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Interactive comment on "BrAHMs V1.0: A fast, physically-based subglacial hydrology model for continental-scale application" *by* Mark Kavanagh and Lev Tarasov

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I would like to apologize to the authors for this much delayed review.

M. Kavanagh and L. Tarasov present a new model to compute water flow under ice sheets, and study feedback processes between subglacial water flow and the much slower dynamics of overlying glacier ice. Thus, the model physics and numerics have been tailored for coupling to ice sheet models which typically operate on continental (thousands of kilometres), and glacial cycle (multi-millenial) scales that characterise the spatio-temporal evolution of the Earth's largest flowing ice masses.

The need for coupled models of ice dynamics and subglacial hydrology has been identified for decades, however it has been subject to two major limitations. First, subglacial water flows much faster than glacier ice, which is an issue for both physical and numerical model implementations. Second, although subglacial hydrology theories are available, physical parameters are largely unconstrained due to the difficulty of observations. In the present manuscript, M. Kavanagh and L. Tarasov address these issues by using simplified physics, a semi-implicit discretization scheme, and a parameter sensitivity study.

The paper contains an introduction summarizing recent advances in modelling subglacial hydrology, a description of the model's physics, an application to a synthetic test case where the model yields expected results, and a more realistic application on the modelled Last Glacial Maximum and early deglacial North American ice sheet complex, including a sensitivity study to the most important model parameters. Discretization schemes for subglacial hydrology are explicated in Appendix.

BrAHMs is coupling subglacial hydrology model to ice dynamics in ways that will facilitate its application to continental-scale ice sheet dynamics. Publication of the model physics, numerics, and the presented test cases in *Geoscientific Model Development* makes a lot of sense and I fully support it. Nevertheless, I am concerned by the fact that source code has not yet been made publicly available, and I think that the manuscript need a few crucial changes before publication in order to ensure reproducibility.

Below I provide comments regarding the points for which I believe changes will improve the manuscript. I hope the authors will find these helpful in revising their manuscript and wish them success with final publication and future applications of this innovative model.

1 General comments

Code availability

I think it is policy of *Geoscientific Model Development* that all computing code accompanying publications should be made publicly available, unless reasons against that are clearly stated. Since BrAHMs is one of the first subglacial hydrology models allowing coupling to an ice sheet model, I think code publication would be strongly beneficial to both the authors and the ice sheet modelling community.

Actually I would even recommend a platform that allows version control and issue tracking. For instance PISM (https://github.com/pism/pism) is another coupled ice dynamics and subglacial hydrology model for which source code publication and public bug tracking has been highly beneficial.

Parameter values

In the present manuscript, Table 1 lists hydrological parameter ranges used in the sensitivity test. However, values for parameters kept fixed in the sensitivity test are not given in the manuscript. These include glacial system model parameters (Eq. 1), subglacial hydrology model fixed parameters (Eqs. 2–5), and parameters defining the synthetic ice surface geometries and melt distributions for the first test case (Eqs. 6–8). For instance, the scale of the synthetic ice sheet and the amplitude of bed perturbations used in the test case are crucial information currently missing from the manuscript.

For the sake of reproducibility, including future reproduction of the synthetic test case by other models, I think all parameter values should be included in the manuscript before publication. I would suggest a separate table containing all fixed parameter values.

Readability of figures

Printer-friendly version

Discussion paper

I found that the current figures don't reflect the scientific quality of the work undertaken by the authors. This is especially destructive given that the manuscript text is actually very well written. Below I suggest a few simple changes that I believe will enhance the readability of figures.

On Figs. 1–3, the choice of colours does not serve the results at all. Since non-null water thickness and pressure is localized around the ice sheet margins, it is very hard to discern the individual colour bands. Instead I would suggest monochromatic (e.g. white-to-blue, white-to-red) colourmaps, preferably different for water thickness and pressure.

Also on Figs. 1–3, contour lines are so thin that they became invisible on my print. Overlayed basal and surface topography contours (Fig. 1b) are also hard to distinguish. I suggest to remove basal topography contours, and slightly thicken surface topography contours.

Finally, Figs. 4–5 are hard to read because many markers overlap. Here my suggestion would be a different presentation, using volume errors instead of total water volume, a logarithmic scale to discern small errors, and perhaps different colours for positive and negative errors.

2 Specific Comments

p. 2, l. 4–7: Only a few subglacial hydrology models have been described in the literature for continental-scale ice sheets. [...] These models take various approaches to simulate the flow of basal water using physically-based equations.

