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Interactive comment on "Local topography increasingly influences the mass balance of a retreating cirque glacier" by Caitlyn Florentine et al.

Anonymous Referee #1
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Author responses in blue.

Review of Florentine et al. - Local topography increasingly influences the mass balance of a retreating cirque glacier (09/04/2018)

Overview ——— The authors present an analysis of the mass balance of a small mountain glacier in North America with respect to regional climatic trends and the influences of local topography. Using a combination of geodetic and glaciological approaches, the authors observe a small reduction of average mass loss in the glacier between three periods of time, namely 1950-1960, 1960-2005 and 2005-2014, despite being strongly distinct to regional mass balance estimates, based upon positive degree days and winter precipitation records since 1950. The paper is concise and very well written with a good amount of thought given to potential sources of error and uncertainty. The topic is relevant to the cryospheric community given the decreasing size of many mountain glaciers and the increased role of local factors on the glacier-wide mass balance. I believe the manuscript to be of sufficient quality and relevance for publication in The Cryosphere and think that the work should be published.

Nevertheless, I believe the authors need to address more the role of the local affects in promoting the slow down of mass loss for a glacier such as Sperry Glacier. The manuscript does well to highlight the assumptions of regional climate and the stark contrasts with the local mass balance, but needs to further highlight the role of local events and their spatial domain, so that such processes may be more readily compared with the observations of mass balance across the glacier. The authors present a nice case study of the glacier with a likely increase in the contribution from local factors, though I believe the information on local factors needs to be quantified more and presented more clearly for the reader on maps that can be interpreted. Various figures do not contribute enough the arguments of the manuscript and thus limits the conclusions that are drawn to some extent. The results presented on regional mass balance estimates vs. the geodetic changes imply that, although local topography/meteorological conditions is likely having a greater influence on mass balance, Sperry Glacier has, since 1950 at least, been decoupled from the regional climate.

One of the largest drawbacks of the paper is the lack of introduction and, importantly, discussion of the literature to contextualise the findings in the Glacier National Park. For a revision of this manuscript, I believe more needs to be added to compare Sperry Glacier with regional vs. local influences as published elsewhere in the world. I provide some suggestions of relevant research that could be included here and specific questions and comments that should be addressed before publication in the journal. I consider, on the whole, a minor revision, though would like to see some larger changes to the introduction, figures and discussion of the local effects on the glacier.

Thank you for the insightful comments and pointers to relevant literature. We have made many of the changes you recommended, namely to bolster the Introduction/Discussion and to revise Figures.

These revisions provide improved, more explicit explanation of the spatial domain and particularities of local topographic processes (avalanching, wind drifting, and shading) at Sperry Glacier. The revisions also provide stronger linkages to glacier mass balance studies elsewhere on Earth.

Abstract ——— P1.L17 ". . .closely predicts the geodetically measured mass loss from 2005-2014." Please quantify 'close'.
P1.L14 Edited to: "…closely (i.e. within 0.08 m w.e. yr^{-1}) predicts…"

P1.L18-20 Overestimates 1950-60 Mass balance – does this not imply that recent mass balance (2005-2014) can be better explained by regional climate? See later comment regarding interpretation of the results with respect to local vs. regional influences.
We write explicitly that recent mass balance (2005-2014) can be successfully explained by regional climate:

P1.L13 "A correlation of field-measured mass balance and regional climate variables closely (i.e. within 0.08 m w.e. yr^{-1}) predicts the geodetically measured mass loss from 2005-2014."

The overestimation implies that the way regional climate relates to recent mass balance (2005-2014) is different than the way regional climate relates to historic mass balance (1950-1960).

We unpack the meaning of this overestimation in the Discussion, using additional analyses. Since the overestimation itself does not implicate the increasing influence of local effects, we edited the word "This" on P1.L16, which referred to the liner regression overestimation, to "Our analysis," which refers to the analysis presented in the Discussion (please see the new, revised Figure 7).

Intro —— P1.L23 Yes, radiation inputs are dominant in summer for most glaciers, but I think it would be appropriate to rephrase this as radiation and air temperature driven (this can often be the case for coastal environments/ maritime glaciers where longwave and turbulent fluxes can sometimes dominate) – Also because you relate mass balance to PDDs in this paper (though the PDDs and shortwave radiation are, of course, well related).

P1.L20 Edited to "…ice mass losses are ultimately controlled by radiation *and air temperature* during summer."

P1.L27 What about Carturan et al. (2012) and the case of Italy's lowest elevation glacier, Montasio Occidentale? I think this should be included in your introduction. Also, what about the variability in meteorological conditions and energy balance processes for a small glacier such as shown by Hannah et al. (2000)? Some mention to the changing role of glacier energy balance would be good.
Sentences referring to this literature added:

P1.L25 "Analysis from Montasio Occidentale Glacier in the Italian Julian Alps demonstrated that avalanche-fed, shaded glaciers can exist at low elevations otherwise climatically unsuitable for the persistence of glacier ice (Carturan et al., 2013). Analysis from a network of on-ice automatic weather stations on a cirque glacier in the French Pyrenees concluded that topographic effects may exert more control on surface energy budgets - and thereby melt - than regional lapse rates in air temperature and moisture (Hannah et al., 2000)."

P2.L2-3 Hoffman 2007 found no trend with winter precipitation in the 20th Century. I think you should add more details about the glacier sizes during that study. Was there a decline in winter precipitation for their study? How else can you state the role of local processes in your following sentence?
P2.L2-3 "In Colorado, glacier mass balance at very small (<0.2 km^2) glaciers showed no statistically significant correlation to winter precipitation during the 20th century, suggesting that winter mass inputs were not connected to regional winter precipitation in a straightforward, linear manner (Hoffman et al., 2007). This result instead implied the importance of processes driven by local topography…"
In your manuscript, you are talking about increased sensitivity to regional climate for your earlier periods of observation (during 20th Century). How will Hoffman's findings compare to your results? I think this is something to be discussed later in your work.
We related Hoffman's findings to the Discussion (see now P13.L18)

P2.L8-10 I think a reference here would be suitable
P2.L8-10 (now P2.L11) Reference Haugen et al. (2010) added.

