Thank you for your substantial contributions to the process and our manuscripts! They were very helpful. However, even after substantial revisions, we feel that Part C requires further work. As a result we have withdrawn that contribution. We have combined what was Part A and B to stand on its own as a singular submission. We greatly appreciate both the editor and reviewers managing the original three manuscript format. We further hope these changes will ease and simplify the future reviewing and editing of our submission.

Changes made to what was Parts A and B:

- Parts A and B are combined into one new manuscript following the editor's recommendation.
  - All sections of the text were updated following the reviewer comments
  - Uncertainties are reported in the text, figures and supplemental.
  - Thermal conductivities, on-glacier air temperatures, and degree-day factor methods have been moved from Part A to the supplemental materials of the new contribution.
    - Internal debris temperatures through time are plotted there.
    - A figure has been added showing the negligible effect of correcting in situ melt measurements to the full study period.
  - Curve fits are justified in detail, especially the sigmoidal fit to debris thickness.
  - Debris thicknesses were extrapolated down medial moraines
    - Debris thickness measurements are plotted down each medial moraine in the supplemental
  - Ice cliff backwasting is now applied uniformly through the study area for distributed melt estimates
    - Ice cliff backwasting is plotted by medial moraine and if streams or ponds are at their base in the supplemental
    - For ice cliff slope uncertainty we completed a compilation of published mean ice cliff slopes from previous studies. This allows for the establishment of uncertainty bounds in the distributed melt estimates
    - We also include in situ measurements of ice cliff slope taken from the summer of 2011.
  - Uncertainty estimates, very similar to those already in the original Part B, are now more clearly stated with the percentage of simulations that fall within the uncertainty bounds clearly stated.
  - 5 new sensitivity tests are applied to explore the robustness of our distributed melt estimates, following reviewer comments. They are in a new greatly expanded supplemental.
  - Thinning data from Das et al., 2014 are moved into the main text from the previous supplemental to support the stable location of the zone of maximum thinning up until 2007.
  - Most figures have been updated.
  - We have cut down on speculation and emphasized in some locations that we are presenting hypotheses.
  - Ponds were moved out of the contribution.
  - Conclusions have been expanded and placed in bullet points.

Replies to the four reviews of the original Parts A and B follow.

Reply to Reviewer 1 Part A

Review of "Debris cover and the thinning of Kennicott Glacier, Alaska, Part A: in situ mass balance measurements" by Anderson et al.

Thank you for taking the time to review our manuscripts. You comments were very helpful.

This study is the first part of three publications that investigate debris cover on Kennicott Glacier in Alaska. Given the limited number of studies that measure properties and melt rates of debris-covered glaciers, these measurements and results are important for advancing our understanding of debris-covered glaciers. This is especially true when one considers the limited knowledge of debris-covered glaciers in Alaska. The measurements and results are presented well. For the most part, the study is easy to follow, well-written, and has sufficient references.

There are a few sentences/paragraphs that could be modified to improve their readability though. The only major comment is to make sure that this study is discussing results that specifically pertain to this part of the three-part study. There are also a couple places where additional detail or analysis would provide useful context to the modeling community; however, this would only require minimal additional work. Therefore, I recommend accepting this manuscript for publication subject to minor revisions. Please see my detailed comments below.

Thank you kindly. We very much appreciate your efforts, especially considering you reviewed two manuscripts.

Main Comments

The reasons for studying Kennicott Glacier largely come across as reporting results across the three papers as opposed to stating what each paper does. For example, L55-57 state that the debris is thinner than most previously studied, but there is no reference to any studies concerning debris thicknesses on Kennicott Glacier. Similarly, L58 states there are more ice cliffs than those previously studied without a reference to a study that shows this. Hence, these appear to be results (and results from other papers) that are stated in the introduction.

This is remedied by combining Parts A and B.

Furthermore, the introduction states multiple times that the thinner debris increases the likelihood that melt hotspots will compensate for the insulating affects; however, thinner debris has higher melt rates, so it's unclear why melt hotspots would be more important for debris-covered glaciers with thinner debris because there would be less contrast between the sub-debris and ice cliff melt rates. If this is a hypothesis, then please state it this way. If this is supported by a physical basis, then please explicitly state this reasoning.

It is not about the relative contribution of hotspots to sub-debris melt but rather a comparison of absolute melt rates. That is a big point here that we will emphasize better. The absolute melt rate is what matters for the debris covered anomaly.

It is the net melt (sub-debris + hotspots) compared to the bare-ice melt rates at the top of the debris cover. Or another way to put it is: where is the maximum glacier-wide melt rate? And does it correspond with the zone of maximum thinning.

Lastly, the interpretation of the transverse variations of debris thickness appear to be poorly supported by the present figures and text. L135-139 state that mean debris thicknesses increase near the glacier margins. However, site a appears to be closest to the center of the glacier, yet it has thicker debris. Similarly, site c is between sites b and d. Perhaps this is complicated by how far downglacier these sites are, but this needs to be elaborated upon. The same is true for the conclusion, where this is discussed. I would suggest removing this from the conclusion.

We see the reviewer's point, but the trend we discuss is also present. We have moved this material out of the new manuscript. We ultimately present distributed debris thickness estimates down medial moraines in the new manuscript.

Specific Comments
Italics indicate suggested grammatical changes

L26 - use of "thick" and "thin" is a relative term. I suggest adding in parentheses what constitutes thick and thin.

We add this distinction.

L35 – consider "and, when thick, suppresses melt rates." or "and suppresses melt rates when thick."

This sentence was removed.

L39 – this sentence is missing its subject, so it's an incomplete sentence. Consider using a semi-colon instead or adding the subject "Alternatively, this anomaly could be caused by...". Also,"or" and "alternatively" are repetitive.

This sentence was removed.

L41 – referring to the debris-cover anomaly here almost across as a result, i.e., Kennicott Glacier experiences the debris cover anomaly. If this is already known, then the reference should be added. If this is not known, then consider changing this sentence to give a broader overview of what's being done, e.g., constrain patterns of ... to understand the role of surface melt and ice dynamics on the surface lowering of Kennicott Glacier.

This is simply an observation derived from the data presented in Das et al., 2014, so we leave it in the introduction of part 1.

L55 – it's not entirely clear why thinner debris would affect the anomalous glacier thinning explained by melt hotspots, since thinner debris will have melt rates that are closer to clean ice. Also, are there previous debris thickness measurements of Kennicott Glacier? If so, this should be cited; otherwise, the fact that Kennicott Glacier has thinner debris than those previously studied is a result.

Thank you for the comment. If rapid thinning under debris cover is primarily caused by melt (hot spots + sub-debris melt) then we are most likely to see this effect where debris is thin and sub-debris melt rates are high. The basic logic we use throughout the former 3 parts is: if melt rates are the primary control on thinning then melt must also be maximized where thinning is greatest. Having thin debris already creates high melt rates, adding a high coverage of ice cliffs means that both components (hot spots and sub-debris melt) are extreme for Kennicott Glacier. We make this clear in the updated manuscript.

L60 – It remains unclear as to why thin debris increases the likelihood that melt hotspots will compensate for the insulating effects of debris.

It is very simply that thin debris reduces melt less than thick debris relative to hypothetical, local bare ice melt rates. If you have a glacier with thick debris cover melt suppression will be higher relative to hypothetical local bare-ice melt rates and will require a much higher contribution of melt from hot spots to compensate for the insulating effects of debris. This is about absolute melt total not the relative contribution of ice cliffs to sub-debris melt.

Conversely, the way the argument is stated sounds like melt hotspots cannot compensate for the insulating effects of debris on glaciers; however, because the debris on Kennicott Glacier is thinner, the sub-debris melt rates are closer to clean ice melt rates and hence the melt hotspots are less important because there's less of a difference to compensate for. The key here seems to be more on the sub-debris melt rates of thin debris than the melt hotspots. Please clarify this.

We are happy to clarify this in the text. Thin debris represents an extreme case where melt rates are already higher, adding on a high concentration of ice cliffs means that we are likely to get high melt rates in the debris-covered area. It is not about the relative contribution of hotspots versus debris, it is about the absolute value of melt.

L61 – typo "similar" should be "similar"

Fixed.

L72 – typo in the reported elevation range? Also, is there a reference for this data? RGI inventory perhaps?

Added the RGI reference and corrected the range.

L73 – consider "... and our study area, the debris-covered tongue of Kennicott Glacier (24.2 km 2), is only..."

Fixed.

L77 – be consistent with reporting elevations. Perhaps "Above 700 m a.s.l.". This should be done throughout the manuscript as well, e.g., L90, L131, L134, caption of Figure 1 "located at 1240 m a.s.l.", etc.

Fixed throughout.

L77-79 – is there a reference for these observations?

Based on our observations from travel on the glacier surface.

L86 – What do you mean by "Kennicott Glacier debris"? The debris properties? If so, state this "Because the debris properties of Kennicott Glacier have not been..."

This was removed.

L88 – consider "internal and surface debris temperatures, and ..."Figure 1 – delete the ")" after panel b in the caption. Change to elevations to m a.s.l. May Creek
meteorological station is not shown on the map. I suggest adding this – perhaps it is covered by

one of the legends.

We prefer not to add the May Creek station to this figure. We now add to the caption where the station is relative to McCarthy direction and distance wise.

Figure 2 – caption is unclear. "Dead" ice portion has daily mean surface velocities greater than 5 cm d -1 only during sliding events? Is this meant to be less than 5 cm d -1 with the exception of sliding events? Also, what does "and the observations of Rickman and Rosenkrans, 1997" refer to? Fix this reference.

We remove the dead ice discussion. The text is also clarified.

L107 – Avoid the use of unnecessary acronyms like LR for lapse rate. This only makes the manuscript less readable, especially for readers who may not be as familiar with a specific acronym.

We moved the LR to the supplemental and removed the LR acronym.

Figure 4 – The 4 panel figure is highly repetitive (e.g., shortwave radiation is shown in all 4 panels, and the MWS air temperature is shown in both panels). I would recommend using only 2 panels. Air temperature can easily show the 3 sites, and the two lapse rates can easily be shown on the same figure by using different colors or styles.

The problem is that the figures become too difficult to read following this suggestion. We are not sure that this is a big issue. We moved this to the supplemental.

L128 – This line doesn't make sense "at 109 locations at the same locations we also measured". Is it means to be two sentences? Otherwise, perhaps "around the locations where we measured ...".

Fixed.

Table 2 – is 0.001 cm an actual measurement? That is incredibly precise and thin for a debris thickness, which is hard to believe.

Changed to 0 cm.

L135-139 - It would be helpful to provide context to the specific sites (panels) for each of these sentences, e.g., "debris thickness did not exceed 15 cm (Fig. 6c)"

Helpful thank you. We apply this throughout.

L144 – Given the use of MF (used by Pellicciotti et al. 2005) instead of DDF (used by Hock 2003), I would consider either changing the "MF" to "DDF" or add the example citation of Pellicciotti et al. (2005). Note that in some fields MF or DDF could refer to multiplying multiple variables. I leave it up to the authors as to whether they want to maintain this original convention or adopt newer uses of it (e.g., degree-day factors shown as f ice (Radić and Hock, 2011)).

Also very helpful. We now use DDF everywhere.

L148 – Why the use of off-glacier air temperatures when you have data from on-glacier air temperatures? It would be interesting to see the off-glacier air temperatures over the same period of time – perhaps this could be added to Figure 4 as this would provide some indication of how much the debris warms the air temperature?

We use the off-glacier air stations because we do not have measurements for the full time period of the field campaign from on glacier. There is a local station in McCarthy but it is not automatic and is recorded only during work hours for the airport. For melt factors it is also common to use off glacier sites and they actually perform better than on glacier sites often times. The idea is that on glacier sites are affected by the ice surface itself but really what is controlling available energy for melt is the integrated temperature from the lower 1 km of the atmosphere.

In addition to this the meltfactor correction provides a minor correction to the melt rates. We include this to be complete and correct measurements for difference measurement intervals.

L153-157 – Given the impressive amount of data collected, it is disappointing that the authors do not provide a "best-fit" Østrem curve for comparison with other sites. While there is considerable variability in surface lowering, especially over thin debris that is dependent on local conditions as the authors state, this is clearly something that would affect all previous curves. Is there a good reason the authors did not do this? This could be a highly beneficial product for modelers. If uncertainty is the issue, the authors could easily add uncertainty bounds to the curves.

A curve fit is in the old Part B. The curve fits and extreme curve fits are clear in the new manuscript. The curve fit parameters are also shown.

L176-177 – What does the "mean" debris surface temperature refer to? Is this the mean temperature over the entire study period (at least one week) or was this used to estimate conductivity on a shorter time period? I assume it is the former, but it may be good to be explicit, e.g., "... we then calculate K e for each temperature profile over the entire duration of the temperature measurements.". This would avoid any misunderstandings because the effective thermal conductivity could vary over time, e.g., if there was a change in debris moisture.

Thank you for this comment. We changed this in the text. It is the mean temperature over the entire study period (at least one week). This is moved to the supplemental material.

Figure 9 – Why is there a point for a debris thickness of 0 with an effective thermal conductivity of 0 W C -1 m -1 ? This seems to be unphysical. I also question the "nonlinear" increase in thermal conductivity as a function of debris thickness. There appears to be a fair amount of scatter such that a linear fit might also produce a reasonable fit? Furthermore, if the (0,0) point is discarded, then the linear fit will likely cross the x-axis around 0.4 – 0.5 W C -1 W -1 , which is near the lower range of that estimated based on physical constants (L181; Nicholson and Benn, 2006). Hence, this would be more physically based. Lastly, why is thermal conductivity plotted on the x-axis? The way this is used in the statement seems to be how thermal conductivity varies due to debris thickness and not the other way around. Hence, the debris thickness is the independent variable (typically plotted on the x-axis) and the thermal conductivity is the dependent variable.

These are all good points and we remove the zero point and curve fit. Moved all conductivity methods and results to the supplemental.

L181 – I question "The apparent non-linear increase". See comment above. It would be good to at least see a linear fit as well.

We remove the non-linear fit.

L182 – typo, "may be due to..."

L185 – it would be valuable to make assumptions concerning the specific heat capacity and porosity such that a comparison could be shown for the differences in thermal conductivity based on the method.

This is a nice suggestion but we are just moving this data to the supplemental.

L206 – type "were made..."

L205-206 – were these debris thicknesses already known from the previous debris thickness and ablation stake measurements or were these new measurements? Furthermore, how many "data points" were collected?

L214-218 - why the switch from backwasting rates to backwasting melt factors? It would be easier to read if it were consistent.
Backwasting melt factors are only discussed in the supplemental now.

Figure 12 – caption, "based on the individual melt factor..."

Moved to the supplemental.

L227 – shouldn't have to restate acronym, although see previous comment about removing it altogether.

Removed the acronyms.

L233 – "related to the large areas..."L245-248 – consider changing these sentences so that two sentences in a row don't start with "But..." as this should make it easier to read and understand.

Text revised.

L255 – Please state the percentage of debris thickness measurements that were derived from the top of ice cliffs to provide the reader with some sense of if this was for 50% of 100% of the measurements. "The majority (X%) of our debris thickness measurements..."

This % was added to the new manuscript.

L278-279 – This sentence about Part B is confusing. What does estimate if ice cliff melt rates correspond to the location of maximum thinning under thick debris on Kennicott Glacier mean? Is "under thick debris" meant to refer to the debris-covered glacier? A specific part of the glacier? Or literally the areas where the debris is thickest? I assume this is generally referring to the debris-covered glacier, but please clarify to avoid confusion.

Removed.

L281-285 – Is (1) different than (2)? Or is the poor representation of air temperature due to using the off-glacier meteorological data, which does not account for the variations in air temperature above the debris? Also, having sentences in the middle of these various points is very hard to read. I would suggest making these three separate sentences.

We see what the reviewer means. This could be clarified with a bit more explanation. This section was moved to the supplemental material.

L285 – What does this sentence of the portion of fine material have to do with ice cliffs? This seems very out of place and appears to refer to the section on thermal conductivities.

This section is actually about ice cliffs (3.4 Ice cliff backwasting). Just needs a bit more of a clear explanation. The section has been re-written to clarify our meaning here.

L297 – missing Oxford comma, which seems to be used throughout the rest of the manuscript

Corrected.

L300 – "transverse debris thickness patterns broadly correspond with surface velocities" is out of place and perhaps meant for paper B or C. This paper showed no data on surface velocities.

We moved out of the new manuscript.

L302 – may want to acknowledge the limitations that were described in the discussion, i.e., that most debris thickness measurements were from on top of ice cliffs and so caution should be used when using these for tuning and validating distributed debris thickness estimates as they may underestimate the actual debris thickness.

We now report the % of debris thickness measurements from the top of ice cliffs. That way the reader can decide.

L305 – reconsider "non-linear" relationship. See comment above. Furthermore, is the larger point that "water" or "porosity" plays an important role in heat transfer? They are certainly related to one another, but most of the discussion seemed to focus on the role of finer debris and porosity. This should be consistent in the conclusion.

We removed the non-linear relationship. All conductivity methods and results are moved to the supplemental.

L308 – there is no evidence in this paper that the ice cliffs counteract the insulating effects of thick debris. More appropriate would be to summarize how the backwasting melt rates compared to the sub-debris melt rates. If this is a conclusion from Part B, then it belongs in that paper.

This is a general statement not a specific statement about the Kennicott. But we clarify this issue throughout.

References (thanks for including these. Very kind)

Pelliciotti, F., Brock, B., Strasser, U., Burlando, P., Funk, M., and Corripio, J. (2005). An enhanced temperature-index glacier melt model including the shortwave radiation balance: development and testing for Haut Glacier d'Arolla, Switzerland, Journal of Glaciology, 51(175):573-587.

Radić, V. and Hock, R. (2011). Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nature Geoscience, 4:91-94.

Reply to Review 2 Part A

Review of ‘Debris cover and the thinning of Kennicott Glacier, Alaska, Part A’ by Leif Anderson et al., under consideration for The Cryosphere

Thank you kindly for taking the time to review our manuscripts. Your comments greatly improved our work.

The manuscript by L Anderson, et al., presents a variety of field measurements on debris-covered Kennicott Glacier, and characterises the debris properties and melt rates under debris or at ice cliffs. These data are an extremely useful contribution to understanding of debris covered glaciers in distinct settings. Very few measurements of debris-covered glaciers are available in Alaska, despite the extensive debris coverage of glaciers in the region. The data presented cover an extensive set of topics, and will be useful in calibrating and applying models developed for other regions to Alaskan sites.

Although there are only minor points of criticism relating to the data presented, the manuscript at present lacks cohesion. The results from this manuscript are key in laying the foundation for Parts B and C of the study by Anderson et al, but I can’t shake the feeling that this would better fit as (largely) supplementary material for Part B, or as a submission to the EGU journal Earth Systems Science Data; the content is unusual for The Cryosphere. In the latter case or if the manuscript will remain as an independent paper in The Cryosphere, I would recommend expanding the discussion of the varied data collected; some opportunities for expanded discussion are identified in my comments below.

This manuscript (Part A) has been combined with the original Part B following this reviewer’s suggestion.

Major Points

As a presentation of diverse field measurements, the manuscript lacks a storyline. I appreciate the effort and value of collecting these measurements, but there is no methodological development, and the results and discussion seem geared towards briefly placing the measurements in the context of observations in High Mountain Asia. The few major outcomes (e.g. aspect dependence of ice cliffs) are not investigated or discussed in much detail, as it is very clear that these measurements are geared towards supporting Part B. Consequently, I feel as though many of the results could be included in Part B without a separate Part A; rather by including these measurements as supplementary material, as they follow more-or-less established methods.

The manuscript organisation is awkward at times. In part this is because measurements and results are presented together, but also because figures are not always associated with the text that pertains to them. More problematic is the lack of an integrating discussion – the individual measurements are discussed but there is not much of a summary characterisation of Kennicott. I appreciate that this is difficult to do from such diverse field measurements. Again, this is in part because the paper is unusual for content in The Cryosphere, and this is another reason why I think this work could be integrated into Part B (or as a manuscript in the EGU journal Earth Systems Science Data, rather than a distinct manuscript.

Data availability. In the modern spirit of open data, I would strongly recommend that these measurements be archived in an open repository.

Off-glacier air temperatures are used to correct short-period met measurements to the full period of record, but these stations have been shown in this manuscript to represent entirely different altitudinal temperature differences compared to on-glacier stations. The use of the off-glacier stations needs to be robustly evaluated at the stations, and the on-glacier stations need to be used to determine melt factors (for the on-glacier air temperature subperiod). Even if this does notchange the pattern of relative melt factors, this represents a (possibly major) uncertainty in all of the analysis.

Thank you for your comment. The DDF approach is always relative to the station data (be it on-glacier or off-glacier). Because we have measured melt rates we can optimize the melt factor for each ablation stake. On-glacier weather stations often perform worse when applying DDFs. We have moved this discussion into the supplement. A figure in the supplemental of the new manuscript shows how small the DDF correction is.

Furthermore, the on glacier temperatures are effected by the glacier surface. While on-glacier sites are best for energy balance approaches, off glacier sites have been shown to perform better when using DDF approaches (Ohmura, 2001; Wheler et al., 2014).

It is actually, as well, and exceptional occurrence that there is a meteorological station above the study area. In Alaska, this is a rather special occurrence. In short we have already made the best correction of theses data possible with what is available and this is simply a negligible issue.

Uncertainty in measurements or calculations is not considered at all in the manuscript. Since these measurements are used in two linked following studies, and to draw important conclusions about the dynamics of debris-covered glaciers, I think it is important to frame the results in terms of uncertainty from the start.

All uncertainties are now described in the new manuscript for all measurements and the supplemental material.

Minor Points
L34. 'when thick it supresses melt rates' – although common knowledge, it is worthwhile to specify a reference here

We add a citation here in the new manuscript.

L41. Not just explain but also examine; we have evidence of the 'debris-cover anomaly' in High Mountain Asia but not before in Alaska, to my knowledge.

The DC anomaly is present in Das et al., 2014. We just highlight that in the introduction here.

L53. Missing 'glacier' – debris-covered glacier mass balance

Fixed.

L55-64. I agree that Kennicott is an interesting case, and a great opportunity to examine the debris-cover anomaly. However, I don't entirely agree with these two justifications in their present form, possibly because a bit more explanation is needed. The presence of thinner debris means that there is less melt enhancement due to cliffs and ponds (ie they may not melt much 'more' than the subdebris ablation), even if their areal coverage is extensive. Your implied point is that the thin debris should lead to less of a melt difference between clean and debris-covered areas, and so the chance of cliffs/ponds/other mechanisms to make up for this is greater. That needs to be made explicit; at present the second rationale is unclear.

Thank you for pointing this out and David's review has a similar comment. The point here is that the relative contribution of ice cliffs versus sub-debris melt is entirely irrelevant from our perspective. Rather what matters are the absolute melt rates.

We clarify this in the new manuscript.

For the third rationale, it would be beneficial to identify the actual density of ice cliffs in the study area (although this is an output from part B).

This is remedied by combining Parts A and B into one manuscript.

Readers should not have to jump between the manuscripts to understand the rationale.

This is remedied by combining Parts A and B into one manuscript.

L80. The reference to Mount Blackburn does not fit into the text very well – what is the relevance to Kennicott? Debris supply mechanisms? Lithology?

It is simply an important local landmark. But we remove it.

L83. The multiple clauses with commas are a bit awkward.

Fixed.

L88. For consistency, this should be debris internal temperature and debris surface temperature.

This is moved to the supplemental and corrected.

L93. I suggest changing 'vary' to 'differ'. Boundary layer conditions also vary widely for debris-free glaciers, and for debris-covered glaciers; without a doubt there is overlap in this variability, but the distributions of conditions differ, which is your point.

This is moved to the supplemental and corrected.

L106. It would be good to include a very brief description of this important transition, or to simply state that this location is at the base of a prominent bulge. It would also be useful to refer to readers to a more specific area of Part C.

This was moved to the supplemental.

L107. These lapse rates are extremely steep, which makes me wonder if the positions themselves are sufficiently representative of the glacier surface. As elevation tends to be a less direct control on air temperatures over debris, I would recommend fitting the regression to all three observations at once (rather than a 2-step regression).

This is moved to the supplemental material and leave the analysis as is. We just reference the data in the main text. This suggestion could be fruitful, we just mention the local conditions now instead of adding new analyses.

It is highly likely that topographic prominence and proximity to water are both controls on both wind and air temperature over debris (e.g. Shaw and Steiner publications, also Miles et al, 2017 [Frontiers], Supplementary Material).

These are great suggestions, thank you! Here we really highlight the proximity to wide stretches of bare ice, which is the case on the Kennicott, unlike many previously studied DCG. We add this to the text in the supplemental of the new manuscript.

L114. 'was' should be 'were' as LRs is plural.L128.

Move to the supplement, fixed.

It is not clear from Figure 2 which are the 109 locations with debris thickness measurements, as there are more than 109 points when combining sub-debris melt, ice cliff backwasting, and debris temperature.

A single debris thickness measurement may represent several backwasting rates if they are measured close to one another. The same applies to ablation stakes which may be measured multiple times.

We drop the surface temperature measurements from the body of work because they emphasized the measurement of thick debris in order to increase the range of debris surface temperatures made.

L130. It would be good to identify these thinner debris positions (especially those with multiple measurements) spatially in Figure 2, rather than just with elevation.

This will make the figure too complex. And there is already a ton in these manuscripts.

L136. The presentation of these data seems to occur with Figure 7, which is not mentioned here but is quite a jump through the paper.

Fixed with combining Parts A and B.

L140-142. Were repeated sub-debris melt measurements made at the same positions? Did the debris thickness change when re-exhuming the stakes? What uncertainty is there in your debris thicknesses or melt rates due to the removal and reburial of debris? (Especially if this occurs repeatedly). A key consideration is that supraglacial debris often presents as sorted, but it is extremely difficult to replace debris in the same state which it was found. This of course is not a problem unique to your measurements, but it should be acknowledged and considered.

Yes this is a potential issue to all sub-debris melt measurements. Is there a citation showing that this effect actually matters for sub-debris melt rates? It seems like a potential minor issue. We consider it negligible but briefly mention it in the supplemental.

L145. This melt factor determination negates SW and LW inputs (and their variability), which may be very important for debris covered glacier surfaces (e.g. Reid, Steiner, Buri ice cliff studies, also Carenzo et al 2016). Although this may not affect your overall results in terms of total melt, it will definitely affect the aspect dependence of subdebris and ice cliff melt. Also, this is clearly determining the mean melt factor for each location; how variable were different melt subperiods for each site?

To us, the degree-day factor (DDF) approach we already use includes these aspect effects. If the melt is higher in a southerly direction then the DDF would be higher. If a north facing ice cliff retreats slower than the MF would be lower. The SW and LW effects may be able to produce more accurate estimates of melt but that would play more of a role if cloudiness changed and the relative effect of SW to LW fluxes changes. But a simple MF approach would also include these effects if the relative effect of SW to LW changes as well.

Our approach here is not to use the most sophisticated melt model possible, that requires may more data input (we are in a relatively data poor region for glacier studies and have no access to these fluxes locally) and increased constraint of parameters. The simple approach used here is effective, and please note how small the corrections are in figure 12 of the original Part A. It won't matter which melt model we use the change will be small because we are correcting the rates for a difference of a few weeks between individual measurements. But the differences between melt models is a worthy target of research.

L148-150. Please explain this estimation of T* more clearly. Are you using the LR between the two off-glacier stations to estimate T* at each location? If so, this estimation needs to be further evaluated relative to the multi-step on-glacier LRs (for the shorter period of measurements for those stations), which differ considerably for the environmental lapse rate.

