Author response for Reviewer 2

I would like to thank the reviewer for commenting on the manuscript constructively with valuable ideas and insights. I appreciate the time and effort you made that will surely improve the quality of the paper. Below are my detailed responses to the Reviewer Comments. The original text is in **black** and my response is in **green**.

Overview

This study investigates the interannual impact of increased basal lubrication on glacier flow using a 1-D physical framework and tested on >100 glacier basins in Greenland and Austfonna Ice Cap Svalbard. Within the model framework, they determine that both the Péclet number over length (P_e/ℓ) and a metric proportional to the product of speed and ice thickness gradient, termed J_0. J_0 reflects the initial response to basal lubrication, and P_e/ℓ reflects a general vulnerability to an elevation perturbation. The model results predict that glaciers are most sensitive to increased basal lubrication (that is, they will undergo greater acceleration given perturbed basal conditions) when J_0 is relatively high and P_e/ℓ is minimized or negative. Finally, these two quantities are calculated from observational data in 1996/1998 and compared to the acceleration observed along flowlines by comparing earlier speeds to those observed in 2018 from ITS_LIVE. They conclude that given a certain combination of glacier thickness, thickness gradient, and speeds are met, enhanced basal lubrication can destabilize and accelerate the full length of the glacier. This is an interesting approach aimed at identifying glaciers that are vulnerable to destabilization and provides useful information on how the baseline glacier geometry informs potential basal vulnerabilities. The manuscript is well-written and presents a creative approach to constraining a complex science question. The figures complementary to the text, and I appreciate the effort to document and archive model code and results through Github and interactive Jupyter notebooks. With some expanded motivation, and polished analysis and figures, this paper could make a valuable contribution to the cryosphere/glaciology community. Below, I've first listed my main comments/concerns, followed by minor comments.

Main Comments

1.) The premise of this work is centered on the concept of a potential *permanent* change to glacier basal conditions and constraining how the related effects on glacier dynamics (thinning and acceleration). It would be helpful to introduce the physical basis for such a change, rather than surge-type glaciers, including explicitly describing what such conditions would look like in reality. I understand that the spatially uniform increase in basal lubrication (reduction in basal friction, or K term) is not meant to imitate reality but is useful as a modeling tool. However, given the strong seasonality observed at Greenland glaciers in response to summertime meltwater and evolving subglacial conditions, what kind of environment meets the criteria of a "permanent change"? One with greater seasonal oscillations between efficient and inefficient drainage systems, one with continuous drainage and elevated basal water pressures throughout the year, or another scenario entirely? There seems to be a missing connection here that makes it somewhat challenging to contextualize how the findings of the paper inform our understanding of future climatic conditions on ice sheets/ice caps.

The original motivation to look into a permanent change of basal conditions comes from the observations of several significant glacier speedups. As in the introduction: "(These events change the basal conditions) via creating a highly crevassed glacier surface which makes meltwater reach the bed more easily." These events are mostly located in the European/Russian Arctics, but a similar finding that excessive melt expedites moulin/crevasse formation has also been proposed for Greenland Ice Cap (Hoffman et al., 2018, https://doi.org/10.1002/2017GL075659). Regardless of whether a Greenland glacier has seasonally varying subglacial conditions, the basal friction can be subject to an interannual (and perhaps continuous) decrease due to the formation of these extra melt routes. As stated in the manuscript, the interannual impact of basal lubrication is less studied than the seasonal signal of speed variation. With this in mind, this paper tries to develop a simple framework to understand the varying response to these interannual dynamic changes. I have updated the manuscript (mostly for the introduction section) with the thoughts above to hopefully help contextualize the findings of the paper.

