This paper describes the implementation of a non-normal flow rule in the VP sea ice rheology. The equational form of the new rheology is well described and several very useful diagrams are included. The numerical implementation is linked to a theory that links the flow rule and the intersection of failure lines within the medium described. A series of idealised numerical experiments are performed which show that the numerical rheology successfully recreates the fracture intersection angles predicted by the presented theory. The authors follow the experiments with a discussion on the implications of using a non-normal flow rule when designing future sea ice rhelogies. They describe the various challenges when using non-normal flow rules. I find that this paper is well written and a valuable contribution to the modelling of sea ice deformation. It is a very useful introduction to use of non-normal flow rules for sea ice modelling for future work in this area. I recommend this paper for publication after a few questions I have.

First of all can you explain why figure 7a contains both theoretical links between the plastic potential and intersection angle and many numerical experiments that back up the theory but 7b contains relatively few numerical results? I can see several cases where additional results from 7a can be copied to 7b and back up your results. Is it true that the full range of values for 7b are not obtainable due difficulties that the authors discuss in getting the model to converge to a solution for highly non-normal flow? If this is case then please tell us.

Several times in the discussion and results the authors say that the intersection angle depends on the confining pressure despite the varying non-normal flow rule. I can see no evidence of this in their results. The presented experiments show changing intersection angle with changing flow-rule (varying plastic potential and yield curve eccentricity), but I see no results where they change the confining pressure. Is this from previous work? Or an interpretation of the results that they do present?

General editing points:

Can you please start the paper with a description of what a flow rule is. Then what a normal flow rule is, and the crucially what the main difference physically and theoretically is between a normal and non-normal flow rule. I see that a definition is on line 90, and then further physical descriptions of the flow rule are in the results. The introduction make much more sense if these can come first.

Can you describe what is documented in this study that is novel and new?

L 20 they are also, more importantly, observed

L 21 Here you LKF's influence in many ways but what follows is not a list. Consider re-writing

L 22 Please define what a lead is. Consider starting with a definition of LKF's that are typically leads or ridges

L 70 Which is the 'standard rheology'? do you mean the VP rheology. Also can you further describe this result. How did Ringeisen find that the angle can't be lower than 30 degrees?

L71 the following list is hard to read. Consider reformatting. Also what does the $\mu = 0.9$, relate to with the Weiss and Schulson reference.
L71 can you confirm that these angles are all comparable? I have found that studies document both the intersection and also the half angle, being the intersection between the fracture and the principal axis of stress.

L80 this paper require a definition for a normal flow rule. This sentence and the following paragraph make little sense without it.

L82 do you mean that the flow rule can be observed by measuring the ratio of shear a divergence along LKF.

L85 were these laboratory observations performed the same way as those of Stern mentioned above?

L89 it will be nice to have the Anisotropic Plastic (Tsamados 2013, 10.1029/2012JC007990) rheology listed here too

L92. Good to see a flow-rule definition here. How does the plastic potential determine the post-fracture deformation? is this through the direction of the principal stress when the yield criterion is reached?

L 115 is f here the Coriolis acceleration as above? Actually can you tell what value was used for the Coriolis acceleration? If it is non-zero (valid to use zero and non-zero for these experiments) then asymmetry will be expected (see comments later)

L120 It is great to read this description of the VP rheology. A really helpful addition.

L 138 is it possible to have a physical description of the plastic potential here? The physical description of what the yield curve represents is very helpful. A similar description of the plastic potential here will be similarly useful. The flow-rule is difficult concept that is explained well here. An additional physical description will make it even better.

L 180 I see that the dilatancy angle was introduced earlier. However it would benefit the paper to include a physical description of ‘dilatancy of a granular material’ either before or here when it is implemented in the model equations.

L 180 and onwards. This section will benefit from an expanded introduction to the theoretical steps performed. From what I can tell, you use the theory that links dilatancy angle to fracture angle as discussed in the the introduction. You have quantified the dilatancy angle using geometrical description of an arbitrary yield curve and plastic potential. This is expanded through the notation to express the fracture angle as a function of yield curve and plastic potential eccentricity. Is this correct?
If so is the motivation behind the description that it is possible to show how the expected fracture angle is expected to change with changing plastic potential?
Can you be clear what the theory of Roscoe is describing. Is the angle you are obtaining the expected angle of fracture due to minimising some sort of energy potential? Or does it relate to an analytical solution of fracture? The mathematical expansion here is clear to follow, but the reasoning behind why you have shown it is less so.
In figure 4 you describe how the ratio of divergence to shear changes with changing plastic potential. Is this the key effect of the non-normal flow rule? In that by separating the yield curve and plastic potential it is possible to change the ratio of divergent to shear stresses whilst under deformation? But without also change the point of deformation (as in the yield curve) If so please emphasise this point throughout the paper! It makes the non-normal flow rule much clearer for me!

