Revision of the manuscript:

A hybrid ice-mélange model based on particle and continuum methods

April 19, 2024,

Dear Reviewer 1,

we thank you for your valuable remarks on our paper, which we address in the revised version of our manuscript. In this revised version, as a novel feature we now represent the ice mélange in a hybrid model based on a sea-ice continuum into which icebergs are embedded as particles. In order to represent the ice mélange as a joint continuum, we integrate the particles into the sea ice as compact pieces of sea ice. The use of particles allows us to describe ice mélange also on a subgrid level. Thus, we do not need meshes that resolve icebergs, which clearly distinguishes our approach from existing ones. The ice mélange is realized in the context of Hibler's viscous-plastic sea-ice model, which is currently the most widely used rheology for sea ice in climate models. To keep icebergs (thick compact pieces of ice) together, we introduce a tensile strength in the viscous-plastic rheology. So far, there is no description for ice mélange within the viscous-plastic model of Hibler. A similar approach was realized by Vaňková and Holland using Flato's rheology. However, in a sea-ice model intercomparison project, it was shown that Hibler's rheology leads to more realistic results than Flato's rheology (Kreyscher, 2000). Therefore, and because of its widespread use, we focus on Hibler's model in this paper.

Due to the particle tracking, the resistance to shear forces and the separation of icebergs is straight forward, as is the handling of multiple icebergs within a grid cell. In addition, we removed the discussion on the solvers. Due to the hybrid approach, the use of coarse meshes is possible such that solving the model with the modified Newton solver is no longer challenging. We now highlight these aspects in the abstract and introduction to more clearly emphasize the novelty of the work, and we rewrote the corresponding parts of the paper.

Please find below the description of the changes we made to the manuscript in response to the comments. Changes in the manuscript in response to comments of Reviewer 2 are marked in blue. All modifications in response to your comments are marked in red. All other changes are coloured in brown. We hope these changes address your suggestions.

Yours sincerely,

S. Kahl, C. Mehlmann and D. Notz

Answer to the Referee's comments

In the following, we respond to the reviewer's comments and explain the changes in the manuscript.

Major comments

1. *As far as I can tell the only new thing in this paper is the implementation of spatially variable strength within the Hibler viscous-plastic rheology.*
   Response: The aspects which are novel in the paper are highlighted above.

2. *The representation of icebergs as thick and compact pieces of sea-ice and the concept of spatial variable strength depending on sea-ice or iceberg label is identical to that of Vankova and Holland. The only differences are the advective scheme and the shape of the yield curve in the implementation.*
   Response: Both approaches use an indicator type function to distinguish icebergs and sea ice via the ice strength. In our approach this modification is justified by a reformulation of the yield curve in the viscous-plastic model. The realization of the iceberg tracking and the resulting consequences differ significantly between the two approaches. We now use particles for icebergs that allow us to describe ice mélange also as a sub-grid process. Therefore, we do not require grids which have at least the same size as the icebergs. In the approach of Vaňková and Holland the mesh size needs to be high enough so that icebergs are resolved.

3. *The yield curve the authors use is identical to Konig and Holland.*
   Response: So far, this modification of the yield curve has been used in different contexts like landfast ice (König and Holland) or as a modification for the sea-ice rheology of Hibler (Ringeisen et al.). In our contribution we show that the modification is also useful for modelling ice mélange in the viscous-plastic sea-ice model. For the sake of completeness we want to keep the derivation of the yield curve.

4. *The authors emphasise throughout the paper the implementation of the strength modifications within viscous-plastic rheology, but it is important to realise that the Flato model, where the same was implemented is also viscous-plastic in its 2-D form.*
   Response: The goal of our paper is to realize ice mélange in the context of Hibler's viscous-plastic sea-ice model, which is currently the most widely used rheology for sea ice in climate models. We consider the full viscous-plastic dynamics of Hibler and present a numerically efficient way to solve it. The model of Hibler differs from the model of Flato. Furthermore, an efficient numerical treatment has not yet been presented for the model of Flato in 2D.

5. *In terms of the advection scheme and labelling icebergs, the authors do not show whether their scheme is able to handle separation of two icebergs that had been joined by convergent winds. I think this is a crucial feature to show. As of now there have been no iceberg-iceberg interactions tested and its unclear how the scheme handles the presence of multiple iceberg portions within a single grid cell. The authors also do not show (although it is claimed they do) that the scheme handles shearing - in test case 3 (which claims to test that) wind shear is applied away from the icebergs, the wind over icebergs is uniform and so the ability to rotate instead of deforming has not been shown.*
   Response: By the use of particles (rigid bodies) for icebergs it is straight forward to handle separation of icebergs, multiple icebergs in a grid cell as well as the resistance of icebergs to shear forces. We added corresponding numerical test cases.

