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Interactive comment on "Modeling Sea Ice fracture at very high resolution with VP rheologies" *by* Damien Ringeisen et al.

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Modelling Sea Ice fracture at very high resolution with VP rheologies

This paper documents idealised very high resolution (25 m) numerical simulations of deformation in sea ice using the viscous plastic VP rheology. The sea ice is predominantly put under uniaxial compression from the top and bottom boundaries and the resulting deformation features are documented. Simulations are performed with longer model run times, decreased spatial resolution, modified boundary conditions, biaxial compression, imposed flaws within the sea ice and alternate rheologies by changing the yield curve shape. The results are well documented, though further detail is required on the model setup. Particular emphasis is put on the resulting deformation or

linear kinematic feature intersection angle, as a means to provide a link between simulated and observed deformation features, and thus provides insight into how to select an appropriate sea ice rheology for simulation within climate models or for future studies. This method presents an exciting way to link observations and simulations of sea ice deformation, but there are certain aspects of the study that, in my opinion, need addressing.

Firstly is selection of model resolution, and consideration of whether to simulate a single floe or a continuum of many floes. The selected 25 m resolution makes this a simulation of a single floe, and the paper describes the study as such, but there is little discussion of whether the selected VP rheology is a valid representation of a single floe. The VP rheology was developed to simulate a continuum of floes over ocean length scales, and it is not immediately obvious to me, that the VP rheology is a valid representation of the deformation of a single floe just by reducing the model resolution to that of single floe, and setting the ice concentration to unity as performed in this study. I am unaware of previous simulations of solid body deformation from other fields, and it may be the case that VP like rheologies are well studied, but this needs to be discussed in this paper. On the other hand this paper may be be a proof of concept that the VP rheology can be used to simulate the deformation of a single floe, and if it is, then it needs to be worded as such.

A further implication of simulating a single floe, rather than a continuum floes, is the observations that the paper discusses when validating the results. The RADARSAT and RGPS data is given as a means to validate the yield curve selected. But the RGPS data is given on continuum length scales, so to validate a selected yield curve the comparison will need to be made with simulations over continuum length scales, not on the floe length scales presented in this paper. To validate the simulations of this paper observations of individual floe shape, aspect ratio and floe-to-floe crack intersection angle from aerial images of floes will be best suited.

Secondly the presented results are often from the order of 1-10 seconds into the simulations. This is in contrast to idealised deformation experiments of Hutchings et al. (2004) and Heorton et al. (2018) where the results are given at 1 - 24 hours of simulation, and explored over multiple days. Within these studies the initial conditions and early stress/deformation states are explored and documented. Also in both of these cases, the initial state of the ice over was seeded with noise (in strength, or thickness and forcing) to allow for features to develop and stop an unrealistic uniform sea ice cover. Were such considerations performed in this study? Are the initial conditions uniform? What are the implications of using results from 1-10 seconds of model run? I would like to see documentation of the time series of stress/strain state in order to validate the idealised experiments and the initial conditions. I personally found the longer documented run of 45 minutes interesting, with individual floe-like shapes appearing that can be compared to images of floes.

Also there is little discussion of the implications and 'robustness' of the presented model results. The authors described the results as 'robust' on multiple occasions but make little effort to inform the reader why they are robust. Figure 5 is presented as a domain/resolution study but only mentioned once in passing as an indication of the models robustness. I'm assuming that the model domain/resolution/run time has been investigated but there is no documentation or discussion of the models limitations. A section describing this is required in order to allow the other results to be published.

Thirdly it is not obvious how the deformation or linear kinematic feature intersection angle were calculated. I would like to see this information given in an appendix, such a method is a very useful contribution to studies of sea-ice rheology and one that I would like to use in the future. A citation to another study where this method was performed and is described is another option. The given appendix showing the theory behind internal friction and Mohr-Coloumb failure criterion, whilst interesting to see, does not appear to be original theory for this paper and is not required and the dependencies can be stated and cited.

Particular comments: Page 1 Line 6-8 What are the dependencies of typical granular

materials? The sand castle analogy is not useful. Line 8, what model? this paper or previous? Line 10-14 More description of 'typical granular materials' that are not accurately described and all comparisons are difficult to follow. I would avoid these loose comparisons in the abstract and stick to definite results. Line 24 are the two citations model studies or observations of sea ice floes? Observational studies are required for this sentence.

Page 2 Line 5 Leads plural, dangerous to use the word memory when describing a computer model, 'emergent anisotorpy' is more accurate. Line 8 The equations are difficult to solve due to their non-linearity and complexity not because of sea ice. It is however difficult to represent sea ice with simple, easily solvable equations due to it's non-continuous features. 24 argues - argued 28 rheologies plural 32 check citations and parenthesis 33 check citations and parenthesis 34-35 'Based on these satellite observations, amongst others (provide some examples), and in-situ. . .'

Page 3 line 6 space before 'Girard' line 13 delete parenthesis line 15 'are appear as line of' - 'appear as lines of', deformation singular, 'with the deformation' - 'with shear deformation', divergence - convergence Line 18 leads - leading line 19-20 check citation parenthesis

Page 4 line 1 Wilchinsky et al. also deduced intersection angles between floes that are relevant to this paper.