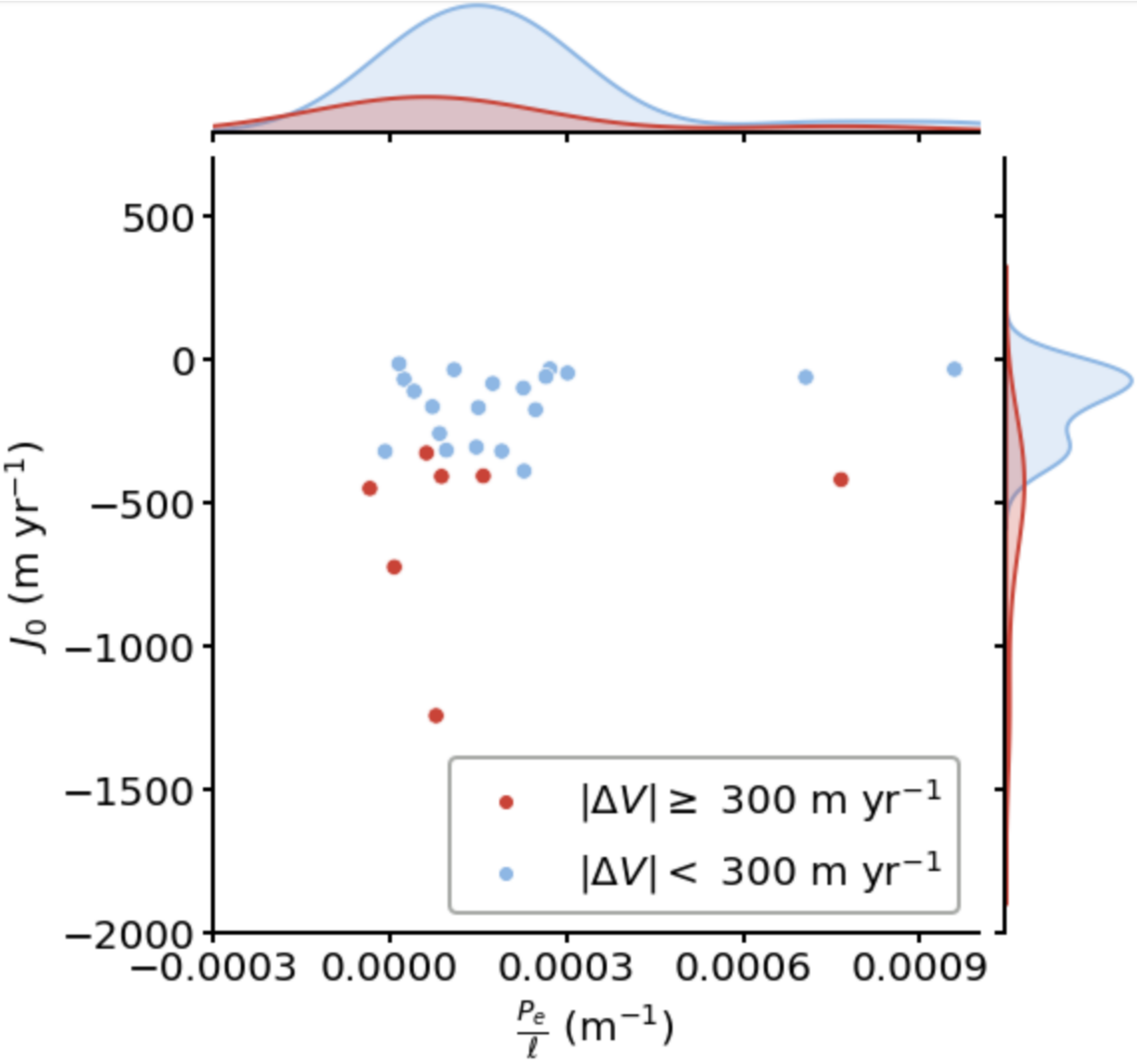
2.) The conclusions include some statements that extent beyond the results presented in the manuscript. do not seem entirely supported by the findings in the manuscript. For example, the phrase in the conclusion on line 239 states that: "The J_o–Pe/ℓ plot (Figs. 5–7) seems to capture the characteristics of glaciers vulnerable to basal lubrication. GrIS and Austonna glaciers with more negative J_o and Pe/ℓ in 1996–1998 are more likely to speed up in the next 20 years." This argument can be made for the GIS glaciers based on the distributions shown in Figure 6, but it is far from obvious for Austfonna glaciers show in Figure 6. I think, with the limited sample of glaciers and subset that include surge types, there is not enough information to assert a distinction based on J_o and Pe/l alone. The conclusion should reflect this uncertainty. Even for the n=104 glaciers in Greenland, where distributions show a tendency for greater accelerations at basins with low/more negative J_o and Pe/l, the text should be careful to emphasize that this reflects results at a specific distance alone a glacier flow line and may not be representative of the entire glacier length.

Agreed. I have modified the discussion section so that it aligns with the results better and more conservatively. The updated manuscript now:

- States that the J_o versus Pe/ℓ plot characterizes GrIS glaciers in terms of their vulnerability to basal lubrication, but for surge-type glaciers in Austfonna we need more data to fully find out the relationship between J_o / Pe and glacier accleration.
- Reflects the uncertainty of the GrIS results in terms of the specific terminal distance analyzed in the paper.

3.) As addressed in the text, terminus retreat is also a common source of acceleration, especially at Greenland glaciers, and retreat impacts are indistinguishable from increased basal lubrication within the presented framework. I think it would be highly valuable to include net retreat when considering acceleration over the 1998-2018 period. For example, how does speed increases observed within subsets with low Pe/l /negative Jo and minimal retreat compare to acceleration observed at glaciers with low Pe/l /negative Jo but significant retreat? Showing that these variables are still applicable to acceleration in the absence of terminus retreat would strengthen the significance of the study.

