Reply to reviewer 3 Part C

Interactive comment on “Debris cover and the thinning of Kennicott Glacier, Alaska, Part C: feedbacks between melt, ice dynamics, and surface processes” by Leif S. Anderson et al.

Anonymous Referee #3

Thank you kindly for taking the time to review this manuscript!

Received and published: 28 October 2019
This manuscript investigates the relation between the pattern of long-term thing of a debris covered glacier tongue in Alaska and the debris cover, surface features (cliffs, channels, ponds), flow dynamics. From this, it convincingly identifies and discusses in detail the emerging feedback between the related processes and quantities and thereby contributes to the very relevant and important discussion of what the role of glacier dynamics and surface features for the thinning (surprisingly high) of debris covered glaciers are. Some new results are also presented in this paper (channel mapping, sinuosity. . .) but the strength of this paper is the very systematic analysis and discussion of the different terms of the continuity equation that determines the thinning of a glacier (see fig 5). The undertaken bulking of the different quantities into few zones (upper/lower limb ZWT,. . .) in the discussion of the results helps thereby to get a clearer picture and to identify the most dominant quantities and feedbacks. There are a few earlier papers available that tried to address the issue of anomalous thinning of debris covered glaciers but with a different approach (maybe that should be referenced better) and i think the identified importance of the reduced ice-emergence (reduced dynamic replacement) is very well supported by the presented data and analysis. Thus, overall this study presents a very interesting and important advance in understanding the dynamics of debris covered glaciers, a topic of high relevance in times of global warming, and hence this manuscript a very valuable contribution at TC. There are a few comments or and issues I have with this paper, but they are mostly rather minor (see list below) but would hopefully further improve an already very interesting, good quality and exiting paper. The figure and visualization are in general effective and the paper is well written.

More general comments 1. This paper is the last (part c) of a series of 3 papers, and one could always ask if not all parts should have been integrated into one paper. I admit that some repetition (in the description of some the data sets for example) is unavoidable, but for me part C works very well as a stand-alone paper and has a very clear own focus on the dynamic feedbacks and interactions and more than enough conclusive results for a stand-alone paper. I have to note that I only briefly looked into the other two papers (part A and B) but it was clear that there the main aim and focus of the otehr parts (A and B) were substantially different and in my view justified as separate papers. Moreover I believe that the main messages and findings of the three papers come in separate papers probably better across than in one huge one.

Thank you kindly. If we do not reply to the comment below we will enact the change in Part C.

2. Abstract focus: somewhat related to the 3-part paper thing, when reading the abstract I got the impression that the main focus of the paper on the feedbacks and interrelations between processes to explain the thinning pattern is rather thinly represented

within the abstract (last 3 lines, and little on feedbacks but rather on correlations) and the results used in this papers but from part A and B get too much space in the abstract. A better balance and more focus on the feedbacks and findings of THIS part C would be useful.

We will follow this advice.

3. Difference in time periods of datasets: One potential criticism of the analysis and conclusions one could have is that the thinning-data represents an average over several decades whereas the velocities and surface features, debris extent etc are the 'now' situation. I myself do not really think this is really a big issue but some more explanation and justification for this maybe useful.

We have additional dh/dt data that covers the in situ measurement time period.

4. Literature: With regard to influence/link of ice dynamics to thinning, debris cover and ice cliffs (e.g. explaining anomalous thinning) the paper by Banjeree (2017, TC), Rounce et al (2017), Ragettli (2016, TC) and potentially Moelg et al. (2019, TC) maybe useful to be considered.

Banerjee A. (2017): Thinning of debris-covered and debris-free glaciers in a warming climate. Brief communication. The Cryosphere, 11, 133-138, 2017 www.the-cryosphere.net/11/133/2017/ doi:10.5194/tc-11-133-2017

Rounce, D. R., King, O., McCarthy, M., Shean, D. E., & Salerno, F. (2018). Quantifying debris thickness of debris-covered glaciers in the Everest region of Nepal through inversion of a sub-debris melt model. Journal of Geophysical Research: Earth Surface,123, 1094-1115. https://doi.org/10.1029/2017JF004395

Ragettli, S., Bolch, T., & Pellicciotti, F. (2016). Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal, Nepal. The Cryosphere, 10(5), 2075-2097. https://doi.org/10.5194/tc-10-2075-2016

Moelg N., T. Bolch, A. Walter and A. Vieli (2019) Unravelling the evolution of Zmuttgletscher and its debris cover since the end of the Little Ice Age. The Cryosphere, 13, 1889-1909, https://doi.org/10.5194/tc-13-1889-2019

Thanks we will include these citations.

