

Initial response to reviewer 1

September 29, 2026

We thank the reviewer for these very useful comments and suggestions. Our responses below are in blue.

This paper presents modifications to the standard ice thickness redistribution formulation to make it compatible with VP rheologies that use a non-normal flow rule. The authors also demonstrate that no modifications to the redistribution formulation are required when tensile strength is introduced. The paper is well written and organised, and the results are presented clearly and concisely. The work is interesting, if somewhat niche.

My only major concern is motivation and context for the results. Since the paper has been submitted for publication in *The Cryosphere*, I would expect a broader discussion of the potential impact these numerical changes may have on our understanding of the physical system. As it stands, the paper is a better fit for, e.g., *GMD*, where I would probably only have asked for minor revisions. However, with some not-very-major revisions, I think the paper would be fit for publication in *The Cryosphere*.

We will provide more context and explain why a non-normal flow rule is a very useful capability (see other comments below) and why consistent ridging and opening coefficients are required.

Introduction: The authors need to expand substantially on why using a non-normal flow rule is of interest. At the moment, only the use of tensile strength is properly motivated. Still, since the default formulation for it is already valid, I would even skip discussing it in the introduction (the paragraph starting at line 40). Also, a brief explanation of what the phrase "non-normal flow" means could be useful in the introduction (even if a more detailed explanation comes later).

There is a lot of interest to better represent linear kinematic features and deformations in general in sea ice models. A conclusion of the sea ice rheology experiment (SIREx) is that VP-EVP models with a smaller ellipse aspect ratio e tend to better simulate pack ice deformations (Bouchat et al. 2022). All the SIREx VP-EVP models used a normal flow rule. However, reducing

e to improve pack ice deformations has the undesirable effects of also impacting pack ice velocity and simulated landfast ice. The addition of the plastic potential of Ringeisen et al. (2021) enhances the capability of VP-EVP models; the parameter e_G for the plastic potential can be used to optimize pack ice deformations while the parameter e_F for the yield curve can be adjusted to better simulate landfast ice and to a lesser extent the drift of the pack ice. The parameters e_F and e_G can therefore be used to optimize different physical processes. We will explain in the introduction what is a non-normal flow rule, that it is a very useful capability and that its implementation is straightforward.

Discussion and concluding remarks: There is no mention here of the impact on simulated volume and ice growth, but this is what a more general (The Cryosphere) audience is interested in. If I understand the paper correctly, your results show that the impact of using a non-normal flow rule is substantially smaller than that reported by Lemieux et al. (2025). Is that correct? This should be highlighted in this section. You should then also discuss the relevance of using a non-normal flow rule for large-scale modelling. If the conclusion is that using a non-normal flow rule has a very limited effect, then that may feel counterproductive, but it's still very important for the community to know. A strong conclusion like that would also make this paper much more interesting than it looks in its current version and significantly improve its impact.

We agree with the reviewer that more information should be provided in the conclusion. We will do so.

Our manuscript indeed shows that the impact of the non-normal flow rule on the sea ice volume is smaller than what was shown in Lemieux et al. (2025). However, as demonstrated here, the conclusions of Lemieux et al. (2025) remain the same. The focus of the Lemieux et al. (2025) paper was on the impact of the non-normal flow rule on simulated linear kinematic features and more generally on deformations. These simulated deformations, determined by the flow rule, are at the GRID-SCALE (~ 4 km in our simulations). Our new manuscript describes how opening and ridging coefficients of the redistribution function should be formulated to represent the SUBGRID-SCALE divergence (opening) and convergence (ridging) events. These subgrid-scale deformations represent the smaller scale deformations inside the ~ 4 km $\times$ 4 km grid cells. The link between grid-scale deformations and subgrid-scale opening and ridging is discussed in Thorndike et al. (1975). Considering pure shear at the grid-scale, Thorndike et al. (1975) argue that subgrid-scale opening and ridging exist and should be represented by the redistribution function. This is well illustrated in their Fig. 10. Fig. 2 in our submitted manuscript show that opening and ridging are simulated for pure shear at the grid-scale ($\theta = 90^\circ$).

We calculated some of the same metrics used by Lemieux et al. (2025) to verify that our conclusions remain qualitatively the same when using the correct formulation for the ridging and opening coefficients (Eq. 21 in our submitted

manuscript)). An important conclusion of the Lemieux et al. (2025) paper is that the ice cover is more active (i.e., more deformations) when decreasing the e_G parameter. Fig. 1 below shows the total length of detected LKFs for different e_G . This figure is similar to Fig. 7 in Lemieux et al. (2025). Compared to Lemieux et al. (2025), $e_G = 1.16$ is not tested as it does not meet the conditions given in section 4 of our submitted manuscript. We used $e_G = 1.25$ instead. We draw the same conclusion as Lemieux et al. (2025); the total length of detected LKFs notably increases when e_G is reduced.