P2.L10-14 Again some more reflection on Hoffman's findings would be good for this introduction. Is Andrews Glacier facing south?
P2.L10-14 (now P2.L12) "Andrews Glacier, an east-facing <0.2 km^2 glacier in Colorado…"
Are the radiation loads or some other factor sufficient to explain why regional climate still outweighs the local influences? In addition, what about the controls of the atmospheric boundary layer adjustment for the retreat of a mountain glacier? For example, one could expect a diminishing katabatic boundary layer for fragmenting glaciers (see Carturan et al. 2015 - TC) and an increase in the sensitivity of the near-surface air to air temperature fluctuations outside the boundary layer (see Greuell and Böhm, 1998 and Shaw et al., 2017 – JoG).
Sentences added to reflect on the meaning of Hoffman's findings on Andrew's glacier:

P2.L10-14 (now P2.L15) "Mechanistically, this could be because Andrews Glacier is small enough to have a diminished katabatic boundary layer at its surface, leaving the glacier sensitive to ambient summer temperatures (Carturan et al., 2015). Regardless, this example shows that regional climate can remain the primary driver of net mass balance, even when local topography plays a strong role."

Study site ———– P2.L24 Please give coordinates centred on the glacier
P2.L24 (now P2.L27) Coordinates added.

P3.L3 Historical photographs from which year?
P3.L3 (now P3.L6) Edited to "Historical photographs and analysis from 1914 (Alden, 1914)…"

Methods ——— P3.L27 Can you provide more information about the area size and locations on 'stable' ground that was used for the co-registration. Was there presence of landslips/rockfalls that may account for some of the large vertical differences? Consider including a figure to the supplementary information.
P3.L27 (now P3.L31) Figure added to the supplement. Text edited to "over stable (i.e. not prone to landslide/rockfall)…bedrock (Fig.S1, Supplement)."

P4.L3 What aerial imagery?
P4.L3 (now P4.L7) Edited to "Worldview aerial imagery (Fig. 1b)…" now shown in Figure 1b. We had mistakenly omitted this image source.

P4.L11 Can you elaborate here why you decided to apply the Huss Approximation for glacier ice density and not use the values provide from the glacier itself in the case of Clark et al., 2017 with an error range?
P4.L11 (now P4.L15) The Clark et al. (2017) density was that reported by Cuffey and Patterson (2010), and was not from the glacier itself. We deleted this sentence as it added little value and confused.

P4.L25 How does the quantity of stable bedrock, to provide more certainty in elevation differences, vary with elevation in your study site?
P4.L25 (now P4.L23) "The quantity of stable bedrock points varied from 14,472 in the lowest elevation band to 1,825 points in the highest elevation band."

P5.L23 Can you also give a bit more detail about how this information was filled? You mean to say that (as with lines 26-27) that you used the 2014 generated DEM elevations for these areas that were missing? You state that the rate of mass change (1950-2014) is the same. . . but you mean to say there is no mass change, as you use the same DEM values? Or there is no DEM information for these years, but just a rate of change for 2005-2014 applied? Perhaps I am missing something clear with this paragraph, though perhaps you can state it more directly?

P5.L23 (now P5.L27) Edited to "By using modern elevation change rate results to infill missing historic data…"

Also, including the elevations that were missing from the 1950-60 photographs and a map of the missing areas with the supplementary information would be valuable for interpretation of your results, despite that you state the differences are small and within the error margins.

The missing upper section is shown in Figure 3 glacier maps (Fig.3a and Fig.3b).

P6.L10 Please provide further details on the calibration of the biases in raw mass balance data on Sperry Glacier here. Please plot the mass balance measurements (I assume stake data?) in the map of Figure 1b.

Stake locations added to Figure 1b. We added text and a supplementary methods section to provide further calibration details:

P6.L10 (now P6.L15) "…which utilized the 2005-2014 geodetic mass balance calculated in this study to correct the absolute magnitude of annual and summer glaciological balances without losing seasonal/annual variability (Zemp et al., 2013), are reported in Table 1. Such calibration ensures that systematic errors in the glaciological method are rectified and englacial and subglacial mass changes not measured at surface stakes are accounted. Details on this calibration are provided in the Supplement."

We also caught an error in our reporting, which led to corrections in Table 1.

P6.L15-16 A very minor point, but can SWE be considered a meteorological variable ('meteorological data')?

Astute point. Manuscript edited throughout to ensure SWE is referred to as climate data rather than meteorological data.

P6.L20-22 I do not argue with the use of Kalispell to represent PDDs for this analysis, though are there no other meteorological information within the greater area that may aid construction of ensemble PDDs for 'regional' climate? Is there any indication of local processes at Kalispell that may obscure the relationships you derive? Furthermore, are there any off-glacier meteorological observations in the basin of the study site that give indication to the representation of PDDs derived from Kalispell?

We have no indication that local processes at Kalispell would disrupt temperature profoundly or systematically enough to obscure the relationship we derived. In fact, our analysis showed that the similarity between lapse-corrected Kalispell temperatures and in-situ measurements from the Sperry Glacier met station was statistically significant:

P6.L20-22 (now P7.L4) "Comparison of lapse-rate-corrected temperatures derived from the Kalispell meteorological station with the 7 year record of in situ July, August, September temperatures measured at the Sperry Glacier meteorological station (Fig. 1b) yielded no statistically significant difference at the 99% confidence interval ($p<0.01$), and the distribution of residuals was normal."

Still, you make a fair point. Assuming that the Kalispell model is representative of regional climate conditions is a source of uncertainty, which we account for with the linear regression confidence intervals:

P6.L20-22 (now P8.L15) "…we used the upper and lower confidence intervals to compute maximum and minimum possible mass balances.…This accounting accommodated uncertainty due to (a) the discrepancy between snow and meteorological station locations and Sperry Glacier…"

We also added a figure to the Supplement and the following sentence to the text, which support our treatment of Kalispell-derived PDDs as definitive of regional conditions:

(now P6.L30) "Temperatures measured at Kalispell are highly representative of regional climate as reflected by gridded values from North American Regional Reanalysis output (Supplement, Fig. S3a)."