Yes we are using two off glacier meteorological stations which has been shown to provide good estimates of melt. As far as we understand off glacier sites provide a better sense of the temperature of the lowest km of the atmosphere which works well for predicting melt. Note too what we use these DDFs for: It is just to correct difference in measurement period so we are deriving DDF from a couple of weeks to estimate melt for another couple of weeks. The effect on backwasting rates is very small and does not change the story here or in part B, even if we used a more complex model we aren't convinced that anything would change, because of the increase in parameter uncertainty.

These air temperatures were moved to the supplemental.

At present, the dependence on off-glacier measurements is not very robust, as your on-glacier air temperature measurements indicate a significant deviation from off-glacier air temperature spatial variability. This will have the effect of smoothing your ice cliff MFs with elevation.

We do not see how this really matters. We use the closest, viable meteorological station. The difference in temperatures observed from the on-glacier stations will be included in differences in the DDF between sites. See Wheler et al., 2014 article on the use of DDF from Canada. That is the advantage of the DDF approach. The DDF includes all these differences in physical variability. Even if an energy balance model includes all the Energy transfer pathways the number of parameters skyrockets such that the issue becomes the constraint of these parameters. If we were using an energy balance approach then yes we need on glacier temperatures, but we are not and we feel that based on a number of studies this approach is well justified.

L156-7. This is an interesting comparison, and should be explored a bit in the Discussion. Is this due to latitudinal controls on Ta or SWin? Presumably these glaciers have differing lithologies, and they certainly differ in climatic setting, so perhaps this is a coincidence? I note that there is still a factor of 2 difference between the other glaciers.

We agree that this is interesting and it is now included in the supplemental.

L161. This is not shown in Fig 2.

This figure was moved to the supplemental.

L176. Please justify the use of a linear extrapolation to surface temperature, which differs from interpretation of many debris internal temperature profiles I've seen (often an exponential form is noted when there are sufficient thermistors).

When integrating over more than a week the temperature profile becomes linear when heat is transferred by conduction (Conway and Rassmussen, 2000).

It would also be good to include 1-2 plots of the internal temperatures – diurnal variations and means.

This is new plot is included in the supplemental.

L181. I have some qualms with the 'non-linear' increase, which is only because you have imposed (0,0) as an additional point for your fit. Surely, an infinitesimally small debris thickness (which is of course unrealistic) should converge on the thermal conductivity of the rock material itself (i.e. no longer an effective conductivity, but the true conductivity of the material). If you neglect the (0,0) point, this looks most like a linear trend crossing the x-axis at about 0.4 W (C m) -1 . Also, I think that the non-linearity, if true, needs more consideration and discussion – what are the effects of sorting, for example? Does this imply a bulk density difference between the upper and lower debris layers?Also, what do you expect conductivity to look like for layers thicker than 1 m (e.g. these would exceed the range estimated by Nicholson and Benn (2006).

We remove the non-linear fit.

L199. It would be good to show the distinct lithological mixes in Figure 9.

We are no longer discussing this.

L205. Please indicate the accuracy of the Fluke Infrared Thermometer.

We removed the surface temperature data from all Parts.

L204-208. This section does not clearly follow the past sections, and also does not integrate very well with the rest of the study at present.

We moved this to the supplemental.

L216. Did you classify cliffs based on the presence of streams as well? Part of the results of Brun et al (2016) and others is that any moving water can have the same effect as ponds. In my opinion (not demonstrated) supraglacial streams are even more effective cliff maintenance mechanisms.

We did take notes on the presence of streams at the base but we found no correlation with the backwasting rate. Ice cliffs with lakes and streams are now designated in a figure in the new manuscript.

L223. It is worth considering these climatological and latitudinal controls in slightly more detail. Is Kennicott really cloudier in the melt season than Lirung (site of Buri and Pellicciott, 2018)? The latitudinal control is not unexpected, but deserves more consideration. Effectively, during the ablation season there should be less diurnal variation in solar zenith angle at high latitude (solar zenith and azimuth are of course correlated seasonally at any latitude).

We no longer consider this in the manuscript.

L233-234. Both instances of 'effected' should be 'affected'.

Corrected.

L264. Are these the (unmodified) measured melt rates or your estimated melt rates from section 2.3?

It doesn't matter which. We will include a plot of measured versus corrected melt rates in the supplemental. The points virtually plot on top of one another the changes are tiny.

L265. The comma here is awkward. Perhaps use 'as compared to'

Removed.

L273. This was only demonstrated for north-facing cliffs in Buri et al (2016b).

Does the reviewer mean south facing? Since north-facing ice cliffs are preserved.

L282. I agree that the representation of air temperatures from off-glacier stations is not robust. This deserves careful comparison of estimated air temperatures from lapse rates derived from your on-glacier stations (for the shorter period) before an extrapolation across the glacier. More importantly, this could lead to a major uncertainty in your MFs for both debris and cliffs, even if the patterns do not change with more realistic air temperatures. At the very least an evaluation of the accuracy of the off-glacier stations for representing the on-glacier observed air temperatures is needed.

We disagree. There is no need for the off glacier temperature to be compared to on glacier sites. DDF are relative parameters only relevant to the air temperature measurements. In addition we could also not do the DDF correction and the melt rate results would be almost the same.

As long as the DDF derived from the air temperature data we used is then used with air temperatures from the same stations the MF extrapolation is viable. We feel that this point is over emphasized. DDF and lapse rates are only relative to the temperatures at station.

See Wheler et al., 2014: Effects of Temperature Forcing Provenance and Extrapolation on the Performance of an Empirical Glacier-Melt Model

We move the on-glacier air temperatures to the supplemental.

L304-307. This list of summary statements is not terribly satisfying, and feels like a list of bullet points. More interesting is whether Kennicott's debris properties generally fit within the range of previous distributions (they seem to) which is meaningful as there are few published debris properties in Alaska generally. At the very least, it would be nice to have some numbers in the text?

These conclusions no longer matter with the re-combination of parts A and B.

Table 1. The estimated debris surface temperature difference is not described in the text.

Moved to the supplemental.

Table 2. I would describe the contents of this table as ‘measurements’ rather than ‘variables’.

Changed.

Table 3. It seems odd to choose Buri and Pellicciotti (2018) to represent Lirung, as that study was primarily modelling synthetic cliffs rather than reporting backwasting measurements. I think the most appropriate study here would be Brun et al (2016).

Reference changed.

Figure 1. At what interval are these contours?

Fixed.

Figure 2. It would be useful to identify the sources and dates of the WV and aerial imagery in this caption or in the text.

All images are referenced now.

Figure 3. I like this schematic, but it’s not quite complete: missing are the thermistor strings and air temperature measurements (possibly others). Also, it would be fantastic to include some field photographs demonstrating the measurements.

This is moved to the supplemental.

Figure 4. Since you rely on the May Ck and Gates air temperature measurements, it would be very beneficial to show them here. Perhaps it would also be possible to combine panels (a) and (c), and (b) and (d).

We feel that combining the panel will make an unintelligible figure. We could add in the off-glacier data but we aren’t sure how it really matters. DDF are all relative to the temperature data they are derived from as long as data from the same stations used to derive the DDF is used for extrapolation the principle holds. There is no absolute DDF it is always relative to the temperature data.

Figure 5. Can you indicate the lithology of the debris thickness in panel (a)?

We did not quantify the lithology, it is not mentioned in the new manuscript, except briefly in the supplemental.

Figure 6. This seems to be referred to out of place in the text. Also, I’d suggest switching the axes (so that elevation is the y axis) for easier comparison with Figures 1 and 5.

We move this to the supplemental.

Figure 7. I didn’t catch a description of the bare-ice melt rate – what elevation was this at? In addition, this content is almost entirely repeated in Figure 8, so I’d suggest eliminating the figure, but depicting the bare ice melt rate in Figure 8.

We will clarify bare-ice melt rate, it is described in the manuscript now. This data is only shown in one plot now.

Figure 9. As described with my comment on L181, I don't think the point at the origin is justified, in which case a linear fit is entirely appropriate. Also, I'm a bit disappointed that we don't see any of the thermistor data!

We will remove the point at 0 and the curve fit. This is moved to the supplemental as well.

Figure 10. I would suggest to merge this with Figure 9, as the content is very closely related. Also, I note that the units here (m 2 s -1) differ from that in the text (mm 2 s -1).

Moved to the supplemental.

Figure 11. Over what time period were these temperature measurements taken?

From 10 am to 4 pm. We remove these surface temperatures from the contribution.

Figure 12. Is it possible to identify the cliffs that bordered ponds or streams within one of these panels?

This is now included in the new manuscript.

Reply to Reviewer 1 Part B

Interactive comment on "Debris cover and the thinning of Kennicott Glacier, Alaska, Part B: ice cliff delineation and distributed melt estimates" by Leif S. Anderson et al.

Anonymous Referee #1

Received and published: 18 October 2019

Review of Anderson et al., part B, The Cryosphere, October 2019

Thank you kindly for taking the time to review these manuscripts. Your comments greatly improved this work.

In this second opus of their trilogy, Anderson et al. deduced the spatial pattern of melt due to ice cliff and under debris, and consider the distribution of supraglacial lakes to conclude that melt hot spots (cliffs and lakes) are not sufficient to explain the pattern of rapid thinning on Kennicott Glacier.

Overall this is a series of paper that bring a lot of new data and contribute to show that melt hot spots (ice cliff and lakes) only modestly contribute to the overall mass loss of a large debris covered tongue. A clear achievement has been to perform such measurements on a very large glacier in Alaska and proposed methods to extrapolate the point wise measurements to the overall debris-covered glacier tongue.

Thank you for the kind summary.

General comments for the three papers.

1/ I am not convinced by the need to split this paper into three parts. It implies lot of repetitions and also mean that the reader as to refer to other parts of the article which is not convenient.

Some data are plot several times in the three articles (debris thickness, dh/dt for 1957-2009 etc. . .) I think the authors missed here an opportunity to put everything together. Specifically in this part B, the discussion (section 4.2.1) whether ice cliff or debris can explain the zone of maximum thinning would be much more straightforward if Part B and C were merged. Right now this discussion is a lot of speculation to finally justify the need for a part C.

We appreciate this perspective on the body of work and we have combined Parts A and B into one manuscript.

2/ One strong limitation (that needs to be emphasized more) is that field measurements over a short period of time in July 2011 are used to interpret a map of elevation change measured over a multidecadal time period. Authors need to recall to their reader that their results apply to 2-month period in summer. The whole discussion would have been much more meaningful if the elevation changes were also measured for the same time period where surface melt features are studied (but the DEM data are probably not available. . .).

The field data is from June to August 2011. We actually have dh/dt estimates that cover the time period derived from ArcticDEMs. New dhdt estimates are provided in what was Part C in another contribution to be re-submitted. The zone of maximum thinning is in the same location as the dh/dt maps from 1957 to 2004, 1957 to 2000, and from 2000 to 2007 from Das et al., 2014. These plots from Das et al., 2014 were in the supplemental material, but are now in the main text of the revised manuscript.

In the discussion of the new manuscript we focus on just the measurement period in 2011.

General comments for part B.

3/ I miss a more thorough description of and comparison to earlier studies mapping ice cliff automatically. In particular Kraaijenbrink et al., RSE, 2016.

We now cite this paper and provide a broader discussion of ice cliff mapping approaches.

4/ I feel it would have been very interesting to see an evaluation of the ice cliff mapping algorithms using independent dataset, for example the Ragletti/Steiner cliff dataset on Lantang Glacier. Maybe this ice cliff automatic mapping part would have deserved a dedicated article, and all the rest of the results would then fit a single contribution?

Interesting point, but ultimately this paper is about evaluating ice cliff extent on a single particularly difficult glacier. If an independent, reliable validation dataset was available for Kennicott Glacier we would use it. But we have already put in a substantial effort to validate this method, having digitized ~ 7 % of the entire surface.

5/ Uncertainties could be treated in a more systematic way so that results in the end should all be quoted together with their range of uncertainties. This applies to all three parts.

Please note that Figure 10 already includes a generous, extreme range of uncertainties, that has been over looked by this reviewer. We report errors more clearly throughout and added a new heading titled uncertainty in distributed melt estimates. We also added 6 additional uncertainty cases in the supplemental.

“results in the end should all be quoted together with their range of uncertainties.”

We consider this to be a style choice. We provide extreme uncertainty estimates because our goal is to determine if ice cliff + sub-debris melt is maximized in the zone of maximum thinning. Including too many different ways of representing uncertainty will confuse the reader. So we place these additional uncertainty estimates in the supplemental.

6/ When authors provide % of melt, they should always make it clear that this is a percentage of the debris-covered tongue (and not the whole glacier!)

We have clarified this.

Specific comments.

L16 What does "enhancing" the mass balance mean. A mass balance can be increased or reduced. Is this formally demonstrated? I thought it was debated.

We will clarify ‘enhancing’ as suggested. In this case just changed to ‘increasing.’

L21 “Total” is ambiguous. Tongue-wide or glacier-wide?

We will clarify this.

L41 One does not expect results in the introduction.

The statement we make is based off of previous work from the area so it is more an observation to set the stage for the rest of the manuscript, not our results.

L51 "surface mass balance" would be a more appropriate way to refer to it

See text immediately below L51.

Eq 1. x,y are not defined.
Fixed.

L58. So do the authors neglect them? It should be stated unambiguously.

We state that we neglect them.

L88ff. Splitting the article into three parts leads to many repetitions such as this section. Problematic in my view.

A and B are now a single manuscript.

L160. Unclear (understated) what meteorological data would have brought, if they had been available.

Removed.

L169-170. This statement that 20% of ice cliff area need to be added is enigmatic at this stage in the paper.

We will clarify this.

Eq (3). How the type of fitting curve was chosen? It seems to come from nowhere. Can it be justified?

We will provide a proper method of justification for the curve fitting based on error metrics. Ultimately, the details of the shape of the curve are secondary (linear or non-linear) to the melt suppression effects of debris. We have added significant supplementary data and plots to show how the specifics of the curve fit do not effect our final conclusions.

L183. I see in part A that your cliff backwasting rate neglect emergence velocity. This needs to be justified.

It is not clear what the reviewer is referring to here. The emergence velocity is not relevant to our backwasting rage here because we measured the rate in situ, on the glacier.

L191. A statement such as (here) "based on an analysis of 2-m ArcticDEMs" is too vague.eq (7). Ice ciff area. Is it planar or real area? I think "i" must be added as superscript with b^dot debris and b^dot icecliff

This has been clarified and fixed. The ‘i’ superscript is not needed because the melt rates are varying pixel to pixel within elevation band ‘i.’

L204. I do not understand why fitting a curve through 25% or 75% of the data points leads to "extreme" cases. Not clear. Why not a curve containing 67% of the data (to have 1-sigma uncertainties). See my general comment about treatment of error bars.

We use 25% or 75% of the data points for debris cover because using 1-sigma uncertainties would result in negative debris thicknesses. There is really no way around this for debris as it varies with elevation.

In the uncertainty estimates we now use 1-sigma bounds for ice cliff backwasting, ice cliff slope, and sub-debris melt. As stated above we don’t see away around the Interquartile range approach for debris thickness.

L226. "error checks" is a strange terminology. Why not "validation dataset"

Adjusted.

L240. Percentage should be 21% and 31%, right?

Fixed.

L244. Where does “11.6%” come from? I read 11.4% and 11.7% above.

Typo, fixed.

L245. This raise the question of whether all studies defined the "debris-covered tongue" the same way. Did the authors check carefully previous studies for this aspect?

We clarify what we mean by study area early on.

L247. “This implies that ice cliff coverage varies with debris thickness”. This seems like a hasty conclusion. . . other example from the literature to support the statement?

There are not many studies that quantify ice cliff distribution and we don’t see anything wrong with highlighting what ‘could’ be a trend.

L257. One expect an error quantification for each term (81% and 19%).

The next sentence does just this for the 19% number, which also does the same for the 81% number so the error quantification is already present.

L268. “Across all of the elevation bands, the ice cliffs between 500 and 520 m generate a maximum of 40% of the total mass loss due to ice cliffs and sub-debris melt.” I am not sure I got the meaning here. Maybe reformulate for clarification. (it is clear from the figure, just a text improvement)

Clarified.

L273 "within" rather than "with" (I think)

Section was moved out of the new contribution.

L289. 19%. Lack error bars and also authors need to remind that this applies to a short period of time during summer 2011. So they cannot draw such broad conclusion.

19% is the most likely case. We choose not to overwhelm the reader with uncertainties quoted in every sentence. The uncertainties were already quoted previously. We also add 6 additional cases to explore the uncertainty.

We do not attempt to extrapolate the melt rates beyond the summer of 2011 now.

I would be curious to see a comparison of this number to the total glacier-wide ablation during this period if available. Is not it just a few percents? Do we need to really worry so much about ice cliffs for glacier-wide or region-wide application (and future projections)?

We could add in this analysis but we aren't sure how it would improve this study and the aims we outlined in the introduction. As we framed the study, we are interested in explaining the thinning patterns of debris-covered glaciers, and Kennicott Glacier specifically. Ice cliffs are an important, proposed contributor to this. Thinning patterns hold implications for longer term thinning patterns and hazards.

L307. the SMB cannot be "suppressed". It can be increase or decrease. (SMB is increased here, or less negative)

Changed to 'melt' instead of SMB.

L321. "This required backwasting rate is well beyond potential biases introduced due to the summer of 2011 having anomalously low air temperatures". Statement not really explained and justified.

What we mean is that the weather during the summer of 2011 was not anomalous in a way that would change the melt rate pattern we present in this study. We looked at pdds from year-to-year and the summer of 2011 is not an outlier in that regard. But we deleted this and just focus on the summer of 2011 in the discussion now.

L324. Is this potential overestimation from the sampling strategy (at top of cliffs) included in the error bars, as it should?

The assertion in the text as it stands is logically correct and we feel is a better way of arguing than adding error bars. We aren't sure how following this suggestion will actually improve the error estimation beyond what is presented. We could include error bars for each backwasting but how would that improve the legibility of our figures? How much of an over estimate is it? We do not know, so where do we end the error bar?

Rather if we know from other approaches that these are maximum estimates we can use that fact, as we do already in the discussion to present these ice cliff backwasting rates as generously high. With the revisions they are even more generous.

The backwasting errors are now presented, and are very small compared to the extreme uncertainty estimates included in the original manuscript.

L334. "mass loss" should be replaced by "melt rate" here.

All lake discussion is moved to out of the new manuscript.

L344. I did not get the point here.

All lake discussion is moved to out of the new manuscript.

L349. The wording suggests that 11.7 % of the glacier is covered with cliffs. No. This is the % of the debris-covered tongue.

All lake discussion is moved to out of the new manuscript. But we are more careful throughout with the study area definitions.

Table2. For the ice cliff backwasting parameter f, the most likely value is not contained by the min/max interval. A typo? Or a real error? For the ice cliff area the most likely and max values are equal. This is also not really expected neither.

Thank you for the comment but this is not an error. We point the reviewer to parameter ‘g’ immediately below parameter ‘f’ which is the y-intercept for the curve-fit. If you also look at the original Figure 4 you will see that these parameters are correct.

Table 3. Ice cliff fractional area, a percentage of what total area?

% of the study area. We clarified this.

L415. I do not understand this note.

Removed.

Figure 2. Are these data from Das et al? Did they use GDEM V2? This would be problematic because it has no defined time stamp. Explain the 1957 and 2015 grey boxes also.

They use a May 4 2004 ASTER DEM. Clarified.

Figure 4. Multiple reference to part A complicate the reading.

Fixed by combining Parts A and B into one.

25 and 50% or 25 and 75?

This is a typo, sorry. Fixed.

Is it "elevation bins"?

Fixed.

Panel B. Why the order of values in both axis are reversed. Why not showing the Ostrem way?

Reversed in revisions.

Authors could refer (in the article, not here) to a
compilation by Kraaijenbrink et al., 2017 in their Nature study.

It is not clear what the reviewer is specifically wanting us to cite.

Figure 5. Can the authors show the location of this small area of the glacier?

Done.

Figure 6. Impressive maps.

Thank you.

Figure 8. Showing percentage for panel c (instead of fractional area) would facilitate correspondence with the text.

We note the difference in the caption.

Figure 9 The sign only make sense if this is referred to as “surface mass balance rate”. If the word “melt” is preferred then positive values should be shown.

Fixed.

Figure 10. See comment on Figure 9 for "melt"

Fixed.

Figure 11. Recall the period of dh/dt. In panel b rather than repeating dh/dt authors could show a map with the density / m 2 of ice cliff.

This figure was moved out of the revised mansucript.

Thank you again for your efforts reviewing this manuscript.

Reply to Reviewer 2 Part B

Review of ‘Debris cover and the thinning of Kennicott Glacier, Alaska, Part B’ by Leif Anderson et al., under consideration for The Cryosphere

Thank you kindly for taking the time to review our manuscripts!

Part B of the Anderson et al trilogy aims to combine empirical relationships of surface properties and melt rates, based on the field measurements presented in Part A, with remote sensing observations of different surface features (particularly ice cliffs) in order to arrive at distributed estimates of melt rates for the period of observations. The analysis then uses these distributed melt values to address whether or not the identified melt hotspots can explain the thinning patterns evident at Kennicott. This is an important question as the glaciological community is trying to disentangle the influence of surface mass balance and ice dynamics for debris covered glacier evolution, and this is the first time the question has been addressed in Alaska, where surface debris is prevalent.

As such, this represents an important contribution to a current topic of research, and provides an answer to that question for Kennicott Glacier – these hot spots do have an important effect on the surface mass balance, but it is not plausible that they compensate for the overall melt reduction due to surface debris. The study could be more systematic to provide a definitive answer, and I have some criticisms regarding the empirical relationships presented in determining the distributed estimates of melt, as well as the difference in temporal scales between long-term elevation change (52 years) relative to single-year field measurements. However, although I have quite a few comments, no changes along these lines are likely to change the conclusions of the study. Rather, my principal concern is that the separation of this analysis from both Parts A and C reduces the strength and presentation of the entire analysis, while also leading to repetition of text and figures, as well as cross references. There are certainly gaps in the analysis because aspects have been included in Parts A or C rather than here, and some restructuring across the three manuscripts might improve the readability of all three. This is a choice for the authors and Editor to contemplate, but my opinion is that some consolidation would be beneficial.

Thank you kindly for taking the time to review these manuscripts!

Main comments:

My principal question in reading this manuscript was whether it should be standalone or integrated with Part A (and possibly C, which I have not reviewed). I appreciate that this is a difficult decision, and that Parts A, B, and C combined represent a substantial body of work.

Thank you for your thoughts. We are submitting one manuscript combining Parts A and B.

There are certainly some advantages to be considered for maintaining separation between the manuscripts, but my impression is that A and B are both weaker manuscripts separated from one another. The field measurements were clearly collected for the purpose of deriving distributed melt rate estimates, which leaves Part A without a compelling conclusion or discussion.

Parts A and B are combined into the new manuscript.

At the same time, Part B requires frequent reference to Part A, or blind faith of the part of the reader with regards to the methods and results of the field data. As a consequence, there is also quite a bit of repeated material to cover (for example, content from 4 figures in Part A is also displayed in Part B).

Parts A and B are combined into the new manuscript.

(for example, content from 4 figures in Part A is also displayed in Part B). My instinct when reviewing Part A was that much of that material could be more meaningful if integrated with Part B, in supplementary information if not in the main text, and I now think that would greatly improve the readability of this manuscript.

Parts A and B are combined into the new manuscript.

I like the ice cliff delineation method in its simplicity (although some details need to be clarified, below), but its transferability is not very clear. Often when developing/proposing a new method it is necessary to see how robust the method is, but in this case the method has clearly been developed specifically to map cliffs in this particular scene, in order to apply the empirical melt relationship. As such, it is a relatively small part of the story in deriving the distributed melt estimates.

Thank you for highlighting this. We present the new ice cliff detection method as a proof of concept for a rather tough case. Kennicott Glacier has more dense ice cliffs than any other debris-covered glacier that we know of. Slope threshold approaches do not appear to be as effective on this glacier. We could include a more thorough comparison with other methods we feel that should be the focus of another manuscript.

But we disagree that the ice cliff delineation method is a small part of the study. We feel it is a clear achievement to delineate ice cliffs so well on such a complex example!

At the same time, the maps of supraglacial ponds are not integrated very well into the story, while the exclusion of supraglacial streams (also mapped from satellite imagery) is a bit

Thank you for pointing this out. We move lakes and stream methods out of the new submission.

The study aims to address the role of melt hotspots in explaining thinning rates. For this to be a definitive analysis in this regard, I feel like this needs to be done in a more systematic manner, whereas the present analysis seems to focus exclusively on ice cliffs.

We will tone down the language about melt hotspots and focus on ice cliffs.

The distribution of supraglacial streams seems to be a major gap in the analysis of this part of the study, especially as the properties of supraglacial streams are assessed in Part C. Streams are mentioned throughout the background as hot spots and possible factors contributing to melt, but are then completely neglected in the methods and discussion.

We mention streams once or twice in the new manuscript.

It is important to note that there are very few studies that address the effect of streams on debris-cover glacier mass balance and to date none have really quantified an effect. We simply will focus on ice cliffs in the new submission.

I understand that the role of surface streams cannot be assessed quantitiavely in this manuscript, but neither can the role of ponds. Similarly, although internal ablation is usually regarded as negligible in this type of specific mass balance assessment, there have been suggestions that this is a non-negligible term for extensively debris-covered glaciers. It is exceedingly unlikely that this mechanism could lead to the debris-cover anomaly, but for completeness I think it should be considered numerically along with the cliffs and ponds.

We will not address this issue as the reviewer states, "It is exceedingly unlikely" to matter despite the suggestion in the literature. Rather we will just focus on ice cliffs in the new submission.

The relationships between elevation and debris thickness, and between elevation and ice cliff backwasting, are very weak. In neither case does elevation appear to be a primary control of the property.

They might be weak but our generous uncertainty analysis makes this point moot.

We are a bit confused about the elevation versus debris thickness statement because lower in this review you state: "In Part A it is clear that while elevation is a principal driver of debris thickness variability, there is considerable heterogeneity within any elevation bin." As we suggested in Part A it would be a nice idea to extrapolate down flowlines, but we felt like this was a methological development to focus on in later studies.

Despite the scatter we agree on, Figure 5 Part A (see below) shows that debris thickness does increase down glacier. We can argue about whether or not that is linear or not but the box-plots show the increase. Here is a reason why Part A standing alone is good for presenting the body of work. We are able to show the box plots that really reveal the thickening of debris down glacier.