Another obvious way to verify that the ice cover is more active is to calculate the density of LKFs as in Fig. 8 of Lemieux et al. (2025). Fig. 2 below demonstrates that our conclusion is maintained: the density of detected LKFs clearly increases when e_G is reduced.

Fig. 13 in Lemieux et al. (2025) summarizes very well the impact of the non-normal flow rule on grid-scale deformations. This figure shows the PDF of the angle θ_r for different values of the yield curve parameter e_F and the plastic potential parameter e_g . θ_r is defined as

$$\theta_r = \tan^{-1} \left(\frac{\dot{\epsilon}_I}{\dot{\epsilon}_{II}} \right). \quad (1)$$

$\theta_r = 0^\circ$ corresponds to pure shear, $\theta_r = -90^\circ$ is pure convergence, $\theta_r = 90^\circ$ is pure divergence while other values are combinations of shear plus divergence/convergence. Note that $\theta = 90^\circ - \theta_r$. We calculated the PDF of θ_r from simulations that used the correct formulation for the ridging and opening coefficients (eq.21 in our submitted manuscript). Fig. 3 below should be compared to Fig. 13a in Lemieux et al. (2025). Overall, our conclusion remains the same: reducing e_G has a strong impact on the PDF of θ_r . A smaller e_G decreases the number of pure shear events and increases divergence and convergence.

As in Lemieux et al. (2025), we find that the total sea ice volume increases when e_G is reduced (Fig. 3b in our submitted manuscript versus Fig. 12a in Lemieux et al. 2025). The effect is however reduced. As the ridging and opening coefficients with the correct formulation are smaller than with the incorrect one, there are less openings and therefore less ice growth. The impact of the ridging and opening coefficients on the sea ice volume is cumulative and this is why the differences with Lemieux et al. (2025) are more apparent.

Minor comments:

L65: I understand that you're implementing your ideas into CICE, but I'd always mention Lipscomb et al. (2007) first and only put CICE in parentheses.

Section 2 should be more general and should not refer to a specific model. This will be rephrased in the revised manuscript.

Eq 14: I think it would help the reader to point out that this is the same equation as Eq (3) with $\alpha_0(\theta)P_o|\dot{\epsilon}|$ added

We will add this information in the revised manuscript.

L180: Why introduce the second incorrect formulation? You show INC1 because that's what Lemieux et al. (2025) did, but INC2 is not well motivated.

We agree that INC2 is not really well motivated. We are afraid that modelers could make the mistake of only using the yield curve aspect ratio (i.e. e_F) for the ridging and opening coefficients. We will remove the results related to INC2 and focus on INC1. We will, however, write a few sentences to warn modelers about this potential mistake.

L248: Shouldn't the limit on $e_F = e_G \geq \sqrt{3}/2$ and not 1? As per eq (36). This is a nice result that deserves better highlighting in the discussion and conclusions. Does this also mean that in a model without an ITD, we should only use $e > \sqrt{3}/2$?

We thank the reviewer for pointing this out. We will make the correction in the revised manuscript. Hum...interesting question regarding models without an ITD (often referred to as one-thickness category models). One-thickness category models rely on many simplifications and have a very crude representation of opening and ridging; there are no opening and ridging coefficients and ridging (opening) only depends on the grid-scale convergence (divergence). One could therefore choose to use $e_F = e_G < \sqrt{3}/2$. However, from a physical point of view, it is difficult to justify a value of e_F smaller than 1. When $e_F < 1$, the simulated sea ice has a higher shear strength than its compressive strength. This is why modelers rarely use a e_F value below 1. e_F usually ranges between 1.2 (Vanachter et al. 2022) and 2.0 (Hibler 1979).