P6.L23 Partly related to the previous point, how did you 'vet' the Kalispell data record using the Sperry Glacier one? The application of an above-ice AWS would reveal not only a reduced average temperature compared to that outside the thermal influence of the glacier, but also a 'dampened' diurnal cycle (again see Carturan et al., 2015- TC).
We clarified our meaning:

P6.L23 (now P6.L29) "To assess the representativeness of the Kalispell temperature record relative to the glacier site, we compared this shorter, discontinuous record with the longer, continuous Kalispell record."

The glacier site AWS station is off-ice, which is now shown on Figure 1b.

P6.L26 Did you utilise only JJA to correct the temperature using the vertical temperature lapse rate? See above point. Where was the Sperry AWS? Plot also in Figure 1b.
Yes, we utilized JAS data to solve for the vertical lapse rate used to correct JAS temperatures. Sperry met station location added to Figure 1b.

P7.L11 State which observations specifically were used for this analysis.
P7.L11 (now P7.L28) "Based on an analysis of the historical snow data from the region against observations from Sperry Glacier, we chose to use Mount Allen snow data for our mass balance regression."

P8.L3 Is there evidence from the glaciological observations on Sperry Glacier to suggest that the melt season does not (in a 'typical year') begin earlier than July?
We now cite glaciological observations to justify our definition of melt season months as July, August, and September and report how JAS results.

P8.L3 (now P7.L8) "The Kalispell record reports continuous daily average air temperatures back to 1950 for the melt season summer months. We follow the convention defined by previous GNP melt modelling (Clark et al., 2017) and confine the Sperry Glacier melt season to July, August, and September. Glaciological observations suggest that although May and June can be warm enough to generate melt at Sperry Glacier, the deep snowpack is not necessarily warmed with pore space filled to saturation, and therefore melt does not necessarily run off the glacier."

P8.L10-12 I think the information on your assessment of the local processes (i.e. avalanching and snow drifts) are lacking in this section. Again, information about where observations from Clark et al. (2017) are in relation to the qualitative information used would be highly informative for the reader to comprehend the arguments about the increased role of local conditions/processes in governing the mass balance of Sperry Glacier.

We have improved illustration of local processes in now Figure 6.

Results ——– P9.L2-3 Is there any information on the development of debris-covered ice at the terminus of the glacier, which may enhance or diminish local melt rates?

P9.L2-2 (now P9.L23) "No development of debris cover at the glacier terminus that might explain this decreased thinning rate is evident."

P9.L26-27 Perhaps I miss something here, but 1950-60 and 2005-14 don't seem all that comparable in Table 3. Admittedly there are not huge differences. . . but still statistically significantly different, no?

Clarified our meaning:

P9.L26-27 (now P10.L25) "…average mass change rates at Sperry Glacier for 2005-2014 (-0.10 ± 0.03 m w.e. yr^{-1}) and 1950-1960 (-0.22 ± 0.12 m w.e. yr^{-1}) were comparable, i.e. within error bounds."

P10.L4-7 This is a nice evaluation of potential energy losses. Could you provide the values in Wm-2 as would be more typically reported for studies for glacier energy balance? Is the 0.36 m w.e. deficit for the whole glacier over the whole period?

Converted and clarified:

P10.L4-7 (now P11.L4) "…decreased by 118,605 kJ m^{-2} (approximately 15 W m^{-2})…"

Added phrase to clarify that the deficit was for the whole glacier over the whole period:

P10.L4-7 (now P11.L6) "…this energy deficit translates to 0.36 m w.e. m^{-2} less potential melt for the summer melt season averaged over the entire glacier…"

P10.L10-13 Can you indicate what evidence you have for wind effects on glacier mass balance? Evidence from Figure 8 show a potentially important source of local mass input, though your reported results here don't strongly support the information you have already presented. Figure 8 does very little alone to bring together your ideas as it does not contain information relating to the elevation ranges of the wind drift snow and thus,

the values of wind scour/accumulation effects in the following sentence suggest large spatial variations in mass balance, but do little more. Perhaps you could provide data on typical wind direction for the basin, based upon the Sperry Glacier AWS records. Do these tie in with more recent wind deposits apart from what was seen in the historic images? Is there a pattern here that might explain the mass balance trends which don't conform to a regional mass balance assumption? I think compiling a more useful figure with combinations from Figure 7 and 8 with a digitised map could be appropriate.
P10.L10-13 (now Figure 6) The new Figure 6 is annotated with more information about wind in the glacier basin.

Furthermore, could you provide information on the exposure of the Sperry Glacier by topographic information from your DEM? For example, the 'Sx' parameter following Winstral et al. (2002) could be appropriate for looking at the potential effects of wind on the initial deposition of snow in the winter mass balance and the re-distribution in summer. Is there anything to suggest these effects have changed through the decades, or just the reduction of glacier ice at lower elevations slowing the total glacier mass loss? A full-scale analysis would be beyond the scope of the paper, though I believe more is required here to argue to the case of local vs regional effects.
The lack of quantitative evidence for mass added to the glacier by wind drifting snow and avalanching indeed limits our argument. However, our task was to assess the time evolution of local influences in bulk. Quantifying and partitioning that evolution would be a logical next step, which we now outline in the Discussion:

(now P13.L7) *"Here we have examined the time evolution of local effects in bulk. To quantitatively partition the mass impact of discrete processes, future work could assess the evolution in geographic parameters for wind (e.g. Winstral et al., 2002) and avalanche (e.g. Carturan et al., 2013) effects."*

P10.L17-18 Again, this gradient really argues the case for avalanching of material, though information about the location of the observations would be both useful and interesting.
P10.L17-18 (now P11.L9-15) These results now refer to the new Figure 6, which conveys the location of avalanche observations.

Discussion ———— P10.L30 I think it could be argued, particularly based upon your results of Figure 6, that even since 1950, the small size and topographical characteristics of Sperry Glacier have limited its mass loss. A 'small glacier' is relative to whom you ask, though in my experience, 3.24km2 (the size of the glacier in the historical images) is small. The key aspect of this paper suggests that further retreat has increased the role of local topography. The evidence from geodetic change, which has been well assessed with regards to errors, would suggest that, indeed, the glacier mass loss has slowed despite conditions favouring its demise. Nevertheless, a point to make here is that, compared to what the regional trends in PDDs and winter accumulation would suggest, the glacier-wide mass balance of Sperry Glacier has since 1950 (and likely

further back in time) been somewhat decoupled from what the regional climate would prescribe. One may have to assess a much more historic form of the glacier, with much greater size, to identify a stronger relationship to regional climatic trends.
We agree, and edited a sentence that summarized this point so that it is not lost on the reader. Rather than conflating the fact that Sperry Glacier mass balance has been affected by local processes since 1950 with the fact that winter accumulation seems to be the more influential local process (that point is now separately discussed in the next paragraph), now the sentence simply reads:

P10.L30 (now P12.L28) "These results demonstrate that local mass balance processes have apparently played a strong role at Sperry Glacier since 1950, and that role strengthened as the glacier retreated."

