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Geoscientific Model Development Discussions
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Interactive comment on "The Utrecht Finite Volume Ice-Sheet Model: UFEMISM (version 1.0)" *by* Constantijn J. Berends et al.

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General comments

The paper presents a new ice sheet model. The model equations are the shallow ice (SIA) and shallow shelf equations (SSA), coupled together using the method of Beuler and Brown (2009). The equations are discretised using a Finite Volume scheme derived by the authors, on an adaptive mesh. The paper is well written and the topic is well suited for GMD. The novel contribution is the use of the Finite Volume Method and to some extent the usage of mesh adaptivity in combination with a SIA/SSA model (although that has been implemented previously). The mesh adaptivity enables a high

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Discussion paper

resolution at the grounding line, but it is not clear to me that a high resolution is worth it as the model equations used are inaccurate at the grounding line. Nevertheless the study could be a interesting contribution if this issue is investigated deeper and if the accuracy and efficiency of the numerical scheme is evaluated more thoroughly. I appreciate that several verification experiments have been made, however, only part of the model is verified in experiments, convergence experiments testing the Finite Volume scheme are missing and more experiments are needed regarding the adaptive meshes. In particular since the numerical scheme is constructed by the authors, it is important to motivate the choice of this scheme and verify it thoroughly. The paper would also benefit from a clearer description of the model and the numerical scheme used. I recommend major revisions.

Specific comments

The SIA-SSA model is known to be inaccurate at the grounding line. A fine grid at the grounding line thus means that the numerical error is low, while the model error is inevitably high. Does it make sense to resolve the grounding line despite that the model errors remain, and if so, how much? Include experiments that shows the balance between model and numerical errors, by using a find grid full Stokes model as a reference solution. These experiments would be of value to all models using SIA-SSA at the grounding line.

The model is only validated for the SIA equations, not the SSA equations. In order for the community to trust the accuracy of the model, the full SIA/SSA model must also be evaluated in experiments in some way. As the authors state, this is more difficult due to the lack of an analytical solution. However, the numerical discretisation can be tested by running convergence experiments, using a fine mesh solution as a reference. Does the errors decrease as expected when the mesh is refined?

The Finite Volume Method is an unusual choice for an ice sheet model, and a motivation of this choice should be given. Add a summary of the method in the main paper, including a statement of the flux approximation (the specific details can remain in the appendix) and the order of the scheme. Discuss if numerical mass conservation is important compared to the model errors, preferably illustrated with experiments. As already mentioned in point 2), include convergence experiments. The convergence experiments in Figure 3-10 only show THAT the model converges - not if it converges with at the expected rate.

Include experiments showing how the mesh adaptivity works. The results shown in Figure 3-10 are done on a uniform grid. These should be done using mesh adaptivity, given that the mesh adaptivity is one of the main contributions of the paper. Experiment with choice of conditions for refinement in these experiments.

Page 2, Line 12: Include a reference to https://tc.copernicus.org/articles/10/307/2016/

Page 2, Line 15: Add a sentence explaining why fine resolution is more important when buttressing is significant.

Page 2, Line 20: Discuss how the time step relates to the mesh size in a non-uniform mesh.

Page 2, Line 28: Define what properly capturing grounding line dynamics means to you, given that the model equations you use do not include all stress components.

Page 3, Line 4: Optimal in which sense? I believe it is a compromise rather than an optimum.

Page 3, Line 5: Why is the model abbreviated UFEMISM, instead of UFVMISM? The name suggests that it is a finite element model.

Page 3, Section 2.1: State here that you use Fortran 90 and motivate this choice

Page 3, Line 20-21: Is there a limit to how fine mesh the user can choose? If so, why?

Page 3, Line 24: Elaborate on why this is important. Why is mass conservation important when the overall mass balance will never be accurate due to model errors and mesh resolution limits?

Page 3, Line 26: Is the number of vertical layers hard coded to 15?

Page 3, Line 30: There are other models that solve simplified equations suited for paleo models and also use mesh adaptivity, for instance the SIA/SSA mode of Elmer/Ice. Include references to these models.

Page 4, Line 12: Specify what is meant by “model content”

Page 4. Line 7-23: Do include a discussion the impact of different choices of conditions for refining the mesh, how do they impact the accuracy of different variables? These kind of conditions makes the mesh refinement interesting.