Figure 3 caption - the arrows are described as orange, but appear red to me.

Figure 4. I see red and orange arrows here, and they are correctly described. Can you check figure 3. Do the colours relate between the two figures?

L 222 is the initial ice state entirely uniform? Or did you seed some noise into the initial state?
L 231 did you test at other time and spatial resolutions? Later you comment that fracture angles were shown in a previous study to be independent of model resolution (we found this too). Did you test this for this study too?
L232 is this equation 4 that is solved for?

L233. What are the non-linear and linear problems ? Can you relate these back to the model equations?
L246 So are the simulations only run for 5 seconds of model time? Have you tested how long the model can run for and its overall stability? I read above that you have used excessive computation to ensure the extra complexity of the non-normal flow rule is accounted for. How successful is this approach? Did you find that certain computational setups did not perform well when attempting to solve the equations? Any insight you can share into how to solve these equations will greatly help the sea ice modelling community

L 263 what is average residual norm R? is this a measure of the solution accuracy?

L 282 is the shear strain rate shown anywhere? Are you relating back to figure 6? If so can you say so? Are you saying the relation ship in figure 6 for eF and shear strain rate is also true for the various values of eF in Figure 7? Or is this a theoretical postulation?

L 282 fracture angle or angles plural? Do you you take multiple angles or just one per simulation?

Figure 7 Is it possible to add the red orange and teal umerical simulations to figure 7 b? If you have added the blue dots then the omission of the others makes me wonder how they will fit? I see that you only have multiple values for eG = 4.0. Though there are 2 points for 0.7 and a single point for 2.0 and 1.0. I also see that the full range of eF was not investigated for each eG. What is the reason for this? Is it the limitations of the model? Or did you choose not to in order to keep the simulations physically relevant?

L 305 this line is very informative to what the non-normal flow rule can achieve. Can you put this information into the introduction and abstract please?

L 309 while you have displayed the agreement to Roscoe for the cases of constant eF the case of constant eG (fig 7b) is inconclusive to the reader due to the lack of numerical simulation data points. Is it possible to fill out figure 7b and thus strengthen this statement?

L 313 Can you sort out the parenthesis on the Ringeisen 2019 citation. It currently doesn’t read very well.

L 317 is this lack of convergence the reason for the lack of results on figure 7b?

L 319 Can you give a citation a description of how this result with the changing fracture angle with changing stress confinement was obtained? I assume it is not from this study as you have not altered the confinement ratio for any of your simulations. Or are you referring to that the fracture angles change as the loading increases with time?

L 321 How do think this result relates to to laboratory experiments on sea ice where two clear fracture angles were found about a critical confinement ratio? (Golding et al. 2010 1359-6454/$36.00, Schulson 2001 10.2138/gsrmg.51.1.201)

L 341 Is this result about pure shear and angle of 45deg. from the Ip et al. 1191 citation? How was it obtained?

L345 angle - angles

L 363 Is it possible to include a diagram of the various yield curves discussed in this section? This would greatly ease the understanding of your arguments. I’m sure others have included such a diagram in previous work so you may be able to cite such a diagram.

L369 Can you explain why non symmetrical deformation features are unrealistic or present an incorrect solution? Do they also correspond to poor numerical solutions? With a non-linear system of equations such as in all sea ice rheologies, asymmetry is often expected. This relates back to most laboratory experiments on ice deformation and even the ill-posedness of divergent weakening (Gray 1999 10.1175/1520-0485(1999)029<2920:LOHAIP>2.0.CO;2). Also if you use a non-zero Coriolis acceleration then asymmetry will be expected as the run progresses. What value did you use?

L371 I’m not sure I understand your argument here. Are you saying; poor non-normal flow model convergence won’t be an issue in realistic simulations as the numerical solver can’t solve the VP rheology anyway? Surely this argument says that there isn’t a hope of using non-normal flow VP rheology in realistic simulations?

L396 These issues are not exclusive to high resolution climate modelling. It can be argued they are even more important for current coarse resolution models which are currently used for long climate simulations and typically perform poorly for reproducing ice drift patterns. LKF intersection angles are also observed over basin length scales (Weiss and Schulson 2009) and your discussion in this paper is relevant for modelling sea ice deformation at these length scales.

L406 I am confused by your conclusion here. Where have you shown that the fracture angles depend on the confinement pressure? Where did you change the confinement pressure? Do not Figure 6 and 7 show clear changes in intersection angle with changing plastic potential in accordance with predictions from the theory of Roscoe?

L 409 again I’m not convinced that symmetric solutions are mandatory for a symmetric experiment? Again can you say whether you used a zero or non-zero value for the Coriolis acceleration? If it is non-zero then asymmetry will be expected.