This paragraph introduces a short review of recent developments in subglacial hydrology modelling (decoupled from ice dynamics), which I found very useful to guide the reader in understanding choices made by the authors in designing their own model. However, one of the first questions I had when opening the manuscript was how BrAHMs differs from the approach employed by Bueler and van Pelt (2015), to my knowledge the first functional model of coupled subglacial hydrology and ice sheet dynamics. I think this review is be the right place to address this point.

p. 4, l. 27–28: We use an empirical relation for water pressure from Flowers (2000).

Here I think it would help to shortly explain the type of measurements and time scale used to develop this empirical relation (Eq. 4), or at least give a page number.

p. 5, l. 1–2: P is limited to ice overburden pressure. h_c equals till thickness times porosity and is effectively the water thickness that the till can hold before becoming over-saturated.

I understand that P is capped at overburden, but additional water could be stored in the till, resulting in $w > h_c$. Is this correct? A short sentence to clarify what is happening over saturation would help here.

p. 5, l. 11–14: From here the model employs a down hydraulic gradient solver (Tarasov and Peltier, 2006) that looks at the neighbours of a tunnel cell and allows water to flow instantaneously down the path of steepest potential gradient (channelizing cells along that path) until there is no cell with a lower hydraulic potential (forms subglacial lake) or the water exits the ice sheet.

I assume that the down gradient solver is the computational bottleneck of the model. I guess that 'instantaneously' means that the hydrological solver is ran offline while the ice model pauses. Here it would help to clarify whether that is the case (or if only the tunnel solver is ran offline at regular intervals), and (already here in the methods) how often would one presumably need to run the hydrology model, and what are the consequences of this assumption in terms of the domain of application of the coupled model.

p. 6, Figs. 1 caption: The symmetric results in a) are due to a known issue with the tunnel solver being slightly asymmetric.

The results in a) look symmetric indeed, but I wonder if the authors meant to write about the asymmetric results in b), which would make more sense.

p. 6, Figs. 1–2:

Eq. 6–8 are given in polar (or at least radius) coordinate. The discretization perfomed in the appendix also uses polar coordinates. However Figs. 1–2 appear to use a regular grid. Labelling the x and y axes would help to resolve this ambiguity.

p. 7, l. 7: The next test placed an ice sheet flattened near the edges on a dilating (sinusoidally-wavy) bed.

Could the authors please include a formula for the sinusoidally-wavy bed?

p. 7, l. 20: Next, the ice dome was placed on an incline to test the flow of water.

Could the authors please include a formula for the inclined bed?

p. 8, l. 5–6: The simplified aquifer drainage of Johnson (2002), uses an aquifer that simply drains a percentage of the present water in a cell. The percentage of water drained in this model is represented by the D_r parameter.

I wonder how this new parameter D_r relates to $d_{s:a}$ (Eq. 2).

p. 8, l. 12–13: The water flux between cells is directly proportional to the hydraulic conductivity of the sediment. For each run, the conductivity was allowed to vary between a minimum and maximum value defined in the range of K_m.

Here it would be nice to have a short explanation as to why this approach (Eq. 9) is superior to a constant conductivity, and whether it is backed up by measurements or theory.

p. 9, l. 4–8: In the hydrology model, this is represented by parameter T_c , which acts to reduce the conductivity as a function of temperature. When the basal temperature is close to the pressure melting point (PMP), there is little change in the hydraulic conductivity. Conductivity decreases to an extremal low value as the temperature approaches the value of T_c.

I wonder if the decrease in conductivity could be described by a function? An equation would be very useful here.

p. 14, l. 1–2: The results of these tests show that the model is mass conserving.

This is not very obvious from the rest of the manuscript. I would suggest to add a plot of mass conservation errors (claimed on the order of 10^{-12} m) or remove this statement.

3 Technical Comments

p. 1, Affiliations: St. Johns / St John's

The spelling probably needs to be homogenised here.

p. 1, l. 13–14: Channel formation [...] display the arborescent

An 's' is missing here.

p. 7, l. 30–31: As such, there are a number of poorly constrained parameters in the model.

This is a good place to reference to Table 1.

References

Bueler, E. and van Pelt, W.: Mass-conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6, Geosci. Model Dev., 8, 1613–1635, doi:10.5194/gmd-8-1613-2015, 2015.

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