**Title**: Response of Pine Island and Thwaites Glaciers to Melt and Sliding Parameterizations
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**Journal**: *The-Cryosphere*
**Reviewer**: Tyler Pelle (Scripps Institution of Oceanography; tpelle@ucsd.edu)

**Overview**:
In this work, Joughin et al. investigate the impact of using both Weertman-style and regularied Coulomb friction law, in conjunction with a linear scaling to the associated basal shear stress field for each law that enhances bed weakening with proximity to the grounding line, on 200-year simulations of Pine Island and Thwaites Glaciers. In addition, this paper also compares the response of these glaciers to an ensemble of randomly generated ice shelf basal melt volumes. The authors find that the choice of friction law has a relatively minor impact on ice volume changes of this sector and recommend use of a regularized Coulomb friction law when only one friction type is used. In addition, parameterized bed weakening led to significant enhancements in the 200-year global sea level contribution of this region, highlighting that such weakening should be included in future ice sheet model simulations either through this explicit manor, or through an effective pressure dependance. Lastly, the sea level response of the system was found to have a strong linear dependance on the total integrated ice shelf melt volume through the 200-year simulations.

I have to admit that I had a bit of a tough time working my way into this paper because the basal friction overview is quite long and involved, which I think might be a bit much and could be simplified to only include information that is needed to support the results/discussion/conclusions. I also found that visualizing differences in some of the figures was challenging because of the use of different y-axes limits, many of which I think can be made consistent. However, once into the results, I found this work to be an absolute pleasure to read and is full of really wonderful conclusions and insights that would be of wide interest to both the ice sheet modeling and broader scientific communities. It is also clear that this manuscript has been built on a long line of research that the authors have been working on for quite some time, so it is great to see everything come together in such a wonderful way. Below, I provide a number of suggested edits the authors can make to improve the manuscript, most of which aside from restructuring are small-technical corrections that should be easy for the authors to address. Due to the restructuring of the beginning, I suggest major revisions; however, I am very supportive of publication once these comments have been addressed.

**General Comments**:
- **Basal Friction Overview section**: This section is quite long and I have to admit that I got a bit confused reading through it, which was challenging because it sets the stage for the rest of the paper. There's a lot of analysis and equations presented and I am wondering if it is possible to shorten this section to only what is necessary for interpretation of

results/conclusions? After reading through the paper, I think the critical information needed in this section is that *a linear scaling that depends on a height above flotation threshold h_{T} (found in previous work to be ~41-46 m for PIG) is applied to \tau_{b}, which is solved for via both RCF and Weertman-style friction law. In this paper, we will investigate how variation in h_{T} applied to both the BCF and Weertman sliding laws, as well as ice shelf melt, impacts future ice loss of PIG and THW.*

Given that, I think both friction laws that are used in this paper, as well as the linear scaling, should be provided, and other information should be limited as needed for clarity. For example, there are a few forms of Weertman sliding laws presented (eqn. 1, 6) and I am not sure which one is used in the simulations. Also, the friction law that combines Coulomb and Weertman (eqn. 4) is not used in the rest of the paper, but stimulates quite a long discussion about h_{f} transition points (L81-89) and effective pressure (L91-109; which is not used in either of the friction laws used in this study since it is subsumed into the friction coefficient solution). While I think this information is really fascinating and I think the authors did a great job on the analysis, I unfortunately don't think it is appropriate in its current place in the manuscript and suggest the authors revise this section and shorten it considerably. Perhaps a lot of this can go into an appendix, with information in the main manuscript saved for only what is most pertinent?

- **Consistency of language and figure axes in manuscript**: I noticed many different forms of "PIG and Thwaites Glaciers", "PIG and Thwaites glaciers", and "Pine Island and Thwaites glaciers". In my opinion, I feel like the "PIG and Thwaites Glacier" would be the most correct, but I am very happy for the authors to choose their favorite variation and use only it throughout the main manuscript, supplement, and in figures and associated captions. I pointed out a few places in the manuscript where I noticed this, but I likely did not catch them all, which is why I raised it as a general issue. On a similar note, I also noticed many variations of y-axes limits on figure panels that could be made consistent across the entire figure. This could help visualize differences in figures where there are many intersecting lines and many panels.

**Line Comments**:

- L8: Specify ice shelf basal melt here so readers know you are not referring to melt of grounded ice.
- L11: Change "above" tp "upstream of"
- L14: remove "work" – i.e. "our simulations suggest"
- L26: "continued melt forcing" – I think you are referring to ocean induced ice shelf basal melt based on the citations, but I think it would be helpful for readers if you were explicit about this here. Perhaps here you can say " . . . continued ocean forcing in the form of ice shelf basal melting (hereon referred to as melt)."
- L33-34: I think it would improve readability if the definition of variables (\tau_{b} and u_{b}) is confined to the "Basal Friction Overview" section.

