Reply to Reviewer 4 Part C

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Thank you kindly for taking the time to review this manuscript! We appreciate it.

This interesting and topical paper synthesizes a range of glaciological data to improve understanding of the process feedbacks between glacier flow, melt distribution under debris cover, and thinning, at a large compound Alaskan glacier. The ambition of the paper is welcome: there is an increasing output of papers dealing with one or two aspects of debris-covered glacier (DCG) monitoring and evolution, many based on state-of-the-art data gathering, but few attempts have hitherto been made to understand interactions at appropriate timescales, and to come up with integrative explanatory models. The paper bases its approach on mass continuity and the debris-thickness/melt relationship (the Ostrem Curve).

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

My general comment is that this is a rigorous and well-argued study which shows some interesting results, different from other papers I am familiar with. The core finding is that the interaction of ice flow, debris emergence, melt and thinning have produced a subtle "bulge" several kilometres above the terminus, marking the transition from active ice flow and debris emergence upstream to relatively stagnant, heavily debris-covered ice downstream. My surprise is that the active/stagnant transition is manifest as a convexity in the long profile, rather than a concavity as described in DCGs elsewhere. While Figs 2 and 5 are vertically exaggerated to show this subtle topographic evolution (as they must be), it is convincingly demonstrated. The transition corresponds to the kink in the downward limb of the Ostrem Curve at which the rate of sub-debris melting becomes less sensitive to debris thickness.

The paper raises some interesting questions, but also contains some inferences of cause-effect which are less well substantiated than others. There is perhaps a tendency in places to make easy inferences of causation based on only the available data, when other variables have not been considered. (This is not to denigrate the high-quality datasets presented). As such, I don't think it provides definitive answers to the problem of quantifying the feedbacks in these complex systems, but it does point to a way forwards.

We appreciate you bringing this issue to light. We agree that some of the inferences are just hypotheses that need to be tested and are better supported than others. We will make sure we indicate more clearly where these hypotheses are less well founded.

Another issue (also in no way a criticism here) is that the literature presents the "debris-covered glacier" as if it is a single class of glacier: this is not the case. DCGs take many forms and origins, and are unlikely to have a single unifying model of behaviour and evolution. This study of Kennicott Glacier is of a very large compound valley glacier terminating in a proglacial lake, whose debris cover is fed by coalescing medial moraines. We might not expect models from this glacier to apply easily to (for example) smaller moraine-dammed DCGs whose flow is obstructed towards the terminus, or single-basin glaciers with transverse foliation. Perhaps some acknowledgement of this diversity would be appropriate.

Thank you for raising this point. We agree that debris-covered glaciers take very diverse forms. We do feel though that it is something of an open question what about differences between these glaciers really matters. We will address this issue in the manuscript.

It isn't clear from this paper (Part C of three) what the ice thickness distribution is, but this information would be useful.

We will be sure to include the ice thickness estimates in the supplemental of Part C.

This is because, while velocity evolution is a key variable, the causes of velocity change and its distribution on the long profile are not covered, yet this information is essential for understanding the dynamic evolution of the glacier. I would like to see some consideration of the effects of both thinning rates and surface gradient changes on the driving stresses, to explore why the observed pattern of stagnation has developed: it implies a collapse in the driving stress from the terminus upstream, which in turn must be some combination of reduced ice thickness and slope. It is noteworthy (though largely unrecognised generally) that very thick, very gentle glaciers such as DCG tongues are sensitive to small changes in slope, at least as much as in thickness. So there is scope for a fuller explanation than is given in the manuscript.

Thank you kindly for this discussion. We agree and we have now extracted earlier annual surface velocities so we also add those to this manuscript. We will further address the topics discussed in this paragraph in the revised manuscript.

I have some minor line-by-line comments to improve the presentation, and to correct minor editorial mistakes (attached). (If we do not respond to the minor comment we will make the necessary change.)

Line 15 How can mass balance be "enhanced": rephrase.

24 Need to define upper limb and lower limb of Østrem's curve, because what is referred to here are really segments of the same limb (debris thicker than effective thickness). Don't hyphenate "upper limb" or "lower limb".

We will clarify this.

26 Suggest "in spite of" instead of "as well as"?

30 "may...control": it clearly does!

36-7 Why is the term "melt hotspots" in italics? Unnecessary.

35 Although the term "debris-cover anomaly" has gained currency since 2015, there is often a careless use of terminology in this context, where glacier thinning and melting are used synonymously. The "anomaly" (if one exists" is in the thinning rates, not the sub-debris melt rates. Make this clear.

We agree that the ‘DC anomaly’ refers to thinning rate not melt rates. This distinction is key for appreciating the three papers we lay out here.

54 “causes”, not “cause” (process is singular).

62-3 One cannot estimate a supraglacial stream. Rephrase.

65 “south-facing”

70 Suggest “more cliffs per unit area”.

83 Add comma after “significantly”.

97 Add hyphen after “column”.

105 Remove hyphen after “corrected”.

135 I take issue with the use of “bi-modal” here, because a bimodal distribution has two modes (peaks). Here, the term is used to indicate an absence of streams on thickly debris-covered ice: this isn’t “bimodal”, rather it’s a threshold control.

We will rephrase this.

147-152 Remove hyphens in “upper limb” and “lower limb”. See comment re. line 24 about clarity of what these terms mean.

157 Remove italics: unnecessary.

164 See l. 147

169 Why use the term “attractor state” here? You imply the glacier is attracted to an equilibrium state of mass balance, but there’s no reason for this to be more likely than any other mass balance state because mass balance is not controlled by internal system dynamics.

