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Discussions

Interactive comment on "Comparison of four calving laws to model Greenland outlet glaciers" *by* Youngmin Choi et al.

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This study compares four quasi-empirical calving laws to assess their suitability in predicting terminus retreat from 9 Greenland tidewater glaciers. The authors optimize unknown parameters in the calving laws to best fit each glacier and then compare the best projected calving front position with observed calving front positions and to project mass loss associated with calving forward. The authors find that so-called von Mises calving is the best fitting calving law for most glaciers.

Although several studies comparing calving laws have been published in the literature, most previous comparisons have focused on flowline models. This study is one of the first to assess the behavior of different calving laws using two-dimensional (map-

view) glacier geometry and is a promising first stab at this problem. Overall, I think the manuscript is quite promising and most of my comments are relatively minor or quaintly technical in nature. Here, I should also disclose, I have found myself reviewing several of the authors prior papers. I think the authors and editor should be cognizant of the fact that my comments likely overlap and they may want to discard or de-emphasize some comments to make sure that the same voice (mine) is not overly contributing to this conversation. My more detailed comments are included below:

The authors come to an interesting conclusion that the Von Mises calving law is the calving law that best describes observed changes and, hence, might be the best to use for future projections of Greenland outlet glaciers. This is an interesting result, but I would encourage the authors to dwell a little bit more on *why* this calving law seems to perform so well and to revisit the limitations associated with making projections based on tuned calving laws. The fact there is such a disparity in best fitting parameters is interesting because it implies there is no single parameter that can be plugged into a calving law that will yield adequate results. This in turn implies that parameters appropriate for one instance of time (or slice of time) may not remain valid in the future. This would significantly impact projections if the so-called best fitting parameters evolved over time.

There is a final interesting point, which is that the Von Mises calving law is fundamentally different from the other calving laws. Each of the other calving laws depends on local (scalar) properties of the glacier at (or at least near) the calving front. These laws are all essentially empirical, but also depend solely on coordinate system independent parameters of the system. The Von Mises calving law, in contrast, depends on the velocity at the calving front and velocity is not reference frame independent. For example, if I were to adopt a Lagrangian reference frame that moves with the glacier calving front, the velocity at the calving front would be exactly zero and, as far as I can tell, the calving rate would also vanish. This dependence of the calving rate on reference frame is something that theorists would find disturbing, but is less bothersome if we think of the law as empirical and calibrated to work well in some defined parameter regime.

Another difference between the Von Mises calving law and the other laws is that the velocity dependence of the Von Mises calving law means that the calving rate is non-locally determined. Changes in faraway boundary conditions (or at least in behavior upstream from the calving front) could instantaneously propagate and affect calving rates. This "action-at-a distance" is also interesting and means that the Von Mises calving law is an integrator of glacier behavior in the vicinity of the calving front. Overall, I do wonder how much of the behavior of the model is due to the appearance of the velocity in the calving rate. I would like to hear the authors comment more on these model formulation differences partly because I think I can rationalize the velocity dependence of the Von Mises calving law as a linearization about steady-state. In this argument we start from a steady-state condition in which calving rate = terminus velocity and then linearize to deduce a velocity dependent calving rate. This linearization, however, does depend on linearizing about a steady-state and thus might explain some of the variability in inferred yield strengths. It would also hint that the calving law would remain appropriate for short periods of time, but could fail when applied to longer time periods. This comes back to my point about uncertainty in projections using a tuned parameterization.

Miscellaneous comments:

Page 4, line 25: I believe that HAB and CD models could also be implemented in such a way that they yield continuous rates. This can be done relatively easily for the HAB criterion by taking the advective derivative of ice thickness at the calving front and determining the rate of advance necessary to maintain a critical height above-buoyancy. I believe one could also do this for the CD model by relating the stress at the calving front to the ice thickness and water depth. This may (or may not) change some of the behavior of these models.

I think it would for beneficial if the authors could state in a few sentences the spatial

and temporal resolution studies they have done to make sure that results are numerically converged. I have often found that accurately simulating advance and retreat of glaciers requires far more resolution than I would have expected. I do wonder if the blocky behavior of the HAB and CD models might be reduced with finer resolution and if any of the other behavior of the models is persistent when resolution is halved or decreased by a factor of 8.

Equations 7-8: I wonder if it would be better to write these equations in terms of deviatoric rather than resistive stresses. Resistive stresses, as defined by Van der Veen, are not the same as deviatoric stresses. Here, it is unclear if deviatoric stresses (e.g., near line 15) or resistive stresses (equations 7-8) are used. Deviatoric stresses are easy to compute using a numerical model and are directly related to the rheology. Resistive stresses have an awkward factor of two difference. Resistive stresses were a useful quantity when attempting to understand which terms in the stress balance are important, but less useful when using an ice sheet model where factor of two errors often creep into calculations.

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