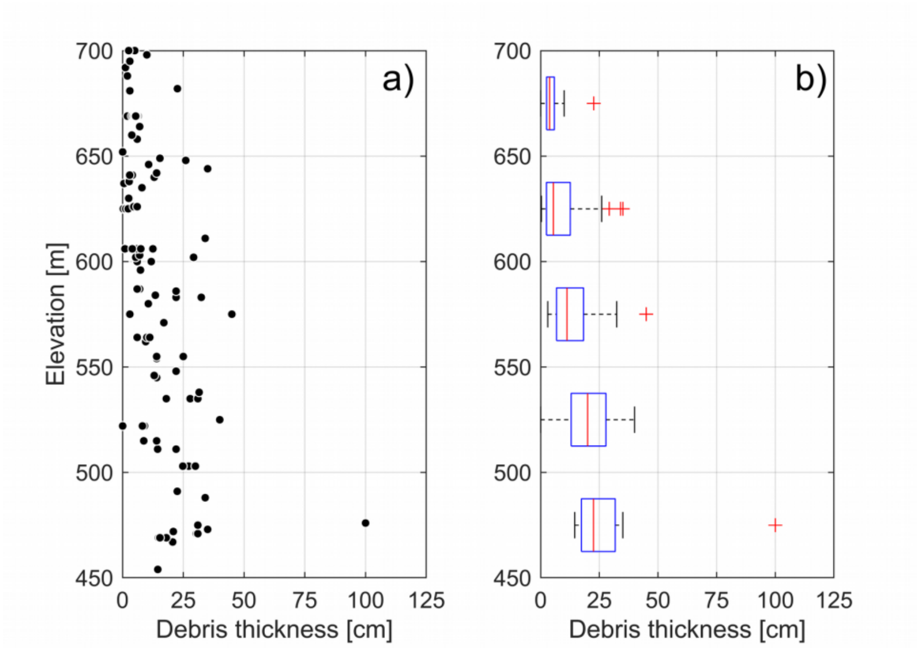


Figure 5. Pattern of debris thickness with elevation. a) In situ debris thickness measurements. b) Debris thickness boxplots in 50 meter elevation bins. Outliers are represented as +'s.

How different would your results be if you interpolated spatially (within flowlines or lithological units for example)? Did you consider alternative methods to provide a distributed debris thickness estimate?

We re-did the distributed debris thickness and melt estimates by extrapolating down medial moraines.

For example, one could consider the radiance measured by satellite thermal infrared imagery as related to debris thickness, and use your measurements to constrain this relationship locally to upscale in space much more meaningfully.

We did consider this approach but because of the number of ice cliffs in the study area we felt that this could be another manuscript in of itself, requiring significant justification and method development. We would need to remove the bare ice effects from each pixel before estimating debris thickness.

For ice cliffs, justification of a fit to elevation needs to be more explicit in this Part of the study.

We now use uniform backwasting rates. The primary results do not change.

The conversion of backwasting rates into ice cliff melt misses a slope correction for the cliff area, which results in an underestimation of melt (see comment on L190).

This was actually already included but not stated in the manuscript.

This raises a difficult question that has not been carefully considered yet for debris-covered glaciers, which is that the real surface area can be 10-20% higher than the planimetric area. For this study comparing geodetic thinning observations with estimated melt, that is an important aspect to consider, as melt occurs relative to the real surface area. This effect is especially pronounced for ice cliffs, but is also crucial for the 'background' melt rate if the glacier surface is highly variable.

We agree and it was already included in the original contribution.

It is too bad that more recent geodetic difference data were not included in the analysis. At present it is not clear how the long-term thinning rate relates directly to the 2011 observations. Would it be possible to use the ArcticDEM datasets to derive a recent-period thinning pattern? This would be more meaningful for a comparison to the contemporary distribution of surface features. The long-term perspective is still useful for understanding dynamic changes, but comparing 50-year lowering rates to one-year melt patterns does not provide a definitive answer, especially for a clearly changing system.

We brought in the Das et al., 2014 datasets from the supplemental into the main text. More recent thinning data was going to be in the new Part 2 but we feel it is better to submit that manuscript elsewhere.

Some rewriting is needed for readability and presentation standards in The Cryosphere. Although the ideas are well developed, some sections of the paper read as bullet points and/or the word choice has not been considered carefully, leading to some of my comments below.

We agree that there is some ambiguity in the writing that needs to be corrected. This review helped us understand where we can tighten the wording up considerably. Thank you kindly!

Detailed comments:

L23. Presumably this 19% of melt is for the debris-covered area?

Yes we will make sure the study area is defined correctly.

L25. Just a comment, for you to adopt or disregard: The literature has tended to use 'ponds' for these features as they are much smaller than supraglacial lakes on, e.g., the Greenland or Antarctic Ice Sheets.

We will switch to ponds. Helpful suggestion and we should be consistent with the literature.

L25. It would be nice to have the %areal coverage numbers here in the abstract, not just 'doubled'.

L27-27. This wording isn't very clear. By average melt rates you seem to mean the average for all surfaces, but as worded this seems to refer only to sub-debris melt. In the latter half of the sentence, do you mean that the overall melt relationship still follows an Ostrem-type relationship, even after accounting for cliffs and ponds?

We will clarify this as it is really important, making sure we emphasize which components we are including in the distributed melt.

Thank you for pointing this out. We will clarify this

Suggested change: Despite abundant ice cliffs and expanding surface lakes, average melt rates are suppressed by debris, with the primary control on elevation-band-average melt rates appearing to be debris thickness.

L34. These are broken sentences. The first half needs a reference even if it is now well understood.

We will join with a comma

L95. Has this happened progressively in the past 82 years, or primarily over some later period?

This is outlined in the citation, Rickman and Rosenkrans (1997).

L98. Why is 'partially' here?

Good catch.

We will change this to: The presence of ice cliffs, surface lakes, and variations in debris thickness on debris-covered glaciers makes distributed estimates of mass balance difficult.

L108. Which spectral bands of the image do you use?

We will add:

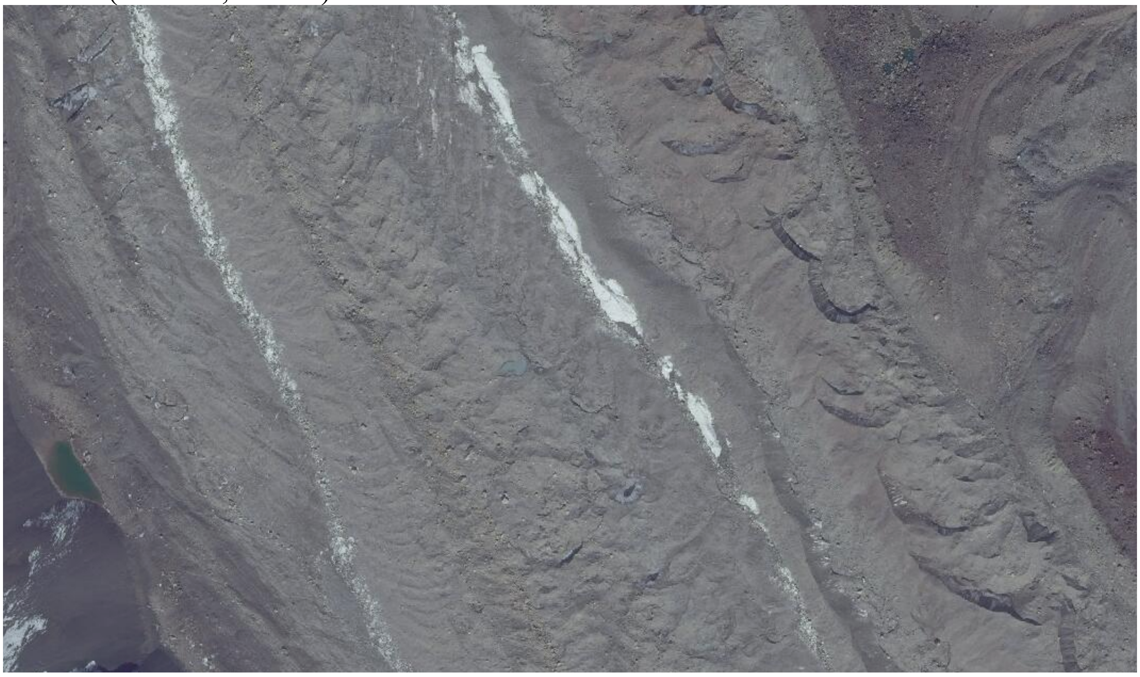
On 109, before “The 2009 WV image…” add “We use the panchromatic band, which integrates radiance across the visible spectrum and provides the highest spatial resolution”.

L113. This is true in certain conditions, depending both on debris lithology and meteorology. Such conditions may be prevalent for Alaskan supraglacial debris and melt seasons, but it is important to think whether such a method is transferable.

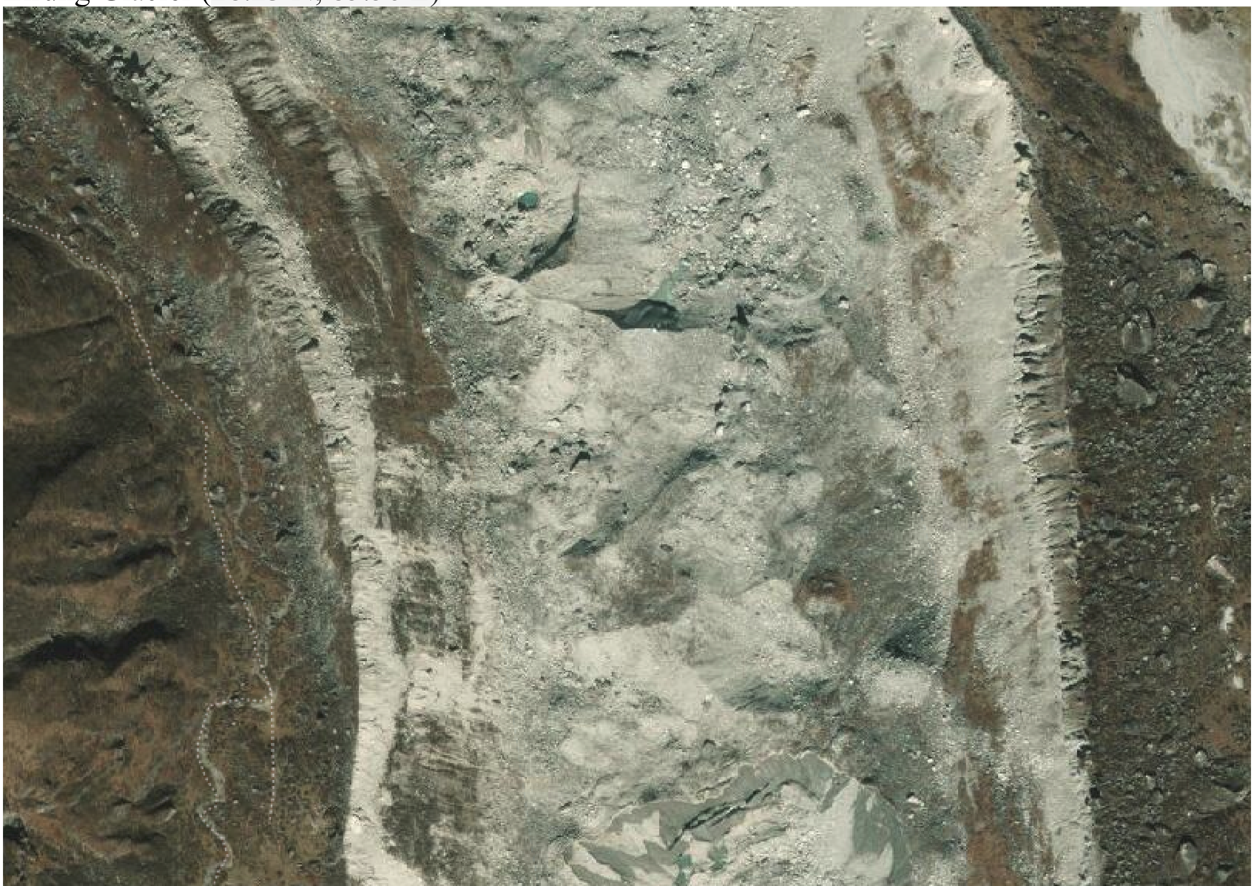
This is a good point. We looked into the universality of this observation that ice cliffs are generally darker than the surrounding debris cover using WorldView imagery in the Digital Globe’s EVWHS viewer. We attach screenshots of Miage, Koxhar, and Lirung glaciers below. These are debris covered glaciers from the Alps and Tibet, which are found at different latitudes and lithologies than Kennicott Glacier. We find that, consistent with our Kennicott Glacier observations, ice cliffs on these other glaciers are generally darker than the surrounding debris cover. We can find examples where this is not true, for example along parts of the southwestern margin of Miage Glacier in the snapshot below. These regions may go undetected in the method we present here. We address this limitation in the manuscript (L281 in the original submission). To address this comment, we add at the end of this paragraph “This observation of darker ice cliffs is generally true for Kennicott and several other debris covered glaciers we examined, but this relationship should be verified before application to a different glacier of interest. There are situations (e.g., variable debris-covered and debris-free ice) where this method could detect darker regions that are not related to ice cliffs. Output should be examined to ensure that such conditions do not contaminate results”. This language also partly addresses your L126-127 comment as well.

Miage Glacier (45.80 N, 6.85 E)

Koxkar (41.78 N, 80.1 E)



Lirung Glacier (28.23 N, 85.56 E)



L118. This is semantics perhaps, but I would argue that this whole workflow is your ‘cliff detection method’ (the name of step 2). It is a bit strange to have a ‘cliff detection method’ as the main step of a ‘cliff detection workflow’.

Yes we need to use consistent terminology here and we will address it in revisions.

We have changed “detection” to “delineation” throughout.

L118. Is the histogram stretch just a linear min/max stretch? Is this histogram stretch applied to the image globally or locally within a patch? What spectral band(s) are used in either approach? I suppose that you also start with a debris outline (and glacier outline), which is important to acknowledge for a remote sensing approach.

We use a linear histogram stretch uniformly across the entire image. We do not clip the raster to the glacier, and include both on-ice and off-ice areas. The method ends up not being sensitive to this because we are tuning histogram stretch parameters to optimize performance on debris-covered ice, so it doesn’t affect the stretch. We have added language at the end of the paragraph to clarify these points.

The step we call “detection” is the ‘heart’ of the ice cliff delineation method. The other steps are essentially pre- and post-processing. We have added these terms to the numbered steps to make this clearer.

Change to “1) processing: stretching the image brightness histogram to a suitable range for our ice cliff detection methods; 2) detection: applying an ice cliff detection method; and 3) post-processing: morphologically filtering of the detected ice cliffs (Fig. 5). We apply a linear histogram stretch uniformly across the image, including both the glacier and surrounding off-ice areas.”

L123. Is the saturation stretch part of your step 1, or a separate part of step 2?

The saturation stretch is a pre-processing step (Step 1). However, we use different stretch values depending on which method we use (edge detection or adaptive binary), because the methods perform best with different exposure levels. We have added language to clarify this.

Change to “In pre-processing, we use separate saturation stretches (Fig. 5) for each method by applying the exposure function in the scikit-image package (skimage). The different methods perform best with different exposure levels, so we create two separate stretched orthoimages in pre-processing

L125. I see that the size of the moving window is included later as one of your parameters in the MC optimization. It might be good to give the reader a warning that that is the direction the methods are going, and that you will start with a description of the implementation of each approach first.

Thanks for this suggestion, we added language to foreshadow this progression.

Add at L120 after (Fig. 5): These steps introduce several processing parameters, which we select using a Monte Carlo optimization method. Below, we first present the processing steps, followed by our parameter optimization procedure.

L126-7. I would certainly not say that adaptive thresholding is insensitive to changes in debris cover and illumination, but it may be less sensitive. Ice cliffs are not uniform in surface character, and can appear both brighter and darker than the surrounding topography in different circumstances. It may be that these nuances are not so evident in the lower portion of Kennicott Glacier, but two particular cases would pose a major challenge for the ABT approach: 1) a population of ice cliffs with variable surface character (debris-free vs covered with fines) which will increase the spectral variance of the cliff population; 2) otherwise dark (potentially wet) debris. This is discussed later in the manuscript, but for a presentation of a new method, I think the accuracy and appropriate application needs some further advertisement/warnings.

We changed this to state that the approach is less sensitive to these variations than a global threshold. We added specific reference to this potentially problematic situation of alternating debris-free vs. debris-covered in the text we describe in response to your comment on L113. In response to that comment, we also added "warnings" that the output should be examined to look for spurious results, and that a user should verify that ice cliffs are in fact darker for their glacier of interest.

Change L126-127 to : "Because the brightness threshold varies across the image, the *ABT* approach is less sensitive to changes in illumination and debris color than a global threshold."

L133. Some of this content is Results

Yes, these can be considered results, but our purpose for including this language here is to motivate our last step in the processing procedure (morphological filtering). We have added a sentence to the start of this paragraph to make this intent clear.

Add to L132 start of paragraph: "The last step in our processing process is morphological filtering to remove spurious data".

L142. Was this 3% disagreement in total area? Can you provide a dice score for the two independent outlines? It is very possible to derive largely different cliff distributions but arrive with the same area.

Yes, the 3% was total area.

L144-149. If I understand correctly, there are thus 6 parameters for the ABT and 5 for the SED implementations, with 4 shared between the two. How did this occur in practical terms? 2500 runs for each implementation, or 2500 runs used the same values for the shared parameters?

More importantly, it is worth noting that with 5 parameters, 2500 runs results in an effective sampling of ~4.8x in each parameter (4.8^5 ~ 2500).

We added text to clarify this procedure. In each of the 2500 iterations, we select the value of every parameter at random using a uniform probability distribution across a set range of possible values for that parameter. The ranges were determined using operator judgement to cover all physically-meaningful values. This method allows searching a wider parameter space with fewer iterations than the approach you describe. Interactions between processing parameters across their entire possible ranges are captured. The parameter space is not sampled as systematically as you describe, but it is covered more broadly.

Change L148 sentence starting with "We ran…" to "We ran the ice cliff detection algorithm 2500 times with differing parameter choice. In each iteration, every parameter is randomly selected using a uniform probability distributions over that respective parameters range of possible values (Duan et al., 1992). This method allows us to efficiently test performance across a wide range of parameter values and is sensitive to interaction between selected parameters across their ranges."

L152. 'The origin' is a bit ambiguous here, as it is true for figure 5, with the x-axis as the negation of the true positive rate. So really this is ranked by distance from (1,0) in your optimization space, correct?

Thanks for pointing out this potential confusion. We added that we mean the origin on Figure 7, which you are right is complicated by the "1 – true positive" term. Perfect model performance is TP,FP=(1,0) like you say, this just becomes (0,0) on that plot due the "1-TP" term.

Change to "Euclidean distance from the origin on Figure 7, which defines…"

L153. Why did you choose to reduce the FP rate (at the expense of TP) from the optimal parameter set? Can you please provide a dice coefficient for this parameter set for each approach?

We will look into the dice coefficient approach. Thank you for pointing this out.

L157. Process observation (2) actually refers to melt rates, rather than backwasting rates.

Good catch we will correct this.

L158. The influence of lakes was noted earlier by Brun et al (2016) and Miles et al (2016), among others.

We cite these works.

L163. In Part A it is clear that while elevation is a principal driver of debris thickness variability, there is considerable heterogeneity within any elevation bin. As your field measurements of debris thickness could not encompass the entire study area (that would not have been feasible), do you think they sufficiently characterise the unmeasured area (particularly the NW of the domain)? Have you tested the importance of debris thickness heterogeneity in your overall melt estimates? The subdebris melt relationship is not linear, so melt calculated with a mean thickness may not accurately approximate the mean melt rate.

This is a good point that is difficult to address for all folks working on debris-covered glaciers. Because we are trying to find out if ice cliffs can compensate for sub-debris melt this bias actually makes our estimate more generous.

Because many of our debris thickness measurements were taken at the top of ice cliffs though we suspect that our estimates underestimate debris thickness. We take our debris thickness measurements to be minimum estimates which means that sub-debris melt rate are likely to be even lower than what we estimate throughout this study, and through the study area.

L167. It is worth noting that you neglect internal ablation as well as other thermokarst processes (ponds, streams) in this computation for practical reasons.

Yes, we will note this.

L176. Please provide a goodness-of-fit for this empirical equation.

We will add this.

L180. It is interesting that as formulated, b_ice is the measured clean ice melt rate near the top of the study area, rather than the lapsed melt rate for each debris point. This is much more practical, but ignores the real melt suppression by the debris as a shortcut to a rate.

This is a good point and you laid out the reasoning, it is simply practical. At one point does emphasizing the details of physical processes (i.e. that bare ice melt rate increases a bit downglacier) get in the way of simple representation of the essence of sub-debris melt? The question really comes down to how important is it that bare-ice lapsed melt rates increase a little downglacier compared to the effects of debris thickening debris. On Kennicott Glacier it is clear to us that thickening debris is much more important than increasing energy for melt at lower elevations. The equation from Anderson and Anderson (2016) can easily be used with increasing bare ice melt rates if the user desires it.

In any case, I presume that the equation (as in Anderson and Anderson 2016) is based on the measurements presented in Part A? Please provide a goodness-of-fit measure.

Yes equation in Anderson and Anderson, 2016 is based on the data from part A. But note that the other fits from other glaciers in Anderson and Anderson (2016) are not necessarily taken across an elevation range. We will report an RMSE for the curve fits, optimizing for h_star.

L185. I am sceptical of this linear fit given the spread of observations in Part A – a goodness of fit would be expected to be very low.

We will provide additional curve fits for ice cliff backwasting and additional versions of the relevant figure to show the effect of this curve fit on our broader results. These figures are placed in the supplemental.

If elevation is a secondary control, what might you presume is a primary control for the difference in backwasting rates?

Not sure!

L187. The similarity of backwasting rates for cliffs with/without lakes may be due to the observation type and period. Ponds and streams tend to incise thermoerosional notches, which can later collapse, thus enhancing the seasonal mass losses but not affecting what one would observe from the top of the cliff over a month or two. This is not a criticism of your work, it is just worth noting that this nonobservation doesn't mean a melt enhancement is not occurring.

This is a very thoughtful comment. We agree. It is a really neat next line of research! We have in fact observed this very collapse phenomenon on a glacier in Switzerland!

L190. The correction in backwasting rates for cliff slope is correct, but it is also necessary to correct the cliff area from planimetric to surface area in order to correctly estimate melt from these inclined features, as melt occurs perpendicular to the surface. Thus

A_i =A/cos(theta)

With theta=40 degrees, this is a factor of 1.3 to all of the cliff-related melt calculations.

This effect was already included in the original manuscript, just to mentioned.

L192. I think it's reasonable to apply a constant slope for the melt calculation, but why is this the 'most likely case'? Can you please provide some supporting information as supplemental figures, etc?

This a good point. The 'most likely estimate' based on our data collection and analysis.

L201. 'Most likely' is superfluous here; it is an estimate. It's nice that you provide bounds!

We will change to 'most likely estimate.'

L202. This 'best estimate' is using the parameter values already given in the text, correct?

Yes we will clarify this.

L213. I suppose you use the lapse rate (per timestamp? Hourly? Daily? Mean?) between the two stations for this estimation? It is notable that this lapse rate approach corresponded poorly to your on-glacier temperature observations (in the debris-covered area, Part A) – how do you think such an approach would correspond to the on-ice calculations?

This is good to clarify. Based on our understanding of melt factors (MFs) they are always relative to the temperature data used to tune the MF. And that off-glacier lapse rates are often a better representation of the lower 1 km of the atmosphere independent of the glacier. We could also just draw a vertical line in Figure 10a, assuming that temperature did not increase at lower elevations and the ice cliffs would still not compensate for the insulating effects of debris.

L218. Did you attempt to digitize ice cliffs in 1957 as well? The mention of ponds (and long-term change) is quite sudden, and should maybe be better integrated with the text.

We did not attempt to digitize ice cliffs, it would not be possible. We will better integrate this text but we feel this adds some good context to the work.

L219. ‘insure’ should be ‘ensure’

we will change this.

L243. Should this be between 520 and 620 m? The fractional area is more meaningful than total area for understanding the cliff distribution.

Good catch we will discuss fractional area here.

L245. Importantly, this is of reported values.

We aren’t exactly sure what is meant here.

L247. N is too small to note any meaningful correlation between debris thickness and ice cliff coverage, unless you have a physical mechanism to implicate.

We agree that N is small but it does suggest a trend non-the-less. We state it as an hypothesis.

L255 and 265. I am still confused about the ice cliff melt rate distribution, for 2 reasons. First, it appears that at high elevations in the study area, it appears that your modelled ice cliff melt rates are lower than the modelled subdebris melt rates.

This is a good observation. We apply uniform backwasting rates through the study area now.

This is not plausible (or there would not be cliffs!). Second, the ice cliff melt rates in this region are also lower than for clean ice, which should be an approximate lower bound for ice cliff melt at all elevations: are nearly bare ice, but with surface debris well below the critical thickness (thus enhancing melt relative to bare ice, if we can neglect increased shading).

Also a good point. This also gets to the issue raised by this reviewer for our curve fits for backwasting rate with elevation. We apply a uniform backwasting rate through the study area.

L257. These rates correspond to a mean cliff enhancement factor of 1.72 relative to the mean subdebris melt rate, which I suppose is lower than anywhere else due to the thin debris.

That makes sense to us. This is a nice way to present the relative effects of the two.

L259. ‘Dominates’ is a strange term here. Certainly the reduced melt rate due to debris thickness is apparent, and debris thickness differences are more important than the difference in cliff density.

We can re-phrase this emphasizing that the melt rates follow more closely the sub-debris melt rate curve than the ice cliff backwasting curve (independent of the curve fit through the backwasting data).

L265. This appears to be a typo – the cliff melt rates are an order of magnitude lower than under debris?

We need to clarify the text here so it it more clear what we are referring to here. If you took all melt from ice cliffs in each elevation band and then calculated how much that lowered the entire area of the elevation band (ice cliffs + debris area) then ice cliffs lower the entire surface by the rates quoted in this sentence.

L271. This is again very disjointed to the rest of the analysis.

We incorporate this better.

Also, the low lake coverage in the upper ZMT makes a lot of sense as this area has steeper surface slopes in 2009 (Fig 2).

We agree with this.

L282. I appreciate consideration of the applicability and extension of this method to other sites/scenes. I think the biggest challenge for application to other scenes is that the tested parameter sets produced extremely variable results, and would need optimisation for every new site and image. There are also seasonality patterns to consider- cliffs often retain snow longer than the debris surface, for example.

We have not rigorously tested application of this procedure to other glaciers and scenes because our primary goal was to estimate ice cliff area on Kennicott Glacier for this study. It is plausible these processing parameters would perform well on other scenes of Kennicott Glacier, and perhaps for other glaciers as well. Illumination and sun angle can vary from scene-to-scene, and debris color can vary across different glaciers. However, Kennicott itself has several debris colors and textures, and the method does not appear to systematically differ in performance from one debris band to the next – this suggests the routine is not strongly sensitive to debris color. Varying illumination may change the ideal processing parameters, but the fact that the adaptive binary threshold is normalized by the brightness of pixels surrounding ice cliffs should mitigate sensitivity to this issue. That being said, you are correct that optimal performance could require training data (i.e., manually delineated ice cliffs) for a new scene to find optimal parameters. Manually digitizing ice cliffs in a few training areas is not incredibly time intensive, so we do not view this as a critical shortcoming of this method. We added text stating that the transferability of these processing parameters requires further investigation.

At L285 before "Using multispectral imagery…" add "The transferability of optimal processing parameters (both across time and space) requires further investigation."

L324. The variability in observed backwasting rate is considerably stronger than any bias due to the observation location – the question is really where the mean lies.

We agree with this and will provide additional analyses to address the curve fit through the backwasting data.

L340. The potential distal effect of these features is conceptually well understood to be via internal ablation along englacial conduits, but is not possible to validate at present. See Benn et al (2001, 2012, 2017), Sakai et al (2002).

We will take a closer look at these papers. We agree that these effects are related to englacial conduits. We are wondering further how then englacial conduit melt out relates to the rest of the debris-covered glacier system. We believe that internal ablation though has a small effect on overall thinning. It isn't clear what physically will produce the heat needed to cause the thinning rates observed from debris-covered glaciers.

