

Initial response to reviewer 2

September 29, 2026

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

This paper presents a correction to derivation of ridging coefficient for the elliptical yield curve with non-normal flow rule that was presented in Lemieux et al. (2025), also published in The Cryosphere.

This paper provides an errata to a previously published paper, however it has more details in the introduction which make me feel the authors want the paper to stand on it's own. Personally: I believe this paper should stand on its own. Whether this is an errata, or a stand alone paper, the introduction and discussion need to be tailored better to the results and should motivate why the model development work was done. There are details missing as to why one might want to use a non-linear flow rule with the elliptical rheology, what the new formulation provides for people using these models, and the context for why you only considered elliptical yield curves allowing variable eccentricity to describe the yield curve and a plastic potential that does not have to follow this. You can, of course, refer to the earlier Ringeisen et al. (2021) paper, but some context is needed in the introduction. Perhaps echo the point made in the 2025 paper that using an elliptical plastic potential requires only small modification to zeta and Delta to implement a non-normal flow rule. I can see that this is attractive to those who do not want to code up different rheological shapes and deal with the issues of convergence that other yield curve shapes can bring.

Reviewer 1 also considers that our manuscript should provide more context and explain why a non-normal flow rule is a very useful capability and why consistent ridging and opening coefficients are required.

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 better describe that the non-normal flow rule is a useful capability and that its implementation is straightforward. We will also mention that the correct opening and ridging coefficients require a minor code modification.

In the discussion it would really help to draw out for the reader why flexibility is needed in defining the flow rule. How would you use the flexibility this flow rule gives to obtain realistic results? You have made a start at understanding the sensitivity of the ice thickness to variations in e_F and e_G , what does this physically mean and how can someone use this information to tune a model? Here I would focus on the discussion of opening vs ridging and why it is so important to get this right, and how one can adjust this behaviour with this model. I realise we may not have data to validate this, but the sensitivity study it itself is useful information.

See our comment above for the flexibility brought by the plastic potential. The obvious approach to optimize e_G (flow rule) would be to compare simulated deformations to the ones derived from satellite observations. For the yield curve parameter e_F , it could be adjusted by comparing simulated landfast ice to analyses of observed landfast ice (Lemieux et al. 2016). To our knowledge, there are no extensive observations linking subgrid-scale opening and ridging to grids-scale deformations. However, it is important to formulate the opening and ridging coefficients in a way that respects the conservation of energy: the work done by internal stresses in deforming sea ice is equal to the change in potential energy and frictional loss during the formation of ridges (Rothrock 1975). The loss of energy due to sliding friction could also be considered (Flato and Hibler 1995).

As this paper is an errata, it should be mentioned if the results in the 2025 paper are still valid. The 2025 paper focuses on LKF intersection angle. In this paper I appreciate your focus on ice thickness distribution, and sensitivity of this to the error and eccentricity of the plastic potential. It is apparent that the LKFs also change (figure 4, you can see changes in thickness along linear features), does this impact your previous reported result about LKF intersection angles for the idealised cases or pan-Arctic run? If there is no impact, that is also important to point out.

Reviewer 1 made a similar comment. 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 coeffi-

coefficients of the redistribution function should depend on GRID-SCALE deformations to represent the SUBGRID-SCALE divergence (opening) and convergence (ridging) events. These subgrid-scale deformations represent the smaller scale deformations inside the $\sim 4 \text{ km} \times 4 \text{ km}$ 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

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

$\theta_r = 0^\circ$ 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 conver-

gence.

Another conclusion of Lemieux et al. (2025) is that reducing e_G (with $e_G < e_F$) for pan-Arctic experiments does not correct the too large intersection angles obtained with the normal flow rule (i.e., $e_G = e_F$). This is in contradiction with the results obtained by Ringeisen et al. (2021) in idealized experiments. Using the correct formulation for the ridging and opening coefficients does not alter the conclusion: the intersection angles are still too large. The PDF of intersection angles for $e_G = 1.25$ and $e_F = 1.75$ is shown in Fig. 4 below. This figure can be compared to Fig. 10c) in Lemieux et al. (2025).

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.

I very much appreciate the additional context this paper brings to the use of non-normal flow laws, and particularly mapping out ranges of realistic e_F and e_G . In my mind, this is worthy of a stand alone paper and so I hope the authors will take into account my concerns that the paper needs more context in the introduction and discussion.

We thank the reviewer for this nice comment. Reviewer 1 also mentions that our manuscript should provide more context and a better motivation for implementing (and using) a non-normal flow rule. More context and motivation will be added to the revised manuscript.

