads of various sizes and for various model resolutions are also tested.

Additional ice features are also added to the domain, showing that the shape of the largest lead is the controlling factor for the highest ice pressures in the model. A ship is then positioned at the end of the largest lead and the stresses upon the ship are documented. Multiple experiments are performed varying the lead length (and also introducing a refrozen sea surface to the lead), ice strength parameter and the compressive and shear strengths of the ship itself. The authors conclude that the defects within a sub climate model grid cell are the greatest controller of sea ice pressure. They lead this conclusion to suggest that the pressure stress on a beset ship at the end of a lead of its own making will reduce as the lead surface consolidates. I can see how the results in this paper will help inform the navigation of ice covered seas.

The paper is in general very well written and the introduction and description are easy to follow. I suggest that is published with some additional explanations. Also the title of the paper show be changed to reflect the specific situation that is being simulated.

Improvements can be made to text in the form of overall motivation of the study. Explicitly saying in the introduction and methods and results that aim of the paper is to focus on the increased ice pressure at the tip of a lead where a ship is likely to be present would be a beneficial addition to the paper. Also the paper needs to clearly state that this study models a single instantaneous stress field for a particular setup. This limitation also needs to be addressed in the conclusions when the case of lead closure is discussed. Whilst the authors mention that waiting for a lead to consolidate will reduce the stress on the ship, how likely is it that the lead will close mechanically before then? Also the authors state that care has been made to avoid all deformation within the model gird, what limitations does this put on the study? The authors mention that there is vast literature on ships navigating ice, does any of this describe the situation being simulated? In particular it would be helpful to discuss whether the modelled setup of a lead created by a ship within ice under uniform pressure, results in the lead remaining open and thus increased lead tip pressure existing as modelled here, is a likely and realistic scenario. I am not convinced that ice under uniform external pressure, when passed through by a ship will not result in lead closure, thus allowing the modelled setup to be encountered.

I find the results and numerical stability sections confusingly arranged. Further sub sectioning to break apart the various studies in the results will help. Collecting together all the cases where the model resolution was varied would be beneficial. After I had worked out what experiments had been performed and how they related to each I found them clear and well documented.

Title

I find that the title is not an accurate description of the paper content. The paper is focusing particularly on recreating the internal ice stresses at lead tips during constant ice compression for the case of ice stresses being low enough to not cause the closing of the lead. The paper content doesn't give a general method of downscaling as all the model setup is directly for the model case presented. The paper title should reflect this.

Abstract -

L6 Can you explain what form of numerical experiments you perform in this study within the abstract? A little extra depth on the nature of the methods used will be helpful here.

L10 The information within the parenthesis doesn't correspond well to the rest of the sentence. Do you mean that your study reveals that that the lead length is particularly important?

L13 I will be helpful here to clearly indicate that ice pressure is a horizontal 2d force.

L15 can you define 'ship besetting'

L16 predict the pressure field from what? using a force balance of applied wind, ocean stresses and sea ice drift.

L50 It might be helpful to include a brief introduction of previous square box ice modelling studies. VP simulations

https://www.researchgate.net/journal/1994-0440_The_Cryosphere_Discussions

More VP
Hutchings, J.K. et al. 2005. Modeling Linear Kinematic Features in Sea Ice. *Monthly Weather Review*. 133, 12 (Dec. 2005), 3481–3497. DOI:https://doi.org/10.1175/MWR3045.1.[1]

Using CICE
Heorton, H.D.B.S. et al. 2018. Stress and deformation characteristics of sea ice in a high-resolution, anisotropic sea ice model. *Phil. Trans. R. Soc. A*. 376, 2129 (Sep. 2018), 20170349. DOI:https://doi.org/10.1098/rsta.2017.0349.

[3]

Discrete element modelling
Wilchinsky, A.V. et al. 2010. Effect of shear rupture on aggregate scale formation in sea ice. *Journal of Geophysical Research*. 115, C10 (Oct. 2010). DOI:https://doi.org/10.1029/2009JC006043.

L114 equation 9. All previous equations are well described, Can you explain the physical reasoning for the replacement closure as well?

L149 An overview explanation here will make the following equations much easier to follow. From what I can tell you impose the total normal and shear stresses. The equations that follow enable you to give the components of the gradient of the internal stress tensor. Is this correct?