L344. This section/paragraph feels orphaned. It is worthwhile to note that even accounting for the hypsometric distribution of cliffs, the spatial pattern still emulated Ostrem's curve (just with different effective thicknesses), suggesting that this concept might be useful as a proxy for the altitudinal SMB pattern even where cliffs account for 40% of melt – just not directly comparable to stake measurements.

Nicely worded. The discussion was re-written.

L353. 'counter' - should be singular

L356. 'trend' should be pattern

Table 3. I don't think that Buri and Pellicciotti (2018) is the most appropriate study for Lirung Glacier for this purpose. Why the comment on EB below the table?

We will adjust the table accordingly.

Figure 2. It is not clear what the bars are in the upper left – is this the domain with supraglacial debris?

Oops that was dropped from the caption, yes it is the extent of continuous supraglacial debris transversely across the glacier.

Figure 3. This is a very nice conceptual summary! Can you include a pond or stream?

No need just discuss cliffs in the re-submitted manuscript.

Figure 4. In the caption for 'c', there is a reference to a 'black line' which corresponds to the 'solid' line I think.

Yes we will correct this.

Figure 5. This is a very nice summary of the method. Can you reproduce the same for the Sobel method to be included in the Supplementary Information?

Thank you. We don't do this as we end up not using the Sobel method further.

Figure 6. Panel (b) does not depict the bare ice area outlines as in (c).

No need as those bare ice delineations are not used in panel b.

Figure 7. Nice depiction of the optimization. No colorscale is shown, though, and due to the different axis ranges, it is difficult to visualize the lowest Euclidean distance.

It is true that the different axis ranges make the Euclidean distance harder to visualize. There can be many more false positives than false negatives. In the limit, you can have as many false positives as you have pixels, whereas false negatives can only occur on ice cliff pixels. We chose the axis limits to show the range of possible outcomes rather than omit many data points to have the plot be at equal scale. We omit a color bar because there is already a lot going on with this figure, the colors are not crucial for understanding the figure, but rather facilitate visualizing distance, and we state the meaning of the colors in the caption. This was moved to the supplemental.

Figure 9. See my comments in the text on line 255. Surely the lowest ice cliff melt rate (here 2.9cm/d) should correspond in space to the highest sub-debris melt rate (5.8 cm/d) – at the highest elevations. But then, the cliff melt rate should not be lower that the subdebris melt rate – that makes little sense. This suggests to me that the linear parameterization of ice cliff melt with elevation may not be appropriate.

We apply a uniform backwasting rate now in the distributed melt estimates.

Figure 10. Nice summary. Can you include a depiction of the cliff-only melt rates vs elevation in panel (a)?

This is a good idea. Yes added this.

It is interesting that the cliff portion of melt is highest high in the ZMT, but still makes little difference in the mean melt rate profile.

Indeed it is :)

Also, it would be very meaningful to complete a version of panel (a) for the min and max melt parameterizations. Effectively these estimates are generous uncertainty bounds for your results.

The red bands are in fact the extreme uncertainty bounds. We need to better emphasize this in the caption and text because seeing that the red band as extreme bounds makes the analysis in section 4.2.1 much more compelling. Just need to clarify this for the reader. We greatly expand the discussion of this in the revised manuscript.

Figure 11. Do you have a depiction of supraglacial streams (density or otherwise) to complete the picture?

We removed any substantive stream discussion from this manuscript.

Figure 12. This is orphaned from the discussion and seems like an odd figure to close on.

Yes we see what you mean. We move it to the supplement.

Thank you for taking the time to review these manuscripts!

Debris cover and the thinning of Kennicott Glacier, Alaska: in situ measurements, automated~~, Part B:~~ ice cliff delineation and distributed melt estimates

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Abstract. Many glaciers are thinning rapidly beneath debris thick enough to reduce melt rates relative to bare ice. Melt hotspots within otherwise continuous debris cover increase area-averaged melt rates, counteracting the melt suppressing effects of debris. Kennicott Glacier, a large Alaska glacier, is thinning most rapidly, upglacier from its terminus, but under insulating debris cover. We explore the role of debris and ice cliffs in controlling this zone of maximum thinning.

We provide abundant in situ measurements of debris thickness (109), sub-debris melt (74), and ice cliff backwasting (60). We also develop a new, accurate method to automatically delineate ice cliffs using high-resolution panchromatic satellite imagery. We then use empirical relationships, to estimate melt area-averaged melt across the lower 8 kilometers of the glacier.

~~**Abstract.** The mass balance of many valley glaciers is enhanced by the presence of ice cliffs within otherwise continuous debris cover. We assess the effect of debris and ice cliffs on the thinning of Kennicott Glacier in three companion papers. In Part A we report in situ measurements from the debris-covered tongue. Here, in Part B, we develop a method to delineate ice cliffs using high-resolution imagery and use empirical relationships from Part A to produce distributed mass balance estimates. In Part C we describe feedbacks that contribute to rapid thinning under thick debris.~~

Ice cliffs cover 11.7% of the debris-covered tongue, the most of any glacier studied to date, which contribute 26~~and they contribute 19~~% of melt in study area with a mean debris thickness of only 13.7 cm. While the relative importance of ice cliffs to melt increases as debris thickens downglacier, the absolute magnitude of area-averaged melt declines towards the terminus~~total melt. Ice cliffs contribute an increasing percentage of melt the thicker the debris cover. In the lowest 4 km of the glacier, where debris thicknesses are greater than 20 cm, ice cliffs contribute 40 % of total melt~~.

The primary control on area-average melt rate across the zone of maximum thinning appears to be debris thickness, but maximum surface melt does not align with the zone of maximum thinning. We therefore suggest that the decline in ice discharge from upglacier is the vital control defining the zone of maximum thinning.

~~Surface lake coverage doubled between 1957 and 2009, but lakes do not occur across the full extent of the zone of maximum glacier thinning. Despite abundant ice cliffs and expanding surface lakes, average melt rates are suppressed by debris, the pattern of which appears to reflect the debris thickness-melt relationship (or Østrem's curve). This suggests that, in addition to melt hotspots, the decline in ice discharge from upglacier is an important contributor to the thinning of Kennicott glacier under thick debris.~~

Keywords: mass balance; WorldView; backwastinglake; WorldView; Østrem's curve, debris-covered glacier

1 Introduction

Loose rock (debris) is common on glacier surfaces globally and is especially abundant on glaciers in Alaska (Scherler et al., 2018). Where debris is thicker than a few centimeters it insulates the underlying ice, leading to the reduction of melt rates (Østrem, 1959; we refer to 'thick debris' as any debris that reduces melt rates relative to bare-ice melt rates). Adding to this insulating effect, debris is expanding for many glaciers even as they contract in response to climate warming (e.g., Tielidze et al., 2020). Expanding and thickening debris cover should reduce glacier thinning relative to glaciers without debris. But the melt-suppressing effect of debris is not always apparent the observed thinning patterns of glaciers even when debris is thick and debris coverage is extensive (e.g., Kääb et al., 2012; Gardelle et al., 2013). In High Mountain Asia many debris-covered and debris-free glaciers are thinning at similar rates (e.g., Kääb et al., 2012; Brun et al., 2018). This apparent paradox, in which rapid thinning is occurring under insulating debris cover is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015). It has been documented in both Asia and in the European Alps (Nuimura et al., 2012; Agarwal et al., 2017; Lamsal et al., 2017; Wu et al., 2018; Mölg et al., 2019).

The 'debris-cover anomaly' may in fact be a global phenomena. A close look at previously published glacier thinning patterns from the Wrangell Mountains of southeast Alaska reveals that maximum thinning rates from within single glaciers are similar whether debris is present or not (Figs. 1 and 2; Berthier et al., 2010; Das et al., 2014). This is a compelling because the Wrangell Mountains occur at 61 to 62 deg. N, a latitude and in a region where the effects of debris on glacier mass balance has received almost no attention.

One of the glaciers within the Wrangell Mountains that is thinning rapidly under debris cover is Kennicott Glacier (Figs. 1 and 2). Greater surface elevation changes are documented from the Kennicott debris-covered tongue than from any portion of the largely debris-free Nabesna Glacier, north of Kennicott Glacier (Fig. 2). Why does the maximum thinning of Kennicott Glacier occur under debris at rates similar to nearby debris-free glaciers? To aid our analysis, we define a zone of maximum thinning or *ZMT* where Kennicott glacier thinned at an average rate greater than 1.2 m yr^{-1} between 1957 and 2004 (Figs. 1 and 2; Das et al., 2014). For Kennicott Glacier, thinning rates this high only occur within 4 kilometers of the terminus and under debris. The *ZMT* occupies a 2-km down-glacier by 3.5-km across-glacier portion of the debris-covered tongue. The *ZMT*, as defined, is consistent with maximum thinning rates between 2000 and 2007 based on lidar profiles (Fig. 2; Das et al., 2014).

1 Introduction

Thick debris insulates ice and reduces melt rates. But debris-covered glaciers often respond to climate change in ways that appear contradictory to this melt-suppressing effect. In High Mountain Asia (*HMA*) many debris-covered and debris-free glacier tongues are thinning at similar rates (e.g., Kääb et al., 2012; Brun et al., 2018). This apparent paradox is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015), and has been documented in *HMA* and the European Alps (Nuimura et al., 2012; Pellicciotti et al., 2015; Agarwal et al., 2017; Lamsal et al., 2017; Wu et al., 2018; Mölg et al., 2019). But the debris-cover anomaly also occurs on glaciers in the Wrangell Mountains of southern Alaska (Das et al., 2014).

Kennicott Glacier is the largest glacier in the Wrangell Mountains with debris cover that extends continuously across its width. As shown in Figures 1 and 2, the maximum surface elevation change on Kennicott Glacier occurs under thick debris. Greater surface elevation changes are documented from the Kennicott debris-covered tongue than from any portion of the largely debris-free Nabesna Glacier,

~~north of Kennicott Glacier (Supplemental Figure 1; Das et al., 2014). It is not clear why the greatest thinning of Kennicott Glacier occurs under thick debris and at rates similar to nearby debris-free glaciers. We define a zone of maximum thinning or *ZMT* under debris cover where the glacier thinned at an average rate greater than 1.4 m yr^{-1} between 1957 and 2009 (Fig. 1; Das et al., 2014). For Kennicott Glacier, thinning rates this high only occur near the terminus under thick debris (Fig. 2). The *ZMT* occupies a 2-km down-glacier by 3.5-km across-glacier portion of the debris-covered tongue.~~

The continuity equation for ice is fundamental for understanding how glaciers thin, with or without debris. It can be formulated as:

~~The debris-cover anomaly can be explained by constraining the individual components of the continuity equation for ice from glacier ablation zones:~~

$$\frac{dH}{dt}=\dot{b}-\frac{dQ}{dx}-\frac{dQ}{dy} \quad , \qquad (1)$$

where H is the ice thickness, t is time, $\dot{b}$ is the annual specific mass balance ~~ablation~~ (or loosely ice melt in the ablation zone), ~~and~~ Q is the column integrated ice discharge (or loosely ice dynamics; ~~)~~ ~~(~~Fig. 3), x is the east-west direction, and y is the north-south direction. Constraining $\dot{b}$ on debris-covered glaciers is particularly difficult due to the presence of ice cliffs, ponds~~lakes~~, and streams within debris covers~~on debris-covered glacier surfaces~~. The annual specific balance in the ablation zone can be sub-divided,

$$\dot{b}=\dot{b}_s+\dot{b}_e+\dot{b}_b \qquad (2)$$

where $\dot{b}_s$ is the annual surface ablation, $\dot{b}_e$ is the annual englacial ablation, and $\dot{b}_b$ is the annual basal ablation rate. Surface ablation typically dominates $\dot{b}$ in most non-polar glacial settings. We neglect the effects of $\dot{b}_e$ and $\dot{b}_b$ because their contribution to rapid thinning is likely small and ~~glacial settings and~~ it is not yet possible, to quantify them ~~or~~ within and under debris-covered ~~glacier~~ tongues. Building from Eq. (1), $\dot{b}_s$ is negative in the ablation zone, and therefore shifts $\frac{dH}{dt}$ towards negative values, thinning the glacier. In the ablation zone, the sum of $\frac{-dQ}{dx}-\frac{dQ}{dy}$ tends to be positive due to slowing ice flow~~, because more ice typically flows into a fixed planview area than leaves it leading to surface uplift~~. This ice emergence velocity counters surface lowering due to~~caused by~~ melt.

Two common explanations for the debris-cover anomaly follow from Eq. (1), which are not mutually exclusive (Immerzeel et al., 2014; Vincent et al., 2016; Brun et al., 2018). First, it is possible that melt $\dot{b}$, when averaged over glacier widths is higher than we expect from the melt reducing debris alone, therefore leading to rapid thinning. Ponds and ice cliffs have been documented to locally increase melt rates on debris-covered glaciers by an order of magnitude compared to adjacent melt rates measured from under debris (e.g., Immerzeel et al., 2014). M*elt hotspots* such as ice cliffs, ponds, streams, and thermokarst counter the insulating effects of debris by raising area-averaged melt rates (e.g., Kirkbride, 1993; Sakai et al., 2002; Reid and Brock, 2014; Miles et al., 2018). Conceptually, melt hotspots perturb the area-averaged melt rate from a melt rate solely defined by the insulating effects of debris (lower melt rates) towards a melt rate solely defined by the melt of bare-ice (higher melt rates). The degree to which these hotspots increase area-averaged melt rates, is an area of active debate within the community. Second, increased melting upglacier of the debris leads to glacier thinning an reduced ice flow to debris-covered portions of glaciers. This leads to reduced ice emergence rates and locally amplified thinning (e.g., Nye, 1960; Vincent et al., 2016).

Kennicott Glacier holds exceptional potential for reveling the role of melt hotspots in debris-covered glacier thinning. In the last 8 kilometers of Kennicott Glacier more than 10 thousand ice cliffs are scattered within otherwise continuous debris (Anderson, 2014). If melt hotspots are the sole control on the *location and magnitude* of the zone of maximum thinning or *ZMT* for Kennicott Glacier then we should expect melt rates (averaged across the glacier width) from across Kennicott Glacier to be maximized there. Here, we to address three questions: (1) *What is the surface mass balance across the debris-covered tongue and zone of maximum thinning of Kennicott Glacier during the summer of 2011?* 2) *Do ice cliffs maximize glacier-wide melt in the zone of maximum thinning during the summer of 2011?*

To address these questions, we quantify the role of ice cliffs and sub-debris melt across the debris-covered tongue of Kennicott Glacier during the summer of 2011. We limit our scope to ice cliffs and sub-debris melt, leaving an examination of surface ponds and streams as later contributions. Our analysis is rooted in the collection of abundant in situ data from the glacier surface, including: debris thickness, sub-debris melt rates, and ice cliff backwasting rates. In addition to helping address the questions raised above, these in situ measurements, from this latitude and Alaska, are vital for developing a global perspective on glacier response to climate change as well as the next generation of global glacier models incorporating the effects of debris cover.

~~Two common explanations for the debris-cover anomaly follow from Eq. (1) (Immerzeel et al., 2014; Vincent et al., 2016; Brun et al., 2018). First, it is possible that ablation within debris-covered areas is higher than we expect, causing thinning. In this case, , averaged across the glacier, is more negative than what insulated, sub-debris ablation rates suggest. Local *melt hotspots* such as ice cliffs, lakes, streams, and thermokarst counter the insulating effects of debris (e.g., Kirkbride, 1993; Sakai et al., 2002; Reid and Brock, 2014; Miles et al., 2018). In addition, lakes can enhance melt on debris-covered glaciers by an order of magnitude compared to proximal sub-debris melt (e.g., Immerzeel et al., 2014). Second, thinning upglacier of the thick debris cover leads to reduced ice flow to the debris-covered tongue, leading to a less positive  , reduced ice emergence rates, and glacier thinning (e.g., Nye, 1960; Vincent et al., 2016; Brun et al., 2018).~~

~~On Kennicott Glacier thousands of ice cliffs are scattered within the otherwise continuous debris cover. These abundant ice cliffs will increase area-averaged melt rates and counteract the insulating effect of debris. Debris thicknesses on Kennicott Glacier are typically less than 50 cm (Part A) reducing the insulating effect of debris relative to many other previously-studied glaciers. If melt hotspots control the location of the *ZMT* then we should expect their effect to be maximized in the *ZMT*. But if melt hotspots are not dominant then we should expect the mass balance profile to be dictated by the debris-thickness melt relationship (or Østrem's curve) downglacier (e.g., Anderson and Anderson, 2018). We therefore address: *What is the mass balance profile within the debris-covered tongue of Kennicott Glacier?* And *do melt hotspots within debris cover maximize glacier-wide melt in the location of maximum glacier-wide thinning (or ZMT)?*~~

To determine the mass balance pattern within the debris-covered tongue, ice cliff extent must be quantified. We therefore present and apply a new method for remotely delineating ice cliffs using high-resolution WorldView 1 orthoimages. We combine our in situ measurements and remotely delineated ice cliffs to quantify surface melt rates in a distributed fashion across the zone of maximum thinning, thereby addressing the questions outlined above.

~~To address these questions, we quantify the role of ice cliffs and sub-debris melt across the debris-covered tongue. In Part A, we show that sub-debris melt rates tend to decrease downglacier as debris thickness increases. Mean ice cliff backwasting rates, on the other hand, increase downglacier. In order to determine the mass balance pattern within the debris cover, ice cliff distribution must be quantified. We therefore present 1) a new method for remotely delineating ice cliffs using high-resolution WorldView 1 images; 2) estimates of the ice cliff distribution; and 3) combined estimates of ice cliff~~

and sub-debris melt across the study area. In order to assess if surface lakes control the location of the *ZMT* we also digitized surface lake extent in 1957 and 2009.

1.1 Study glacier

Kennicott Glacier is a broadly south-southeast facing glacier on the south side of the Wrangell Mountains. The glacier exists across a 4600 m elevation range between 4996 and 400 m a.s.l. (Fig. 1; 387 km^2 area). For comparison, Khumbu Glacier, in Nepal, has an area of 26.5 km^2 and spans an elevation range of 3950 m from 8850 to about 4900 m a.s.l. (Pfeffer et al., 2014). Kennicott Glacier covers almost 15 times more area than the Khumbu Glacier and our study area, the debris-covered tongue of Kennicott Glacier (24.2 km^2), is only slightly smaller than Khumbu Glacier itself. The main trunk of Kennicott Glacier is 42 km long and is joined by two primary tributaries, the Root and the Gates Glaciers. Kennicott Glacier has only retreated 600 meters since its maximum Little Ice Age extent in 1860 (Figure 4; Rickman and Rosenkrans, 1997; Das et al., 2014; Larsen et al., 2015).

As of 2015, 20% of Kennicott Glacier was debris-covered. At elevations below the equilibrium-line altitude at about 1500 m a.s.l. (Armstrong et al., 2017), 9 medial moraines are identifiable within the debris-covered tongue. These medial moraines form primarily from the erosion of hillslopes above the glacier and express themselves as stripes on the glacier surface (Anderson, 2000). Above 700 m a.s.l., debris is typically about one clast thick (Anderson, 2014). The medial moraines coalesce in the last 7 km of the glacier where ice cliffs, surface ponds, and streams are scattered within otherwise continuous debris cover (Anderson, 2014).

Kennicott Glacier is a broadly south-southeast facing glacier located in the Wrangell Mountains, Alaska (Fig. 1; 42 km long; 387 km^2 area). As of 2015, 20% of Kennicott Glacier was debris-covered. Below the equilibrium-line altitude at about 1500 m (Armstrong et al., 2017), 11 medial moraines (e.g., Anderson, 2000) can be identified on the glacier surface. Above 700 m elevation debris is typically less than 5 cm thick, although, locally, areas with low surface velocities tend to have thicker debris (Anderson and Anderson, 2018). Medial moraines coalesce 7 km from the terminus to form a debris mantle with ice cliffs, streams, and lakes scattered within an otherwise continuous debris cover. The first sinkhole lakes and collapse features are documented in aerial imagery from 1937 within 400 meters of the terminus (Rickman and Rosenkrans, 1997). As surface slopes have lowered in the lowest four kilometers of the glacier, thermokarst collapse features and surface lakes have expanded upglacier (Rickman and Rosenkrans, 1997).

2 Methods

Our methods fit into three broad categories: 1) in situ measurements; 2) automatic ice cliff delineation; and 3) distributed melt rate estimates. In situ measurements were made within the broad study area shown in Figure 1C, which is within 8 kilometers of glacier terminus. Distributed melt estimates on the other hand are made across the delineated medial moraines shown in Figure 4A. In total the distributed melt estimates were made over 24.2 km^2 which we consider here to be the 'debris-covered tongue' of the glacier. In situ measurements were all made within the full field campaign duration and study period from 18 June to 16 August 2011. We correct each measured melt rate to represent the full duration of the study period, as described below.

The presence of ice cliffs and surface lakes on debris-covered glaciers partially makes distributed estimates of mass balance difficult. The extent of melt hotspots must be defined to make distributed melt estimates. A new method for the detection of ice cliffs has been developed using high-resolution digital elevation models (DEMs) with 5-meter resolution (Herreid and Pellicciotti, 2018). Despite the efforts of projects like the ArcticDEM (Porter et al., 2018), glacier coverage with high resolution DEMs is still rarer than coverage with orthoimagery. Here we introduce a new method to delineate ice cliffs using solely high-resolution satellite imagery. We use this method to delineate ice cliffs on the

~~surface of Kennicott Glacier. Using the delineated ice cliffs and the in situ measurements described in Part A and shown in Figure 4, we estimate ice cliff and sub-debris melt across the debris-covered tongue.~~

2.1 In situ measurements

~~2.1 Remote sensing methods~~

The presence of ice cliffs, surface lakes, and variations in debris thickness on debris-covered glaciers makes distributed estimates of mass balance difficult. In order to remedy this issue we make abundant in situ measurements of debris thickness, sub-debris melt, and ice cliff backwasting across the glacier tongue from late June to late August 2011. Partly because of the significant effort required to make in situ measurements, mass balance research of debris-covered glaciers has been focused on a few keystone glaciers in the Himalaya (e.g., Lirung, Ngozumpa, and Khumbu Glaciers; Benn et al., 2012; Immerzeel et al., 2014) and European Alps (e.g., Miage and Zmutt Glaciers; Brock et al., 2010; Mölg et al., 2019). Sparse in situ observations, relative to bare-ice glaciers, mean that global projections of glacier change cannot yet robustly incorporate the effects of debris cover. Measurements from debris-covered glaciers in new regions like Alaska are therefore needed. In order for debris-covered glacier mass balance models to be applied regionally, basic debris properties and the meteorology above the debris must also be measured. In addition to the measurements presented in the main text, we also present on-glacier air temperatures and debris thermal conductivities from the summer of 2011, which we provide as supplementary, supporting material.

~~We describe an automated algorithm to delineate ice cliffs from optical satellite imagery. We use 0.5 m resolution WorldView (WV) satellite imagery acquired on 13 July 2009 (catalog ID: 1020010008B20800) to delineate ice cliffs across the study area. The 2009 WV image was the closest high-resolution image available in time to the 2011 summer field campaign. We used WV stereoimagery from 2013 to produce glacier surface DEMs at 5 m spatial resolution using the Ames Stereo Pipeline (Shean et al., 2016), which we use to represent the glacier surface in 2011.~~

2.1.1 Debris thickness ~~Automated ice cliff detection methods~~

We measured debris thicknesses at 109 sites. Debris measurement locations coincide with the sites that we also measured ice cliff backwasting and sub-debris melt (Fig. 4; Supplemental material). We measured thicknesses by digging through the debris to the ice surface (after Zhang et al., 2011). Where debris was thinner than ~10 cm we dug 5 pits and recorded the average debris thickness. While we did not measure debris thickness below 450 m a.s.l., visual inspection from across the proglacial pond suggests that debris exceeded 1 m above some ice cliffs. The mean uncertainty of the debris thickness measurements is ±0.3 cm, with a standard deviation of ±1.8 cm, and a maximum error of ±6.7 cm (Fig. 5). Error estimates were based on repeated measurements, but measurement error is a negligible compared to the changes in debris thickness down and across the glacier.

2.1.2 Sub-debris melt

We measured sub-debris melt at 74 locations (Fig. 4). At each site, we removed debris, installed ablation stakes and then replaced the debris (Supplemental Figure 1). We placed stakes in debris up to 40 cm thick. Sub-debris melt ($\dot{b}_{debris}$) was measured by removing the debris and measuring ice surface lowering. The mean uncertainty in the sub-debris melt rates was ± 0.1 cm d^{-1}, the standard deviation was 0.05 cm d^{-1}, and the maximum error was 0.25 cm d^{-1} for the three ablation states with the shortest measurement period of 8 days. These measurement uncertainties are small compared to the changes in melt rate with debris thickness (Fig. 6).

Because melt measurements were made over different time periods we corrected each measurement to represent the full study period. A degree-day factor for sub-debris melt was therefore calculated for each measurement (see supplemental for the full explanation; Hock, 2003). This has a negligible effect on the curve fits we apply below, and the uncertainty added is well within the uncertainty bounds of the distributed melt estimates. We apply this correction non-the-less for completeness.

2.1.3 Ice cliff backwasting

Previous studies have estimated ice cliff backwasting rates as they vary in space using DEM-differencing, models, and in situ measurements. These approaches have shown that 1) ice cliff survivability varies strongly with aspect at lower latitude (Sakai et al., 2002; Buri and Pellicciotti, 2018); 2) ice cliff melt rates are highly sensitive to cliff slope (Reid and Brock, 2014); 3) local topography plays an important role in local ice cliff backwasting rates (Steiner et al., 2015); and 4) ponds allow for the long-term persistence of ice cliffs (e.g., Brun et al., 2016; Miles et al., 2016). On Kennicott Glacier, we take advantage of a rich dataset of in-situ backwasting rates from 60 ice cliffs.

We made repeat horizontal distance measurements between the upper ice cliff edge and a stationary marker (in a moving reference frame; after Han et al., 2010). Ice cliff backwasting rates were extrapolated to the full study period by calculating a degree-day factor for each ice cliff using data from the off-ice meteorological stations (see supplemental for full methods). The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1} (Fig. 7; Supplemental Figure 9). Maximum error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval (21 days). The standard deviation of errors is ±0.2 cm d^{-1}.

2.2 Automated ice cliff delineation methods

Ice cliffs are common on debris-covered glacier surfaces and important for the surface mass balance, yet quantifying their extent is difficult. Following Herreid and Pellicciotti (2018), previous efforts to delineate ice cliffs have relied on field mapping (e.g., Steiner et al., 2015) from the manual digitization of remotely-sensed data (Sakai et al., 1998; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017), automatically by object based image analysis locally derived with unmanned aerial vehicles (e.g., Kraaijenbrink et al., 2016) or automatically by principal component analysis using visible near-infrared and shortwave infrared satellite bands (Racoviteanu and Williams, 2012). A new method for the delineation of ice cliffs has also been developed using high-resolution digital elevation models (DEMs) with 5-meter resolution (Herreid and Pellicciotti, 2018). Despite the efforts of projects like the ArcticDEM (Porter et al., 2018), glacier coverage with high resolution DEMs (or high-resolution hyperspectral imagery) is still rarer than coverage with orthoimagery. Here we introduce a new method to delineate ice cliffs using only high-resolution satellite imagery. We use this method to delineate the abundant ice cliffs on the surface of Kennicott Glacier.