P11.L8 Why is there a sudden steepening of the summer mass balance for the top of the glacier? Is there not just a lower mass balance record between the 2420 and 2550 values in Figure 9? What can explain this?
P11.L8 (now P11.L16) "Field-measured summer data at high elevations are sparse, but these summer point balances also show a sudden steepening of the summer mass balance gradient above 2475 m (Fig. 7c), likely because these high reaches of the glacier are shaded by the headwall."

P11.L10-17 I think I miss something with regards to the representation of information in this figure (10). The regional 'lapse rates' (a term I would consider changing to mass balance gradient) is that derived from Figure 5, I presume? However, for which periods of time are these mass balances shown, the complete period? Maybe the reflection of mass balance relating to glacier hypsometry needs some further clarification here.
Figures combined and edited to clarify. The revised Figure 7 is now annotated to describe how we applied field-measured local and regional mass balance gradients to 1950 and 2014 glacier hypsometry to parse local from regional mass balance effects.

P11.L19 79% of what, exactly? Is this evidence shown in Figure 10? To me, these contributions of summer and winter do not show such a strong difference as 79:21.. Again, please provide greater clarification to the reader.

Text and now Figure 7 edited to clarify:

P11.L19 (now P12.L31) "The impact of topographic effects is not evenly partitioned between seasonal components. The differences between the solid and dotted lines in Figure 7b and Figure 7d illustrate local effects: suppression of summer melt (light red area), surplus in winter accumulation (light blue area), and net mass balance enhancement (light gray area). We find that winter local effects (i.e. the surplus in winter accumulation due to avalanching and wind loading) account for 79% of the discrepancy between the mass balance defined by regional mass balance gradients alone versus that defined by both regional and local gradients. Summer local effects (i.e. the mediation in summer melt due to shading) accounted for 21% of the discrepancy."

P11.L26 The findings of Mattias Huss are highly relevant in this discussion, though I would like to see more of this discussion section related to the information which is in (and should be added to) the introduction. See comments on introduction section for suggestions on linking your discussion more with past work on small mountain glaciers.
Discussion bolstered accordingly, with literature presented in the Introduction added.
P11.L26 (now P13.L10) "Sperry Glacier's increasing sensitivity to local mass balance drivers is consistent with studies of 20th century glacier change elsewhere in the Rocky Mountains (DeBeer and Sharp, 2009), and is commensurate with modeled projections of future changes to cirque glaciers in the Swiss Alps."

P13.L32 (now P13.L17) "…suggests that local mass balance drivers do not interrupt the synchronicity of glacier response to climate change on global, century-long scales. Indeed, very small (<0.2 km^2) glaciers in Colorado showed a strong annual mass balance response to 20th century summer temperatures despite being heavily influenced by winter topographic effects (Hoffman et al., 2007). Thus, the evolving relationship between climate and mass balance demonstrated by Sperry Glacier reveals the complexity in interpreting glacier changes in Glacier National Park and at small cirque glaciers elsewhere on Earth, but does not preclude the reality of a climate that is trending toward conditions that mandate glacier disappearance.

Figures ——– Generally, the figures are well presented and clear. I have a few suggestions about combining figures and using others to a greater effect:

Figure 1b should display the locations of the mass balance observations for reference of the reader.
Figure 1b: Done.

Figure 2 could be combined with Figure 1 and set as a larger typeset figure for the article. The map information in both is relevant to the location of things in your study basin which can be referred to many times to aid your conclusions.
Figure 2: We chose to leave Figure 2 as a stand-alone figure, so as to maintain the non-square aspect ratio (width) and thereby include moraines on the edge of the photo.

Figure 3: Can you change the elevation interval averages and error bars (light green) to a different colour? Perhaps red?
Figure 3: Green changed to red.

Figure 4: I think there is perhaps a bit too much information contained within the caption which is sufficiently explained in the text.
Figure 4: Caption edited for brevity.

I think it could be useful to combine Figures 5 and 6 and stack them vertically as they

show similar information and time-series trends. The results of Figure 6 are clearly very strongly influenced by the winter precipitation in Figure 5 and combining these figures would aid interpretability.
Figure 5: Combined with Figure 6. We agree that this will aid reader interpretation.

As mentioned in the review, Figure 7 and Figure 8 provide some potentially useful information, though it is not used to great effect. Some information about the locations, elevations and extent of these observations (where possible) would be useful in comparison to the digitised glacier map of the same (or approx.) time period. This should be leveraged to explain some of the mass balance behaviour of Sperry Glacier in your study. As suggested previously, some information about the consistency of wind drifts and/or wind scouring (and a better map of the location(s) could be useful). For example, how could we then treat these effects in future modelling efforts to better represent the future of small glaciers? Should we/could we at all?
Figure 7/8 (now Figure 6): Figures combined as recommended. Location and elevation information added.

Figure 9: I think this figure is very important to the suggestion of localised processes, particularly during winter. However, it is not clear to me, the derivation of regional and local ‘lapse rates’ here. Again, I would suggest an alternative term for this too, perhaps mass balance gradient.
Figure 9 (now Figure 7): Language changed as advised.

Figure 10: Again, I think this a good and valuable figure to the paper. I’m not convinced that the text explains the information of the figure fully, or perhaps I miss something. Please try and make this clearer to the reader. For example, which are the gradients (here referred to as gradients) which are mapped onto the glacier hypsometry in these two years?
Figure 10 (now Figure 7): Figure annotated and text added to clarify.

Supplementary information ———————————- I’m not completely sure what Figure S2 is showing to support your work here and appears to only show a corrected result despite being intended to show a pre- and post-correction.
Figure S2: Agreed; the small change between pre- and post-correction is sufficiently communicated in the test. This supplement figure served no clear purpose and so has been removed.