6. *Finally, I think the second selling point, after Hibler rheology, is the improved computational efficiency. The conclusion of the authors is that modified Newton leads to 40% improvement over*

Picard. However, there have been much more efficient solvers developed for the same system of equations. See for example Lemieux et al 2012, they show that Jacobian-Free Newton–Krylov (JFNK) solver is 3–7 times faster than the Picard solver for the same system of equations. The thing that makes the equations less likely to converge to a solution is whenever there is large stress buildup, which is what happens over the thick and compact bits of mélange as material strength scales with thickness per the parameterization (that is typically an issue for thick and compact sea-ice cover in continuum sea-ice only models as well, but the presence of thicker icebergs this is made worse). The test case on which the authors calculate the convergence properties is not one that experiences large stresses - it is icebergs moving through very thin and not very compact sea-ice, so they are essentially freely drifting. In summary, I don't think there has been made any improvement towards computationally efficient tractability of mélange as a continuum.
Response: We removed the discussion on the solver. To answer your question: The main point is that the Picard solver failed to reach the required residual in 19 steps. The solver has been stopped after 100 iterations, with a much higher residual than the modified Newton solver. Whether or not a Newton solver converges depends on whether the initial guess is in the area of Newton convergence. There are situations in which the Newton method (also JFNK) does not reduce the nonlinear residual while the Picard solver does. However, in such cases the reduction by the Picard solver is very slow, see e.g. Mehlmann and Richter (2017). In the paper "*Robust and efficient primal-dual Newton-Krylov solvers for viscous-plastic sea-ice models*" as well as in the PhD thesis of Mehlmann it has been shown that the modified Newton solver is much more robust and efficient than the JFNK solver. In the first submission we demonstrate that the modified Newton solver is also more robust in the ice mélange setting, which is in line with previous results for the standard viscous-plastic application.

Minor points

1. *Good chunk of the abstract sounds like copy pasted abstract from Vankova and Holland 2017. It would be good to separate out clearly what it is that has been done before and what is the new development and lay that out unambiguously. Arguably the new thing is that the existing sea-ice/iceberg prototype model (continuum model with spatially variable rheology and icebergs represented as thick and compact pieces of sea-ice held together by large shear and tensile strength) was implemented within the much more frequently used Hibler rheology instead of the original Flato cavitating fluid one.*
Response: We reformulated the abstract and highlighted the novelty of our approach.

2. *The references are bit out of date - there have been some more new observational and modeling papers out that should probably be mentioned in this paper (I made a few notes in the pdf, but there is more out there). Some of the provided references are inaccurate (e.g. observational reference for a modeling claim). I didn't get to check all, but a few random ones were wrong so please check and fix all references.*
Response: We reformulated the introduction and checked the references.

3. *There is an imbalance between the description of the equations which is quite comprehensive although already present in the literature, and the numerics section which is really thin and barely touched on. We don't even learn what grid the authors use.*
Response: We now describe the numerical setup more in detail.

4. *figs 2-4: arrows are not clear - it was those figures that made me thing the grid might be unstructured, but then I realized it is just arrows overlapping which makes it difficult to compare their relative size.*

Response: We changed the representation.We removed the velocity from the plot and show now the sea-ice thickness and the iceberg contour.

5. *Fig6: why is 48th time step interesting? Show all time steps or some statistics from them so that we can see the spread. Here Picard actually does better than Newton in this case, it seems, which is not typical.*
   Response: We removed the discussion on the solvers.

6. *Conservation of shape rectangle vs cylinder - this is a big misconception. The preservation of the shape of a moving object has to do with the advection scheme properties, not with the shape of choice.*
   Response: We removed the sentence. Now icebergs are introduced via particles.

7. *Line 17: "Observations show that the seasonal pattern of glaciers and ice mélange overlap" → There are also observations pointing to no relation between the two, e.g. Amundson et al 2020*
   Response: We rephrased the introduction.

8. *Line 19: suggested*
   Response: Done.

9. *Line 20 - 21: I don't think this is a correct definition of buttressing. Buttressing and calving are not necessarilly related. See e.g. Reese et al 2018 for buttressing.*
   Response: We removed the sentence.