Minor/specific comments

p. 1 Line 15: the term 'melt hotspots' is here not really clear maybe specify a bit more what it is ('melt hotspots such as ice cliffs or channels')

p 1 lines 23-27: maybe make clearer what of these results from this part C paper and what is from earlier (or really focus on part C part).

P 1 line 24-25: high melt and HIGH melt gradients? here and also on next line it is not so clear to me what you mean by 'melt gradients' here, 'spatial gradients in melt' along flow, gradients in melt with regard to changing debris thickness. . .. be clearer.

P1 line 31: a brief explanation why ice cliffs are most abundant at the upglacier end

maybe useful here (I think you have some idea about this or am I wrong?).

P 2 line 50: I think 'surface' uplift is here not quite correct, ice emergence is the relative movement to the surface or particle uplift against the surface, so maybe 'ice' uplift is more appropriate.

Thanks for clarifying this for us.

P 2 line 56-57: '. . .will facilitate the INTERPRETATION AND prediction of. . .'

P 2 line 62-63: importantly in part C you not just present data on ice dynamics and supraglacial streams but crucially in part C these data and all components of the mass conservation equation (thinning, flluy divergence. . .) are analysed for relation and feed-backs between them. Also say this here, as it is the backbone and most exiting part of this part C.

Thanks for this.

p. 3 lines 73-79: is this paragraph on the water pressure variations and sliding really needed? Maybe just summarize it in one sentence in the section 2.1 or 3.1 on the velocity data.

We will clarify this and make the connections more clear.

p 4 line 116: what is grid size chosen?

We will mention the grid size here.

p. 5 lines 143-153: maybe this paragraph (together with next paragraph) can be short-ened a little bit as already presented in part A and B.

p. 5 line 165: be clearer here on: 'THE ALONG FLOW/PROFILE PATTERN OF annual surface velocities. . ..

p. 6 line 171: this link between debris thickness and flow dynamics is a consequence of the continuity equation, so maybe be more explicit on this. '. . .controls the melt rate and which a consequence of mass continuity is linked to ice dynamics.

p. 6 line 174-176: this complementation of debris thickness melt rates and surface velocity probably is meant in a steady state sense, otherwise the dhdebris/dt should also be mentioned (maybe clarify). Further to this sentence, with patterns I assume SPATIAL (along flow) PATTERNS are meant?

We will clarify.

p. 6 line 183: again, '. . .SPATIAL /ALONG FLOW gradients in melt are low. . .'

p. 6 lines 186-191: good point!

p. 6 line 197-198: maybe explain why streams disappear in lower limb, is it because the drain through moulins in transition, but why are moulins there, connection to strain rates (longitudinal stretching? Not so clear in Fig. 5.)

We will explain this.

p. 7 line 234: should it not be ’The lowest 4 km of the glacier ARE. . ..’ (it is 4). And again why is this disconnection there, because water is drained though moulins to bed. . ..

p. 8 line 255. Maybe refer to Fig. 5b+f after (ZMT). Further with ’changes in ice flow’ you probably mean along flow changes in ice flow, or more specifically the flux divergence or emergence rate.

p. 8 line 251: ’Process links . . .’

p. 9 line 273: not sure why you are so vague in your statement herewith ’may’ be related. Why not be a bit more direct and say ’seems related to. . .’. Further do you mean to the ’SPATIAL/ALONG FLOW pattern’?

p. 9 line 290: ’increased ice strain’, I struggle to see longitudinal extension (strain)here at the transition from the upper to the lower limb, the velocities clearly decrease down glacier there, so it would rather mean ’compression’ or do I get something wrong here?

