

## Response to Reviewer 2

*Thanks for these comments, which greatly improved the paper.*

Joughin et al. presents here a manuscript about the variability of Jakobshavn Isbrae using dense time series of speed and surface elevation over the period 2009-2019. The main conclusion is that the front advances and retreats of Jakobshavn, which is the major forcing for seasonal fluctuations of the glacier (in terms of thickening/thinning and acceleration) is controlled by the rigidity of the mélange and not submarine melt as proposed in previous studies. If true, this could have major implications about the main mechanism leading to rapid retreats of tidewater glaciers around glacier and therefore projection of the evolution of the Greenland Ice Sheets. Another major conclusion concerns the steep ice cliff of Jakobshavn that are not collapsing contrary to the instability mechanism proposed for the rapid retreat of the ice sheet. Finally, they provide interesting insights into calving mechanism through the formation of basal crevasses that seems to initiate necking process leading the future large calving.

*Summary comment, no action taken.*

They are no questions about the quality of data collected and processed here. It is quite a impressive work. The conclusions about the basal crevassing and the absence of ice cliff failure seem robust. My main concern comes from the conclusion on the mélange rigidity versus submarine melt as forcings for the calving rate and so terminus position. Indeed, submarine melt rate stated in Khazendar et al. 2019 are 2 orders of magnitude smaller than those used here. I believe that 8-10 m/yr (line 276) should actually read 8-10 m/day as in Fig. 3a from Khazendar et al.

*Yes - this was a typo by an author long used to working in units of m/yr. These were corrected to m/day throughout the text.*

Values for submarine melt of tidewater glaciers published in other studies (Sciascia et al. 2013, Slater et al. 2018, Sutherland et al. 2019, etc. . .) are similar to those of Khazendar et al., which consequently, although not perfect, seem realistic.

*Our argument is not with the melt rate values, but rather how they are presented. We offer additional context and evaluate the Khazendar et al. numbers. For example, while their results show that while a single plume may have localized melt rates of ~10 m/d, this would produce a ~100-200 m wide "slot" in a 4-km-wide by ~1 km thick ice front. The maximum localized plume melt rate of ~10 m/day averaged across the full width is less than 1 m/d ((~100 m wide plume \* 10 m/day)/4000 m is ~0.25 m/day).*

*Due to the non-linearity between subglacial melt and terminus melt, you will get more terminus melt by spreading the same subglacial meltwater volume across*

*multiple plumes, tending toward a maximum for a uniform distribution. For example, on another large glacier with similar ocean temperatures, Moon et al. (2018) estimate melt rates of  $38 \text{ m}^3/\text{s}$  for 10 plumes at Helheim Glacier. If we assume that all of the melt is from subglacial discharge at Helheim (ignoring input to this number from the two smaller adjacent glaciers), a back-of-the-envelope estimate for melt rates is  $\sim 1.1 \text{ m/day}$  for a 6000 m wide terminus with most of the melting on the lower 500 m ( $38/(6000 \cdot 500) \cdot 86400 \text{ m}^3/\text{s m}^{-2} \cdot \text{s/d}$ ), which is small relative to the advance rate of either Helheim or Jakobshavn.*

*In any event, whether single-plume (least total melt) or evenly distributed subglacial melt (maximum total melt) the maximum estimate for width-averaged melt for Jakobshavn is still  $< 3.5 \text{ m/d}$  based on the Khazendar et al provided scale factor, which is small relative to the observed terminus speed of  $30\text{--}45 \text{ m/d}$ .*

*So, we did not change the text in direct response to this comment, but we improved the melt discussion in response to other comments.*

**The proper melt rate of 8-10 m/day is therefore about one third of the ice motion at terminus (30-45 m/day) and it becomes obvious that the ice is not replenished "far faster" than the melting (as stated in line 284) and therefore could potentially lead to the undercutting process proposed and sometimes observed in other studies (Sutherland et al. 2019).**

*As noted above, the 8-10 m/day melt rate estimate applies to a  $\sim 100 \text{ m}$  wide plume, which could produce a cavity of about that width (or perhaps a factor of  $\sim 2\text{x}$  wider), but this would result in one "slot" carved in 4-km wide ice cliff.*

*Todd et al. (2018) show that at slightly larger plume rates COMBINED with 3.1 meters of uniformly distributed melt there is very little seasonal effect on the speed and terminus position of a slower glacier. They also show that the influence of the melt plume/evenly distributed melt diminishes once the stabilizing influence of *mélange* is included in the model – compare case 011 (plume 12 m/d and 3.1 m/d evenly distributed melt) with 111 (melt as in 011 but with *mélange*) in their Fig. 6. There is no evidence to support melt rates any larger than those used by Todd et al. (2018) at this time and they may be overestimates (see also next paragraph).*

*The paper by Sutherland et al finds both some undercutting and some overcutting, but doesn't comment on finding related calving enhancement. A central point they make is that distributed (ambient) melting is greater than plume theory would predict, which is relevant to our results. There are, however, some important differences. For the LeConte glacier the water at depth ranges from  $\sim 4$  to  $7.5 \text{ deg}$ , compared with  $\sim 3.5 \text{ degC}$  for Jakobshavn. For*