- L40: By models, do you mean basal friction parameterizations? If so, please specify because you use “models” twice in this sentence that means two different things.
- L50-54: As per line comment L33-34, I think this would be a perfect place to introduce variables \tau_{b} and u_{b}.
- L51: Is this the Weertman sliding law used in the simulations, or is it eqn. 6?
- L70-90: I think there is a lot of interesting information here but it is quite lengthy. If the main point is that we expect Coulomb sliding behavior near the GL and at some transition point, we expect Weertman sliding, maybe this can be said more succinctly with less analysis? This seems very in-depth for a section that is not either the results or discussion.
- L81-89: I have to admit that I got a bit lost with some of the analysis here. In particular, I am a little confused about where the value of 45 m came from and why this is only computed for the near GL region (Fig. 1a) - can a similar value be computed and added to the plots for trunk (Fig. 1b) and inland tributary (Fig. 1b)? Also, in figure 2, are you plotting h-h_{f} as per the equation at the end of line-83? If so, this should be mentioned in this paragraph and also in the figure caption of figure 2. For figure 2, why are the values of h-h_{f} (1, 41, 86, 176) chosen?
- L93-95: There are recent modeling efforts that model upstream Thwaites/PIG effective pressure with subglacial hydrology models (e.g., Hager et al., 2022; Dow et al. 2023) that show low effective pressure far upstream of the grounding line - I would recommend citing them here since they support your claim. It is difficult to know how accurate these model simulations are, but they are likely the best we can do at this point!
- L129: “Close to the grounding line” is defined as h-h_{f}<41, but figure-2 shows that there are numerous regions where the contour of h-h_{f}=86 is nearly superimposed onto the line h-h_{f}=41; why was the value of 41 m chosen?
- L135: When you say “as the surface elevation approaches flotation”, are you referring to in figure 3 when h-h_{f} approaches 0, meaning when h=h_{f}? In line 78, you defined h as the ice thickness, so is surface elevation accurate? Perhaps just saying “as ice approaches flotation . . .” would be more clear?
- L140-145: While I think it is obvious in eqn. 8, I think it should be reiterated that this linear transformation applied to \tau_{b} evolves in time to the changing ice thickness in your simulations.
- L161: You have two section-2’s (the friction overview and methods section).
- L177: Need a new paragraph space between these paragraphs
- L178: Do you mean Equation 7?
- L186: I think it is worth mentioning that your computed fields for the friction coefficient and A do not change in time.
- L197: Is the ice front fixed (i.e. no calving is simulated)? Is this a major limitation given that your 2021a work indicated that ice shelf retreat was the primary driver of recent

speedup of Pine Island Glacier? If so, I think this should be mentioned somewhere in the text.

- L199: I'm just noticing this now, but I think it would be more correct to say "PIG and Thwaites Glacier" since PIG stands for Pine Island Glacier. See general note about consistency through manuscript.
- L208-215: This compiled velocity map is very interesting, it would be great to see a figure of it somewhere in this paper! Perhaps the same can be done for the SMB and combined into one figure?
- L220: Does SMB vary in time in the simulations?
- L240-245: Another interesting pattern in figure-5 is that at higher melt rates (panels c/d), corresponding Weertman and RCFi mass loss time-series seem to align more than for lower melt simulations (in the top two panels, the Weertman lines are all clumped above the RCFi lines). That is, it seems like the choice of sliding parameterization becomes less important when the system is forced with higher melt rates. Do you agree? This could be an interesting point for the discussion.
- L250: Please change "Thwaites" to "Thwaites Glacier" here and also through the manuscript. Also, there are times when you capitalize "Glacier", and when you keep it lowercase (i.e. Thwaites glacier, L261) - I think it is correct for it to be capitalized, so please make that consistent throughout the paper as well.
- L263: Change ". . . sensitivity for PIG is -0.24 to -0.51 mm Gt^{-1}yr sle for PIG and . . ." to ". . . sensitivity is -0.24 to -0.51 mm Gt^{-1}yr for PIG and . . ." (you said "For PIG" twice here)
- L270: Is the unit supposed to be "a few hundred m/yr" or "a few hundred m", which seems more in line with the values in figure-8.
- L277: Change "above the grounding line" to "upstream of the grounding line" here and throughout the manuscript.
- L281: The notation "Figure 9e&f" seems a little messy, perhaps could use "Figure e/f"? I think this is personal preference and maybe  a little pedantic, but I have not seen the "&" symbol used in this manor in a manuscript before.
- L287-289: It would be nice to see what some of these melt distributions look like since they seem like a primary control on the spatial distribution of retreat of Thwaites Glacier.
- L317-318: I would even say that simulations with greater h_{T} values lose less mass than those with higher h_{T} values for these PIG simulations, which is pretty fascinating! I really enjoy your call to earlier work here that investigated this paradox.
- L346: I'm not sure if it is just the way my computer rendered the PDF, but it seems like there is an unnecessary space in the word "ri ght", but I'm not sure if this is a typo.
- L350-357: I really enjoy this discussion and am excited with the prospect of future work that compares such implementations of bed weakening near the grounding line.
- L359-374: I understand the reduction of section "Basal Friction Overview" might cause issues with this and the preceding discussion paragraph, but I think if you put a lot of the