Review to Florentine et al. (2018): *Local topography increasingly influences the mass balance of a retreating cirque glacier*, submitted to The Cryosphere.

Author responses in blue.

General

The authors present a study of glaciological and geodetic mass balance estimates from Sperry Glacier, a small cirque glacier in Glacier National Park, Montana, USA. Modelling of past surface mass balances applying a statistical model, which was calibrated with recent mass balance observations, yields a bias between the modelled surface mass balance and observed geodetic mass balances. The authors interpret this bias as an increased control of local climatic mass balance drivers and a decreased regional climatic influence.

The study is a decent example of the climate proxy potential of small glaciers and is therefore a valuable contribution to the journal. However, the key findings do not completely exclude alternative interpretations and thus, I'd like to address three concerns, which may sum up to a major revision.

We appreciate your resolute comments and have revised the manuscript accordingly.

1. Quality of SWE data (section 3.5.1): Mount Allen SWE measurements serve as input to the regression model. Hence the data quality is decisive for interpreting model results. From visual analysis Figure 5b suggests a step change of peak SWE on Mount Allen in the mid 1970s. Does this change also appear in the other SWE observations listed in Table S3 or is it a local effect or an inhomogeneity of the data series?

The mid 1970s step change appears in other SWE observations. We have defended the quality of SWE data by adding text, a supplementary figure, and references that speak to the regional consistency of this step change and its likely cause:

(now P10.L18) "The step change in peak SWE during the mid-1970s is consistent with other regional SWE records (Fig. S3b, Supplement), and has been interpreted as a result of a modal change in the Pacific decadal oscillation, a pattern of ocean climate variability which is closely tied to peak SWE in this region (McCabe and Dettinger, 2002; Pederson et al., 2011; Selkowitz et al., 2002)."

2. Kalispell air temperature data: Assuming one climate station in ~50 km distance to the glacier representing the regional climate needs more justification. How do the summer temperatures compare to e.g. the NCEP North American Regional Reanalysis (to the closest grid point to Sperry Glacier or to Kalispell climate station)?

To justify our assumption, we added analysis of North American Regional Reanalysis output:

(now P6.L30): "Temperatures measured at Kalispell are highly representative of regional climate as reflected by gridded values from North American Regional Reanalysis output (Supplement, Fig. S3a)."

Why is the ablation season confined to the summer months JAS? Degree-day approaches are based on the correlation of ablation to positive air temperature sums (parametrizing the available energy for melt) over the whole ablation season or even the whole year (e.g. Hock, 2003). How would the results of the mass balance regression change using air temperatures for the whole year or at least for the months MJJAS instead of JAS?
We added text to explain our confinement of the melt season to JAS, and describe the effect of instead considering MJJAS:

(now P7.L8) "We follow the convention defined by previous GNP melt modelling (Clark et al., 2017) and confine the Sperry Glacier melt season to July, August, and September. Glaciological observations suggest that although May and June can be warm enough to generate melt at Sperry Glacier, the deep snowpack is not necessarily warmed with pore space filled to saturation, and therefore melt does not necessarily run off the glacier."

(now P8.L19) "To test the sensitivity of our results to this assumption, we computed a summer linear regression using MJJAS PDD. Ultimately, the median difference between mass balance values produced by the MJJAS versus JAS regressions was 0.04 m w.e. yr^{-1}."

3. Discussion of the mass balance regression and the interpretation of the increase of local topography to the mass balance: The regression model is based on two proportionality factors (ms, mw). The discussion implicitly presumes both factors constant over time, but this needs to be addressed more comprehensively.
This comment is rooted in a misunderstanding, which reflects shortcomings within the paper that we have addressed by making the following three edits:

(1) The assignment of time-constant proportionality factors is now more explicit and purposeful:

(now P8.L23) "The linear regression quantifies the 2005-2014 relationship between Sperry Glacier and regional climate, and is fixed with respect to this time. Yet we have hypothesized that this relationship changed as the glacier retreated. By fixing the proportionality factors m_s and m_w to the modern glacier-climate relationship, and then forcing this modern regression with historic climate data, we test our hypothesis that the glacier-climate relationship changed as the glacier retreated."

(now P9.L1) "Attributing the hypothesized change in the glacier-climate relationship to the increasing influence of local topographic effects requires inspection of topographically influenced processes at Sperry Glacier."

- Winter proportionality factors might be variable (Galos et al., 2017; Huss et al., 2008), causing random errors, but systematic errors due to changes in large and meso scale atmospheric flow patterns (Huss et al., 2010) will alter the mass balance regression and weaken the argument of the increasing influence local topography to the mass balance. Can the authors exclude systematic changes of mw?

(2) We clarified how systematic changes of winter precipitation are captured by the snow data used as input to the linear regression:

(now P7.L24) "The 1950-2014 period is long enough to encompass meso-scale changes in atmospheric flow patterns, which elsewhere have been shown to have an important impact on winter accumulation and glacier mass balance (e.g. Huss et al., 2010). The peak SWE data we analyzed have been shown to reflect such meso-scale, decadal shifts in snow (McCabe and Dettinger, 2002; Pederson et al., 2011; Selkowitz et al., 2002)."

- Degree-day factors (i.e. the summer proportionality factor) are not constant over time, if the glacier surface area is largely changing. The major reason for this systematic change of the degree-day factor is the albedo feedback (e.g. Naegeli and Huss, 2017). An approximation to this feedback is the change of accumulation area ratio (AAR). Results of the geodetic survey show a thickening of the accumulation area and a concurrent glacier retreat, which means that the accumulation area remained rather constant, while the glacier lost wide parts of its ablation area. Hence, in relation to the total glacier area the AAR increased, resulting in higher mean albedo of the glacier and thus a lower degree-day factor. This effect would indeed strengthen the finding of the increasing influence local topography to the mass balance. (Interestingly, in all studies I'm aware of, the albedo feedback increases melt because the glaciers generally lose their accumulation areas due to rising equilibrium line altitudes.)