We describe an automated algorithm to delineate ice cliffs from optical satellite imagery. We use 0.5 m resolution WorldView (WV) satellite imagery acquired on 13 July 2009 (catalog ID: 1020010008B20800) to delineate ice cliffs across the study area. We use the panchromatic band, which integrates radiance across the visible spectrum and provides the highest spatial resolution. The 2009 WV image was the closest high-resolution image available in time to the 2011 summer field campaign. We used WV stereoimagery from 2013 to produce glacier surface DEMs at 5 m spatial resolution using the Ames Stereo Pipeline (Shean et al., 2016), which we use to represent the glacier surface during the study period.
Our method for detecting ice cliffs relies on the observation that ice cliffs are generally darker than the debris around them. Ice cliffs, when actively melting, ~~-~~are typically coated with a thin, wet debris film, which appears darker than the adjacent, dry debris in panchromatic optical imagery (Fig. 8~~5~~). In addition, steep ice cliffs are often more shaded than nearby lower-sloped debris-covered surfaces.

The workflow we outline relies on open-source Python packages, which facilitates the method's replication and improvement by other researchers. Our workflow consists of three general steps: 1) processing: stretching the image brightness histogram to a suitable range for our ice cliff detection methods; 2) detection: applying an ice cliff detection method; and 3) post-processing: morphologically filtering of the detected ice cliffs (Fig. 8). We apply a linear histogram stretch uniformly across the image, including both the glacier and surrounding off-ice areas. These steps introduce several processing parameters, which we select using a Monte Carlo optimization method. Below, we first present the processing steps, followed by our parameter optimization procedure~~5)~~.

We use two methods to detect ice cliffs: i) the adaptive binary threshold method (*ABT*; skimage.filters.adpative_threshold tool; e.g., Sauvola and Pietikäinen, 2000); and ii) the Sobel edge delineation~~detection~~ method (*SED*; skimage.filters.sobel tool; Richards, 2013). In pre-processing, we ~~We~~ use separate saturation stretches (Fig. 5) for each method by applying the exposure function in the scikit-image package (skimage). The different methods perform best with different exposure levels, so we create two separate stretched orthoimages in pre-processing.

The *ABT* approach runs a moving window over the image, calculates the mean brightness value within that window, and then uses a threshold to binarize the image. Because the brightness threshold varies across the image, the *ABT* approach is less sensitive ~~insensitive~~ to changes in illumination and debris color than a global threshold.

The *SED* approach estimates spatial gradients in image brightness. The Sobel operator detects high contrasts between light-colored debris and dark-colored ice cliffs. The saturation stretch applied on the orthoimage causes dark ice cliffs to appear as featureless black regions, which the Sobel operator returns as low gradient values. We apply a brightness gradient threshold to isolate ice cliffs.

The last step in our processing process is morphological filtering to remove spurious data. Both delineation~~Both detection~~ methods (*ABT* and *SED*) produce false positives from shaded, over-exposed, or textureless debris cover (*SED* only). The *SED* approach produces many false positives, which generally have a characteristic speckled appearance, and often occur in small, isolated groups. We apply morphological opening (Dougherty, 1992) to remove these isolated, distributed false positives (skimage.morphology.opening; Fig. 8~~5~~). In addition, the *SED* approach creates false positives in regions that have been over-exposed by the saturation stretch and therefore lack texture. We remove these *SED* false positives by masking pixels with the maximum brightness.

To maximize correct ice cliff identification and minimize false positives we compare our ice cliff estimates to hand-digitized ice cliffs from twelve 90,000 m^2 regions. The cumulative area used in the validation dataset~~error checks~~ was 1.8 km^2, approximately 7.4% of the 24.2 km^2 study area (Fig. 9~~6~~). There is some operator subjectivity in delineating ice cliffs from satellite imagery, especially for smaller ice cliffs. To minimize this issue, two different human operators independently delineated ice cliffs. As these independent delineations agreed within 3% in their ice cliff area, we consider operator misidentification to be a negligible source of error.

Seven parameters determine the success of these ice cliff delineation~~detection~~ methods: i-ii) the low and high end brightness values used for the saturation stretch; iii-iv) the window size and offset from mean brightness in the *ABT* method, v) the high-end value to use for thresholding in the *SED* method, and; vi-vii) the kernel sizes used in morphological filtering of the *SED* and *ABT* results. To find the best parameter set we use a Monte Carlo approach for multi-objective optimization (Yapo et al., 1998). We ran the ice cliff detection algorithm 2500 times with differing parameter choices. In each iteration, every parameter is randomly selected using uniform probability distributions over that respective parameters range of possible values ~~, while varying parameters sampled from uniform distributions~~ (Duan et al., 1992). This method allows us to efficiently test performance across a wide range of parameter values and is sensitive to interaction between selected parameters across their ranges. We evaluate algorithm performance by comparing ice cliff area from the automated routine against the hand-digitized validation dataset~~ice cliff areas~~. Our optimization simultaneously seeks to maximize true positive ice cliff delineation~~detection~~, while minimizing false positives and false negatives. We manually inspect the top-performing parameter sets, ranked by Euclidean distance from the origin (see Supplementary Figure 14), which defines perfect algorithm performance (Supplemental materials~~Fig. 7~~; Reed et al., 2013). We chose image processing parameters slightly off the set with the smallest Euclidean~~euclidean~~ distance to reduce false positives (Supplementary Table 3). We reduce false positives at the expense of true positives because this led to a higher ratio of true positives to false positives, so we are more certain that a given detection is likely to be a real ice cliff~~Table 1)~~.

2.3 Distributed melt estimates

~~2.2 Distributed estimates of melt~~

~~Previous studies have estimated ice cliff backwasting rates as they vary in space using DEM-differeneing, models, and in situ measurements. These approaches have shown that 1) ice cliff survivability varies strongly with aspect at lower latitude (Sakai et al., 2002; Buri and Pellicciotti, 2018); 2) ice cliff backwasting is highly sensitive to cliff slope (Reid and Brock, 2014); 3) local topography plays an important role in local ice cliff backwasting rates (Steiner et al., 2015; Part A); and 4) lakes allow for the long-term persistence of ice cliffs (Watson et al., 2017). Although, we lack detailed on-glacier meteorological data, on the Kennicott Glacier, we take advantage of a rich dataset~~

~~of in-situ backwasting measurements from 60 ice cliffs (Part A). We use an alternative approach to distributed melt estimation by extrapolating our in situ measurements across the debris-covered tongue.~~

In order to produce distributed melt estimates, we extrapolate our in situ measurements ~~We extrapolate the empirical measurements from Part A (Fig. 4)~~ across the area of the 9 defined medial moraines in Fig. 4. ~~study area.~~ We use empirical curve fits of debris thickness as it varies with elevation and flow path (i.e., by medial moraine), ~~,~~ sub-debris melt as it varies with debris thickness, and ice cliff backwasting uniformly ~~as it varies with elevation to distribute our measurements~~ across the medial moraines (Figs. 5-7). ~~study area.~~ These estimates ~~are meant to~~ represent the period from 18 June to 16 August 2011 ~~(Part A)~~.

The summer specific mass balance $\dot{b}_s$ is divided into contributions from sub-debris and ice cliff melt: $\dot{b}_{debris}$ and $\dot{b}_{icecliff}$. Each 0.5~~1~~ m pixel is designated as debris or ice cliff using the *ABT* ice cliff delineation method. We use the *ABT* method because it consistently performs better than the *SED* method (see Results section). For the best~~most-likely~~ case we apply a bias correction by adding 20% to the ice cliff area in each elevation band based on the consistent underprediction of ice cliffs. Extreme ice cliff areas are represented with ±20% areas from this most likely case.

We extrapolate debris thickness across the study area by applying the elevation dependent curve fits to ~~to all~~ debris-designated pixels. For the five medial moraines in the center of the glacier (labeled 4 -8 in Figure 4A) in which 69% of debris thickness measurements were made, we apply a sigmoidal curve fit (Fig. 5). Within these five medial moraines, debris~~Debris~~ thickness h_{debris} varies with elevation z according to:

$$h_{debris} = \frac{a}{\left[1+10^{b(z-c)}\right]} + d \quad , \qquad (3)$$

where *a*, *b*, *c*, and d are fitted parameters derived using Matlab's polyfit function (Table 1). We apply this sigmoidal curve fit because it best matches the pattern of debris thicknesses within these five medial moraines when they are binned in 50 m elevation bands. For other medial moraines with fewer debris thickness measurements we apply linear curve-fits. For the western most medial moraine (# 9 in Fig. 4A), which was difficult to access, we apply uniform debris thicknesses based on a few measurements. We test the importance of the debris thickness applied to medial moraine # 9 in the Supplemental material, the importance of this assumed debris thickness is minor and viable debris thicknesses fit well within the uncertainties explored.

~~where the fitted parameters *a*, *b*, and *c* have values of 25.7 cm, 571 m, and -0.24 cm, respectively.~~

We apply sub-debris melt-debris thickness relationship (or hyper-fit model after Anderson and Anderson, 2016) to all debris-designated pixels. In the model, the~~The~~ relationship between specific sub-debris melt $\dot{b}_{debris}$ and debris thickness is:

$$\dot{b}_{debris} = \dot{b}_{ice} \frac{h_*}{\left(h_{debris} + h_*\right)} \quad , \qquad (4)$$

where $\dot{b}_{ice}$, the bare-ice melt rate measured near the top of the study area, and h_* the characteristic debris thickness ~~h_{star}~~ have values of 5.87 cm d[-1] and 8.17 cm respectively (Fig. 6). Sub-debris melt rates under debris h_* thick will be half the value of the bare-ice melt rate. If ice is assumed to be at 0° C, h_* can be estimated from physical inputs and parameters following:~~. The hyperbolic fit between debris thickness and sub-debris melt assumes that energy is transferred through the debris by conduction (see Anderson and Anderson, 2016).~~

$$h_* = \frac{k\,R}{(1-\phi)} \quad , \qquad (5)$$

where k and φ are the thermal conductivity and porosity of the debris cover and R is the thermal resistance of the debris layer. Here we define R as:

$$R = \frac{\bar{T}_s}{L \rho_{ice} \dot{b}_{ice}} \quad , \quad (6)$$

where L and ρ_{ice} the latent heat of fusion and density of ice, $\bar{T}_s$ the average debris surface temperature over the period used to estimate h_* and $\dot{b}_{ice}$ is the bare-ice melt rate over the period used to estimate h_*. The hyperbolic fit between debris thickness and sub-debris melt assumes that energy is transferred through the debris by conduction. While these debris parameters can be measured, in practice they are difficult to measure across debris-covered glaciers so we use an empirical fit to debris thickness-melt data to constrain h_*.

We ~~then~~ apply the ice cliff backwasting-elevation relationship to all ice cliff pixels. We ignore ice cliff backwasting variation with orientation, as there is no clear relationship between backwasting rate and orientation in our measurements (Fig. 7). We did not find a consistent difference between backwasting for ice cliffs with and without ponds at their base (Fig. 7) and no clear ~~Based on the results from Part A, we ignore ice cliff backwasting variation with orientation. We fit a linear~~ relationship between backwasting rate and medial moraine is apparent either (Supplementary material). We apply the mean ~~elevation z and~~ specific horizontal ice cliff retreat across the study area:

$$\dot{b}_{backwasting} = f \quad , \quad (7~~5~~)$$

where f is the mean backwasting rate 7.1 cm d^{-1} (an elevation-dependent pattern is explored in the supplementary material). ~~the fitted parameters f and g are -0.0123 cm (m d)$^{-1}$ and 13.94 cm d^{-1}, respectively. In Part A we did not find a significant difference between backwasting for ice cliffs with and without lakes at their base.~~
Because the backwasting rate is measured horizontally, we apply an average dip relative to the horizontal plane (θ) to estimate the melt perpendicular to the ice cliff surface:

$$\dot{b}_{icecliff} = \dot{b}_{backwasting} \cos(90 - \theta) \quad (8~~6~~)$$

In the best~~most-likely~~ case we assume a uniform ice cliff slope (θ) for all ice cliffs of 48~~40~~° based on the mean of slope measurements made at the top of each of the 60 ice cliffs where backwasting rates were measured in the study area (following Han ~~an analysis of 2m-ArcticDEMs (Porter~~ et al., 2010). The mean of average ice cliff slopes from 6 other glaciers is 49° (Supplemental materials). Including the mean slope estimate from this study, the standard deviation of mean ice cliff slopes is 5°, which we use for our uncertainty estimates~~2018) over several seasons~~.
In order to estimate the mass balance with elevation we integrate the contributions of ice cliff and sub-debris ablation across 50 meter elevation bands:

$$\bar{b}^i = \frac{\iint^{A^i_{debris}} \dot{b}_{debris}\, dx\, dy + \iint^{A^i_{icecliff}} \dot{b}_{icecliff}\, dx\, dy}{A^i} \quad (9)$$

where $\bar{b}^i$ is the mean ablation rate within the elevation band i in units of m d^{-1}, A^i_{debris} is the total debris-covered area, corrected for the surface slope of each debris-covered pixel using the 2013 WV-derived DEM discussed above, within the elevation band, $A^i_{icecliff}$ is the total ice cliff area, correcting for the slope of each ice cliff pixel based on the assumed ice cliff slope, within the elevation band, A^i is the total planview area within the elevation band ,and dx and dy are both 0.5 m the original resolution of the WV imagery used for ice cliff delineation.

2.3.1 Uncertainty of distributed melt rates

We present one best distributed empirical melt estimate, which we bound with two extreme cases. These bounds are based on the compounding uncertainty of parameter choices meant to tilt the estimates in the direction of reduced or increased melt, this allows us to test the plausibility of ice cliffs leading to maximum melt within the zone of maximum thinning. For the best case the curve fits through debris thickness is calculated using the median of data from the 50-m elevation bins (Fig. 5). See Table 1 for the extreme parameters used for the distributed melt estimates. In the extreme cases for the debris thickness, curve fits were made through the 25% and 75% data points in each elevation bin. We use the interquartile range because the debris thickness within each elevation band is skewed towards values closer to 0, such that a normal distribution is not applicable (Fig. 5; Supplemental Material). We also apply ±1σ range for sub-debris melt and ice cliff backwasting rates, and a ±1σ range for ice cliffs slopes. Extreme ice cliff coverage was defined by ±20% of the bias corrected coverage within each elevation band. With these parameter choices 98.4 %% of all simulations lie inside the uncertainty range for combined sub-debris and ice cliff melt (Fig. 12).

In addition to the uncertainty evaluation presented here we also explore four additional cases in the supplemental materials. There we extrapolate debris thickness down each medial moraine using linear curve fits, using a single sigmoidal debris thickness-elevation relationship across the study area, using a linear relationship between backwasting and elevation, with even more uncertainties for each curve fit (in which the error envelope includes greater than 99.996 % of possibilities), and with different debris thicknesses for the westernmost medial moraine. All explorations produce similar area-averaged melt-elevation relationships.

2.3.2 Bare-ice melt rates extrapolated across the study area

For reference we also estimate the bare-ice melt rate through the study area for the summer of 2011, in the hypothetical case that no debris was present on the glacier. We calculate the bare-ice degree-day factor from several ablation stakes in bare-ice in the northeastern portion of the study area near 700 m a.s.l. We calculate the degree-day factor for ice (e.g., Hock, 2003) using measured bare-ice ablation and air temperatures interpolated onto the glacier (Supplementary material). We use hourly air temperature data from the Gates Glacier and May Creek meteorological stations to estimate the air temperature at each measurement location. Gates Glacier station is located just off the glacier margin at 1240 m a.s.l. and May Creek station is located at an 490 m a.s.l. located 15 km to the southwest of the town McCarthy (Fig. 1).

Results

3.1 In situ measurements

Figure 5 shows debris thickness as it varies with elevation. Debris thickness tends to increase downglacier and varies from less than a few millimeters above 700 m a.s.l. to as high as 1 meter above an ice cliff at 475 m a.s.l. (Table 2). Debris cover tends to be thicker in the medial moraines near the glacier margin, where ice margin retreat has been small (Fig. 4; Supplementary Figure 15). Debris greater than 40 cm thick was measured in medial moraine 3 above 600m a.s.l. And debris consistently 1 m thick was observed just out of the study area but still in moraine 9 at 730 m a.s.l. Toward the glacier interior and between 650 and 700 m a.s.l. debris thickness did not exceed 15 cm.

Debris thicknesses on glacier surfaces can vary by meters over 10-meter scales (e.g., Nicholson et al., 2018). Some of the scatter in our debris thickness measurements is derived from debris thickness variability caused by the local transport of debris by surface processes, in addition to the inevitable stochastic delivery from hillslopes above the glacier. 53 % of our debris thickness measurements were derived from the top of ice cliffs. This potentially biases our measurements toward thinner values because surface debris tends to be thicker in topographic lows.

Figure 6 shows the relationship between sub-debris melt rate and debris thickness (or Østrem's curve) during the study period (Table 2). Highly variable melt rates beneath debris less than 3 cm thick prevented the establishment of a relationship accounting for the melt-increasing effects of thin debris (e.g., Østrem, 1959).

The mean ice cliff backwasting rate was 7.1 cm d^{-1} and the standard deviation for all measured ice cliffs was 2.5 cm d^{-1}. The maximum and minimum measured backwasting rate were 15 and 2.5 cm d^{-1} respectively (Table 2). Figure 7 shows measured backwasting rates. While there is significant scatter within any elevation band a weak negative relationship between ice cliff backwasting and elevation is apparent (Supplemental Figure 7). Ice cliffs backwasted at rates similar rates with and without ponds and streams at their base and there is no apparent aspect dependence on backwasting rates (Fig. 7) .

3.2 Remotely-sensed ice cliff extent

3.2.1 Performance of automatic ice cliff delineation methods

The adaptive binary threshold (*ABT*) method outperforms the Sobel edge delineation (*SED*) method. Averaged across the validation dataset, the *ABT* method correctly identifies 58% of ice cliff area, with 21% false positives. Percentages are relative to the hand-delineated validation dataset. The *SED* method yields a lower percentage of correctly identified ice cliffs (45%), but also produces fewer false positives (14%). In regions where we do not have manually digitized ice cliffs, our estimates of ice cliff area represent both true and false positives. Assuming our success rate is consistent across the glacier, we expect the *ABT* and *SED* approaches to detect 79% and 69% of the true ice cliff area, respectively.

Some systematic errors are evident, as anomalously light and dark regions of the glacier produce higher error. Regions of thin debris are especially problematic when using the *SED* method (Fig. 9; see also Herreid and Pellicciotti, 2018). To correct for this error in the *SED* results, where debris is very thin, we manually removed areas with highly erroneous ice cliff delineations; these only occur at higher elevations in the study area (Fig. 9). Due to its poorer performance, we do not use the *SED*-defined ice cliff area for the distributed mass balance estimates.

3.2.2 Spatial distribution of ice cliffs

The two delineation methods produce broadly similar ice cliff distributions. The *SED* method, specifically, overestimates ice cliff area at high elevation due to the thin, dark-colored debris. Over the 24.2 km^2 debris-covered portion of the study area, we estimate that ice cliffs cover 2.14 km^2 (8.8%) and 2.32 km^2 (9.7%) of ice cliff planview area using the *SED* and *ABT* methods, respectively (Fig. 10). If we apply a bias correction to the *SED* (31%) and *ABT* (21%) estimates based upon under-delineation rates in manually digitized areas, the ice cliffs cover 11.4% and 11.7% of the glacier respectively. Focusing on the *ABT* results, which provide the most accurate estimate, we find a "humped" profile in the elevational distribution of ice cliff fractional area. Ice cliff fractional area peaks between 520 and 620 m a.s.l. Below this elevation, ice cliff area decreases (Fig. 10).

In total, 11.7 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs. See Anderson (2014) for an estimate using an independent method on Kennicott Glacier that is consistent. 11.7 % is 60% more coverage by percentage than on the Changri Nup Glacier, the glacier with the second highest coverage of ice cliffs studied to date (Table 4). The Kennicott Glacier has the lowest mean debris thickness (13 cm) of glaciers with reported ice cliff coverage percentages and supports, by far the highest percentage of ice cliffs. This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness (Table 4).

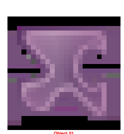
We normalized ice cliff area by glacierized area within each elevation band, which we refer to as ice cliff fractional area. Ice cliff fractional area is relatively uniform at 7-8% except for a broad peak between 500-660 m a.s.l. within which fractional area reaches 13% at 540-560 m. The lower edge of this peak overlaps with the upper end of the *ZMT*.

3.3 Distributed estimates of melt

Figure 11 we show the best distributed estimate of melt split into sub-debris and ice cliff contributions across the study area. While sub-debris melt decreases toward the terminus due to thickening debris, we apply uniform ice cliff backwasting rates with the debris-covered portion of the study area.

When averaged across the entire study area, 8% of melt is derived from sub-debris melt and 26 (20 , 40)% from ice cliff melt. Figure 12 shows that the insulating effects of debris cover is more important in setting the area-averaged melt rate than ice cliffs, especially where debris is typically thinner at higher elevations. Modeled bare ice melt rates, which are meant to represent the hypothetical melt rate if debris were absent from the study area, increase towards lower elevations and range from 5.9 to 7 cm d^{-1} (Fig. 12). The dominance of decreasing sub-debris melt downglacier, due to thickening debris, results in a deviation from the bare-ice melt rate above 700 m a.s.l. (relative to the 2013 glacier surface). Elevation-band averaged sub-debris melt rates decline from 4.2 cm d^{-1} (3.2, 5.1) at the top of the study area to 1.6 cm d^{-1} (0.98, 2.0) near the terminus.

Ice cliffs, when their total melt contribution is averaged over entire elevation bands, produced rates of 0.73 cm d^{-1} (0.31, 1.29) at the top of the study area and 0.69 cm d^{-1} (0.33, 1.4) near the terminus. The maximum contribution of ice cliffs to band-averaged melt occurs near 500 m and has a value of 1.3 cm d^{-1} (0.58, 2.4). Ice cliffs contribute most to mass loss in the 500 to 520 m a.s.l. elevation band, close to where the ice cliff fractional area also maximizes. Ice cliffs between 500 and 520 m a.s.l. generate the highest percentage 42% (34, 58%) of the total mass loss due to ice cliffs and sub-debris melt within the study area.



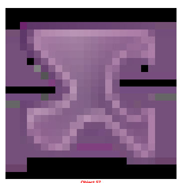
(7)

where is the mean ablation rate within the elevation band i in units of m d^{-1}, is the total debris-covered area within the elevation band, is the total ice cliff area within the elevation band, is the total area within the elevation band ,and dx and dy are both 1 m.

We present one most-likely distributed empirical melt estimate, which we bound with two extreme cases. For the most-likely case the curve fits are calculated using the median of data from the 50-m elevation bins (Fig. 4). See Table 2 for the extreme parameters used for the distributed melt estimates. In the extreme cases for the debris thickness and ice cliff backwasting, curve fits were made through the 25% and 75% data points in each elevation bin (Fig. 4; Supplemental Figure 2).

2.3 Modeled bare-ice melt rates across the study area

For reference we also estimate the bare-ice melt rate through the study area for the summer of 2011, in the hypothetical case that no debris was present on the glacier. We calculate the bare-ice melt factor from several ablation stakes in bare-ice in the northeastern portion of the study area (Part A). We calculate the melt factor for ice (e.g., Hock, 2003) MF_{ice} using measured bare-ice ablation () and air temperatures interpolated across the glacier:



. (8)

where T^{+} is the positive degree-days defined as the mean daily air temperature when above 0° C and Δt is one day. Air temperatures did not drop below freezing during the study period. We use hourly air temperature data from the Gates Glacier and May Creek meteorological stations to estimate the T^{+} at each measurement location. Gates Glacier station is located off-glacier at 1240 m elevation and May Creek station is located at an elevation of 490 m located 15 km to the southwest of the town McCarthy (Fig. 1).

2.4 Digitization of surface lakes from 1957 and 2009

In order to compare the extent of surface lakes with the ZMT we hand-digitized lakes from the 1957 and 2009 summer images. Lakes were searched for using a fixed grid to insure complete coverage of the study area. Digitized lake extents were confirmed by independent operators. Depressions on the glacier surface with exposed ice and/or ice-cut shorelines were digitized and assumed to be former lakes that subsequently drained.

3 Results

3.1 Remotely-sensed ice cliff extent

3.1.1 Performance of ice cliff detection methods

The adaptive binary threshold (*ABT*) method outperforms the Sobel edge detection (*SED*) method. Averaged across the error checks, the *ABT* method correctly identifies 58% of ice cliff area, with 21% false positives. Percentages are relative to the hand-digitized ice cliff areas. The *SED* method yields a lower percentage of correctly identified ice cliffs (45%), but also produces fewer false positives (14%). In regions where we do not have manually digitized ice cliffs, our estimates of ice cliff area represent both true and false positives. Assuming our success rate is consistent across the glacier, we expect the *ABT* and *SED* approaches to detect 79% and 69% of the true ice cliff area, respectively.

Some systematic errors are evident, as anomalously light and dark regions of the glacier produce higher error. Regions of thin debris are especially problematic when using the *SED* method (Fig. 6; see also Herreid and Pellicciotti, 2018). To correct for this error in the *SED* results, where debris is very thin, we manually removed areas with highly erroneous ice cliff detections; these only occur at higher elevations in the study area (Fig. 6). Due to its poorer performance, we do not use the *SED*-defined ice cliff area for the distributed mass balance estimates.

3.1.2 Spatial distribution of ice cliffs

The two detection methods produce broadly similar ice cliff distributions. The *SED* method, specifically, overestimates ice cliff area at high elevation due to the thin, dark-colored debris. Over the 24.2 km^2 study area, we estimate that ice cliffs cover 2.14 km^2 (8.8%) and 2.32 km^2 (9.7%) of ice cliff planview area using the *SED* and *ABT* methods, respectively (Fig. 8). If we apply a bias correction to the *SED* (30%) and *ABT* (20%) estimates based upon under-detection rates in manually digitized areas, the ice cliffs cover 11.4% and 11.7% of the glacier respectively. Focusing on the *ABT* results, which provide the most accurate estimate, we find a “humped” profile in the elevational distribution of ice cliff area. Ice cliff area peaks between 600 and 620 m a.s.l. Below this elevation, ice cliff area decreases (Fig. 8).

In total, 11.6 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs. This is 60% more coverage by percentage than on the Changri Nup Glacier, the glacier with the second highest coverage of ice cliffs studied to date (Table 3). The Kennicott Glacier has the lowest mean debris thickness (13 cm) of glaciers with reported ice cliff coverage percentages and supports the highest percentage of ice cliffs. This implies that ice cliff coverage varies with debris thickness.

We normalized ice cliff area by glacierized area within each elevation band, which we refer to as ice cliff fractional area. Ice cliff fractional area is relatively uniform at 7-8% except for a broad peak between 500-660 m elevation within which fractional area reaches 13% at 540-560 m. The lower edge of this peak overlaps with the upper end of the *ZMT* (see Part C for further discussion).

4 Discussion

3.2 Distributed estimates of melt

In Figure 9 we show the distributed estimates of melt split into sub-debris and ice cliff contributions across the study area. While sub-debris melt decreases toward the terminus due to thickening debris, ice cliff backwasting rates increase toward the terminus due to increasing energy available for melt.

When averaged across the entire study area, 81% of mass loss is expected to come from sub-debris melt and 19% from ice cliff melt. Maximum bounds for the total contribution of ice cliffs to mass loss are 12% and 28%. Figure 10 shows that the insulating effects of debris cover dominates the melt-enhancing effect of ice cliffs when averaged across elevation bands. Modeled bare ice melt rates, which are meant to represent the hypothetical melt rate if debris were absent from the study area, increase towards lower elevations and range from -5.9 to -7 cm d^{-1} (Fig. 10). The dominance of decreasing sub-debris melt downglacier, due to thickening debris, results in a sharp deviation from the bare-ice melt rate near 700 m elevation (relative to the 2015 glacier surface). Elevation-band averaged sub-debris melt rates decline from 5.7 cm d^{-1} at the top of the study area to 1.6 cm d^{-1} near the terminus.