"Basal Friction Overview" information in an appendix, you can still keep these paragraphs (with references to the equations in the appendix), which I think are very important findings and thoughts from your work.

- L377: I've noticed a few variations of "PIG and Thwaites Glacier" (L377), "PIG and Thwaites glaciers" (L261), and "Pine Island and Thwaites glaciers" (L770). Please pick one and keep consistent throughout the manuscript, supplement, and all figures and figure captions.
- L406-417: See note for figure 10 below - In short, I would recommend a different way of showing these results. Given that this paragraph focuses mainly on the associated r^{2} values, I'm wondering if figure 10 could be consolidated into a table?
- L427-429:I got confused by the phrasing "results lie along a line" and "results that fall well off a line"; it took me a second to realize you are referring to a linear regression line. Maybe rephrase to clarify.
- L430-432: Seroussi et al. (2023) found that treatment of ice dynamics was the main driver of uncertainty in the ISMIP6 ensemble through 2100; however, this was across the entire AIS. In line-431, maybe specify that you are only referring to the ASE (i.e. ". . . suggests that differences between models in this sector may largely . . .").
- L440: This is true for the ASE, but would these conclusions hold for other sectors of Antarctica? If you are not sure, it might be worth specifying here that you are referring to coupled ice-ocean models of the ASE.
- L502: Consider rewording: " . . . our results suggest that melt-driven losses from PIG and Thwaites Glacier over the next two centuries likely will not exceed 10 cm."
- L511-512: Please remove hyperlinks – also, I think "comit" should be changed to "commit" in this section.
- L797: Magenta box in panel-a denotes domain for figure 9 (not figure 10)

**Figure Comments**:

- It can be quite challenging to compare VAF losses between panels in figures 4-7 since the y-axis limits are all different. Where appropriate, can you please use the same y-axis limits? I think this would be very helpful for all panels in figures 4-6, as well as panels B/C of figure 7. Otherwise, all of the curves look fairly similar and it can be difficult to visualize differences between them, which I think is the ultimate goal of these figures.
- Figure 2: Perhaps it was said in the main text, but it would be good (in the figure caption) to reiterate the friction law that was used to compute the basal shear stress that is shown in panels-A/B.
- Figure 3: The text and lines in this figure are a little blurry and/or choppy (as with figure 1 as well). Will you output these as PDF's in the final submission?
- Figure 8: It doesn't seem like two color bars are needed, but rather you could use one that diverges at 0, with blue (negative) trailing off to the left, and red (positive) trailing off to the right. Also, would it be possible to scale the intensity of the blue so that it uses the

same color scale as red (i.e. reaches maximum intensity at -500 m). This should result in very pale shading of blue where you have height above flotation gains, which would seem more appropriate since now, it appears like the gains in the bottom and upstream parts of the domain are stronger than the losses Thwaites Glacier experiences, which is not true.

- Figure 10: I believe I understand that the main point of this figure is to show that the linear relationship between total integrated melt volume and VAF change holds for various other melt parameterizations, but I think the number of different-shaped symbols is very distracting and is rather uninterpretable for the reader. Many of the symbols are clumped over each other at lower x-values and also, the meaning of the different symbols is not explained in the main text (i.e., I know the different symbols are different melt function outputs, but I have no idea what “mr_1”, “mr_4”, “80_700”, etc. are specifically), and I don’t think readers should have to read the supplement to interpret a main-text figure. Ultimately, I don’t think the symbols matter given that the analysis is not dependent on individual melt functions, so I wonder if the authors can remove the 10 symbol-types and use just one symbol and the different colors to represent the different melt function outputs? I per line comment L406-417, I think this figure could also be consolidated into a table given that the main piece of information that is used from it are the r^{2} values.
- Figure S1: No change is needed in the text, but I am just curious what metric you use to prescribe your mesh resolution?
- Figure S2: In the figure caption, please include the full in-text citation for Barnes and Gudmundsson (2022).