Page 5 Figure 1. What is 'Mohr-Coloumb flat' In general I found the figure captions to be lacking in content. Can they all be expanded to directly describe what simulation they are from, and the part of the figure that is of interest? A reference link to where in the paper (section number) it is described and discussed is also required. I found myself flipping back and forward trying to work out what simulation was illustrated in which figure, please include more information to avoid this please. Line 5 to 15. I am assuming that this paragraph describes the physical phenomena that the viscous plastic rheology and associated yield curve are designed to replicate. However this paragraph is worded such that it is an accepted and proved fact that sea-ice is viscous plastic and has behaviour that follows all these rules. Also the paragraph contains no citations. Rewriting this paragraph to emphasise that the viscous plastic rheology is designed to simulate the stress/strain relationship of sea ice over continuum length scales is required. It will also help to address the theoretical implications of using a rheology designed for the continuum approximation of sea-ice to simulate the deformation of a single floe.

Page 6 line 11 check parenthesis line 15 Is this 'theoretical angle' the one used to retrieve the LKF intersection angles from simulation results, and also with previous studies? If so can you state it here. The paper has not informed me how this study, and previous studies obtained the intersection angles widely discussed.

Page 8 line 6 is the model domain used in all experiments? If there are exceptions please list them. line 10 - 11 This statement about the robustness of the results is not backed up. Please refer the reader to the results that back up this statement. The proof of the robustness of this model needs to come first before any other results. Lines 11 - 17 Please state how the model time step works? I am not familiar with how the LSR solver for the VP rheology works. How does the model work in time? I am familiar with models that have a constant time step with solution iterations per time step. The model then continues time stepping for the required simulation period. Does your model work in the same way? Or is there a selected simulation time, and then the documented 1500/1500 iterations performed to cover the simulation time? If so then can you describe why the simulation time was selected as you have done with the spatial resolution. Is the simulation time and temporal resolution/number of iterations the same for all simulations? Results section A paragraph describing which simulations have been performed will be useful here. This will save having to flip back and forward through the paper to match results discussion and figures. The simulation 'robustness' results need to come first in order to validate the following results. line 29 Figure - figure (no capital), 'measured intersection angle' how was this angle measured? line

27, quantify 'right away' and how can a fracture appear but not in the deformation field? what field did it appear in? Can you comment on this time scale compared to observations of floe fracture (Dempsey et al. 2011 Fracture of a ridged multi-year Arctic sea ice floe)

Page 9 line 7 The 'robustness' results need to come first, then the model resolution and time period choice can be validated against them. line 9 extended time period, what was the original time period? line 10 total iterations or iterations per time step? what is the time step?

Page 10 Figure 3 Bottom left pane. Please use a bipolar colour scale for bipolar data. As in a different colour for +/-, white for zero for example. These scales are easily selectable. Line 8 'similarly as' - 'similar to' Section 3.3 If this section addresses the robustness then it needs to go first and also discuss the results in figure 5. Please also comment on the limitations of this model.

Page 11 Figure 5. First change or rescale the colourscale to highlight features. The max deformation appears to be around 10ˆ-4, so limit the colour to this point, Also please label the colour scale legend with units. Why have you selected only 2 seconds of model run. what happens later in the run? Is this on a similar time scale to observations of floe fracture? Consider plotting a later time point if available or discuss how the model proceeds.

Page 12 again bipolar colour scale for bipolar field would be appreciated. All of your plotted fields so far have been for deformation, a plot of a stress field, if available, will be nice to see. There are lots of crack intersections in this plot. Is it possible to obtain all of these intersection angles? A distribution of angles could then be presented.

Page 13 Line 5 Comment on ice strength/thickness vs fracture angle. Is this a result you have observed? Or is it a theory that you are testing? Is there a citation for this theory? Line 17. You start this paragraph with statements about the link between initialised faults and deformation. Is this a theory you are testing? If so give a citation. Is it your interpretation of the results? if so you need to state the results and the reference the figure first.

Page 14 Figure 8 caption is lacking detail. Is this the figure for the lateral confinement experiments, or ice thickness experiments? Please describe what is shown in every pane. Page 15 Figure 9, please label colour scale legends.

Page16 Figure 11, again please described the simulation this figure corresponds to? The colourscales are saturated so consider rescaling.

Page 17 line 18, A lot of LKFs - how many? Or is it more than compared to another simulation? rephrase or quantify. line 21 space before \theta

Page 18. Figure 12, are these Coulombic curve simulations? again this caption needs more detail. line 4 'realistic manner' how are they realistic? what simulations are you comparing to what observations? A figure reference and a citation are both needed for this statement.

Page 19 line 12 please refer to the section or figure or both that show the resolution and scale non-dependance. line 15 'appear' - 'appears' line 26 please give a citation for the statement on granular material.

Page 20 line 22 Citation required for 'Arctic-wide simulation' line 28 why is it unsurprising? Do mean that your results fit with previous theory and results? If so can you say this and cite them? line 33 'The ice open and create leads' - The simulated sea ice opens and creates leads

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