Interactive comment on "Sea-level response to melting of Antarctic ice shelves on multi-centennial time scales with the fast Elementary Thermomechanical Ice Sheet model (f.ETISh v1.0)" *by* Frank Pattyn

Anonymous Referee #1

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General comments:

This paper presents a thorough and clear description of a new ice sheet model, akin to hybrid dynamics SIA/SSA models currently used for Antarctica, but with some reasonable and innovative simplifications so it is computationally fast. The model is implemented in MATLAB and will be a useful tool to engage students in teaching and workshop environments, as well as being capable for many research applications.

In this paper the model is thoroughly tested against established benchmarks (EISMINT, MISMIP) and validated vs. modern Antarctica. Sensitivity experiments of Antarctic re-

treat for simple warming perturbations are described. One important result is that much larger grounding line retreat is obtained with a Coulomb-friction based parameterization of grounding line flux, compared to that based on power-law sliding, but further testing may be desirable (see below).

Specific comments:

(1) The treatment of ice temperatures is based on classic vertical profile equilibrium solutions which allow for vertical ice velocity, and then time lagged with an e-folding relaxation towards these solutions at each grid point. The timescale of the e-folding lag is based reasonably on the local Peclet number (pg. 17, eq. 42). This is probably the most drastic simplification from other 3-D hybrid models, and neglects horizontal advection (which cools mid-level interiors as cold surface ice is advected downwards and outwards, and cools the cores of ice shelves supplied by flow across thick grounding lines. A fairly arbitrary compensation for this lack of cooling is attempted by reducing the strain heating (pg. 17, line 6). This simplified temperature treatment is evident in the benchmark intercomparisons in the Appendices, where basal temperature is the only field with poor results.

As a suggestion, perhaps basic horizontal temperature advection could be added to the model, ust by adding an additional term in Eq. (41): ... + u dT/x + v dT/dy with (u,v) given by (12) and T is the column mean temperature. That probably would not require much CPU or slowdown of the model.

Given this concern, I suggest that a map of the models basal temperatures for modern Antarctica be shown, and compared with existing model and data based maps (of which the author is a leader).

(2) It is puzzling why the inverse procedure for basal sliding coefficients (p. 23-24, Fig. 5) yields quite large errors in surface elevation (∼200 m) in some regions of the interior East Antarctic plateau. The inverse procedure should reduce them to 10's m (Pollard and DeConto, 2012b) (even if the bed elevations are in error, model or observed, cf.

pg. 24 line 19).

Perhaps these larger errors are due to regions of the bed erroneously being frozen. In frozen basal regions the inverse procedure cannot reduce the model's surface elevation errors. So this is an additional reason to request a basal-temperature map.

nb: "ice thickness", pg.24 line 1, should probably be "ice surface elevation".

(3) One important result is the greater grounding line retreat with TGL (Coulomb-friction based grounding line flux parameterization, Eq. 25), vs SGL (power-law sliding based, Eq. 23). All experiments shown use power-law sliding (Eq. 15) for the interior grounded ice, and none use Coulomb sliding (Eq. 21). My concern is that the combination of TGL with power-law interior sliding is not compatible, and the mismatch in the physics may lead to spurious behavior in grounding zone regions. (The discussion on pg. 13, lines 24-27 may be relevant).

To address this concern, I would request additional runs be made with Coulomb friction law (Eq. 21) and the TGL grounding line parameterization. This would ideally also involve re-doing the optimization spin-up for basal properties, which may still be feasible by changing phi (till friction angle) instead of A_b in Eq. (55). Alternatively, the combined Eq. (22) could be used instead of (21).

(4) The use of driving stress instead of basal stress in the basal sliding law to avoid iterations (pg. 10, Eqs. 15,16) is one of the features used to speed up the model. But maybe the 20% of the ice sheet where driving stresses are not essentially balanced by basal stresses (p.10, lines 16-17) are in important regions such as ice streams. This concern could be addressed by one sensitivity test in which the approximation in Eq. (16) is not made (requiring expensive iteration).

(5) The subglacial water pressure p_w in Eqs. (19) and (20), pg. 11, is assumed to depend on elevation minus sea level, which is a common step in many models. But it is hard to see how the subglacial water system can sense hydrostatic pressure from

the ocean at all, more than $\sim$ 100 or 200 km inland from the grounding line.