We need to clarify this. What we mean is that changes in surface mass balance translate into changes in ice dynamics they feedback into one another. We will work to make this more clear for the reader.

179 Commas after “are high” and “are low”.

186 Re. chicken-egg quandary: this disappears if a longer-term view is taken, in which velocity is the ultimate control, because the glacier must slow down to allow debris cover to accumulate (“ablation-dominant” conditions of Kirkbride (2000 IAHS))”. So the question becomes what causes change to the longitudinal velocity profile of the glacier over time, where does velocity reduce earliest on this profile, and why? (See my general comments).

Great topic, worth further exploration outside of this manuscript though.

194 See l. 135

197 See l. 135

197 et seq. It’s really no surprise that streams are more abundant on steeper gradients, and lakes on gentle gradients, since water flows downhill. What point is being made here?

We are just setting up the observations of surface features related to Ostrem’s curve so we can discuss them below. We will ad text so the reader feels more grounded in revisions.

216 I’m perplexed by the conclusion that ice cliff abundance is related to basal sliding rate. I simply don’t see a direct connection here, and wonder whether you are taking spatial associations too far down the line of causal relationships. If the connection is indirect, it needs to explained clearly and in full.

Here is a place where we need to be more clear about the potential connection. In the summer basal sliding produces high gradients in glacier surface velocity. It may be that high gradients of surface velocity disturb debris-covered slopes leading of the failure of debris and the exposure of ice which can then become ice cliffs.

231 I don’t understand how stream undercutting od ice walls increases debris thickness at the base of the ice slope. This implies that the ice slopes must decline in angle, for which no evidence is given: parallel retreat will give the same thickness at the base as at the top. (More likely, fluvial removal ofdebris occurs, so an apparent thickening as seen in Fig 9 may be debris brought to the site from upstream). Suggest omitting these two sentences.

Again we need to be more clear. Often times, and we will highlight this with photo evidence, sinuous streams persist at the base of ice cliffs. These sinuous streams tend to produce ice cliffs that have an arc shape. The arcuate planform then tends to focus debris at its base. Furthermore, sometimes ice cliffs have drainage basins on their surface which we observed to also funnel debris towards their base.

234 I disagree that the lower glacier is “hydrologically disconnected”. Supraglacial drainage becomes englacial (and subglacial?) which isn’t the same as being disconnected (see Fyffe et al 2019 J Hydrol 570, 584-597).

We can rephrase this such that the ‘surface hydrology is disconnected.’ We observed the termination of surface streams in a chain at this transition. The digitization of the streams highlights this.

236 “Ice cliffs are ... more likely to be buried”. Buried how? This assumes a process of disappearance which isn’t explained. I agree with the general point about their removal, but the process needs careful explanation.

Yes we will explain it in more detail as per many of the other processes.

237 Debris cover and surface drainage basin relationships are shown nicely in Catriona Fyffe’s recent paper (see l. 234 comment).

We will be sure to cite this paper. We may also have time to produce a similar surface drainage map as well for Kennicott Glacier.

242
The effect of this slope reduction is probably a key observation, because on thick, gentle glaciers the driving stress can be at least as sensitive to small changes in slope as to ice thinning. It would be interesting to see how this slope reduction plays out with changes to the basal stress profile over time, which may show something useful re. Velocity.

Great idea we will look into this.

255 See l. 242: on steep, thin glaciers, thickness change is the main control: on gentle, thick glaciers, slope is more important. Perhaps refine this sentence in the context that DCGs are characteristically thick and gentle.

Yes we will do this.

273 Replace “pattern of debris” with “distribution of debris thickness”: be specific.

273 “... this pattern over time”

278 Desperately needs a comma after “ thinned” , otherwise the sentence makes no sense.

279 “have”, not “has”. The stated change in the surface flow field is not supported by any evidence. Either omit this point, or provide evidence for it. If true (which I’m sure it is), clean ice would be redistributed as well as debris-covered ice, so is it an explanation at all?

This is an interesting point. We will think more about how to explain this. We are convinced based on the mass conservation equation for debris that surface velocity gradients are key for velocity change. We will highlight this effect based on this equation.

299 See l.147

310 Spelling “Glaicer”

317 “DS” is acknowleged here, but isn’t a named author of the paper.

Captions

Fig 1 Panel (a) doesn’t show the location of Panel (b).

Fig 2. I would go further in saying the elbow of the curve lies between 12 and 14 cm. Could you fit best-fit lines to each segment iteratively to find the location of the angle? Also, highlight the bare ice point more clearly. Which altitude does this point originate from? (it can’t be a unique point).

We will better clarify the bend we refer to.

Fig 5. The key figure in the paper, and really interesting to absorb. One query is why in (e) the elevation difference decreases below c. 3km above the terminus, but in (f) the surface lowering rate increases over the same distance? This seems inconsistent.

Hmmm. Just how the data work out. We will confirm that the origin of each data profile is the same, but it is likely just the result of the data.

Fig 7. While interesting in its own right, I’m sure what data on stream sinuousity contributes to the overall interpretations and conclusions. This figure and the accompanying text could be omitted, unless a stronger case is made for its inclusion.

We will better explain this effect. The more sinuous a stream the more length of ice cliff the stream can undercut. The more sinuous the stream the more ice cliffs will be arc shaped and the more likely these ice cliffs are to focus debris at their base.

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 feed-backs 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.