10. *Line 23 - 24: That is not what is driving sea-level rise, the effects described here are minor and only come down to the difference of densities between freshwater and seawater. Sea level rise is mainly driven by acceleration of grounded ice towards the margins and enhanced ice flux across the grounding line.*
    Response: We rephrased the introduction

11. *Line 28: "satellite images" → There are other methods for observing the ice mélange, e.g. terrestrial radar interferometry. See e.g. Xie et al 2019, Cassotto et al 2021*
    Response: We rephrased the introduction.

12. *Line 30: what do you mean by explicit, there are still parameterizations within mélange models*
    Response: We mean modelling the dynamics of the ice mélange. We reformulated the sentence.

13. *Line 37: Peters et. al., 2015 → not a modeling paper*
    Response: We rephrased the introduction

14. *Line 40 - 41: Vankova and Holland, 2017 → this is not a particle model reference*
    Response: The aspect is discussed in the paper of Vaňková and Holland. We rephrased the sentence.

15. *Line 41: "currently unclear" → Are there really no particle models coupled to continuum models in any fluid application?*
    Response: We removed the sentence.

16. *Line 41: "coupled" → coupling of what to what do you mean here?*
    Response: We removed the sentence.

17. *Line 41 - 42: "used continuum sea-ice formulation" → there are also particle sea-ice models being developped/used, perhaps worth mentioning*
Response: In this paper, we focus on the realization of ice mélange in climate models. So far, no sea-ice particle model is part of a climate model.

18. *Line 46:* cavitating
Response: Done.

19. *Line 48: "viscous-plastic material" → The 2D Flato model is also viscous-plastic*
Response: Thanks for pointing this out. We do, however, not consider Flato's model in this sentence as indicated by the references: "So far, most climate models, treat sea ice as a viscous-plastic material using the viscous-plastic (Hibler, 1979) or elastic-viscous-plastic (Hunke, 2001) sea-ice rheology."

20. *Line 51: "productive" → what is the measure of productivity? provide reference*
Response: We rephrased the sentence.

21. *Line 52: "valid" → depends on the timescale of interest*
Response: We rephrased the sentence.

22. *Line 53: "modification of the viscous-plastic material law" → you haven't introduced one so it is unclear what and why is being modified*
Response: The paragraph has been rephrased.

23. *Line 55: Here we develop*
Response: Done.

24. *Line 55 - 56: "viscous-plastic rheology, introducing a spatially varying strength parameterization" → Probably should cite here Vankova and Holland as that is exactly what they did, and not only later on*
Response: We restructured the introduction. Thus, the sentence has been removed.

25. *Line 58: "sea-ice" → and also use a spatially variable strength parameterization within a viscous-plastic continuum model*
Response: The sentence has been removed.

26. *Equation 1: You should first include all terms before dropping selected ones and you should provide justification for dropping terms - the advective term is missing at the moment*
Response: It is standard to neglect the advection term in the viscous-plastic sea-ice model. We follow the notation e.g used in a comparison paper (Mehlmann 2021).

27. *Line 151: prove*
Response: The sentence has been removed.

28. *Line 153: "Essential for this proof" → where is this proof?*
Response: The paragraph has been removed. To answer your question: The proof is given in the mentioned paper Mehlmann and Richter 2019.

29. *Line 162: "shear (Section 3.3) strength" → unlike announced here, the 3rd experiment does not test the ability of the iceberg part of mélange to withstand shear forcing without deformation, for that you would have to place the sheering wind on top of the iceberg*
Response: See our response to major comments point 5.

30. *Line 163: "extreme" → extreme in which sense?*
Response: We removed the sentence.

31. *Line 164: "play a major role in the center of the fjord. " → depends on the fjord shape*
Response: We removed the sentence.

32. *Line 165: "neglected" → there is a difference between being neglected and being set to zero, presumably you are still keeping the ocean stress term that depends on mélange velocity as well?*
Response: We set the ocean velocity to zero. The sentence has been rephrased.

33. *Line 171: "A grid cells size of 110m is used" → You haven't said anything about the grid cells and stencills etc yet, are the regular? c grid?*
Response: We added more information to the numerical methods section.

34. *Line 176: "the iceberg and the sea-ice move" → you are modeling one material so it is just mélange....*
Response: We rephrased it.

35. *Line 176 - 177: "he glacier and accumulate in front of the glacier terminus" → isn't it really just the iceberg getting deformed what we see? sea-ice should indeed move and accumulate towards the terminus but the figure doesn't show that*
Response: Thanks for pointing this out, we rephrased the sentence to reflect this notion.