Page 5, Figure 1: The mesh extends into the ocean. Are there passive volumes out side the ice domain? Clarify.

Page 5, Line 16: Is the partitioning updated as the mesh is updated to maintain proper load balancing? If so, how? If not, motivate why this is not needed.

Page 6, Line 10. Did you consider simply deforming the mesh instead of generating a new mesh, or using deformation to decrease the frequency with which the mesh has to be updated.

Page 7, Line 1: The SIA is formulas to evaluate rather than equations to solve, since the velocity and pressure is already solved for.

Page 7, Line 2-4: It could be potentially confusing to discuss Finite Difference schemes while the model in the paper is based on Finite Volumes. I suggest clarifying this paragraph by beginning the discussion with a couple of sentences explaining the conceptual difference between FD and FVM, then move on to describing how the flux is approximated, and lastly relate this to the FD references and Type I / Type II models.

Page 7, Line 2-4: Add some references to FVM literature and relate your flux approximation to existing schemes.

Page 7, Line 2-4: I would like to see the formulas of ice fluxes and how they are used to calculated SIA velocities here, since the FVM is usually used for solving equations rather than calculating formulas.

Page 7: Write down not only the SIA formulas but also the SSA equations for consistency, together with a brief explanation of how they are merged.

Page 7, Line 9: Add a summary of the FVM approach for solving the SSA.

Page 7: State the theoretical order of accuracy of the FVM scheme

Page 7, Line 13: Clarify that it is Finite Differences in time (not space)

Page 7: Add reference to strain heating form (equation 4)

Page 7, Line 20: Is 15 layers hard coded?

Page 7, section 2.4: What is the spatial discretisation of the temperature equation?

Section 2: Specify how the free surface variable h is updated

Section 2: Specify which equation is limiting the time step - the free surface or the temperature equation?

Section 3: Elaborate on the purpose of each experiments Experiments section 3: These should be done using adaptive meshes.

Page 9, Line 6-7: This sentence needs clarification. As you are looking at numerical error, clarify how the surface slope impacts it so that it is clearer to the reader what is model error and numerical error

Page 9, Line 10: Does it make sense to reduce the error to an error of 10 km, when the SIA is very inaccurate at the margin? How large is the model error?

Figure 5-8: Can you include results from the EISMINT benchmark for in the figure for comparison?

Section 3.2: Explain the EISMINT experiment in such a way that a reader does not have to be familiar with the original publication. Describe e.g. how a fixed versus moving margin is achieved.

Results in Figure 9 and 10: Would it be possible to instead look at the margin, since this is where the resolution matters?

Page 15, Figure 12: Why is SIA so expensive?

Page 15, Figure 12: In which part is the free surface update included?

Page 16, paragraph 1: Discuss why you think mesh update scales less well

Page 16, Line 7: Move the definition of b_r to the next paragraph

Page 17, Line 8: A dynamic time step is mentioned here. An ellaboration on the dynamic time step for SIA/SSA should be added in the model description

Page 17, Line 11-26: Do this experiment with some of the conditions for refinement that were discussed on page 4 rather than explicitly setting the refinement

Page 17, Line 11-26: These results need to be presented more in detail in a figure or table, since this experiment leads to the result that UFEMISM is 10-30 times faster than ANICE.

Page 18, line 5: The claim that the numerical scheme is valid should be supported by convergence experiments and tests of the SSA discretisation

Page 18, Line 11-26: Try to use a fine resolution full Stokes MISMIP solution as a reference solution, in order to evaluate the SIA/SSA model and the convergence of the numerical scheme

Appendix A: Why did you choose to go through this derivation instead of employing some standard FVM scheme? Why did you choose to start from a finite difference scheme?

Appendix A: As FVM is not commonly used in ice sheet modelling, write down the basics of finite volumes and describe your scheme in that framework.

Technical corrections

Page 3, Line 20: “Paradox” -> compromise.

Page 3, Line 21: “config file” -> “configuration file”

Page 4, Line 2: “ refinement ” -> refinement

Page 4, Line 17-20: The sentence starting with “Other conditions” is a bit unclear and long

Page 10, Equation 10: Add spaces between formulas

Page 11, Table 1: Order the rows so that they are consistent with the order of the figures, or vice versa

Page 12, Line 14: Vertical discretisation -> Vertical resolution

Page 14, Line 11: “shared memory” -> shared memory

Figure 12: Include in the caption an explanation of what bc and br are.

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