Referee comment on ‘Performance analysis of high-resolution ice sheet simulations’ by Ed Bueler

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Summary

In this short manuscript, the author provides a prospectus on the benefits of adopting implicit methods for the time-discretization of the equations of ice sheet motion, and in particular how such methods may improve model efficiency relative to the use of explicit methods (which represent the current dominant, though not universal, paradigm). Beginning with some background on the relationship between ice sheet velocity (which is diagnostic) and geometry (which is prognostic) under different simplifications to the stress balance, the manuscript then goes through various scaling arguments that establish the essential amount of work needed to evolve an ice sheet model for a given length of time. The author re-establishes the classical result of fourth-power in spatial resolution effort for the shallow ice approximation, but presents the surprising result of (pessimistic) sixth-power growth for Stokes’ equations (which is quite oppressive), then shows that these resolution-dependent challenges can be significantly ameliorated with implicit schemes, which have the potential to realistically reduce computational cost to cubic in resolution (at least asymptotically).

Overall, the manuscript is a worthwhile contribution that will help to guide future model development and to justify why such developments are worth the effort. It is, in a sense, an opinion piece, so there is little to criticize with respect to scientific merit. I do have a limited set of comments that might help clarify points and answer questions that some readers may have.

Title I don’t find this title to be a particularly helpful characterization of the work. Maybe something more specific e.g. ‘Asymptotic analysis of implicit versus explicit methods in ice sheet models’ would be better.

L25 ‘it is generally accepted...’ I am not sure that I agree that this is generally accepted. There remain important works in Antarctica where models are run at 20km resolution or more and I’m not sure that they are ‘invalid’. It is worth perhaps being more specific about the resolution requirements of specific tasks, e.g. capturing detailed perturbations to the grounding line or calving front, the influence of steep subglacial topography, etc.

L34 While explicit time stepping is indeed the paradigm, the 'very few exceptions' ought to be referenced. While I am sure there are more, here are three papers that use a coupled and implicit geometry-non-SIA-velocity solution scheme: Gudmundsson (2013); Brinkerhoff et al. (2017); Shapero et al. (2021)

L57–60 'Unconditional stability' is a useful shorthand here, and I'm alright with its use, but it also deserves a bit of an asterisk (stated here or elsewhere) that there is a finite radius of convergence that when combined with a practical initialization procedure can still yield some kind of time-step restriction. This type of thing was seen, for example, with too-rough topography in Bueler (2016). In addition, there are other considerations that might yield only conditional stability: complicated boundary conditions like calving fluxes (and especially knowing where to impose them) come to mind.

L83 It might be useful to state here that velocity depends also on the gradient of the bed elevation.

L92–94 This sentence is a bit mysterious. Is this trying to describe the instability caused by violating the CFL or a different type of wiggle?

L101 I'm not sure what 'primary' means here. Perhaps something like 'The parameters that we consider model efficiency with respect to are ...'.

L111-112 Perhaps clarify that these are diagnostic (and thus not 'state variables') because the time-derivative in the more general Navier-Stokes equation has been set to zero due to the very-viscous situation (or the low Reynolds number).

L133-134 I like casting things as optimistic and pessimistic, but I think that a more technically descriptive phrasing might be 'advective stabililty condition' and 'diffusive stability condition'.

L212 'Not enough better'. Not enough better for what?

L225 'The Table' → 'Table 2'.

References

Brinkerhoff, D., Truffer, M., and Aschwanden, A. (2017). Sediment transport drives tidewater glacier periodicity. *Nature Communications*, 8(1):1–8.

Bueler, E. (2016). Stable finite volume element schemes for the shallow-ice approximation. *Journal of Glaciology*, 62(232):230–242.

Gudmundsson, G. (2013). Ice-shelf buttressing and the stability of marine ice sheets. *The Cryosphere*, 7(2):647–655.

Shapero, D. R., Badgeley, J. A., Hoffman, A. O., and Joughin, I. R. (2021). icepack: A new glacier flow modeling package in python, version 1.0. *Geoscientific Model Development*, 14(7):4593–4616.