Specific Comments

In the interest of completeness, do you need to mention Babko's work to add rafting to the redistribution function. I realise that you may not want to do the math to include these terms, and your numerical model might not include rafting in its redistribution function, but I feel you could be more comprehensive in the introduction.

Babko, O., Rothrock, D. A., & Maykut, G. A. (2002). Role of rafting in the mechanical redistribution of sea ice thickness. *Journal of Geophysical Research: Oceans*, 107(C8), 27-1.

Rafting is already included in the ridging mode. This is explained in Lipscomb et al. 2007 (see their Eq. 34 and the text related to this equation).

Make sure you have the correct reference for Lemieux et al. (2025), I think

the preprint is referencing the discussions rather than the final version.

This will be corrected in the revised manuscript. Thank you.

Line 248: "unridging" is actually not unrealistic. I have observed this. When ice diverges at the start of the melt season, ridges can fall apart and blocks create brash fields between flows. I agree that this is not something we consider in our models, and it is un-realistic in the ridging process. But I do want to point out that it is possible for pack ice to "extrude" into a thinner material in divergence. No need to fix anything here, unless you agree with me that we should not constrain future readers imagination as to how the thickness distribution evolves. I have no idea how large an effect this collapse of ridges is in the thickness distribution, it is only an anecdotal observation I (and others) have seen with our own eyes.

We thank the reviewer for this interesting comment.

Figure 6: I find myself curious what the difference is between INC2a and CORRa.

There is no clear motivation for the INC2 formulation. We have decided to remove it from the paper.

A concluding paragraph is missing from the paper. Perhaps you can use this to better provide context as to what your findings mean for Joe-modellor who might find themselves implementing your flow rule or questioning if they need to in order to represent ridging and lead opening correctly. Do we really need this added complexity in the EVP model?

See our comment above that explains why the plastic potential (and non-normal flow rule) is a very useful capability.

Jean-Francois Lemieux

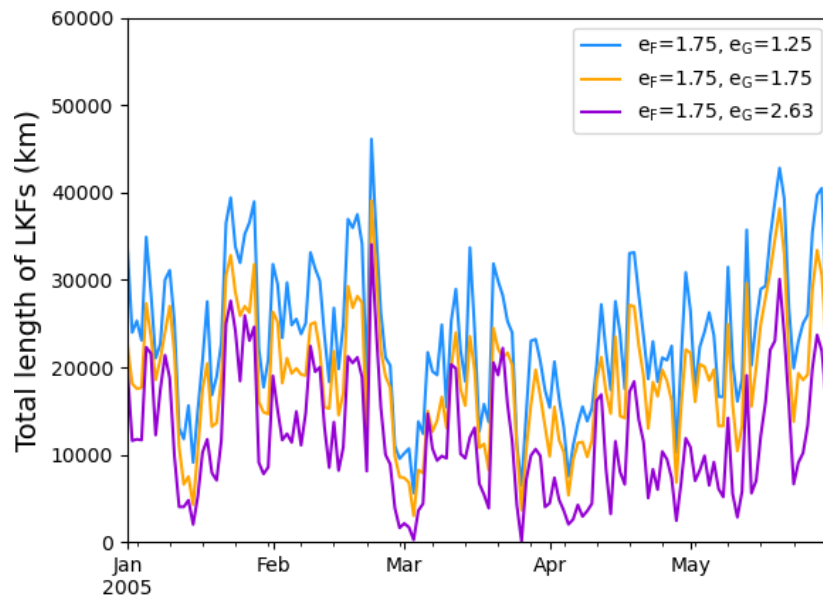


Figure 1: Total length in km of detected LKFs as a function of time for the period 1 January to 31 May 2005.

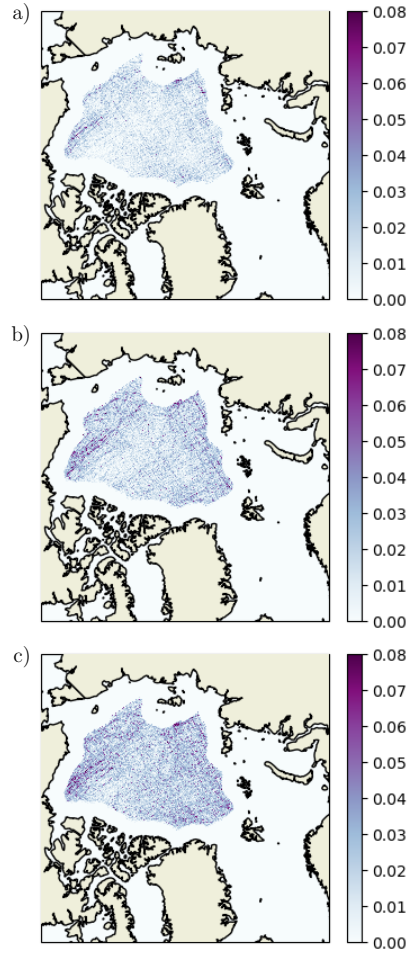


Figure 2: LKF density for the period 1 January to 31 May 2005 for $e_F = 2.63$ (a), $e_G = 1.75$ (b) and $e_G = 1.25$ (c) (violet).