36. *Line 187 - 188: "This test case shows in particular that the iceberg maintains its shape even under diverging wind conditions at the location of the iceberg." → That is by design, isn't that the whole point of the experiment? why the word even?*
Response: We removed even from the sentence.

37. *Line 189: "Two travelling icebergs" → this test properties of the advection scheme, not ability of iceberg to withstand shear*
Response: We changed the setting.

38. *Line 220: "The" → In line with prior findings, the*
Response: Done.

39. *Line 224 - 225: "Furthermore, the volume-in-fluid method cannot represent the corners of the rectangles exactly such that the corners are easily smoothed out by the advection scheme." → but that doesn't have to do so much with iceberg corners does it? if there is a cylinder peaking into a corner of a grid cell, its shape will too get diffused, right?*
Response: We removed the sentence..

40. *Line 226: "whose shape is easier to conserve." → provide reference*
Response: We reformulated the paragraph.

41. *Line 228: "representation" → do you mean preservation of shape?*
Response: We reformulated the paragraph.

42. *Line 247 - 248: "Likewise, we demonstrate that icebergs can also interact while maintaining their shape" → no iceberg interaction has been shown*
Response: We added an numerical test case.

Thank you for all your very helpful comments and suggestions for improved. We feel that our paper has much improved by taking them into account!

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April 19, 2024,

Dear Reviewer 2,

we thank you for your valuable remarks on our paper, which we address in the revised version of our manuscript. In this revised version, as a novel feature we now represent the ice mélange in a hybrid model based on a sea-ice continuum into which icebergs are embedded as particles. In order to represent the ice mélange as a joint continuum, we integrate the particles into the sea ice as compact pieces of sea ice. The use of particles allows us to describe ice mélange also on a subgrid level. Thus, we do not need meshes that resolve icebergs, which clearly distinguishes our approach from existing ones. The ice mélange is realized in the context of Hibler's viscous-plastic sea-ice model, which is currently the most widely used rheology for sea ice in climate models. To keep icebergs (thick compact pieces of ice) together we introduce a tensile strength in the viscous-plastic rheology. So far, there is no description for ice mélange within the viscous-plastic model of Hibler. A similar approach was realized by Vaňková and Holland using Flato's rheology. However, in a sea-ice model intercomparison project, it was shown that Hibler's rheology leads to more realistic results than Flato's rheology (Kreyscher, 2000). Therefore, and because of its widespread use, we focus on Hibler's model in this paper.

Due to the particle tracking, the resistance to shear forces and the separation of icebergs is straight forward, as is the handling of multiple icebergs within a grid cell. In addition, we removed the discussion on the solvers. Due to the hybrid approach, the use of coarse meshes is possible such that solving the model with the modified Newton solver is no longer challenging. We now highlight these aspects in the abstract and introduction to more clearly emphasize the novelty of the work, and we rewrote the corresponding parts of the paper.

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We hope these changes address your suggestions.

Yours sincerely,

S. Kahl, C. Mehlmann and D. Notz

Answer to the Referee's comments

In the following, we respond to the reviewer's comments and explain the changes in the manuscript.

Major comments

1. *In its current form, the manuscript is a straightforward model description paper, which looks at how to get from existing sea ice models to this new model, and certain improvements in accuracy and computational performance by adding tensile stress and using a modified Newton Solver. At that level, this paper is more appropriate for a journal like Geoscientific Model Development than The Cryosphere. To be of interest to the broader readership of The Cryosphere, the authors could take this wonderful new tool and use it to answer certain outstanding questions about ice melange that current tools cannot answer. One is how ice melange responds differently to forcing than just sea ice. Why does it matter that you have bits of thick ice which can resist tensile stress embedded within sea ice? The answer would likely be from a ocean/atmosphere perspective, as the manuscript does not currently argue that this tool would necessarily be used in conjunction with ice sheet models..*
   Response: We show that our new ice-mélange model allows for a realistic physical description of the composite of icebergs and sea ice. Our approach is realized in Hibler's viscous-plastic sea-ice model, which is currently the most widely used material law for sea ice in climate models. Therefore, we think it is a topic that is of interest for a large community. Furthermore, the Cyropshere invites for contributions in numerical modelling and the ice mélange fits into overarching topics of the journal such as sea ice and ice sheets. This is why we think the Cyrosphere is an appropriate choice, but of course this decision ultimately rests with the editor. We believe that in the revised version, among others the fact that grounded icebergs on a subgrid-scale allow for the formation of a polynya on the coarse gird is of interest for the realistic modelling of sea-ice-ocean interactions in particular in the Southern Ocean, where such situations frequently occur.