(3) We included this valid, strengthening point the Discussion:

(now P11.L30) "Glacier elevation changes reflect both surface mass balance and ice flow processes (Cuffey and Patterson, 2010). However, if we were to attribute geodetic results solely to surface mass balance, then our results (Fig. 3) suggest that the equilibrium line altitude remained relatively constant from 1950-2014 despite climate warming. Thus as Sperry Glacier retreated, its accumulation area ratio (Cogley et al., 2011) increased. With an increased fraction of the glacier remaining snow-covered throughout the melt season, the average glacier albedo increases (Naegeli and Huss, 2017). Such time changes in glacier albedo must have affected the summer proportionality factor, i.e. the amount of area averaged melt relative to regional summer temperature, which in part explains the discrepancy between the linear regression and the 1950-1960 mass balance (Fig.5c)."

Introduction

This chapter must more elaborate on the peculiarities and the definition of a small glacier, which in the manuscript seems to be synonymous to a cirque glacier and a very small glacier.
Introduction edited to define and related small glaciers to cirque glaciers:
(now P1.L21): "However, prior studies of small (i.e. <0.5 km2) mountain glaciers, which are often located in cirques…"
Whatever classification is used, the important message in this study is that the local topography has a high influence on the accumulation regime of the Sperry Glacier. In the last paragraph the authors describe briefly the areal change of Sperry Glacier and formulate their research question. At this point I suggest introducing the term accumulation area ratio (AAR) (Cogley et al., 2011) as it (i) presumably describes that the glacier lost its ablation area while the accumulation area almost remained constant and (ii) this fact is crucial to interpret the findings later in the manuscript.

We have added the accumulation area ratio topic to our Discussion, but opt not to include it in the Introduction, so as to keep the opening text streamlined and focused.

Methods

I suggest adding a paragraph that the two mass balance methods used (geodetic and glaciological) consider different processes of mass change (e.g. Klug et al., 2018; Zemp et al., 2013). In this study the differences will presumably be smaller than the given errors. The exclusion of methodological differences will support the discussion of the regression model later in the manuscript.

Text speaking to the different processes of mass change represented in the glaciological and geodetic mass balances added:

(now P6.L15): "The results of this calibration, which utilized the 2005-2014 geodetic mass balance calculated in this study to correct the absolute magnitude of annual and summer glaciological balances without losing seasonal/annual variability (Zemp et al., 2013), are reported in Table 1. Such calibration ensures that systematic errors in the glaciological method are rectified and englacial and subglacial mass changes not measured at surface stakes are accounted. Details on this calibration are provided in the Supplement."

In Eq. 1 the authors derive the geodetic mass balance based on the initial glacier area. By convention (Cogley et al., 2011), the mean area between initial and final state is used (Andreassen et al., 2016; Klug et al., 2018; Lang and Patzelt, 1971; Zemp et al., 2013 etc.), thus a recalculation of the geodetic mass balance is required.

Equation and text corrected on (now P4.L11).

We recalculated geodetic mass balances using the initial glacier area (A_{t1}) instead of the average glacier area (A), and the reported values did not change. An example for the 2005-2014 geodetic mass balance is provided here to illustrate:

$$\Delta B_a = \frac{\Delta V}{A}\left(\frac{\rho_i}{\rho_w}\right) - \frac{\Delta V}{A_{t1}}\left(\frac{\rho_i}{\rho_w}\right)$$

$$\Delta B_a = \frac{900{,}000\ m^3}{860{,}000\ m^2}(0.9) - \frac{900{,}000\ m^3}{830{,}000\ m^2}(0.9) = 0.03 \text{ m w.e.}$$

This difference, when expressed as an annual average over 2005-2014 (0.003 m yr^{-1}), is less than the uncertainty on the geodetic mass balance (0.03 m w.e. yr^{-1}) and therefore does not change the geodetic mass balance reported for 2005-2014 in Table 3 (-0.10 $\pm$ 0.03 m w.e. yr^{-1}).

Results

Section 4.3 supports the albedo feedback mentioned above.

The albedo feedback is now discussed on (now P12.L2-7)

Figures & Tables

Figure 1a: Explain HCN.

Done.

Figure 1b: Give exact date of the aerial image. Add the location of the mass balance stakes and the meteorological station.
Done.

Figure 4b: Indicate source of the peak SWE data.
Done.

Figure 6: Add the glaciological mass balance values.
Done.

Figure 10: Add labels a-d.

Figure S2: What is the added value of this Figure? The grey line is hardly visible.
Figure removed.

Figures 5, 6, S2: Figures do not depict continuous data as suggested by the x-axis. Use a bar chart instead of a line graph.
Discrete points on the line graphs convey that these are annual data, and we have added text to the new Figure 5 caption to clarify this point. (The new Figure 5 combines the original Figure 5 and Figure 6, and the original Figure S2 has now been omitted.)

Table 1: Add columns of ELA and AAR.
ELA does not follow an elevation band on Sperry Glacier. See snowline traced in Figure 1b. Thus we decided that listing the seasonal snowline (i.e. annual ELA) as a single elevation in this table would not be meaningful.

We added AAR reported by Clark et al. (2017) to Table 1.

Table 2 and S2: As glacier hypsometry is generally not normally distributed the median elevation is preferable to the mean elevation.
Median results are now reported in Table 2 and Table S1.

Table S3: Explain mw in the table capture.
Done.

Specific comments
P 1, L 15 and elsewhere in the manuscript: Are negative mass loss rates a mass gain? This is pedantic but I suggest using neutral formulations that do not compete with the sign of the corresponding value.
Fixed.

Glaciologists traditionally use m w.e. as mass balance unit. Let's convert to kg/m² (≡ mm w.e.), because this is the SI unit and outside the glaciological community nobody understands w.e.
We acknowledge this point, but opt to stick with the glaciological convention of m w.e. to make our work directly comparable with other glacier mass balance studies (Andreassen et al., 2016; Huss et al., 2009, 2010; Klug et al., 2018; Zemp et al., 2013).

P 2, L 20: relative to what?
Text edited from (now P2.L29): "We leverage relatively unique observations…" to "To test this hypothesis, we leverage field measured (glaciological) surface mass balance record and repeat geodetic mass balances."

P 6, L 26: The air temperature lapse rate must be a negative value.
Fixed.

P 6, L 27: Rephrase the sentence. 7 years ago is not recently.
Removed the words "recently installed."