Ice cliffs produce mean elevation-band averaged melt rates of 0.33 cm d^{-1} at the top of the study area and 0.78 cm d^{-1} near the terminus. The maximum contribution of ice cliffs to band-averaged melt occurs near 500 m and has a value of 1.1 cm d^{-1}. Ice cliffs contribute most to mass loss in the 500 to 520 m elevation band, close to where the ice cliff fractional area also maximizes. Across all of the elevation bands, the ice cliffs between 500 and 520 m generate a maximum of 40% of the total mass loss due to ice cliffs and sub-debris melt.

3.3 Surface lake coverage

In 1957, lakes would have covered only 0.4 % of the study area. By 2009, surface lakes had expanded upglacier and more than doubled their surface area compared to the 1957 image, covering 0.94% of the study area. Lakes occupied 2.0% of the portion of the glacier with 4 km of the terminus and 0.39% of the upper portion of the study area in 2009. In both the 1957 and 2009 images lake coverage is almost zero in the upper portion of the zone of maximum thinning (Fig. 10).

4 Discussion

4.1 Field measurements

4.1 Ice cliff detection methods

Our ablation stake derived sub-debris melt rates are highly variable beneath debris less than 3 cm (Fig. 5). It appears that local environmental conditions are as important as the potential for melt enhancement due to thin debris (see Mihalcea et al., 2006; Reid and Brock, 2010 for similar observations). Our measured sub-debris melt rates are consistent with the observations made by Fyffe et al. (2020): a consistent melt enhancing effect due to debris less than 3 cm is not apparent. Debris typically forms parabolic-shaped medial moraines in cross-section (e.g., Anderson, 2000) suggesting that the melt suppressing effect of debris dominates, in the study area (and upglacier as well). Despite this the melt enhancing effect of debris less than 3 cm remains an important potential melt-enhancing effect of debris cover, that is most likely to increase surface melt at the upglacier end of debris covers.

Based on our debris thickness to sub-debris melt measurements, the characteristic debris thickness (h_*) was 8.17 cm. Practically an h_* of 8.17 cm means that sub-debris melt rate will be 50% of the bare ice melt rate at 8.17 cm debris thickness

(Eqn. 4). The relationship between melt rate and debris thickness from Kennicott Glacier is similar to those derived from other debris-covered glaciers at similar latitudes (Supplemental Material). The consistent decline in sub-debris melt rates as debris thickens is not unexpected considering that the global mean value of h_* is 6.6 ± 2.9 m (1 σ)(based on 15 glaciers from Anderson and Anderson, 2014).

Significant scatter is present in the ice cliff backwasting rates as they vary with elevation, suggesting that controls independent of elevation are important. But when our backwasting rate data are binned in 50 m elevation bands a weak increase in backwasting rates towards lower elevations is apparent. Potential causes of higher backwasting rates at lower elevations are: 1) increased air temperatures. Increased debris thickness leads to higher debris surface temperatures, longwave fluxes, and energy available for melt (e.g., Brock et al., 2010); or 2) increased debris veneers and lower ice cliff albedo at low elevations (e.g., Reid and Brock, 2014). Because ice cliffs, by definition persist above the angle of repose, large clasts (pebble-sized and larger) tend to trundle to the base of ice cliffs. But fine materials (clay and sand sized particles) on the other hand are more likely to persist on steep ice cliff surfaces. This could be due to local surface roughness on the ice cliff allowing for fine material to accumulate. For finer grains attractive inter particle surface forces, frictional interlocking of grain aggregates, and electrochemical forces are more likely to adhere debris to cliff surfaces (e.g., Jain and Kothyari, 2009; Supplementary Photos 1-3). When melt is occurring on the ice cliff, the adhesive and cohesive properties of liquid water may also also help retain fine debris on cliff surfaces. It follows that fine debris will be more likely to decrease ice cliff albedo where debris cover above ice cliffs are composed of more fine material. It has been noted in several studies of debris cover grain size that the percentage of fine material composing debris covers tends to increase towards glacier termini (Owen et al., 2003; Kellerer-Pirklbauer, 2008).

Thicker debris cover leads to higher debris surface temperatures, and higher longwave radiation fluxes received by ice cliffs. Despite this physical relationship, the backwasting rates measured on Kennicott Glacier are similar to those measured on glaciers with thicker debris cover and at lower latitude (Table 3). The similarity in backwasting rates suggests that there may be compensating effects between latitude, day length, and altitude. i.e., Himalayan glaciers are present at a lower latitude but they also tend to persist at high elevations compared to, for example, Kennicott Glacier which persists at a much higher latitude but also lower elevation. Ultimately the lack of aspect control on backwasting rates on Kennicott Glacier contrasts with observations from lower latitudes (e.g., Buri and Pellicciotti, 2018), suggesting that there may be a latitudinal control on ice cliff backwasting rates as they vary with orientation.

In this study, backwasting was measured at the top of ice cliffs. Based on the modeling of Buri et al. (2016b) from Lirung Glacier, Nepal (28° N), the highest backwasting rates tend to occur near the top of ice cliffs (noting that only northwest and northeast facing ice cliffs were modeled). But making in situ measurements across a representative population of ice cliffs is very difficult. We assume that a single measurement from 60 ice cliffs would better represent the mean backwasting rate across the thousands of ice cliffs in the study area. The validity of this assumption should be explored in future field campaigns. If it is true that ice cliff backwasting is maximized at the top of ice cliffs then distributed estimates of surface melt using our backwasting rates could overestimate ice cliff backwasting when averaged across entire cliffs. It could be that our ice cliff backwasting rates overestimate the melt potentially skewing our estimates towards higher than actual melt rates in the zone of maximum thinning.

4.2 Ice cliff delineation methods

Our automated methods provide an accurate estimate of ice cliff area, though both the *ABT* and *SED* ice cliff delineation~~detection~~ methods underpredict ice cliff area, without bias corrections. These methods require that ice cliffs are dark relative to surrounding debris cover. This observation of darker ice cliffs is generally true for Kennicott and several other debris covered glaciers we examined, but this relationship should be verified before application different glaciers. Output should simply be examined to ensure that such conditions do not contaminate results. Ice cliffs may be brighter than the surrounding debris if the ice cliffs are not covered with thin debris films or if they are strongly illuminated. Our method will therefore likely underpredict south-facing ice cliffs, although we observe many correct delineations~~detections~~.

Future improvements to these delineation~~detection~~ methods may be achieved using more advanced image segmentation techniques (e.g., Leyk and Boesch, 2010), by utilizing image texture analysis, or by adaptively changing image processing parameters within a window moving across the image and mosaicing the results. The transferability of optimal processing parameters (both across time and space) requires further investigation, but none-the-less we present a promising approach for the large-scale delineation of ice cliffs. Using multispectral imagery would also likely improve delineation~~detection~~, although such imagery is less readily available. The delineation~~detection~~ methods presented here could be compared to the cliff delineation algorithm of Herreid and Pellicciotti (2018) using existing high-resolution DEMs on Kennicott Glacier.

4.3~~2~~ Distributed estimates of melt

On Kennicott Glacier, ice cliffs most likely contribute 26% (with extreme bounds of 20 and 40%) of melt of ~~19% of volume loss of~~ the debris-covered tongue. This percentage is more than twice the percentages reported from other glaciers with mean debris thicknesses less than 50 cm (Table 4~~3~~). This is likely due to the high fractional coverage of ice cliffs on the Kennicott Glacier. For glaciers with mean debris thicknesses much larger than 50 cm, ice cliff contributions are larger than 26~~19~~% and are as high as ~~reach~~ 40%. For these other glaciers ~~These~~ high ice cliff contributions occur despite much lower ice cliff coverage ~~when~~ compared to Kennicott Glacier (Table 4). It follows that relative ice cliff contribution will be higher where sub-debris melt rates are low~~3)~~.

Ice cliffs tend to contribute a higher fraction of mass loss as debris thickness increases. This trend is visible on Kennicott Glacier as debris thickens toward the terminus (Fig. 12~~10~~). This relationship also appears to hold when considering debris-covered glaciers from different regions (Table 4~~3~~). As debris thickens the contribution of ice cliff melt also tends to increase. This appears to occur even though the fractional coverage of ice cliffs tends to decrease as mean debris thicknesses increase.

Ice cliffs do not counteract the insulating effects of debris on Kennicott Glacier (Fig. 12). The thin debris within the study area ~~Figs. 10 and 11). Thin debris~~ leads to melt rates closer to bare-ice melt rates than most other studied debris-covered glaciers. Measured ice cliff backwasting rates are comparable or higher than measurements from other studies (Table 3. ~~.~~ Kennicott Glacier also has the highest fractional coverage of ice cliffs, relative to other studied glaciers, which also serves to increase melt rates (Table 4~~3~~). Despite this, ice cliffs on Kennicott Glacier do not compensate for the insulating effects of debris. This ~~strongly~~ suggests that the presence of ice cliffs is unlikely to ~~completely~~ counter the insulating effects of debris on ~~other~~ glaciers with thicker debris and/or lower ice cliff coverage.

4.3.1 *Do ice cliffs maximize melt in the ZMT in the summer of 2011?*

During the measurement period between mid June and mid August of 2011, the melt within the zone of maximum thinning (*ZMT*) is strongly suppressed by insulating debris cover. For this discussion we make the assumption that the *ZMT* – which was stable between the 1957 to 2004 and 2000 to 2007 time periods-- remained in the same location during summer of 2011. Note that from 1957 to present the *ZMT* of Kennicott Glacier has been debris covered (Supplemental Figure 26). All explored debris thickness extrapolation approaches presented here show that the melt profile is strongly suppressed by thick debris, a pattern that remains consistent even when extreme parameters are chosen to increase the melt rate of ice cliffs (Supplemental Material). All of these estimates also include the potential slight biases of our measurements towards 1) thinner debris, and 2) high backwasting rates. We further assess what changes in debris thickness, sub-debris melt rate, ice cliff coverage, or backwasting rates would be required to produce the highest glacier-wide melt rates within the *ZMT*. The point of this exercise is to show how extreme the parameter choices would be to maximize melt within the *ZMT*.

~~**4.2.1 *Do melt hotspots maximize melt in the ZMT?***~~

~~In order to discuss the relationship between debris, mass balance, and ice dynamics to the thinning of Kennicott Glacier we must address the assumptions inherent in using the melt pattern from the summer of 2011 to represent the melt pattern over the last 60 years. At least from 2011, the surface mass balance within the zone of maximum thinning (*ZMT*) is strongly suppressed by thick debris cover. We assess what changes to our melt estimates would be required to produce the highest glacier-wide melt rates within the *ZMT*.~~

Debris cover and sub-debris melt: Debris thickness would have to decrease, specifically in the *ZMT*, from ~20 cm to 2 cm (a reduction factor of 0.1) ~~would have to decrease to 10% of its current thickness~~ to produce maximum glacier-wide melt rates there. 53 % ~~. In Part A, we noted that most~~ of our debris thickness measurements were derived from the top of ice cliffs and topographic highs. Because debris tends to concentrate in topographic lows our debris thickness measurements may be biased toward thinner debris, making the required reduction in debris thickness even more extreme. Melt would also be maximized in the zone of maximum thinning, where measured debris is ~20 cm thick, sub-debris melt rates would have to increase from ~ 1.6 cm d^{-1} by a factor of 3 to 4.8 cm d^{-1}.

The *ZMT* has been continuously debris covered since at least 1957 (Fig. 12). The presence of thermokarst features, ice cliffs, and lakes in the lower 4 km of the glacier surface imply that debris greater than 5 cm was present in the *ZMT* between 1957 and 2009 as is the case for other debris-covered glaciers with abundant surface ponds and thermokarst features (e.g., Sakai et al., 2000; Benn et al., 2001; Wessels et al., 2002; Thompson et al., 2016). Debris cover expanded upglacier by 1.6 km between 1957 and 2009, but upglacier from the *ZMT* (Figs. 2 and 12). This suggests that sub-debris melt did not control the location of the *ZMT*.

Ice Cliffscliffs: In order for ice cliffs, in the *ZMT*, to enhance melt and produce maximum glacier-wide melt rates in the *ZMT*, backwasting rates would need to be 67.5 times higher than those measured in the summer of 2011. This required backwasting rate is well beyond potential biases introduced due to the summer of 2011 having anomalously low air temperatures. Our backwasting estimates are based on repeated measurements at a single location at the top of each ice cliff. Maximum But as described in Part A maximum backwasting rates across each ice cliff are more likely to occur near the top (Buri et al., 2016). Applying our measurements across single ice cliffs or the entire ice cliff population may therefore overestimate ice cliff melt. The hypothetical backwasting rates required to maximize melt in the *ZMT* are therefore unreasonable; a compilation of previously published backwasting rates inshown in Part A and Table 3 support this.

In order for ice cliffs in the *ZMT* to compensate for the insulating effects of debris and enhance melt in the *ZMT* beyond bare ice melt rates, ice cliff area would need to increase from 11.7% to 90% of the glacier surface. This again suggests that ice cliff melt does not control the location While aerial photos from the summers of 1957 and 1978 reveal an anecdotal increase in exposed ice (Fig. 12), at the upper end of the *ZMT* at least during the summer of 2011, far less than 90% of the glacier surface was occupied by ice or ice cliffs. This suggests that ice cliff melt did not solely control the location of the *ZMT*.

Surface lakes: Figure 11 shows that in both 1957 and 2009 lakes are most abundant near the terminus and immediately downglacier from the *ZMT*. Surface lakes and thermokarst depressions do not coincide with the full extent of the *ZMT* and are most notably absent in its upper reaches (Fig. 11; Rickman and Rosenkrans,1997). Mass loss beneath lakes surfaces in the *ZMT* would have to be 190-times the local sub-debris melt rate for sub-aqueous melt to compensate for the insulating effects of debris in the *ZMT*. This further suggests that sub-aqueous melt under lake surfaces is unlikely to compensate for the insulating effect of thick debris.

But the mottled nature of the thinning pattern in the *ZMT* highlights the melt-enhancing effects of melt hotspots. The patches of most rapid thinning occur near the 2015 glacier margin which are bordered by alluvial-bedded streams and ice cliffs. While the local effect of these processes is apparent in the thinning map, it is unclear how thermokarst, surface lakes, and ice-marginal streams enhance melt outside of the hotspots themselves.

4.43 Østrem's curve expressed in the mass balance profile

On debris-covered glacier termini, debris tends to thicken towards debris-covered glacier termini (e.g., Anderson and Anderson, 2018) as is the case for Kennicott Glacier**.** This leads to the expectation that sub-debris melt rates will decline towards the terminus reversing the mass balance gradient, similar to the results and conclusions for glaciers in the Khumbu of Nepal (Bisset et al., 2020). The overall mass balance profile for the summer of 2011 (Fig. 12) shows this Østrem's curve like pattern, suggesting that it is more strongly influenced by debris thickness than melt hotspots. Future efforts to represent the effects of ice cliffs on glacier mass balance at the regional scale could consider using a modified debris thickness-melt relationship with a percentage enhancement based on empirical relationships between debris thickness and ice cliff melt contribution. Even where ice cliffs contribute 42 % of melt the surface mass balance pattern still largely follows Østrem's curve.

~~Debris tends to thicken towards debris-covered glacier termini as is the case for Kennicott Glacier (e.g., Anderson and Anderson, 2018). This leads to the expectation that sub-debris melt rates will decline towards the terminus. At least on Kennicott Glacier it appears that melt hotspots do not compensate for the melt-insulating effects of thick debris. Figure 10 shows this Østrem's curve like pattern. The low-melt, low melt gradient portion of the mass balance profile extends further than the high melt high-melt gradient portion of the mass balance profile. Similar theoretical expressions of this mass balance profile can be seen in the numerical simulations presented in Anderson and Anderson (2016).~~

5 Conclusions

The melt within a debris-covered tongue of a large Alaskan Glacier has been quantified. We conclude that:

- For Kennicott Glacier the zone of glacier-wide maximum thinning occurs under melt-reducing debris cover, up-glacier from its terminus. Based on the periods 1957-2004 and 2000-2007 the zone of maximum thinning appears to be in a stable location (Das et al., 2014) and has been continuously debris covered since at least 1957.
- Kennicott Glacier is covered by thinner debris than most previously studied glaciers (mean debris thickness of ~14 cm). Debris thickness tends to increase down glacier. It is thickest near the terminus near the margin of Kennicott Glacier.
- We see significant scatter in melt rates for debris under 3 cm thick. In some locations melt is amplified relative to bare ice melt rates and in others melt is suppressed, suggesting that local glacier surface hydrology or meteorology may be important in determining whether or not melt amplification occurs under debris less than 3 cm thick.
- Measured ice cliff backwasting rates from Kennicott Glacier are as high as those measured from any other glacier measured to date. We find no consistent control of backwasting rate by orientation, or whether streams or ponds are present at the base of the ice cliff. More measurements are needed to robustly test these results. A slight dependence of backwasting rate with elevation may be present, although there is considerable variability within any elevation band.
- A new ice cliff delineation method is presented using high-resolution panchromatic WorldView1 satellite imagery. This method provides a robust estimate of ice cliff extent for a particularly difficult test case in which ice cliffs are abundant, and often small. The method is robust even as debris surface color varies across 9 medial moraines.
- Within its debris-covered tongue, Kennicott Glacier hosts the highest percentage of ice cliffs by area (11.7%) of any previously studied glacier.
- Abundant in situ measurements allow extrapolation of debris thickness, sub-debris melt, and ice cliff backwasting, across the study area. Debris thicknesses are extrapolated down individual flow paths.
- During the summer of 2011, approximately 26% of melt in the entire debris-covered tongue is attributable to ice cliffs while covering 11.7% of the study area. In the lowest 4 kilometers of Kennicott Glacier where debris tends to be thicker than 15 cm and hence sub-debris melt rates are low, ice cliffs constitute up to 42% of melt.
- Ice cliffs strongly contribute to the surface melt of Kennicott glacier. Ice cliffs contribute a larger percentage of mass loss in places where debris cover is thick, a pattern observed across the Kennicott Glacier and for other studied glaciers from other regions.

- The mass balance profile within the debris covered portion of the glacier appears to follow the debris-melt relationship or Østrem's curve.
- If surface melt was the sole control on the location of the zone of maximum thinning (*ZMT*) then surface melt must peak within the *ZMT*. The thin debris, high ice cliff backwasting rates, and abundant of ice cliffs found on the debris-covered tongue of Kennicott Glacier (relative to previously studied debris-covered glaciers) all suggest that the ice cliffs should compensate for the melt-suppressing effects of debris (relative to bare-ice melt rates). However even with extreme parameter choices and extreme uncertainty scenarios melt rates in the zone of maximum thinning, neither match hypothetical bare-ice melt rates at the same elevation nor result in glacier-wide maximum melt rates within the *ZMT*.

~~Our new ice cliff delineation method using high-resolution satellite imagery reveals that Kennicott Glacier supports the highest percentage of ice cliffs (11.7%) of any debris-covered glacier studied to date. Ice cliffs within the debris-covered portion of Kennicott Glaicer partly counters the insulating effect of debris. Approximately 19% of melt in the study area is attributable to ice cliffs. In the lowest 4 kilometers of Kennicott Glacier, debris is thick, ice cliff coverage is low, but ice cliffs still contribute up to 40 % of mass loss in this area. Ice cliffs contribute a larger percentage of mass loss within thicker debris covers, a trend that can be seen across the Kennicott Glacier and for other studied glaciers.~~

~~The zone of maximum thinning of Kennicott Glacier has been continuously debris-covered since at least 1957. Debris cover in the interior of the glacier expanded upglacier from 1957 to 2009. From 1957 to 2009 surface lakes have expanded upglacier and almost doubled their areal coverage in the debris-covered portion of the glacier (see Rickman and Rosenkrans, 1997). But lakes are not exensive enough to solely control the location of maximum thinning.~~
Because melt hotspots do not appear to control the *ZMT* location, during the study period, we suggest that ice dynamics and the decline in ice discharge from upglacier appears to be vital to explain high glacier thinning rates despite thick, melt-insulating debris cover.

~~It appears that melt hotspots (ice cliffs and surface lakes) are unable to compensate for the insulating effects of thick debris cover on Kennicott Glacier. This suggests that, in addtion to melt hotspots, ice dynamics and the decline in ice discharge from upglacier has played an important role in the thinning of the glacier under thick debris. The mass balance profile within the debris covered portion of the glacier appears to follow Østrem's curve (the debris thickness-melt relationship). In Part C we explore feedbacks that help define the rapid thinning of Kennicott Glacier under thick debris.~~

Data availability

Datasets and results are available upon request.

Author contribution statement

LSA, WHA, and RSA ~~-~~designed the study. LSA ~~,~~ composed the manuscript, collected all field data, and completed ~~and~~ all analyses besides the automatic ice cliff delineation method. WHA developed the ice cliff delineation method, delineated ice cliffs, ~~-~~and wrote the associated text. RSA advised LSA and WHA through the study and contributed to the text and figures. PB contributed to the text and added important discussion that improved the manuscript. All authors aided in composing~~revised~~ the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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Tables

Table 1. Parameters used for the best distributed melt and uncertainty estimates

Parameter name	Parameter symbol	Min.	Best	Max.	
Debris thickness [cm]	a	17.6	21.55	34.3	Interquartile range
	b	0.016	0.13	0.01	
	c	538	551	556	

	d	2.1	2.1	2.6	
Sub-debris melt rate [cm d^{-1}]	$\dot{b}_{ice}$	4.87	5.87	6.87	± 1σ
	h_*	8.17	8.17	8.17	
Ice cliff backwasting [cm d^{-1}]	f	2.18	7.1	12.0	± 1 σ
Ice cliff slope [degree]	θ	43	48	53	± 1σ

Table 1. Optimal image processing parameters for ice cliff delineation in the July 2009 WorldView scene, as determined by a Monte Carlo method.

Adaptive binary threshold (ABT)	Min brightness [DN*]	Max brightness [DN]	Window size [px]	Brightness offset [DN]	Opening kernel size [px]
	20	42	267	52	3
Sobel edge detection (SED)	Min brightness [DN]	Max brightness [DN]	Threshold gradient [DN px^{-1}]	Opening kernel size [px]	
	32	55	22	4	

*DN = digital number, a 0-255 representation of relative radiance of each pixel.

Table 2. Statistics of debris- and melt-related measurements for Kennicott Glacier

Table 2. Parameters used for distributed melt estimates

Measured variable	Mean	Std.	Minimum	Maximum
Debris thickness [cm]	13.7	13.9	0	100
Sub-debris ablation [cm d^{-1}]	4.0	1.8	0.8 (37 cm of debris)	7.3 (1 cm of debris)
Ice cliff backwasting [cm d^{-1}]	7.1	2.5	2.8	13.8

Parameter name	Parameter symbol	Most-likely	Min.	Max.
Debris thickness (h_{debris}) [cm]	a	25.7	20.5	40.2
	b	571	545	607
	c	-0.24	-0.15	-5.3
Sub-debris ablation [cm d^{-1}]		5.87	4.87	6.87
	h_{star}	8.17	8.17	8.17
Ice cliff backwasting [cm d^{-1}]	f	-0.0123	-0.0079	-0.0111
	g	13.94	10.25	15.11
Ice cliff slope [degree]	θ	40	30	50
Ice cliff area (%)	-	11.7	9.7	11.7

Table 3. Comparison of ice cliff backwasting rates and debris thicknesses with other glaciers

Glacier	Region	Latitude [deg.]	Mean study area elevation [m]	Range of backwasting rates [cm d-1]	Mean debris thickness [cm]	Reference
Kennicott	Alaska	61	600	3-15	13	This study
Miage	Alps, Italy	46	2200	6.1-7.5	26	Reid and Brock, 2014
Koxkar	Tien Shan, China	42	3500	3-10	53	Han et al., 2010; Juen et al., 2014
Lirung	Himalaya, Nepal	28	4200	7-11	50-100	Brun et al., 2016
Changri Nup	Himalaya, Nepal	28	5400	2.2-4.5	-	Brun et al., 2018

*Sorted by latitude

Table 4. Comparison of ice cliff coverage and melt contribution with other debris-covered glaciers

Glacier	Region	Ice cliff fractional area (%)**	Ice cliff mass loss (%)	Mean debris thickness [cm]	Study
Ngozumpa	Himalaya, Nepal	5	40	0-300	Thompson et al., 2016
Lirung	Himalaya, Nepal	2.0	36	50-100	Buri and Pellicciotti, 2018
Changri Nup	Himalaya, Nepal	7.4	24 (±5)	-	Brun et al., 2018
Langtang	Himalaya, Nepal	1.3	20	-	Buri and Pellicciotti, 2018
Kennicott	Alaska	11.7	20 (±8)	13	This study
Koxkar	Tien Shan, China	1.4	7.4-12	53	Han et al., 2010; Juen et al., 2014
Miage	Alps, Italy	1.3	7.4	26	Reid and Brock, 2014

*Sorted by mass loss % due to ice cliffs
** % relative to each study area

Table 3. Comparison of ice cliff coverage and melt contribution on debris-covered glaciers

Glacier	Ice cliff fractional area (%)	Ice cliff mass loss (%)	Mean debris thickness [cm]	Study
Ngozumpa, Nepal	5	40	0-300	(Thompson et al., 2016)
Lirung, Nepal	2.0	36	50-100	(Buri and Pellicciotti, 2018)

~~Changri Nup, Nepal~~	~~7.4~~	~~24 (±5)~~	~~-~~	~~(Brun et al., 2018)~~
~~Langtang, Nepal~~	~~1.3~~	~~20~~	~~-~~	~~(Buri and Pellicciotti, 2018)~~
~~Kennicott, Alaska~~	~~11.6~~	~~19 (±8)~~	~~13~~	~~This study~~
~~Koxkar, China~~	~~1.4~~	~~7.4-12~~	~~53~~	~~(Han et al., 2010; Juen et al., 2014)~~
~~Miage, Italy~~	~~1.3~~	~~7.4~~	~~26~~	~~Reid and Brock (2014)~~

~~**EB refers to energy balance~~

Figures

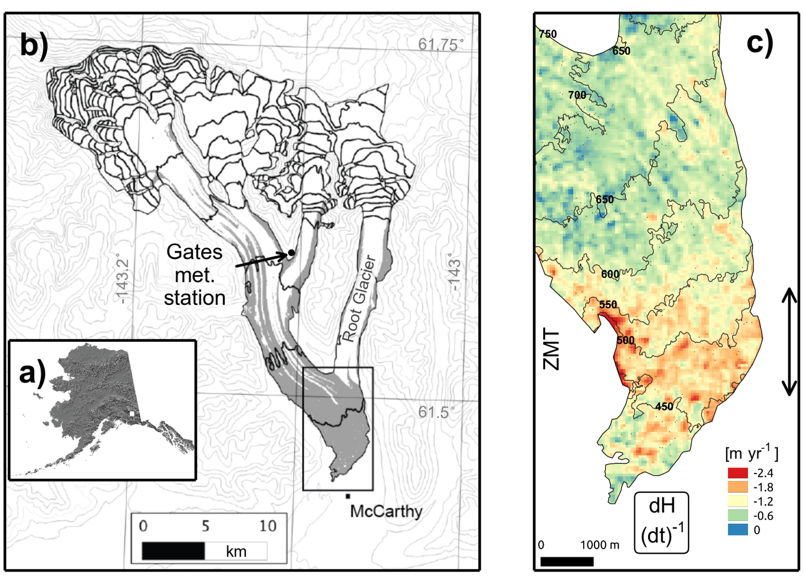


Figure 1. Map of Kennicott Glacier and the study area. a) Map of Alaska showing the location of panel b and the Wrangell Mountains. b) The Kennicott Glacier with the location of the Gates Glacier meteorological station (1240 m a.s.l.), discussed in the supplementary material. May Creek meteorological station is located 15 km to the southwest of McCarthy at 490 m a.s.l.. Contour intervals are 250 m based on the ASTER GDEM V2 (2009). c) Map of the general study area with dH $(dt)^{-1}$ from 1957 to 2004 see Das et al. (2014) (mean error 0.04 m yr^{-1} and 1 std 0.15 m yr^{-1} based on 3 km^2 area within 4 km of the modern terminus). *ZMT* refers to the zone of maximum thinning, the extent of which is shown with the double-headed arrow. This map of the study area includes the bare-ice parts of Root and Kennicott Glaciers, where some ablation measurements were made. Elevation contours are from 2013.