Jean-Francois Lemieux

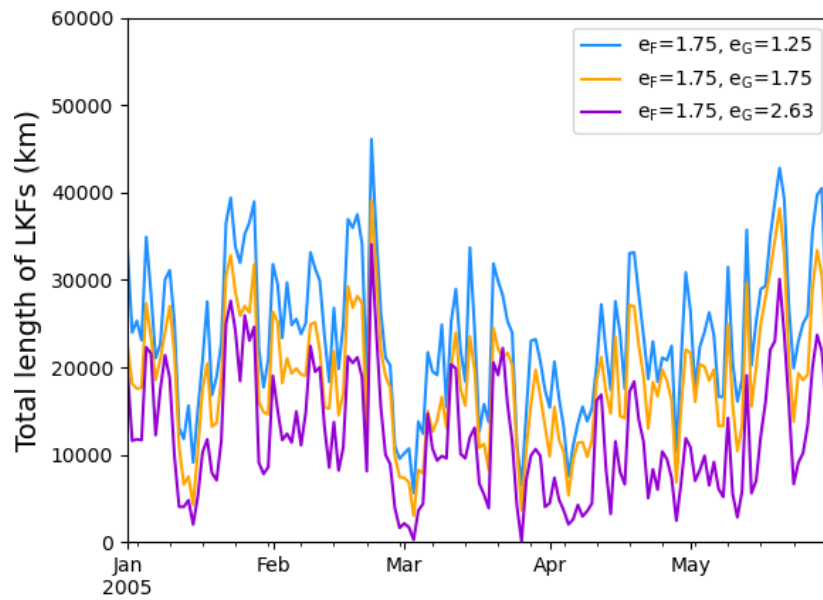


Figure 1: Total length in km of detected LKFs as a function of time for the period 1 January to 31 May 2005.

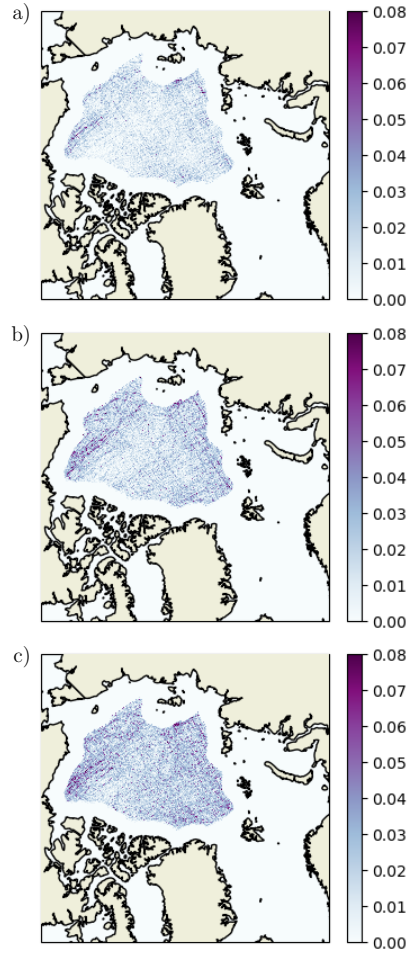


Figure 2: LKF density for the period 1 January to 31 May 2005 for $e_F = 2.63$ (a), $e_G = 1.75$ (b) and $e_G = 1.25$ (c) (violet).

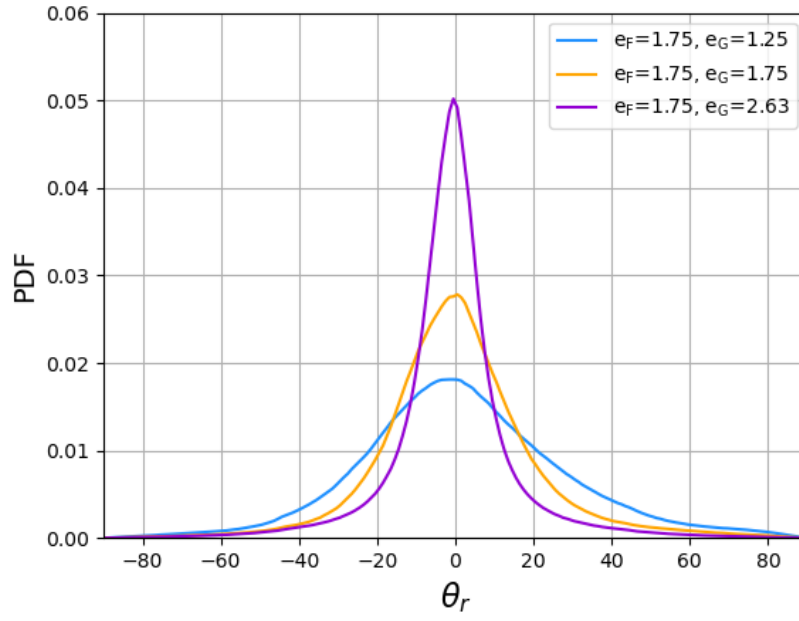


Figure 3: PDF of θ_r for a fixed value of $e_F = 1.75$ and $e_G = 1.25$ (blue), $e_G = 1.75$ (orange), and $e_G = 2.63$ (violet) and .