*the 4-degC case, which still exceeds the water temperature at Jakobshavn, the average melt rate is 0.9 m/d (compare with back of the envelope calculation above), which doesn't change our central point that rates of this magnitude are small relative to the calving rate. Another central point of the Sutherland et al paper is that flux gate methods tend to overestimate melt by about a factor of 2, which would mean earlier melt-rate flux-gate estimates for Greenland may be too high by about a factor of two (e.g., Rignot et al,2010; Xu et al, 2013. For the latter paper, if such a bias exists and could be removed it would bring their model results into better agreement with their observations). The upshot though is that Todd et al., 2018 already include both plume and distributed melt at rates that probably exceed that for Jakobshavn based on our interpretation of Sutherland et al (e.g., 4deg -> 0.9 m/d) and other results. Hence, Sutherland et al further support our hypothesis rather than weaken it. We do not cite this paper because a comprehensive review of the various melt rates methods is beyond the scope of our paper. (We do cite work that includes Sutherland - Moon et al 2018 - that looks at Greenlandic glacier - see Helheim discussion above).*

**Considering this, the authors can absolutely not rule out that submarine is a main driver in controlling the terminus position. In addition, the observations of "strong" mélange during period of advance and weak mélange during retreat could be just coincidental as ice mélange is most probably weak during period of high submarine melt and vice-versa. The discussion would also be strengthened if recent modeling studies and mechanisms that would prevent ice calving in the presence of ice mélange were included (such as Krug et al. 2015).**

*We do not attempt to offer absolute claims, but present evidence that supports the hypothesis that mélange has greater influence than submarine melting for Jakobshavn during the period of our study.*

*There is some degree of correspondence employed in both arguments. We feel that the timing of slowdown and the onset of mélange rigidity makes a more compelling case. As does similar degree of retreat the first summer the water was cold. And we believe that the model studies we cite better support our hypothesis. As do similar correspondences on other glaciers (e.g., Bevan et al). Neither hypothesis can be fully proved at this point - but we feel ours better fits the observations and other results in the current literature.*

*Thanks for bringing our attention to this paper, which supports our hypothesis. We added "A more complex time-dependent model that includes calving with damage indicates that the effect mélange on seasonal variation in terminus position and speed is far greater than that of melt undercutting (Krug et al., 2015)." We also add text citing other modeling studies.*

**The last comment is about the implications for other glaciers in Greenland that is not mentioned in the paper. The presence of such "thick" mélange is particular to**

**Jakobshavn Isbrae, where icebergs are well confined in a long fjord. Glaciers along NW coast also display seasonal variations but it is less obvious that such a thick ice mélange is present for these glaciers that are more open on the ocean. Would the presence of relatively thin sea ice also have the same impact on the calving rate ?**

*This a good point and a good question. Certainly, work by Reeh suggests that for some glaciers (e.g., NE Greenland), sea ice alone can suppress calving. But that work applied to rather thin, extended ice shelves. There certainly is winter mélange near many glaciers along the NW coast (e.g., see Moon et al. papers on subject), but the record of its rigidity is less certain than in regions that were imaged more frequently (like Jakobshavn).*

*A detailed analysis of this question is beyond the scope of this paper. To acknowledge this point, however, we added as the paper's last sentence "While our results should be applicable to glaciers with high calving rates that yield a thick mélange [Bevan et al., 2019; Kehrl et al., 2017], more work is needed to understand the influence of thinner mélange on smaller glaciers that calve less rapidly."*

**That said I still believe that the discussion about the mélange rigidity is interesting and it is possible that both mechanisms (submarine melt and ice mélange) are influencing the calving rate. I appreciate the effort made for gathering and processing all these datasets and the interesting conclusions on the formation of basal crevasse and ice cliff failure. I would therefore recommend revision of the paper according the above comments and much milder conclusion on the influence of submarine melt vs ice mélange concentration.**

*We agree this not the final word on the subject, but we disagree with the reviewer's recommendation. We present a hypothesis that can be tested in the future. Our more extensive literature review, completed in response to reviewer comments, has strengthened support for this hypothesis.*

*We feel that the text and qualifying language (e.g., "may", "suggests") in the paper emphasize that this is a testable hypothesis supported by a large body of observational and modelling work. For example, our statement in the abstract says "Thus, along with the relative timing of the seasonal slowdown, our results suggest that the ocean's dominant influence on Jakobshavn Isbrae is through its effect on winter mélange rigidity, rather than summer submarine melting.", which we note is comparable to the level of certainty in the Khazendar et al abstract. As we note in the response to the Khazendar et al comment, additional observations and study will provide further evaluation of these competing hypotheses.*

Khazendar, A., Fenty, I. G., Carroll, D., Gardner, A., Lee, C. M., Fukumori, I., et al. (2019). Interruption of two decades of Jakobshavn Isbrae acceleration and thinning as regional ocean cools. *Nature Geoscience*, 12(4), 277-283. <https://doi.org/10.1038/s41561-019-0329-3>

Krug, J., Durand, G., Gagliardini, O., and Weiss, J.: Modelling the impact of submarine frontal melting and ice mélange on glacier dynamics, *The Cryosphere*, 9, 989-1003, <https://doi.org/10.5194/tc-9-989-2015>, 2015.

Sciascia, R., Straneo, F., Cenedese, C., and Heimbach, P. ( 2013), Seasonal variability of submarine melt rate and circulation in an East Greenland fjord, *J. Geophys. Res. Oceans*, 118, 2492- 2506, doi:10.1002/jgrc.20142.

Slater, D. A., Straneo, F., Das, S. B., Richards, C. G., Wagner, T. J. W., & Nienow, P. W. (2018). Localized Plumes Drive Front-Wide Ocean Melting of A Greenlandic Tidewater Glacier. *Geophysical Research Letters*, 45(22), 12,350-12,358. <https://doi.org/10.1029/2018GL080763>

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