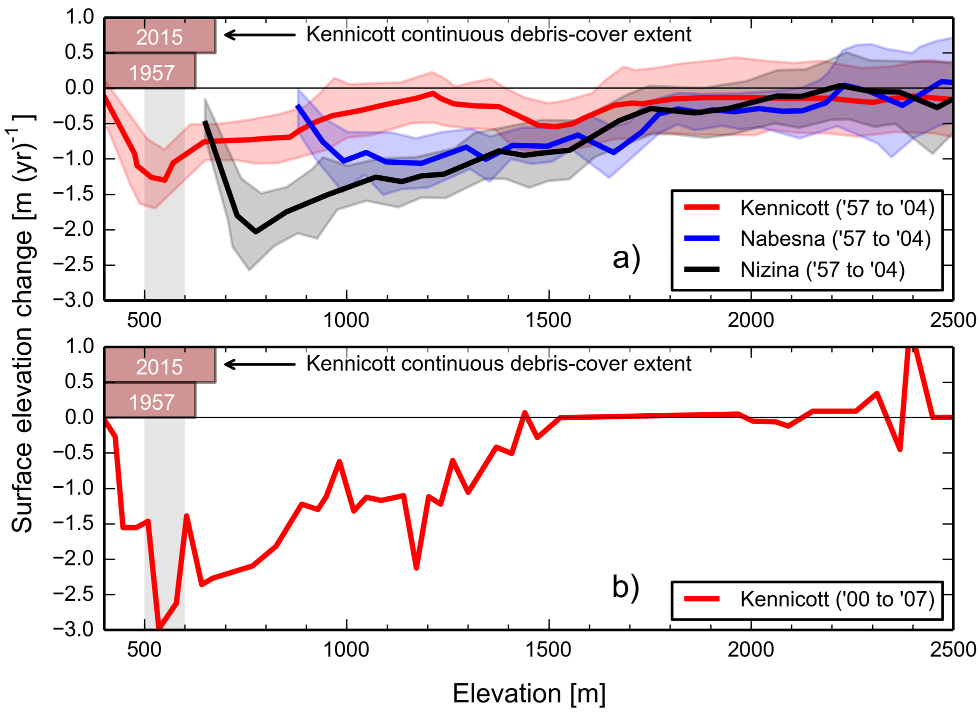


Figure 2. Surface elevation change from three glaciers in the Wrangell mountains. Surface elevation change data from Das et al. (2014). Elevations on the x-axis are derived from the 1957 digital elevation model (DEM). Take care in comparing these data to those presented in other figures as they are referenced to the 2013 glacier surface. a) Surface elevation change derived from the difference between DEMs. The shaded areas reflect the standard deviation of DEM differencing (see Das et al., 2014). The Kennicott Glacier is the only glacier in the figure with a continuous debris-cover spanning its entire width. The Nabesna and Nizina glaciers have individual medial moraines at the terminus but the majority of the glaciers' termini are debris-free. The vertical grey bar is the zone of maximum thinning corrected for elevation differences. The greatest change in glacier surface elevation occurs within the portion of the glacier where debris spans the glacier width continuously between 1957 and 2015 (shown as brown bars; see Supplemental Figure 26). The *ZMT* remains in a consistent location between 1957 and 2000 as well (Das et al., 2014). b) Surface elevation change derived from laser altimetry profiles differenced from a DEM from 2000 to 2007. See Das et al. (2014) for the laser altimetry path and a discussion of uncertainties.

Figures

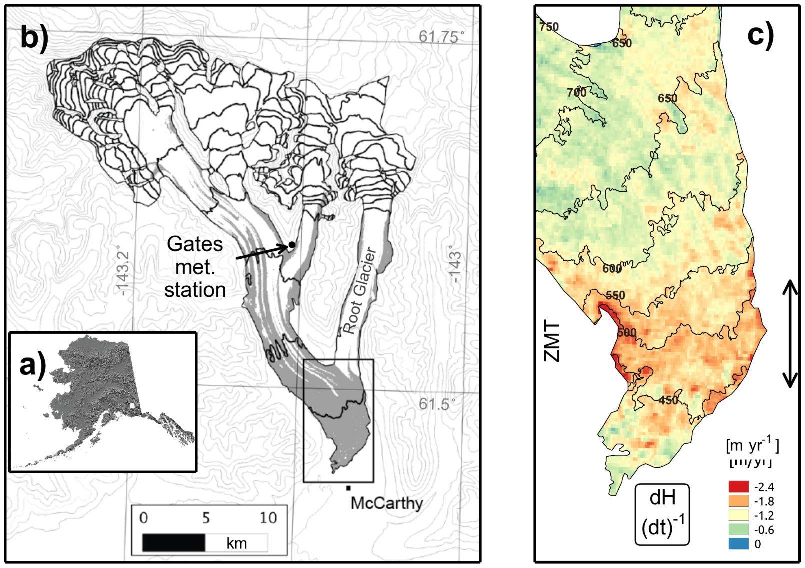


Figure 1. Map of Kennicott Glacier and the study area. a) Map of Alaska showing the location of panel b and the Wrangell Mountains. b) The Kennicott Glacier with the location of the Gates glacier meteorological station (1240 m a.s.l.). c) Map of the study area (24.2 km^2) with dH $(dt)^{-1}$ from 1957 to 2009 see Das et al. (2014) (mean error 0.04 m yr^{-1} and 1 std 0.15 m yr^{-1} based on 3 km^2 area within 4 km of the modern terminus). *ZMT* refers to the zone of maximum thinning, the extent of which is shown with the double-headed arrow.

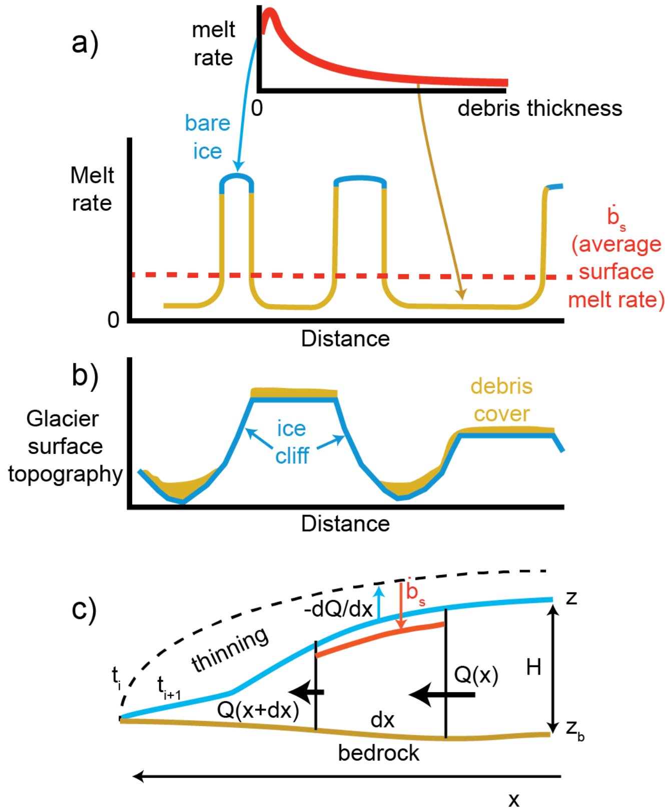
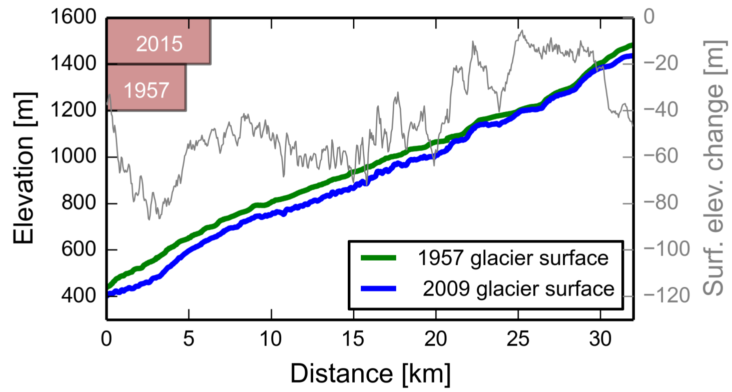


Figure 3. Schematic comparing the relative roles of ice cliff backwasting, sub-debris melt, and ice surface uplift (ice emergence rate) to the lowering of an idealized glacier terminus. a) Idealized relationship between ice cliff backwasting and sub-debris melt. Noting that the inclined facing and low albedo of ice cliffs can lead to melt rates that exceed bare-ice melt rates on a flat surface. b) Glacier surface topography with debris cover and ice cliffs compared to melt rates in panel a. c) Schematic showing the relationship between surface melt, ice dynamics, and the thinning of the glacier through time.

~~Figure 2. **Glacier surface elevation change between 1957 and 2009.** Surface elevation profiles from USGS DEM (1957) and the ASTER GDEM V2 (2009) along a swath profile following the centerline of the Kennicott Glacier. The greatest change in glacier surface elevation occurs within the portion of the glacier where debris spans the glacier width continuously between 1957 and 2009. Note the topographic bulge in the 2009 profile at the upper end of the zone of maximum thinning. Note the substantial thinning that has occurred upglacier from the continuous debris cover.~~



~~**Figure 3. Schematic comparing the relative roles of ice cliff backwasting, sub-debris melt, and ice surface uplift (ice emergence rate) to the lowering of an idealized Kennicott Glacier terminus.** a) Idealized relationship between ice cliff backwasting and sub-debris melt. Noting that the inclined facing and low albedo of ice cliffs can lead to melt rates that exceed bare ice melt rates on a flat surface. b) Glacier surface topography with debris cover and ice cliffs compared to melt rates in panel a. c) Schematic showing the relationship between surface melt, ice dynamics, and the thinning of the Kennicott Glacier through time.~~

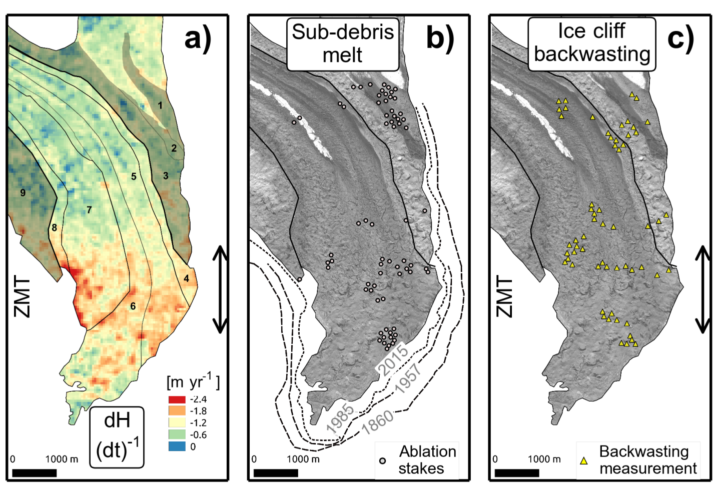


Figure 4. The study area with defined medial moraines and in situ measurement locations. This map of the study area includes the bare ice parts of Root Glacier, which are excluded and masked when making distributed melt estimates in which we use the area defined by the 9 medial moraines. a) dH (dt)$^{-1}$ from 1957 to 2004 see Das et al. (2014). Same thinning data as in Fig. 1C but with 9 distinct medial moraines defined and labeled. The shaded medial moraines are treated differently for distributed debris thickness estimates (see Section 2.3). Note that medial moraines # 4 through 8 contain the

majority of the zone of maximum thinning. Medial moraines # 3 and 9 show much thicker debris at the same elevation than the others (Supplementary Material). The labeled and delineated moraines define the extent of the area (24.2 km^2) used for the distributed melt estimates described below. The zone of maximum thinning (*ZMT*) is shown by the double-headed arrow. b) Sub-debris melt rate measurement locations. Debris was measured at all locations in panels b and c, in some cases ice cliffs and sub-debris measurements were proximal and only one debris thickness measurement was made between them. The five central medial moraines are within the two black lines, within which 69% of debris thickness measurements were made. c) Locations where ice cliff backwasting was measured.

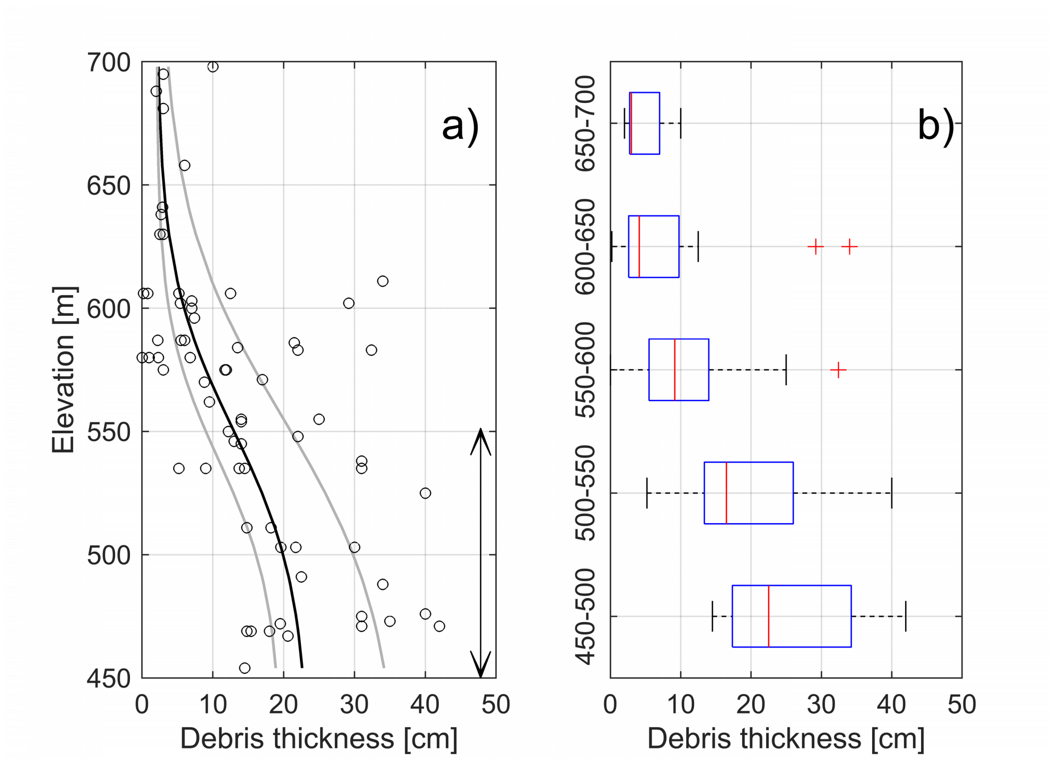


Figure 5. Debris thickness measurements for the five central medial moraines. a) Debris thickness measurements as they vary with elevation. The points plotted are the mean measured debris thicknesses with symmetrical uncertainties around them. The mean uncertainty of the debris thickness measurements is ±0.3 cm, with a standard deviation of ±1.8 cm, and a maximum error of ±6.7 cm. Error estimates were based on repeated measurements. With curve-fits through the median debris thickness (bold line) and the 25 and 75% quartiles (grey lines) from 50-m elevation bins shown in b (see Table 1 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning. b) Box plots of debris thickness binned in 50-m elevation bands. The red bars the median and the vertical blue bars are the 25 and 75% quartiles respectively. Note the sigmoidal shape of debris thickness with elevation. See the supplementary material for curve fits applied to the other medial moraines as well as linear estimates of debris thickness with elevation.

~~**Figure 4. Data used to extract curve fits for the distributed melt estimate.** See Part A for a full description of the methods. a) Debris thickness as it varies with elevation. The grey line is the best fit polynomial. The dashed lines are based on best fit polynomials through the 25 and 50% elevation bins. The double-headed arrow represents the zone of maximum thinning (*ZMT*). b) Melt rate as it varies with debris thickness. More negative melt is the equivalent to larger magnitude melt. The solid line is~~

~~the curve-fit for the most likely ablation-debris thickness relationship. The dotted lines represent the error bounds used in the distributed estimate of melt. The axes are flipped so the orientation is consistent with other figures. e) Ice cliff backwasting rate as it varies with elevation. The solid grey line is the linear best-fit through the median of each 50 m elevation bin. The black line is the best-fit through all of the data. The dashed lines are linear fits through the 25% and 75% of each 50 m elevation bin (see Table 2 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning (*ZMT*).~~

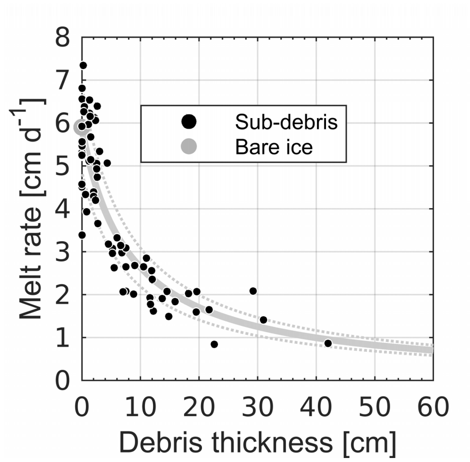


Figure 6. Sub-debris melt rate measurements. a) Melt rate as it varies with debris thickness. Sub-debris melt rates are corrected for the different measurement periods (Supplemental Materials). Individual melt rate measured error is smaller then the marker for each measurement, except one due to ablation pole tilt (Supplemental material). The solid line is the curve-fit using the hyper-fit model for the most likely debris thickness-melt relationship (RMSE to the data is 0.8 cm). The dotted lines represent the ±1σ error bounds used in the distributed melt estimates.

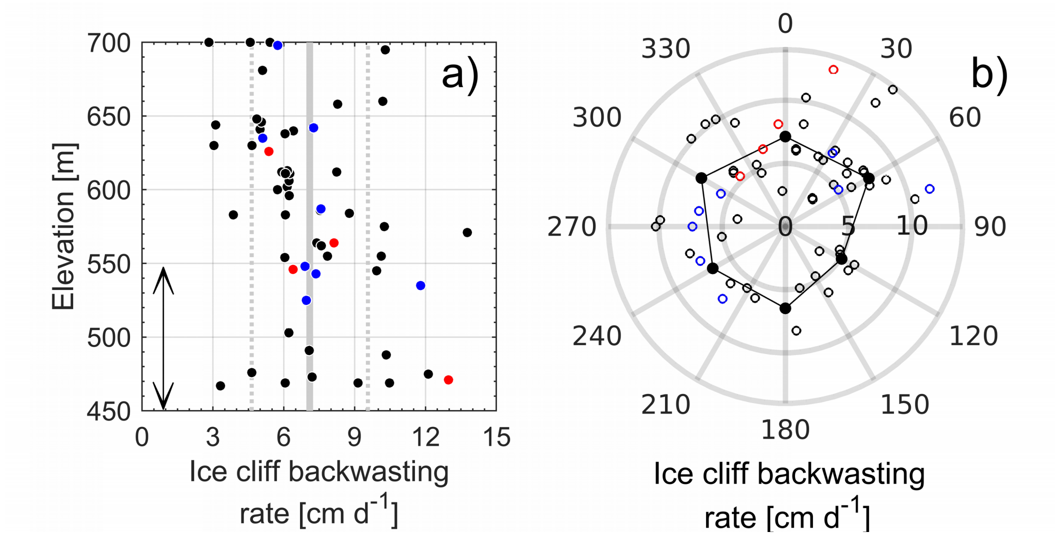


Figure 7. Ice cliff backwasting rate measurements. Ice cliff backwasting rates are corrected for the different measurement periods (Supplemental Materials). Cliffs with streams at their base are blue. Cliffs with ponds at their base are red. The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1}. Maximum error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval of all measured ice cliffs (a three week period). The standard deviation of ice cliff backwasting errors is ±0.2 cm d^{-1}. a) Ice cliff backwasting rate as it varies with elevation. The solid grey line is the mean of all data 7.1 cm d^{-1}. The dashed lines are ±1σ bounds used in the distributed melt calculations (see Table 1 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning (*ZMT*). b) Ice cliff backwasting rate as it varies with aspect. The solid black markers represent the mean backwasting rate from 60° bins. During the field survey, ice cliffs with ponds at their base were only found to face between 300 and 60 degrees (northward).

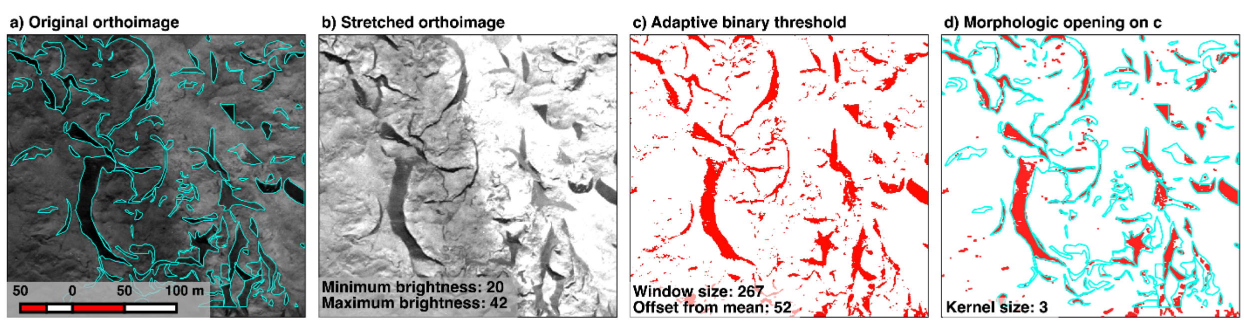


Figure 85. Ice cliff delineationdetection workflow for the adaptive binary threshold (*ABT*) method. The extent of this area is shown by the third cyan box from the right in Figure 9. a) Original orthoimage with manually digitized ice cliffs shown in cyan. b) Orthoimage after histogram stretch using a set of well-performing brightness values from the parameter optimization. c) *ABT* on stretched orthoimage. d) Morphologic opening on adaptive binary threshold to remove small isolated false positive ice cliff delineationsdetections. Manually digitized ice cliffs used as the validation dataset are again shown in cyan.

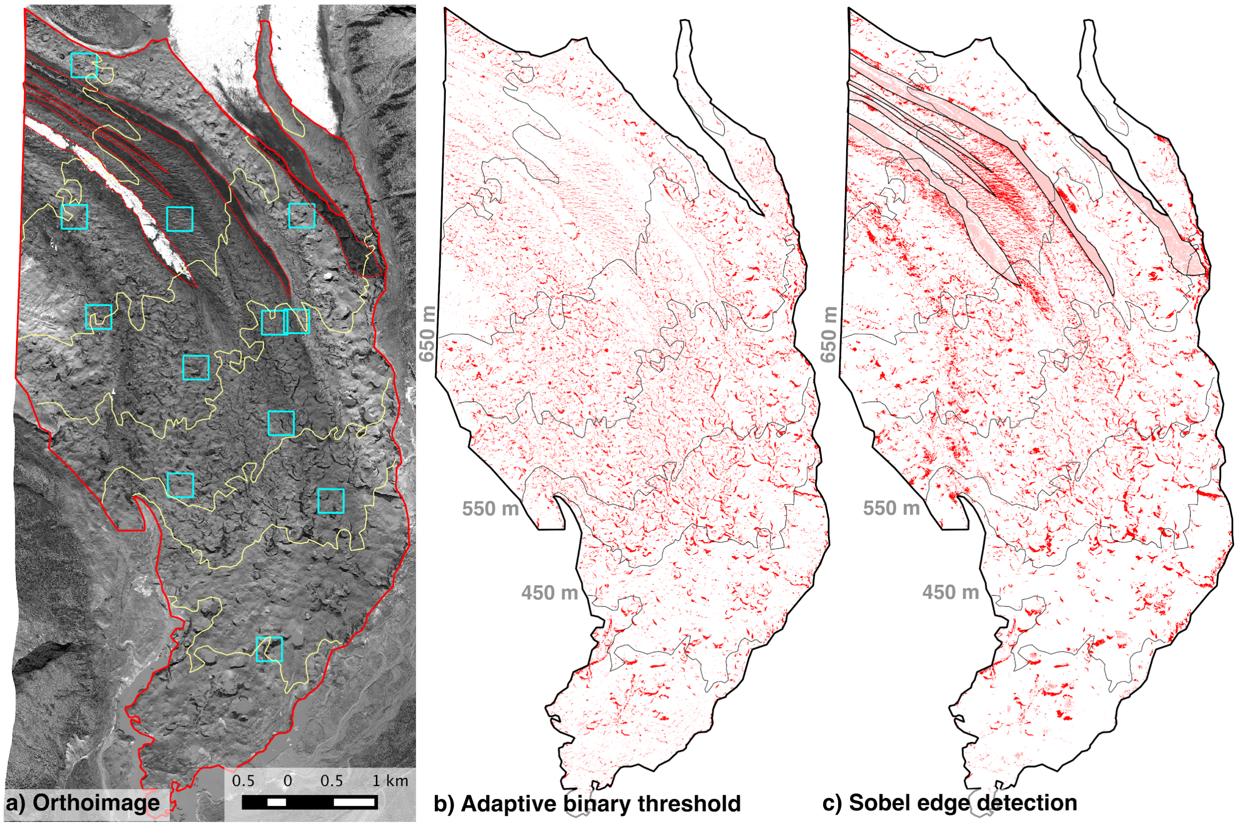


Figure 6. Results from the two ice cliff detection methods. a) Orthoimage of the terminus of Kennicott Glacier, with the debris-covered study area outlined by the thick red line. The thin red lines show regions of dark and light bare ice that required special treatment in the *SED* method. Thin yellow lines are elevation contours with a 50 m contour interval. Blue boxes show the locations of manually digitized ice cliff area, used for error analysis and parameter optimization. b) Ice cliff spatial distribution as estimated by the adaptive binary threshold (*ABT*) method, with overlaid elevation contours from 2013. c) Ice cliff spatial distribution as estimated by the Sobel edge detection (*SED*) method, with overlaid elevation contours from 2013.