2. *The motivation for this work, as described in this manuscript, it to be able to efficiently include ice melange into climate models. However, the test cases here exclusively look at cases where the resolution is much, much finer (0.1 km) than it is in any global climate model (10-100 km). What do the author's anticipate being the specific use case for such a formulation? Should it be used in global simulations? Should it only be used for regional simulations at very high resolution? Is the indicator function Phi (Equation 20) strictly necessary to have a discrete division between grid boxes with sea ice and icebergs, or could one have a continuous function (phi) between 0 and 1 that can capture the scenario where you have a large climate model grid box with some icebergs in it (but not completely filled with them)?*
   Response: Thanks for bringing this point up. We now changed the iceberg tracking and use particles to model icebergs. This allows us to describe ice mélange also on a sub-grid level. Thus, we do not need meshes with a high resolution that resolve icebergs, making our approach suitable for implementation in low resolution global models.

3. *It remains unclear how the results shown here with the new method specifically improve upon the method of Vankova. The comparisons made in section 3 are between a standard VP rheology versus a VP rheology with tensile strength, whereas Vankova uses an entirely different rheology with tensile strength. Section 3.1 makes the most direct comparison by looking at a similar setup, but there needs to be a specific argument made about why the inaccuracies in Vankova's method are problems (i.e. related to error in representing aspects of the physical climate system that we care about). In general, this comparison with Vankova is critical to arguing why this new method is necessary, and it should be explored in more detail throughout the results and*

discusison section.
Response: First, Hibler's model has been shown to give more realistic results for the simulation of sea ice than Flato's rheology as used by Vaňková and Holland. Second, the idea of our method is that one can still model sea ice with the viscous-plastic rheology of Hibler, and simultaneously implement a description of ice melange. Thus, our approach can straightforwardly be implemented in existing sea-ice modules in climate models, which to a large extent use Hibler's viscous-plastic material law. In the approach of Vaňková and Holland, sea ice is represented by a different material law, which makes an integration into sea-ice modules more difficult. Third, the method of Vaňková and Holland requires that the resolution of the grid is at least of the size of the icebergs. By using a particle tracking, we can represent ice mélange on a sub-grid level.

Minor points

1. *Line 1: influence on sea-ice-ocean interactions. Ice melange currently is not represented in climate model as numerically efficienty realizations do not exist. This motivates our development*
Response: We modified the sentence.

2. *Line 11: Newton's method*
Response: We removed the sentence.

3. *Line 12: melange into climate models*
Response: Done.

4. *Line 14: Fjord with marine-terminating glaciers can be filled with sea ice into...*
Response: Done.

5. *Line 17: the ice melange at some glaciers disintegrates [melange is year-round at some glaicers]*
Response: We removed the sentence.

6. *Line 17: ...the seasonal cycle of glacier flow is in phase with the presence of ice melange, leading to the...*
Response: We rephrased the sentence accordingly.

7. *Line 22: First sentence of this paragraph can be deleted as its redundant*
Response: Done.

8. *Line 24: through releasing their freshwater storage from icebergs.*
Response: Done.

9. *Line 25: delete "also"*
Response: Done.

10. *Line 28: Delete "This is the more the case as"*
Response: Done.

11. *Line 29: and the challenges of taking in-situ measurements within densely packed melange or near claving fronts*
Response: We rephrased the sentence accordingly.

12. *Line 39: several studies have implemented a particle-based approach for representing icebergs into large-scale ocean models, including those by Alon Stern and Anders Damsgaard.*
Response: Since the topic of the paper is ice mélange, we want to focus in the introduction on how ice-mélange is currently modelled.

13. *Line 41: to commonly used continuum sea-ice formulations.*
Response: The sentence has been removed.

14. *Line 43: model using a continuum approach.*
Response: We rephrase the paragraph and remove the sentence .

15. *Line 45: Using such an approach*
Response: We rephrase the paragraph and remove the sentence .

16. *Line 46: cavitating*
Response: Done.

17. *Line 50-53: Amundson and Burton (2018) don't do a direct comparison between observations and a VP rheology. They do conclude that continuum granular rheologies based on non-local or friction dependent on inertial number work well in describing granular flow through channels, but they don't directly compare to observations. My suggestion is to rewrite this sentence to make it a more accurate reflection of that paper. Even if there isn't observational support for using a VP rheology for ice melange, there are good modeling reasons, and for now, that is sufficient.*
Response: We rephrased the sentence.