P 7, L 1: Was the glacier surface on average 35 m lower in elevation or just the terminus?
Changed to (now P7.L13) "…the surface of Sperry Glacier was on average 35 m lower in elevation…"

P 7, L 4: Change the units to °C and maybe rephrase the last part to "..., and cumulatively -24°C and -14°C changes to PDD."
Done.

P 9, L 5+6: Replace million and billion by 106 and 109, respectively.
Done.

P 9, L 9: Link to Table 3?
Fixed.

P 9, L 28: Rephrase the sentence beginning with "Enough years are positive…"
Rephrased to (now P10.L28) "Sufficient individual years are positive during the mid-20th century to yield positive averages…"

P 10, L 4: Explain how you derived this number.
Radiation calculation method explained in section 3.6 Shading, avalanching, and wind-drifting (now P9.L1-9).

P 11, L 1: Explain the meaning of uniform mass balance gradients. Gradients in the ablation area are usually different from those in the accumulation area, mainly because of the higher albedo in the latter (Kaser et al., 1996; Kuhn et al., 1999).
Phrase removed as it did not accommodate the complexity you note, nor did it advance the purpose of the paragraph, which is to introduce the mass balance gradient at Sperry Glacier.

Table 2 and S2: As glacier hypsometry is generally not normally distributed the median elevation is preferable to the mean elevation.

Median results are now reported in Table 2 and Table S1.

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Zemp, M., Thibert, E., Huss, M., Stumm, D., Rolstad Denby, C., Nuth, C., et al. (2013). Reanalysing glacier mass balance measurement series. *Cryosphere* 7, 1227–1245. doi:10.5194/tc-7-1227-2013.

Local topography increasingly influences the mass balance of a retreating cirque glacier

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Abstract. Local topographically driven processes such as wind drifting, avalanching, and shading, are known to alter the relationship between the mass balance of small cirque glaciers and regional climate. Yet partitioning such local effects ~~apart~~ from regional climate influence has proven difficult, creating uncertainty in the climate representativeness of some glaciers. We address this problem for Sperry Glacier in Glacier National Park, USA using field-measured surface mass balance, geodetic constraints on mass balance, and regional climate data recorded at a network of meteorological and snow stations. Geodetically derived mass changes between 1950-1960, 1960-2005, and 2005-2014 document average mass ~~loss~~ change rates during each period at -0.22±0.12 m w.e. yr^{-1}, -0.18±0.05 m w.e. yr^{-1}, and -0.10±0.03 m w.e. yr^{-1}. A correlation of field-measured mass balance and regional climate variables closely (i.e. within 0.08 m w.e. yr^{-1}) predicts the geodetically measured mass loss from 2005-2014. However, this correlation overestimates glacier mass balance for 1950-1960 by +1.18±0.92 m w.e. yr^{-1}. ~~This~~ Our analysis suggests that local effects, not represented in regional climate variables, have become a more dominant driver of the net mass balance as the glacier lost 0.50 km^2 and retreated further into its cirque.

1 Introduction

Glaciers are sensitive indicators of climate (Dyurgerov and Meier, 2000; Roe et al., 2016) because ice mass gains are ultimately controlled by winter precipitation, and ice mass losses are ultimately controlled by radiation and air temperature ~~inputs~~ during summer. However, prior studies of small (i.e. <0.5 km^2) mountain glaciers, which are often located in cirques, show that local topographic effects, including avalanching, wind drifting, and shading, enhance winter mass gains or mediate summer mass losses (e.g. Hock, 2003; Kuhn, 1995; Laha et al., 2017). These topographically driven mass balance processes complicate the relationship between regional climate and cirque glacier surface mass balance.

Such complications have been documented in high relief areas worldwide. Analysis from Montasio Occidentale Glacier in the Italian Julian Alps demonstrated that avalanche-fed, shaded glaciers can exist at low elevations otherwise climatically unsuitable for the persistence of glacier ice (Carturan et al., 2013). Analysis from a network of on-ice automatic weather stations on a cirque glacier in the French Pyrenees concluded that topographic effects may exert more control on surface energy budgets - and thereby melt - than regional lapse rates in air temperature and moisture (Hannah et al., 2000). T~~t~~he small glaciers of the North American Rocky Mountains have also been shown to have a disrupted, complex relationship to regional climate. In Colorado, glacier mass balance at very small (<0.2-km^2) glaciers showed no statistically significant ~~relationship~~ correlation to ~~variations in~~ winter precipitation during the 20th century, suggesting that winter mass inputs were not connected to regional winter precipitation in a straightforward, ~~1:1~~linear manner (Hoffman et al., 2007). This result instead implied the importance of processes driven by local topography, including snow avalanching and wind drifting. In the Canadian Rockies, an inventory of nearly 2,000 glaciers showed that while larger glaciers retreated during the last half of the 20th century, very small glaciers did not change (DeBeer and Sharp, 2007). A follow-up analysis showed that the stability of these very small (<0.4 km^2) glaciers was closely related to their topographically favorable setting (DeBeer and Sharp, 2009).

~~Since~~ Because local topography can substantially influence the mass balance of small and sheltered mountain glaciers, it follows that as glaciers retreat further toward cirque headwalls, the direct control of regional climate on glacier mass balance should diminish, and local processes should become more influential (e.g. Haugen et al., 2010). That said, direct mass balance data from Andrews Glacier, an east-facing <0.2 km^2 glacier in Colorado, exhibited a strong correlation (r = -0.93) between summer temperature and net annual balance (Hoffman et al., 2007), despite enhanced accumulation via wind drifting and avalanching during the winter: ~~the~~ glacier mass losses during summer outweighed the extra snow provided by topographically driven snow redistribution. Mechanistically, this could be because Andrews Glacier is small enough to have a diminished katabatic boundary layer at its surface, leaving the glacier sensitive to ambient summer temperatures (Carturan et al., 2015). Regardless, this example shows that regional climate can remain the primary driver of net mass balance, even when local topography plays a strong role.

This paper examines the time evolution of the partitioning between regional climate and local influences on glacier mass balance of a glacier retreating into its cirque. Since 1966, Sperry Glacier, Montana has reduced in area by 40% and retreated 300 m ~~hundreds of meters~~ (Fagre et al., 2017). We hypothesize that during a recent interval (2005-2014), as a larger proportion of the glacier surface has become sheltered by its cirque headwall, the relationship between specific mass balance and regional climate is quantifiably distinct from that during mid-century (1950-1960), when the glacier extended further downslope from its cirque headwall. To test this hypothesis, we leverage field measured (glaciological) surface mass balance record and repeat geodetic mass balances.