Technical points:

p.3, Fig. 1. I suggest indicating in the figure that sea level is at z=0, as seems to be required in Eqs. 18, 19 and 20. And z_{sl} must = 0 (p.7, line 3). Alternatively, replace b throughout p.11 with $b - z_{sl}$.

p.7, Eq (2). More correctly, $v_{sia} = v_b + ... |tau_d|^{n-1} tau_d$

p.9, line 7 et seq. To avoid confusion, say explicitly that tau_f is the free-floating stress, used later in Eq. (24) as well as in (3),(4) via eta in (11).

p.11, line 3: Why might the friction angle phi be a function of bedrock elevation, physically?

p.12, lines 6-7. The sentence " However, expressed as a ..." is unclear to me.

p.13, lines 7-10. Here, it might be helpful to mention that a staggered grid (Arakawa C) grid is used as shown in Fig. 2.

p.14, Eq. (27). Say that this is only applicable for SIA advection.

p.14, lines 11-22: Say whether this 'maximum strain check' is applied everywhere, on ice shelves, or just at the grounding line.

p.17, line 24 and Eq.(42). Say that this is vertical advection (not horizontal).

p.18, line 13. Specify the value of E_f used for ice shelves.

p. 19, lines 1 and 10. Say that the equilibrium bed topography and loads (b_{eq}, h_{eq}, $h_{w eq}$) are taken from modern observed fields (Bedmap2), if that is the case.

p.19, line 18.Say that the local numerical integration is for Eq.(38) (I think).

p.19, line 24. Iterations are also eliminated due to the approximation of driving = basal stress in Eq. (16).

p.21, line 24. A simple one-valued PDD is ok for modern Antarctica with little surface melt. But the surface melt treatment will need improving (snow vs. ice, refreezing, etc.) to represent greatly increased surface melt around the Antarctic margins in warm future climates.

p.22, line 9. Say where ocean temperatures T_oc are obtained from. Actually it seems that Eq. (53) and T_oc are not used in any experiments here, for which the melt rate M is simply prescribed region by region (p.30, lines 17-19).

p.22, line 16. Eq. (53) produces higher melt rates closest to the grounding line not because it's quadratic, but because the freezing temperature T_fo decreases with depth (noting h_b in Eq. (54) is negative below sea level).

p.23, line 1. Perhaps change "further constrained by" to "driven by".

p.25, line 14. Change "back by" to "back to".

p.27, line 3. Perhaps change to "of the model and the approximations..."

p.28, Fig. 9 caption, 2nd line. Remove "(a)".

p.30, line 8. Perhaps change "provoked" to "applied".

p.30, line 10. *Why* are TGL runs characterized by higher driving stresses?

p.31, Fig. 11 caption, 2nd line. Say "Atmospheric temperature forcing is..."

p.34, line 22. Mention that the agreement with the benchmark(s) is shown in the Appendices.

p.34, lines 27-28. Change to "Despite the approximations, the results of thermomechanical coupling of ice sheet flow are also in good agreement with the EISMINT benchmark..."

pg.34, line 29: Perhaps change to "compared to the other benchmarks,"

pg.35, lines 7-8. Change to "requires membrane stresses at both sides of the ground-

ing line to be resolved with sufficient detail (Schoof 2007a),"

pg.35, line 10. Mention in parentheses that this rule is that on pg. 13, lines 9-10.

pg.35, lines 28-29. Change to "Direct comparison is not possible with recent studies of Antarctic ice mass loss that are forced by atmosphere-ocean models following so-called RCPs (Representative Concentration Pathways). Direct comparison with the SeaRISE..."

pg.36, line 8. Perhaps describe in a few words what "RCP8.5 amplification" is.

pg.36, lines 28-29. Perhaps change to "with the exception of grounding-line zones with small-scale bedrock variability, where grounding-line response to atmospheric and oceanic forcing is sensitive to spatial resolution."

pg.37, line 8. The "dominance of ocean forcing" in this paper relies on the absence of physics such as hydrofracturing that occur due to large increases in surface melting around the margins. With RCP8.5 at least, there will be a huge increase in the latter within ~100 to 200 years, which could affect the ice sheet in unexpected ways.

Appendices, figure captions A2 to A5. It would help to specify the benchmark experiment (EISMINT I or II, MISMIP, etc) in each caption, especially if the figures appear on different pages than the relevant text.