Reply to RC2

We thank the referee for the time and effort spent on reviewing our manuscript. A point-by-point reply (in blue) to each comment is given below.

Anonymous Referee #2

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In this paper van Dongen et al. undertake a detailed study of Bowdoin Glacier, NW Greenland, utilising an impressive combination of remote sensing and field data. Utilising these data, they argue that there has been a change in calving style from submarine melt driven calving to buoyant flexure driven calving. Overall I'm convinced by the arguments presented in the paper, though have a few minor points outlined below.

However, the article is generally very well written, and the authors should be congratulated on pulling together such a nice range of data.

Thank you.

L185-6 – a bit more explanation as to why figure 5 shows the vertical tidal modulation being significant would be beneficial. At present it's unclear why results are significant in panel b but no in panel c/d

Thank you for pointing this out. This was only a visual interpretation, for which 'significant' was a too strict formulation. We have now calculated correlation coefficients for a linear regression between the tidal height and ice elevation for each year, yielding Pearson r correlation coefficients of 0.27 for 2015, 0.29 for 2016, 0.71 for 2017 and 0.58 for 2019 (all significant). We will add this information to the revised manuscript:

"*GPS data show that the vertical tidal modulation increased since 2017 (Fig. 5), with a stronger correlation between detrended elevation and tidal height in 2017 and 2019 (r = 0.64) than in 2015 and 2016 (r=0.28).*"

L248 (& L155) – it's mentioned earlier on that Sentinel 1 data are analysed – how are these processed to ensure comparability/homogeneity with optical data?

We will add the following information on the processing of Sentinel-1 data:

"*Sentinel-1 data were downloaded using the Google Earth Engine (Gorelick et al., 2017) which provides backscatter coefficients orthorectified using the ASTER DEM to the same coordinate system as Sentinel-2 imagery (UTM 19N). To minimize incidence-angle dependent effects and also artefacts due to inaccuracies in the DEM, we processed data from a single orbit (026, descending). To correct for sub-pixel shifts between the orthorectified images, we coregistered them to a common reference (intensity average of all scenes) using intensity cross correlation (Strozzi et al., 2002).*"

L263 – I would change "expect" to a phrasing that is a lot less definitive. Unless you have thickness information to demonstrate that thinning is sufficient to lead to the terminus becoming fully ungrounded, it would be more appropriate to say that the terminus is getting closer to floatation.

We have rephrased '*the terminus is now closer to flotation and thus may have become subject to buoyant calving.*'

L260 – I quite like the your intro to the discussion (just having now deleted my comment saying it wasn't needed!). For a data heavy paper like this it lines up and signposts the main points in the discussion nicely.

Thank you.

Section 5.1 – compelling case that the terminus was partially ungrounded.

L299 – are these crevasses visible from satellite or available time lapse imagery? I'm not 100% convinced that the photographs provided do actually give definitive evidence of calving being propagated from extensional rifts in 2015/17. It may be worth reiterating evidence from previous studies backing submarine melt undercutting as the mechanism. However, I agree that the GPS observations point towards a buoyant flexure style of calving in 2019.

Yes, these crevasses are visible from time lapse but the crevasse in 2017 was not visible from satellite (as mentioned on L350 of the discussion paper). We will move the first paragraph (L299-301) to Sect. 5.4, and will reiterate the evidence from previous studies there, as explained in more details in the reply to your last comment.

L328-331 – figure 4 is very small, which makes clear identification of the small scale variability of thinning and also the location relative to the moraine. I suggest this figure be made larger and an extra panel showing a satellite image of the glacier (with centreline marked) that would allow clear identification of these. Regarding the dynamic thinning hypothesis I'm not entirely sure what you mean by this with respect to the shear zone. Similarly with the mechanism for shear forming basal channels beneath the depressions. This section would benefit from clarification.
We will increase the size of Figure 4, and add a reference to the satellite image in Fig. 1a on which the moraine is marked. For clarification purposes, we suggest to rephrase the section as follows: '*Because the strongest thinned area also coincides with the shear zone, the large velocity gradients likely caused this surface depression by dynamic thinning. A similar case was reported by Alley et al. (2019), who used satellite data to show that high shear resulted in surface depressions. Their observations suggest that the locally thinned ice was subsequently pushed upward by buoyant forces, and basal troughs formed beneath the depressions. Plumes were observed to focus into these basal troughs, which amplified melt locally and thinned these areas further. This proposed shear thinning mechanism agrees with our observations at Bowdoin Glacier ...*'

Section 5.4 – showing panels for each year of the glacier terminus positions used to derive the calving event sizes would be useful to compliment figure 12, showing where and how each calving event occurred. It would also aid the discussion in this section (5.4) which is a bit tricky to follow. As it is, figure 1a showing ice front info is not especially useful/relevant to the study as it is annual and goes back to 1973, whereas the period under investigation is 2015-19.
We will adapt Fig. 1A, to show the front positions of 1973, 2008, 2013 and 2015-2020, as we agree that it would be helpful to show the front positions of 2015-2020 here. However, we do find it relevant to show the retreat history of the glacier, although in less detail than in the discussion paper to have more focus on the recent front positions. This will make Fig. S4 obsolete, so we propose to remove that figure.

More generally, I would say that the observations presented do not represent clear cut evidence of a transition from one calving style to the next. For example, given the stochastic nature of calving I would be a little cautious in ascribing too much meaning to a few individual events that happen pre/post initiation of melt, even though they may be substantial. What is more convincing for me is the combination of the previous studies (Jouvet et al., 2017; van Dongen et al., 2020a,b) identifying that large scale calving events occurred due to hydrofracture/melt undercut, the arguably circumstantial evidence presented here, and evidence for recent ungrounding combined with GPS data showing evidence of calving by buoyant flexure. I think the discussion would benefit if these lines of evidence were linked more strongly.
We agree that the observations do not represent a clear transition, which is why we deliberately avoided the use of the word 'transition' and rather expressed that the observations suggest that buoyant calving has occurred more frequently. We do not argue that *all* recent calving events were a result of buoyant forces, but that buoyant calving has been playing a more important role since 2018, responsible for a larger part of the mass loss by calving.
In order to more clearly link the evidence from the previous studies to the findings in this paper, we will move the first paragraph of Sect 5.2 (L299-301) to Sect. 5.4, and add more information about the mentioned previous studies, such that Sect. 5.4 starts with:

“Numerical modelling showed that an undercut is necessary in order to reproduce the initiation of the crevasse which lead to calving in 2017 (van Dongen et al., 2020b). Furthermore, high-resolution terrestrial radar interferometry data revealed that crevasse opening prior to calving was fastest at low tide, which suggests a non buoyant calving style (van Dongen et al., 2020a). Additional modelling work identified the crevasse water level, and thus hydro-fracturing, as a key driver of opening rates (van Dongen et al., 2020a). Unlike the deep and most likely water-filled surface crevasses which formed prior to calving in 2015 and 2017 (Fig. 2), no precursor crevasse was visible in the field prior to the major calving events in July 2019. This suggests that the calving events in July 2019 were not triggered by extensional stress at the glacier surface, but resulted from basal crevasse propagation due to buoyant flexure instead.”

New references
Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, Remote sensing of Environment, 202, 18–27, https://doi.org/10.1016/j.rse.2017.06.031, 2017.
Strozzi, T., Luckman, A., Murray, T., Wegmuller, U., and Werner, C. L.: Glacier motion estimation using SAR offset-tracking procedures, IEEE Transactions on Geoscience and Remote Sensing, 40, 2384–2391, https://doi.org/10.1109/TGRS.2002.805079, 2002.