L159 does this mean that v(1m) will be solved for in the model? Can you list the components that need to be imposed for this side of the grid structure and those which will be left free?

L165 what happens to this simulation when the normal stress on the east and west side are not equal? I assume that there will be a large E-W ice drift which i understand is best avoided for your study. This information will be very helpful for those who wish to recreate your model setup.

L168 This information doesn't require its own section, though including it is very useful. Perhaps put it with the coarse grain results, or in the previous or following section. Actually if all the methods are placed in a 'methods' section and subsections are used the paper format will be easier to navigate.

L175 so you have two masks - one defines the ship internal, one defines the ship contour. On which contour iare the ice force balance equations solved? This section defines the technical boundary conditions of the mask, but a descriptive overview of what is done where on which mask will aid the readability of the technical description.

L181 does the ship ice strength imply that this ship is deformable? Was this done for realism or to allow the model to run effectively?

L183 Is the ships resistance to shear representing the shear strength at the ice/ship hull interface (so a form of friction between ice and steel) or the resistance the ship itself has to shearing? I guess the former as it seems as if the ship itself can not deform as it is fixed to the grid.

L189 ah you've mentioned the ice sliding around the ship. Do you apply different shear condition for each mask?

Section 7

Can you include some basic information about the model setup either here or back in section 3? What model simulations are you seeking? It seems that you are looking for static solutions, invariant in time, or a snap shot of ice stress, is this the case? What are you hoping to show us with these validations? You are comparing to idealised numbers of ice pressure. Do these validations show that the numerical model generates the correct pressures for a static field? For the lead cases presented here i was expecting to see the closing of the lead, though this makes little sense if the simulations just show the immediate pressure field of ice with a lead present.

From reading ahead to the results it appear you are particularly interested in the increased stresses in the ice at the end of a lead, which a location where a ship is likely to be present. Informing the reader of this before the validation section will show why you are checking the pressure states to show that these regions are correctly simulated.

L207 how is it obtained from the model?

L222 what conclusions will you be seeking in the results section? The validations show that your model is good for the stress states you hope to test, but to fully show this you need to state what these stress states are and why the model and its setup work for them.

L350 my understanding is that the model gives the solution of a single ‘snap-shot’ of ice stress. The acceleration argument then surely does not matter?

Comments on paper tc-2020-134

The work is correctly done, but it may be a little overly enthusiastic in applying the conclusions of the analysis to ship operations in ice. The problem analysed in the paper is one in engineering; the stress field around a void and/or inclusion in a large plate under stress. A ship moving through an ice field under pressure is a much more complex problem.

The work merits publication but the conclusion that the ship creates a stress concentration by breaking a channel might be couched in a more conditional manner. Experience generally shows that if the channel does not close, the ship is experiencing little or no pressure. The rate of channel closing and closing distance is proportional to the ice pressure that the ship feels. A longer open channel behind the ship is an indication of lower ice pressure, not higher.

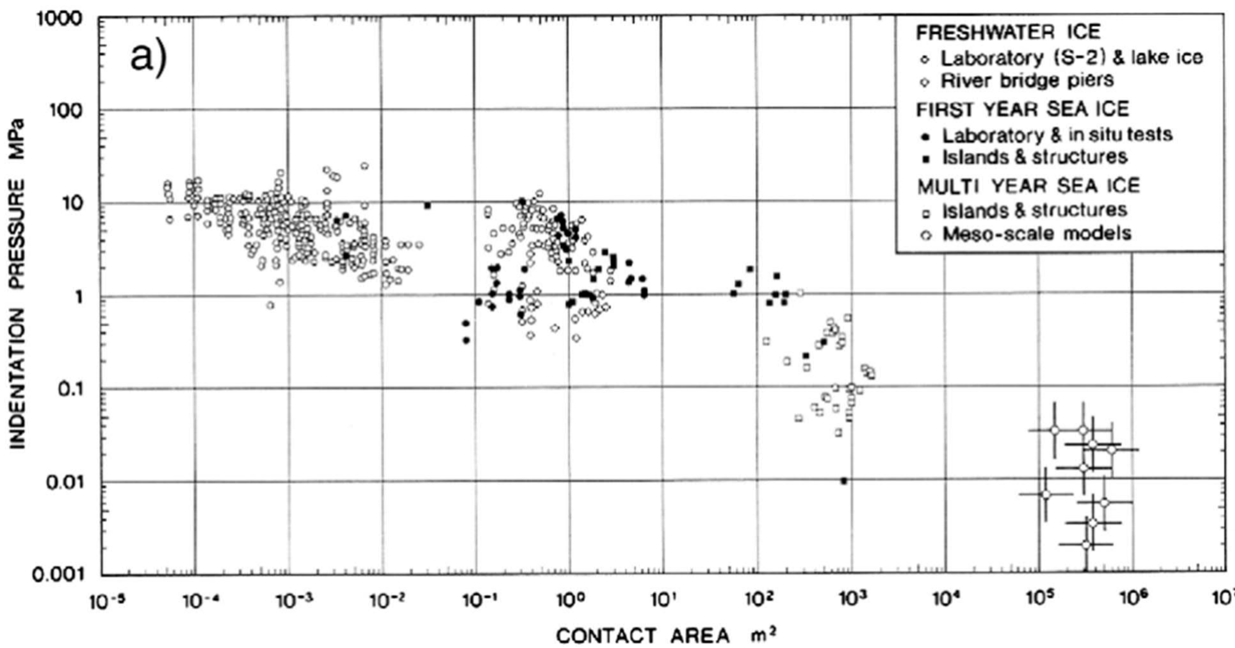
Some specific corrections, improvements or comments:

- Larger font on some of the plots in figures would help readability.
- For Fig. 1 add the surface wind scale to panel b).
- Line 51; the author should be Loset?
- Line 175; would it complicate Fig. 2 to also show M_i and M_c on it?
- Line 211; Figure 4 a) and b) look very similar to results of finite element analysis of an elastic plate with a crack or void.
- Line 113; stress concentration at the tips of the lead and zero normal pressure on the boundary of the lead translate to the maximum and minimum pressures in Figure 4 c). I looks like the probability is greater than 1 for pressure 10 kN/m, check the y-axis scale. For the 10 m grid size the 28 cells that border on the lead versus the $512^2 - 40$ cells in the ice field give a 28/262104 (1.07E-04) probability of zero pressure. This doesn't seem to agree with Fig. 4 c).
- Figure 5 presents results of experiments with refrozen lead and ridged ice in addition to the 1 km lead. Not surprising is the result that there is no change of zero stress on the lead boundary or stress concentration at the tips of the lead. It seems that doubling the ice thickness from 1 to 2 m, Figure 4 versus Figure 5, the maximum stress at the tip of the leads is increased. Any explanation? Is it fair to compare maximum pressure in Fig. 6 b) with $P^* = 20$ kN/m^2 for a 1 km long lead with Figure 5. Both are for 2 m ice thickness.
- For Figure 8 add a label to the x-axes, resolution and units of m. The maximum pressure of Figure 8 a) agrees with that in Figure 5 c), about 38 kN/m in both cases.
- The pressure field in Figure 9 seems reasonable given that a relatively stiff object (the ship) is placed at one end of a long cavity (lead). Your analysis only considers pressures, the ice also deforms and the further from the tip of the crack (lead) the greater the closing of the lead and thus higher lateral pressure.

The results presented in Figures 9 and 10 are quite consistent with the analysis model of a stiff object (ship) at the end of an elongated cavity (lead) in a more compliant medium (ice field). The results are consistent with stress analysis around inclusions. The analysis is correct, but it may be premature to draw conclusions about applying the results to operation of a ship in pressured ice.

There is literature in the Arctic engineering field that considers scale effect of ice pressures. The authors could look to this literature as they continue working in this field. See for example;

Sanderson, T.J.O., 1988. Ice Mechanics Risks to Offshore Structures. Graham and Trotman, London, UK.



Croasdale, K.R., 2009. Limit force ice loads – an update. Proceedings 20th POAC Conference, Paper POAC09-030, Lulea, Sweden.

The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-134-RC1, 2020

Interactive comment on "Toward a method for downscaling sea ice pressure" *by* Jean-Francois Lemieux et al.

Anonymous Referee #1

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I think this paper is well-written, presents important new results on the downscaling of pack ice pressure in models for application to ships in ice, and should be accepted with only the following minor revision.

On Figures 4 and 5, panel (c): can the authors please specify what type of distribution was fitted to the data, provide the distribution parameters, and the 95% confidence intervals of the distribution parameters?

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-134, 2020.