18. *Equation (in general): typically div is written as "del dot" ($\nabla \cdot$ in LaTeX) since the term "divergence" is not the same in all languages, whereas "del dot" is more "universal" notation*
Response: Done.

19. *Line 75: describes the divergence of the two-dimensional...*
Response: Done.

20. *Equation 2: I'm a bit confused by how forces and stresses are being mixed here since they do not have the same units. Either some notation is mixed up, or some constants are missing.*
Response: The units are the same. We now state the term of the Coriolis force and the changing sea surface height explicitly to improve clarity.

21. *Equations 3-4: why does the melange velocity enter into equation 4, but not 3? (In the most general sense)*
Response: The wind velocity is much larger than the sea-ice velocity. Therefore, we follow the traditional approach in sea-ice modelling where the sea-ice velocity in the atmospheric drag term is negelcted.

22. *Line 88-89: this sentence is a bit odd. Ice melange is melted from below by the ocean, this is an important sink term. I think the point is that you are just considering idealized cases where melting is ignored. If so, then just state that.*
Response: We reformulated the sentence.

23. *Equation (6): It would help the exposition to explain what e and P are right after this equation*
Response: We restructured the paragraph.

24. *Line 92: expressed in terms of the principal components...*
Response: We rephrased the sentence accordingly.

25. *Line 105: It would help if equation 14 came before equations 12 and 13 as a way to explain that there are two regimes with a smooth transition between them before giving equations for the two regimes.*
Response: We changed the order of the equations.

26. *Line 107: what is meant by the "viscous closure"?*
Response: We rephrased it to the viscous regime.

27. *Line 118: strength lead to a...*
Response: Done.

28. *Line 126: what is meant by "normal flow rule"?*
Response: We added an explanation and a citation to make the meaning of "normal flow rule" more explicit. It is assumed that ∂F and the strain rates are perpendicular to the surface of the yield curve. So a change of strain is only allowed in normal direction to the stress on the yield curve. The model assumption goes back to Druckers postulate and is explained in the book by Leppäranta, 2011.

29. *Equation 19: Why is the indicator function Phi needed if you already have phi? Also, what is the meaning of phi? It seems like a concentration of icebergs. The reason for this question relates to major point #2 above. If you are allowed to have a continuous concentration of icebergs between o and 1, then the model could make sense at grid resolution compared to global climate model, where a grid box might have some icebergs in it (while not being fully filled with icebergs).*
Response: We changed to a particle method and derive an iceberg concentration, which allows us to apply the model at grid resolution used in climate models.

30. *Equation 19: What is c and how is it set?*
Response: We added the information in the text.

31. *Line 141: Is this the same thing as operator splitting? If so, that seems like the more common terminology to me.*
Response: We rephrased the sentence. Splitting in time means that some terms are treated implicitly in time and others explicitly, such that the coupled system of equations is split in the momentum equation and the transport equation which can be solved after each other.

32. *Line 151: prove not proof*
Response: We removed the paragraph.

33. *Figure 2-4: it is somewhat confusing to me why P-T is the correct contour to plot here (as opposed to concentration), and also that there are maybe three different quantities plotted? (P-T, arrows and a black contour for the iceberg, but not clear what quantity that represents). There should probably be a legend for these plots and a better explanation of what is plotted in the caption. It is also unclear why the quiver arrows indicating melange velocity have such variable velocity.*
Response: We now show the sea-ice thickness and the contour line of the iceberg. The contor of the iceberg is given by Eq. 34

34. *Line 200: Vankova and Holland (2017) stated the need for efficient*
Response: The paragraph has been removed.

35. *Line 204: what about the third setup makes it "difficult"*
Response: The paragraph has been removed.

36. *Line 213: residual threshold for convergence*
Response: The paragraph has been removed.

37. *Line 218: It would be useful to have some kind of explanation as to why the modified Newton solver appears to work so much better than the others.*
    Response: The paragraph has been removed. The method makes use of the structure of the momentum equation. Details can be found in (Mehlmann and Richter, 2017).

38. *Line 222: icebergs*
    Response: The paragraph has been removed.

39. *Line 231: Most climate models represents the*
    Response: The paragraph has been removed.

40. *Line 232: Delete "An"*
    Response: The paragraph has been removed.

41. *Line 233: we recommend implementation*
    Response: The paragraph has been removed.

Thank you for all your very helpful comments and suggestions for improvement. We feel that our paper has much improved by taking them into account!