Fig. 1: the label dH/dt in the figure is rather confusing to read, make sure all is on one line e.g. dH*dtˆ(-1). Caption line 6: do you mean opposite ’sign’ rather than ’sight’?

Caption line 7: ’The black line shows the profile used . . ..’

Fig. 2: I know that the exact threshold between upper and lower limb is not crucial but in the text a rough transition between 10cm and 20cm is given why not indicate this in the figure maybe as a grey shaded bar in the background.

We will.

Fig. 3: caption line one I would add at end of first sentence ’. . . along the profile indicated in fig. 1c.’

Fig. 4: a detail but the map could do with a scale. More importantly, where in the figure/map is the box indicating the extent of Figure 11? I can simply not find it.

Fig. 5: in sub-fig (f) and in caption line 8, strictly speaking the label should be ’elevation change rate’ as the sign is already negative and a lowering rate that is negative would then mean thickening again. Caption line 1: again make clear that the show data are ’. . . for the swath along the profile indicated in fig. 1c.’

We will change this.

Fig. 7: here an elevation threshold/bands are used to summarize/group the sinuosity data, but am I right that these are both above the ZMT and in the upper limb of the oestroem curve. This maybe useful to be explained in the caption.

We will change this.

Fig. 10. I found this figure rather difficult to read, there is a lot of information and detail and I initially expected from this schematic to better get the big picture. Maybe I just

expected the wrong thing and the colors (blue or red) were not so clear to me and I wondered if it really helped me a lot. If I see it as complete documentation of all different relations and feed backs it is maybe fine, but then maybe it should be phrased as such. More importantly, in the caption the colors red and blue refer to positive effects or negative effects but it is not so obvious to me what you mean by positive and negative. Does this refer to positive and negative FEEDBACKS (self enhancing/reducing) or positive/negative from a glacier health (negative mass loss, reduced speed,. . ..). should be clarified.

We will clarify this figure or remove it.

Part C: proposed changes

We want to emphasize here that we do outline new feedbacks in this paper.

From Reviewer 3 from Part C:

"P 2 line 62-63: importantly in part C you not just present data on ice dynamics and supraglacial streams but crucially in part C these data and all components of the mass conservation equation (thinning, flux divergence. . .) are analysed for relation and feedbacks between them. Also say this here, as it is the backbone and most exiting part of this part C."

On Kennicott Glacier there is a strong correspondence between ice cliffs and active ice flow. While weak relationships have been suggested here on Kennicott the correlation is more clear than anywhere else.

The highest concentration of ice cliffs occurs at the upper end of the zone of maximum thinning. The high concentration of ice cliffs also corresponds to where we expect ice emergence rates to be high. These ice emergence rates uplift the glacier surface, working to counter glacier thinning. But ice dynamics, which produce this surface uplift also seems to produce more ice cliffs (see the physical descriptions within the main article). These ice cliffs counter the effect of surface uplift, they are essentially a negative feedback on the effect of ice dynamics.

In addition to this new feedback we also present a number of new hypotheses for the interaction of surface processes with melt and ice dynamics with a new, holistic perspective.

We feel that there is more than enough new material here for a stand alone paper, but in order to improve the manuscript we propose that we add these additional datasets/ideas to Part C:

- New annual surface velocities from 2000-2010
  - These velocities allow us to calculate changes in ice emergence rate and ice flux over the in situ measurement period
  -More detailed discussion of the reduction of ice emergence rate through time.

- Delineation of drainage basins on the glacier surface (new figure) to support the stream story already within the manuscript.

- Tie in a discussion about glacier surface topography. Ice cliff maximum heights (from in situ measurements), the number of individual ice cliffs with elevation band, and calculated glacier surface relief down glacier.

- New processes drawings to show the important new observations that we are highlighting in this paper. This will greatly improve the reader's ability to see the new process links we are describing.

- Additional photo evidence from the field outlining these new processes links. Many will go into the supplemental but they will support and clarify the process links we are highlighting.

- Description of a new ice cliff burial mechanism. Timelapse movies from the Kennicott and Ngozumpa glaciers (in the supplemental) showing a new mechanism for the burial of ice cliffs. The actual process is not yet described in detail in the text.

- A paragraph that is the same for each of the 3 parts that outlines how they build off of one another.