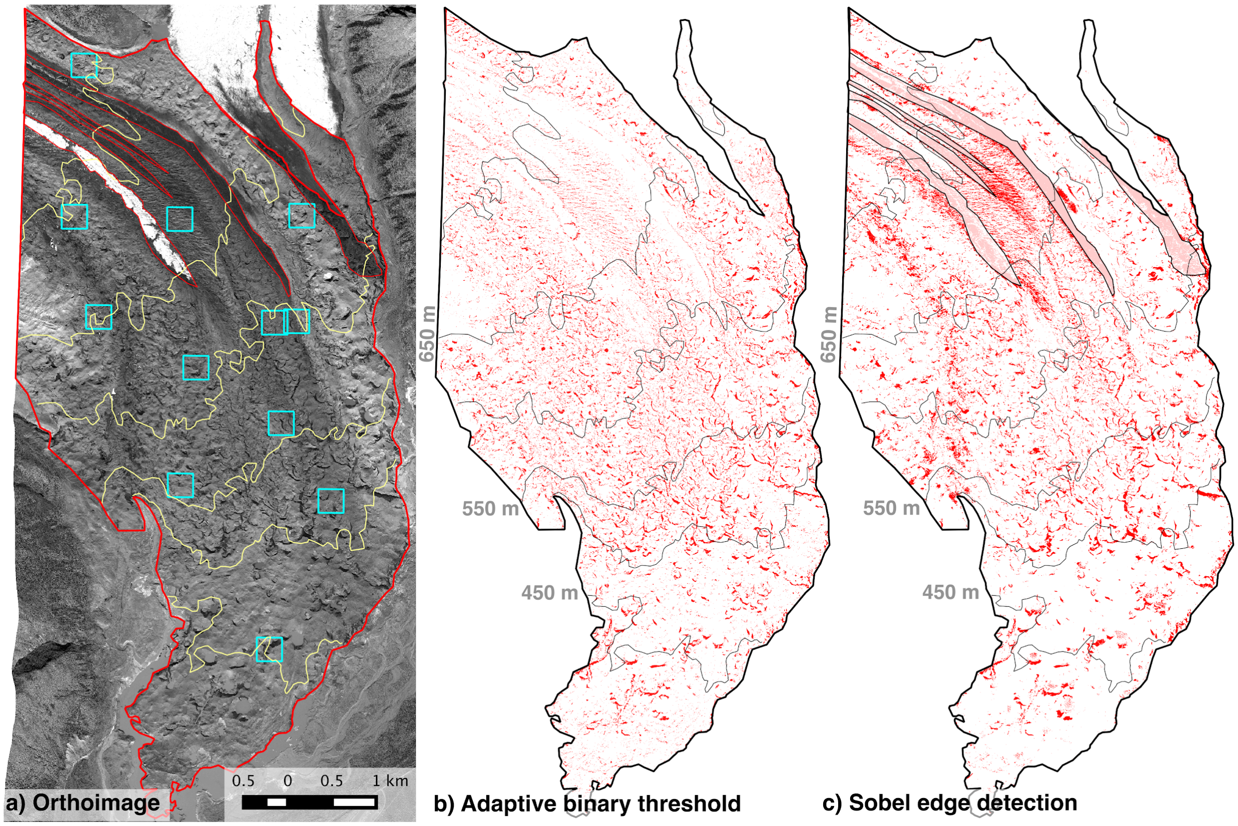
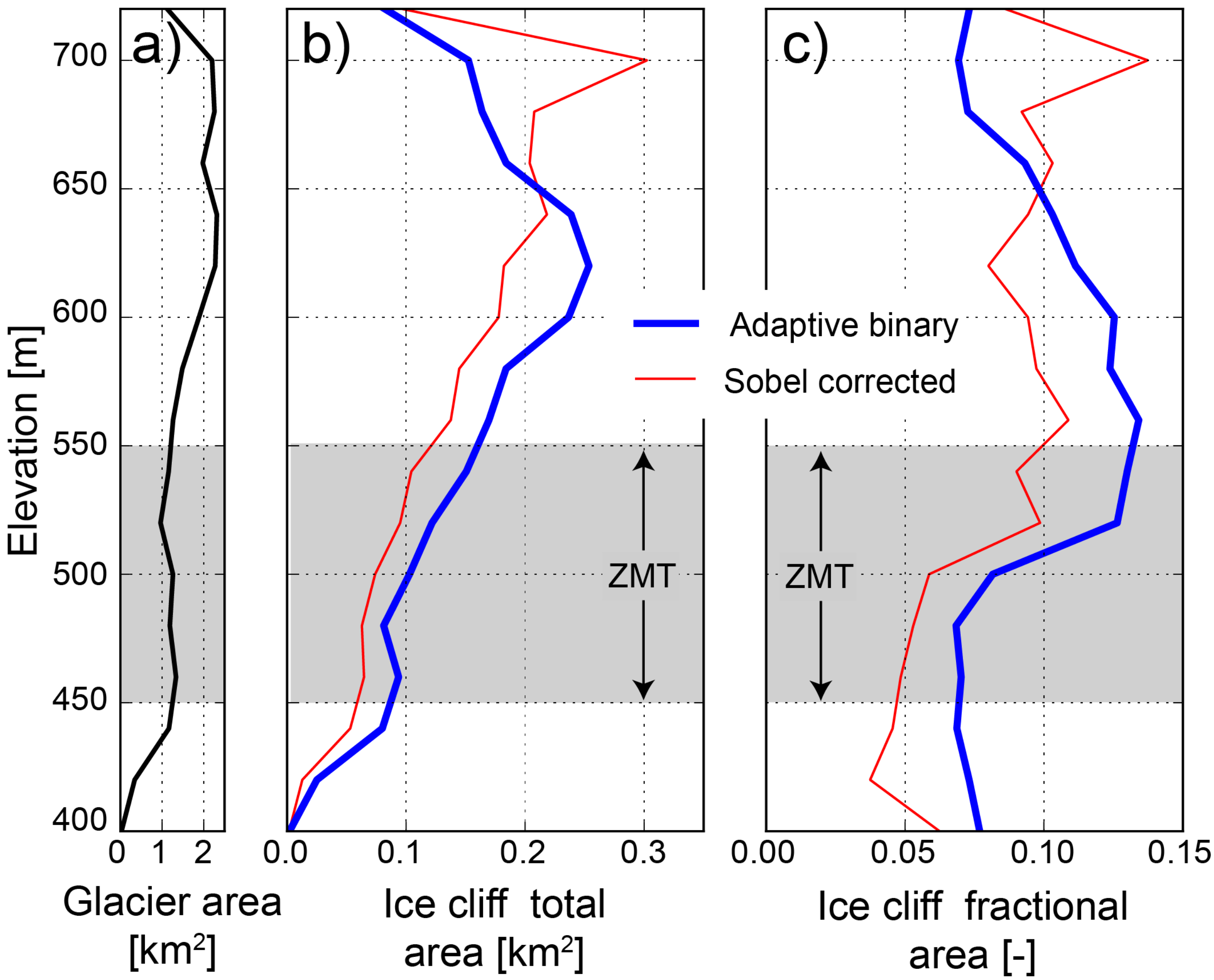
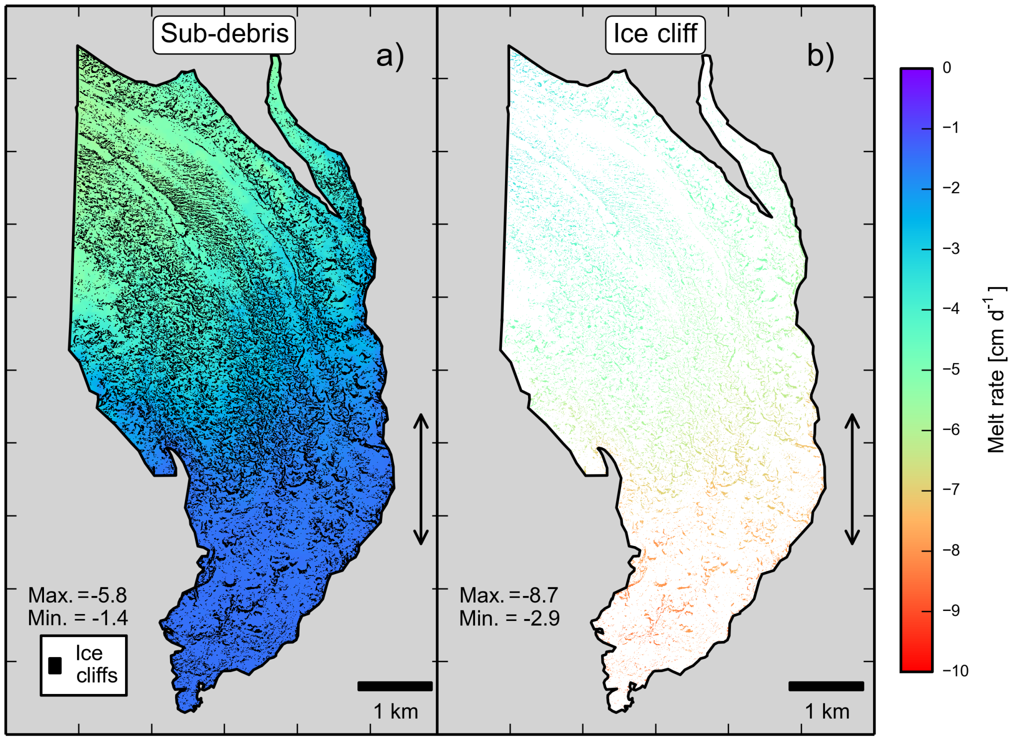


Figure 9. Results from the two ice cliff delineation methods. a) Orthoimage of the terminus of Kennicott Glacier, with the debris-covered area used for distributed melt estimates outlined by the thick red line. The thin red lines show regions of dark and light bare ice that required special treatment in the *SED* method. Thin yellow lines are elevation contours with a 50 m contour interval from 2013. Blue boxes show the locations of manually digitized ice cliff area, used for error analysis and parameter optimization. b) Ice cliff spatial distribution as estimated by the adaptive binary threshold (*ABT*) method, with overlaid elevation contours from 2013. The outline in panels a and b show the area used for distributed melt calculations. c) Ice cliff spatial distribution as estimated by the Sobel edge delineation (*SED*) method, with overlaid elevation contours from 2013.

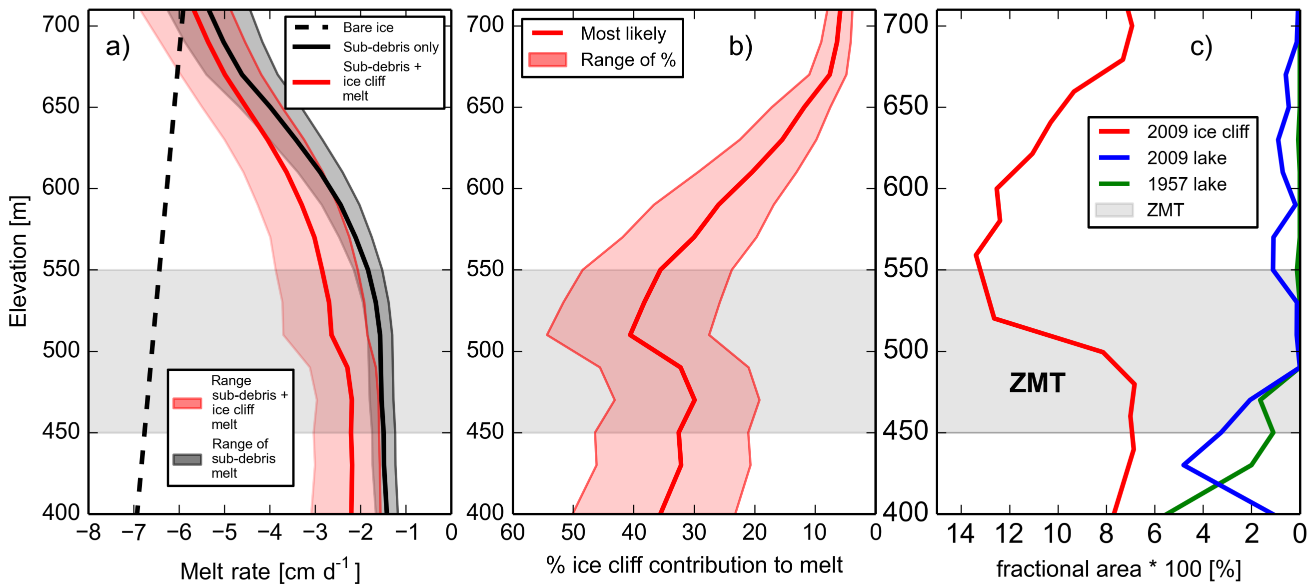
~~**Figure 7. Parameter optimization for a) adaptive binary threshold (*ABT*) and b) sobel edge detection (*SED*) ice cliff detection algorithms. On each plot, every point represents algorithm ice cliff detection error averaged across twelve manually digitized zones. The horizontal axes show true positives (i.e., automated and hand-digitized ice cliffs agree) and vertical axes show false positives (i.e., automated method predicts ice cliff where none exists). Perfect algorithm performance would plot on the origin. The coordinates for our chosen parameter sets provide an estimate of the error associated with the method. Note the differing axis limits on the horizontal and vertical axes. Markers are colored by Euclidean distance from the origin.**~~



1050 ~~**Figure 8. Results from the two ice cliff detection methods with elevation.** a) Glacier area as a function of elevation. b) Ice cliff area as a function of elevation. The red line shows results from the *SED* approach after false positives on dark colored ice are removed. c) Ice cliff area as a function of elevation, normalized by the glacier area within each elevation band.~~



~~**Figure 9. Extrapolated ablation based on elevation across the study area.** The more negative number the more the melt. The zone of maximum thinning (*ZMT*) is defined by the double-headed arrows in each panel. a) Most-likely sub-debris melt rate which decreases in magnitude downglacier. b) Most-likely ice cliff backwasting rate which increases in magnitude down glacier.~~



~~**Figure 10. Melt-related estimates with elevation.** Elevations are relative to the 2013 glacier surface. The zone of maximum thinning (*ZMT*) is represented by the grey bands for both panels. a) The elevation-band-averaged melt over the study period combining in situ measurements of ice cliff and sub-debris melt. The expected melt pattern primarily follows the shape of Østrem's curve. Bare-ice estimates are based on the near-surface air temperature lapse rate and melt factor for ice (Part A). The more negative the number the more the magnitude of melt. b) The percent contribution of ice cliffs to mass loss (sub-debris + ice cliff) with elevation. c) The fractional area of ice cliffs, and surface lakes. Note that the fractional area of ice cliff coverage maximizes and surface lake coverage minimizes in the upper portion of the ZMT (see Part C).~~

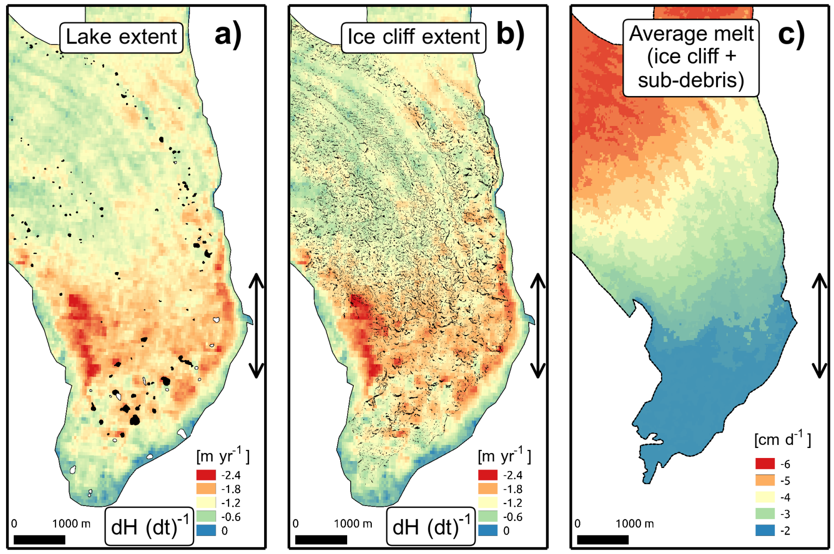


Figure 11. Comparison ice cliff and lake extent with the *ZMT* and estimated melt rates. a) Glacier surface lowering and surface lake extent. Observed surface lakes from the 1957 aerial photo are shown with white fill and black outlines. Observed surface lakes from 2009 from WV imagery are shown in black. b) Glacier surface lowering and 2009 ice cliff extent based on the *ABT* method. d) Elevation-band averaged melt due to ice cliffs and sub-debris melt from the summer of 2011.

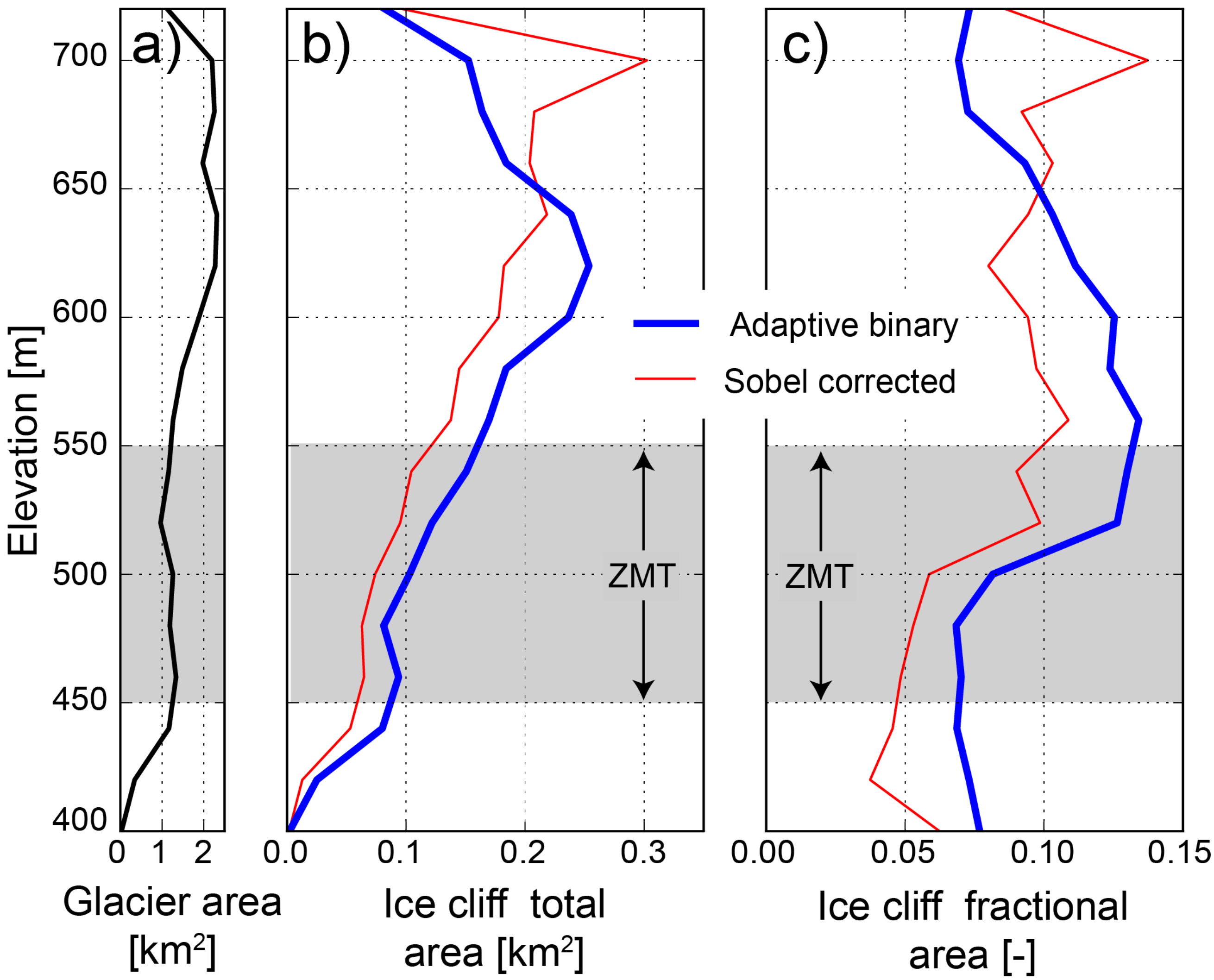


Figure 10. Results from the two ice cliff delineation methods with elevation. a) Glacier area as a function of elevation. b) Ice cliff area as a function of elevation. The red line shows results from the *SED* approach after false positives on dark colored ice are removed. c) Ice cliff area as a function of elevation, normalized by the glacier area within each elevation band. Note that fractional area * 100 is the percentage of ice cliff coverage.

~~**Figure 12. Aerial imagery of the study area from 1957, 1978, and 2009.** Imagery of the Kennicott Glacier from 1957, 1978, and 2009, showing changes in the glacier surface through time. The arrows show the zone of maximum thinning (*ZMT*) between 1957 and 2009. The *ZMT* has been continuously debris covered since at least 1957. a) Aerial photo from July 29 1957 (courtesy of the USGS). b) Aerial photo from 25 August 1978 (courtesy of the USGS). The darkening of the glacier surface on the western portion of the glacier in the 1978 image may represent an increase in ice cliffs or a change in illumination angle. c) WorldView image from 13 July 2009. Note the expansion of debris upglacier in time.~~

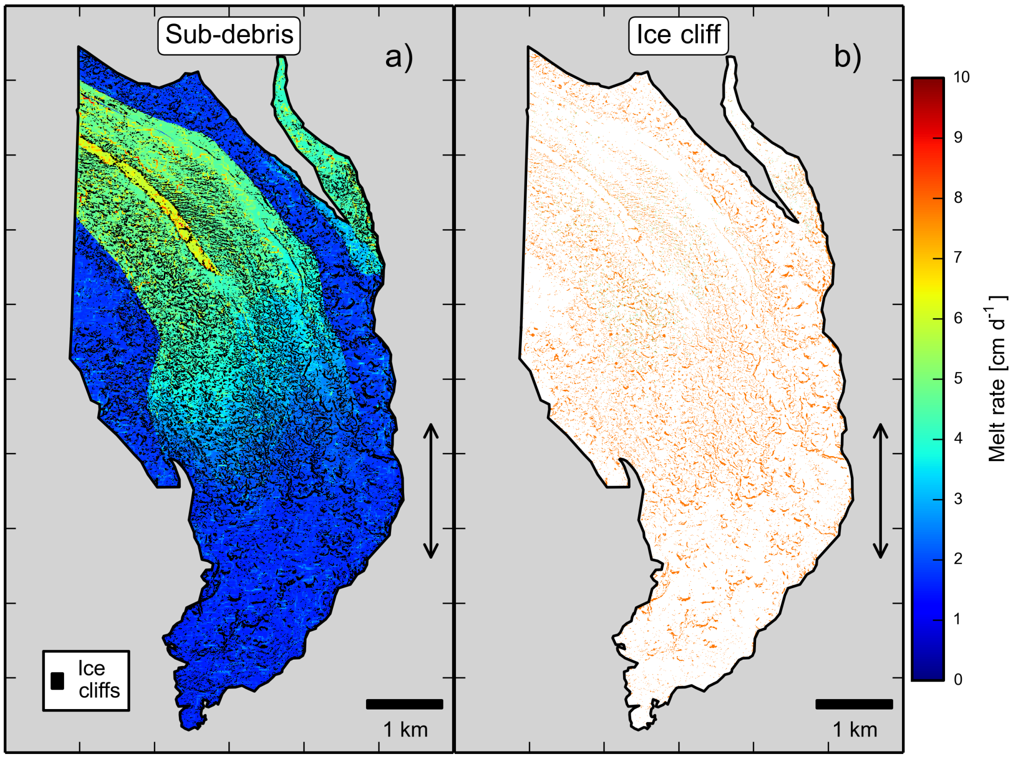


Figure 11. Distributed melt rates based on elevation and flow path (medial moraines). The zone of maximum thinning (*ZMT*) is defined by the double-headed arrows in each panel. a) Best sub-debris melt rate estimate which decreases in magnitude downglacier in the central part of the glacier. Medial moraines near the edge of Kennicott Glacier were composed of thicker debris. b) Most-likely ice cliff backwasting rate which we assume is uniformly distributed across the study area with a value of 7.1 cm d^{-1} (see Supplementary Material for the case of backwasting rate varying linearly with elevation). Note that no clear trends were present in ice cliff backwasting rate from medial moraine to medial moraine so the same backwasting-elevation relationship is applied across the study area (Supplementary Figure 9).

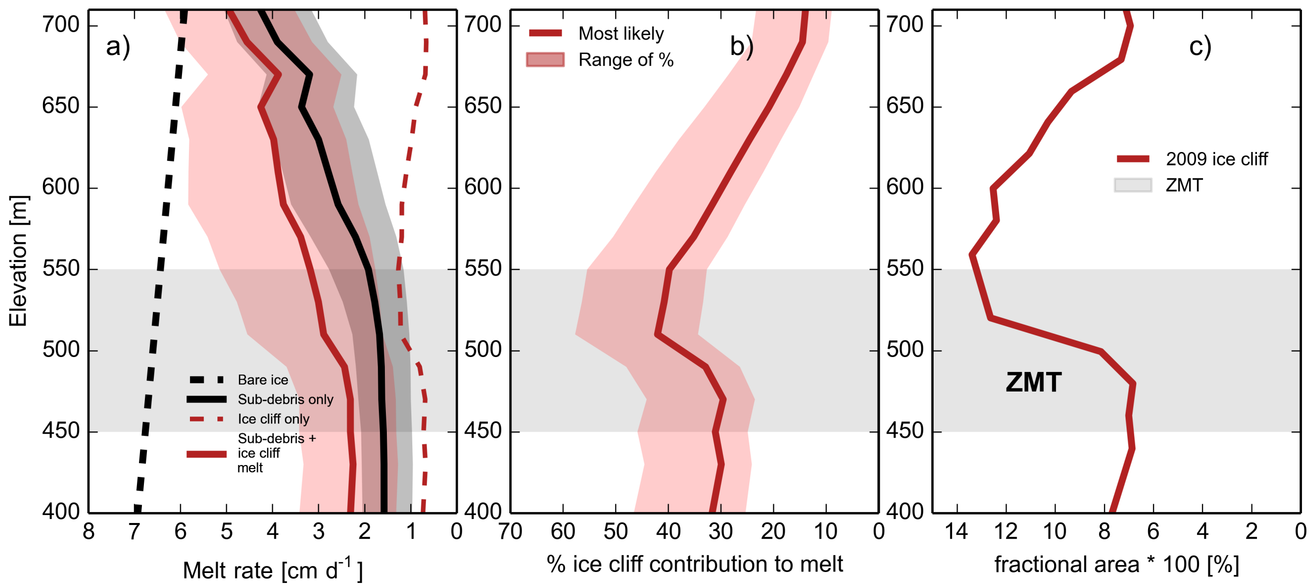


Figure 12. Distributed melt rate estimates with elevation. Elevations are relative to the 2013 glacier surface. The zone of maximum thinning (*ZMT*) is represented by the grey bands for all panels. a) The elevation-band-averaged melt over the study period combining in situ measurements of ice cliff, sub-debris melt, and debris thickness. The red bad contains an extreme range of sub-debris plus ice cliff melt based on compounding parameter choices such that 98.4 % of estimates lie within it (see section 2.3.1). 84.1% of estimate for sub-debris melt are within the grey shaded band. Four additional distributed melt rate scenarios are presented in the Supplementary Materials, and even with extreme parameter choices to increase melt rates, none of them maximize melt rates in the *ZMT*. Bare-ice estimates are based on the near-surface air temperature lapse rate from off-glacier meteorological stations and degree-day factor for bare-ice melt (Supplementary Materials). The decrease in sub-debris melt rate at 670 m a.s.l. is related to the increased area of medial moraine # 9 within the study area, which is covered with relatively thick debris. b) The fractional contribution of ice cliffs to the area-averaged melt rate (sub-debris + ice cliff) with elevation. The red band contains the extreme range of melt contributions from ice cliffs. c) The fractional area * 100% (percent) coverage of ice cliffs. Note that the fractional area of ice cliff coverage maximizes in the upper portion of the *ZMT*.