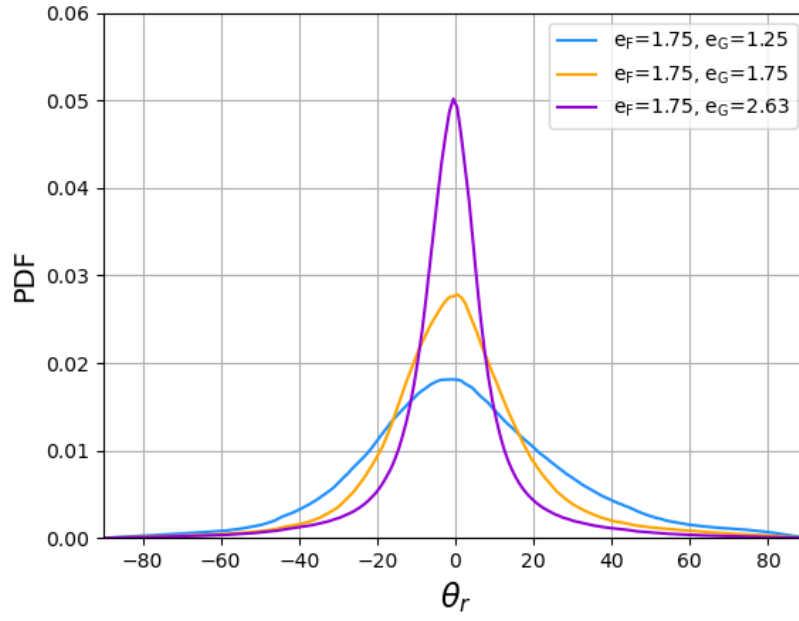


Figure 3: PDF of θ_r for a fixed value of $e_F = 1.75$ and $e_G = 1.25$ (blue), $e_G = 1.75$ (orange), and $e_G = 2.63$ (violet) and .

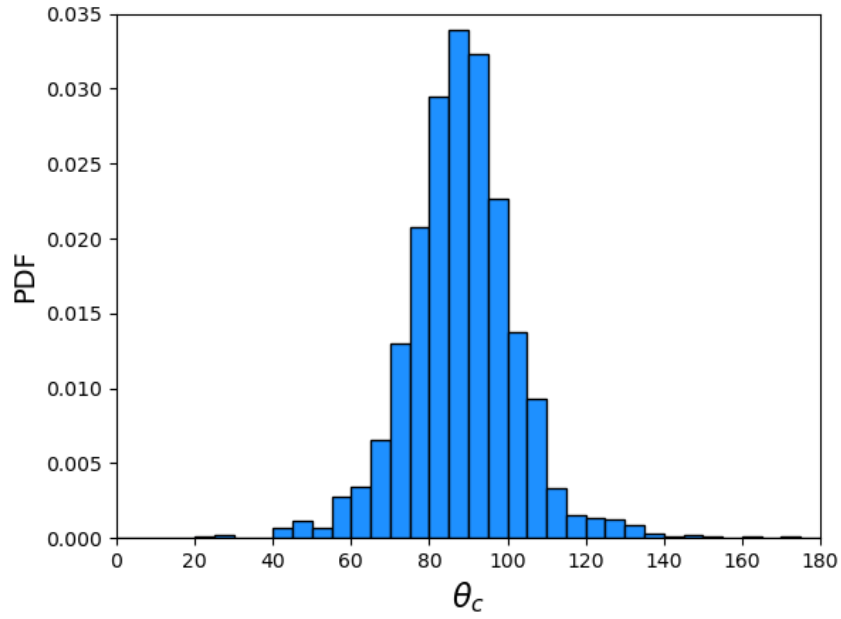


Figure 4: PDF of the intersection angle θ_c for $e_F = 1.75$ and $e_G = 1.25$. The PDF is calculated from daily snapshots for the period 1 January to 31 May 2005