Answers to tc-2022-163 RC3

September 6, 2023

Note:

- The referee comments are shown in black,
- The authors answers are shown in blue,
- *Quoted texts from the revised manuscript are shown in italic and in dark red.*

* The exact pages and line numbers in our responses are subjected to change as the revised manuscript is being prepared.

Review #3

First of all I want to thank you for submitting a well edited and relatively easy paper to read. I am happy to see the new methodology applied to the viscous-plastic model and believe the information presented will be of use to others contemplating using such a model for modeling situations where discontinuities exist in the ice pack.

Overall I think this is a useful paper and the new method to solve the model is well described. I particularly commend you for introducing the limitations of the method and discussing clearly where it can be used. My only concern is that you present only two idealized case studies to demonstrate the model works. The reproduction of the analytic solution for 1-D motion against a wall is a good test and a useful bench mark. Did you consider the range of test cases that you would need to do to demonstrate the model performance? An arching case is a classic example with a free ice edge that is a good test of the models ability to handle the discontinuity. Have you considered the work by Billy Ip and Hibler on the VP model representation of ice arching. The set up they use is different to yours, with a conical domain. They present the flow states involving arching with dimensionless numbers, and demonstrate the impact of yield curve shape on the flow through the channel. This might provide a framework for you to test your solution against.

References

Flato, G. M. (1993). A particle-in-cell sea-ice model. Atmosphere-Ocean, 31(3), 339-358.

Hibler, W. D., Hutchings, J. K., & Ip, C. F. (2006). Sea-ice arching and multiple flow states of Arctic pack ice. Annals of Glaciology, 44, 339-344.

Ip, C. F. (1993). Numerical investigation of different rheologies on sea-ice dynamics. Dartmouth College.

We have not considered the range of test cases to demonstrate the model performance yet. At this point, we mostly want to present a proof of concept showing that the SPH method can be adapted for sea ice applications, but there is still work to do before it can be applied to different model domain and forcing. The comparison of the SPH framework with standard approaches for ice arching experiment (as done in Ip and Hibler) will be addressed in future work.

Minor Suggestions

In the introduction you jump in sentence 2 stating general sea ice model architecture to the constitutive relation. For readers who are new to modeling it might help to include the information that this constitutive relation is one of the terms in the momentum balance, and how it is the continuity and momentum equations that are discretized. This is very basic, but helps guide new readers.

Agreed.

The second sentence in the introduction, l. 16, has been replaced by: " *…climate projection. Generally, numerical models used for geophysical sea-ice simulations and projections are based on a system of differential equations assuming a continuum. The equations that predict the sea ice dynamics are a combination of the momentum equations, which describe the drift of sea ice under external and internal forces, and the continuity equations which ensure mass conservation. The external forces include everything that creates a stress on sea ice and the internal forces simulate the response of the material to the external stress. The internal forces are based on various constitutive relations which can differ between models. The more commonly used constitutive laws are the standard Viscous-Plastic model (Hibler, 1979) or modifications thereof (e.g., Elastic-Viscous-Plastic or EVP and Elastic-Plastic-Anisotropic or EPA; Hunke and Dukowicz, 1997; Tsamados et al., 2013). They are typically discretized on an Eulerian mesh using finite-difference method (FDM). FDM is the simplest…*"

line 35: increase -> increased

Done.

line 45: Have you considered the work of Greg Flato under Bill Hibler? He presented a semi-lagrangian approach for solving the VP model. In his manuscript there is an example of a test case that could provide insight if used with your method. This is a free sea ice edge with a vortex forcing applied over it. In a sense you can think of this as an idealized ocean eddy at the ice edge. It was a good test case for showing how Flato's method reduced diffusion at the edge that was apparent in Hibler's solution.

We have not considered the test case of an enclosed vortex in our study because, at the moment, the boundary treatment of the SPH model is not physical and only supports free-slip conditions. The suggested work of Greg Flato would be an excellent benchmark problem to add once the model is more mature.

This has been clarified in the conclusion at l. 491: " *For future work, before exploring new features enabled by the numerical framework, a more physical treatment of the boundary conditions should be investigated — e.g., using the immersed boundary method (Tu et al., 2018) with a fixed grid for the boundary and an interpolation scheme to apply force on the particle to simulate the grounding of sea-ice near the coast. Once the boundary treatment is physically sound and enables no-slip condition, the model will be tested against other* *benchmark problems like the ice edge modification and LKFS formation under vortex forcing (Flato, 1993; Mehlmann et al., 2021), the stress field under specific wind and water drag in an enclosed domain (Hunke, 2001; Danilov et al., 2015), or the sea ice arch problem described in n Hibler et al. (2006) to further understand and compare the effect of the SPH method. Also…"*

line 69: throughout -> through

Done.

Please check that algorithm 1 (and the tables/figures) are all referenced in the text and in order. I note that figures 8 and 9 are referenced in the text out of order.

Hopefully, everything is in order now.

We also added the following sentence at l.170 to better incorporate the algorithm in the text: "*This makes the parallelization of particle interactions algorithm mandatory for any practical applications. For further details on the computation tasks required by our application of the SPH method see Algorithm 1 below."*

equations 33 and 35: The O(xx) terms are not explained in the text.

We clarified the terms at l.163 with the new sentence: "*In the above equations, $O(\Delta t^2)$ and $O(\Delta t^3)$ represent second-order or third-order terms and higher, which are ignored by the scheme. "*

line 203: Should there be a space between Kappa and l? Or is l a subscript? Also, please check that you are not referring to two different variables with the same variable name. Kappa is used again in equation 41, with subscript n. Do you need to use the same symbol for these two different variables?

A multiplication operator has been added between kappa and l for readability. The constant name in equation 41 has been changed to mu to avoid the possible confusion highlighted by the reviewer.

line 358: grammar is off in this sentence. I think it should be "The water drag also causes a longer time to reach steady state, since the ice drift speed is slowed."

Agreed. The sentence at l.354 is now: *"The water drag also increases the time needed to reach steady state, since the ice drift speed is slowed."*

line 368:"than what is common" remove what.

We changed the sentence at l.363 to : *"We use a weaker wind than commonly used in Nares Strait ice arches simulations …"*

equation A17 and A18: Why use a number 1 here in place of a variable symbol?

We felt it makes it easier for the reader to associate the equation A19 this way. But as suggested, we now use the variable symbol "a".