Thank you for your insightful suggestion. I have retrieved the terminal retreat data from Wood et al. (2021, https://doi.org/10.1126/sciadv.aba7282, Data repository http://doi.org/10.7280/D1667W) and made a comparison with J_0 and P_e/ℓ. This figure shows how J_0 and P_e/ℓ scatter for all glaciers with terminal retreat < 0.5 km:



The red group now only contains 7 glaciers since the other accelerating glaciers typically have a significant terminal retreat, but the rest of the data points clearly separate two glacier groups based on their J_0 and P_e/ℓ. I have updated the manuscript with this additional analysis and results, including the data description, two extra figures, discussion text, and supplementary Jupyter Book pages.

It also may be worthwhile to evaluate the two groups of glaciers (here divided based on

acceleration greater than or less than 300 m/yr) based on the percent increase in speed (such as > or <= 10%), rather than an absolute (300 m/yr) threshold.
Using the percent increase instead of the absolute increase results in a more compacted histogram with a few glaciers exceeding +100% of the speed change. It is thus harder to justify the separation of two groups of glaciers regardless of the chosen threshold value. I have added the histogram to the Figure 6 Jupyter Book page for a comparison with the existing histogram made using the absolute increase.

Secondary/Minor Comments

Figures

-All axis labels and unit font sizes need to be enlarged.
Done.

-Please include lettered labels (a, b, c, etc.) on the subplots corresponding to the labels mentioned in the figure captions.
Added the missing panel letters in Figures 3, 4, 5, and 7.

-Include a scale bar for zoomed inserts in Figure 1 and in Figure 2.
Both figures already have a scale bar for the zoomed inserts, and instead, I added an extra sentence in both captions clarifying what panels use the scale bar. For Figure 2, I also added an extra panel C showing the geographical location of Austfonna Ice Cap.

-Please also include legends for your figures. This includes a color bar for speed increases in Figure 5 and 7.
Done.

Figure 3
Køge Bugt (glacier 0207 in Figure 3) has retreat around 2 km between 1998 and 2018. This site also appears to have the greatest Jo values of the Greenland sample (shown in Figure 5), which would imply the most diminished sensitivity to respond to basal lubrication. This seems at odds with the statement on line 193, that states that Jo is a good predictor of glacier speed up at this Basin.
As long as J_0 is away from zero, basal lubrication would lead to an initial forcing of elevation change and further perturb the dynamic discharge. Køge Bugt has a $|J_0|$ = ~500 m yr^{-1} around the terminus, which seems to be sufficiently high to cause such a forcing. What makes this glacier interesting is the sign of J_0 since this is the only glacier outlet with J_0 > 100 m yr^{-1} among 187 basins. A positive J_0 requires a decreasing ice thickness from terminus to upstream (Eq. 17), which is unusual for a typical Greenland outlet glacier. As Figure 3 is meant to provide a typical case of what a glacier with flow speed change looks like, I agree that Køge Bugt may not be an ideal example for that and have replaced it with Jakobshavn Isbræ (glacier 0001) for this figure. I have also edited all the corresponding descriptions and analyses in the manuscript.

Figure 6

Are the differences between the two groups' distributions statistically significant?

I have performed a two-sample, two-sided Kolmogorov–Smirnov test for both J_0 and Pe/ℓ, and both the test statistics indicate two groups are from different distributions (p-value = 0.003 and 0.006, respectively). I have added the statements above and relevant analysis in Section 4.2 and the corresponding Jupyter Book supplemental pages.

On the 3km flowline position analyses

Why is this position (3 km for 1998-2018 speed change and mean 3-5 km parameters) used for the majority of the analyses? Can you provide justification for why this distance from the terminus is most representative of glacier sensitivity to basal lubrication?

You can find my explanation as to why it should be good to use the data as close to the terminus as possible in my response to Reviewer 1. Practically, the data closest to the terminus cannot be properly smoothed using the Savitzky–Golay filter (Section 3.1) due to an insufficient window length, and I arbitrarily discard the data between 0 and 3 km away from the terminus to avoid potential bias from that, making the 3 km parameters the closest among all data analyzed in this study. I use the 3 km parameters for the following quantitative analyses (e,g, Figure 6 and the significance test above). The 3-5 km parameters are solely used for illustration in Figures 3, 4, 5, and 7 which provide an idea about how these values change along the flowline. I have experimented with different length segments and determined that showing the first two km of the valid data helps recognize the parameter pattern and change direction the best without being confused by too many data lines crossing each other in the figure (especially for Figure 5).

Line 232

The range in Jo should be to -1500 m/yr, not 1500, correct?

It should be 1500 m/yr because the absolute value of J_0 is discussed here. For clarity, I have added a note in the paragraph below Eq. 13 where the $|J_0|$ notation first appears in the text.