2 Study area

Sperry Glacier (48.623° N, -113.758° W) sits just west of the Continental Divide, occupying a cirque that abuts the 2,801 m high Gunsight Peak, and is roughly in the center of Glacier National Park (GNP), Montana (Fig. 1a). A bedrock headwall, crested by a ridgeline that runs 2 km toward the northeast from Gunsight Peak (Fig. 1b), rises 100-300 m above Sperry Glacier (Fig. 2). This headwall is 0.17 km^2 in area, and has slopes between 50° to near vertical. A sub-ridge extends 500 m toward the north, bordering the glacier's western margin (Fig. 1b). Between the headwall and this sub-ridge, Sperry Glacier has a 40° ramp extending to the top of Gunsight Peak, so that some ice overlaps the ridge (Fig. 1b). A cornice that can be 10-20 m high develops every winter along this topmost section of the glacier (Fig. 2). A distinctive bergschrund separates the top 50-150 m of the glacier from the main ice body (Fig. 2). The terrain in front of Sperry Glacier is relatively low angle (<15°).

Moraines located 1 km from the ice terminus (Fig. 2) indicate that in the geologically recent past, the glacier covered most of a topographic bench now bare of ice. These moraines were likely deposited when the glacier was at its Little Ice Age maximum extent (Carrara, 1989)(Carrara, 1989). Historical photographs from 1914 (Alden, 1914) show ice once covered 3.24 km^2. Since that time Sperry Glacier has steadily retreated, decreasing in area to 1.58 km^2 in 1938 (Johnson, 1980), and to 0.80 km^2 in 2015 (Fagre et al., 2017).

3 Methods

3.1 Elevation data

Modern Digital Elevation Models (DEMs) of Sperry Glacier and adjacent terrain were derived from National Technical Means ~~(NTM)~~ imagery collected in 2005 and DigitalGlobe Worldview imagery collected in 2014 (Fahey, 2014)~~(Fahey, 2014)~~. Both images were collected in September, when glacier mass is at an assumed annual minimum, on 02 September 2005 and 07 September 2014 respectively. The DEMs were generated with SOCET SET® software, which uses photogrammetric methods to extract terrain data from imagery (Zhang, 2006). Grid cell resolution was 5 m. The absolute accuracy of the DEM with respect to an independent vertical datum was 3.05 m in the horizontal and 7.54 m in the vertical. The precision of the DEM was 0.44 m and 0.47 m in the horizontal and vertical respectively.

U.S. Geological Survey (USGS) topographic maps at 6.1 m (20 ft) contour resolution were available for Sperry Glacier for 1950 and 1960 (Johnson, 1980). These maps were originally created using aerial photography and Kelsh plotter techniques, guided by 13 plane table bench marks. Both maps document elevation near the assumed September glacier mass minimum, on 01 September 1950 and 08 September 1960. We digitized these historic elevation data by first manually tracing scanned maps to produce digitized contours, and then interpolating digitized contours using a natural neighbor interpolation tool (ESRI, 2014; Sibson, 1981). Grid cell resolution was 5 m. We found that the historic elevation data from the original Johnson ~~(1950, 1960)~~ maps from 1950 and 1960 were 56 m lower than the modern vertical datum ~~(EGM96)~~ due to the authors' sea level datum assumption. We remedied this error by adding 56 m to the 1950 and 1960 DEMs.

3.2 Geodetic mass balance and DEM co-registration

The 1950 and 1960 DEMs did not require co-registration ~~since~~ because they were originally mapped using a common vertical datum and spatial reference frame. We co-registered the 2005 and 2014, and the 1960 and 2005, DEMs following universal co-registration methods outlined by Nuth and Kääb (2011). The method used a statistical approach that minimized vertical differences over stable (i.e. not prone to landslide/rockfall), vegetation-free, snow-free, and low-sloping (< 30^0) bedrock (Fig. S1, Supplement). After co-registration, the root mean squared error of elevation differences over stable bedrock improved from 8.43 m to 6.91 m for the 1960 and 2005 DEMs, and from 2.48 m to 2.01 m for the 2005 and 2014 DEMs. The mean of bedrock elevation differences after co-registration was effectively zero, i.e. < 10^{-15} m, but differences over individual pixels still ranged from -42 m to +83 m for the 1960 and 2005 DEMs and -15 to +14 m for the 2005 and 2014 DEMs (Fig. S2~~1~~, Supplement). These large differences tended to occur over steep terrain, and are included in our elevation error estimate.

Glacier margin data for 2005 and 2014, used to clip DEMs to glacier extent, were derived from aerial and satellite imagery (i.e. Fig. 1b) and ground-based GPS surveys of the glacier terminus. We defined 1950 and 1960 glacier margin data by digitally tracing the glacier from the same historic topographic maps by Johnson (1980).

We generated a record of geodetic mass balance for Sperry Glacier, given by

$$B_a = \frac{\Delta V}{A\ \cancel{A_{t1}}}\left(\frac{\rho_i}{\rho_w}\right), \tag{1}$$

where B_a is the specific surface mass balance expressed in meters of water equivalent, ΔV is the change in glacier volume (determined from DEM data described in Sect. 3.1), ρ_i is the density of ice, ρ_w is the density of water (1000 kg m^{-3}), and A $\cancel{A_{t1}}$ is the ~~initial~~ average of initial and final glacier area. To convert volume to mass, we adopted the approximation outlined by Huss (2013), and assigned ice density as ρ = 850 ± 60 kg m^{-3}. ~~Note that this differs somewhat from the 874 kg m^{-3} used for Sperry Glacier glaciological mass balance by Clark et al. (2017), but that this value falls within the uncertainty bounds of our assigned ice density of 850 ± 60 kg m^{-3}.~~

3.3 Geodetic mass balance assessment

There are three main sources of uncertainty in our geodetic mass balance calculation: elevation errors ~~which~~ that affect the volume calculation, density errors which affect the volume to density conversion, and map coverage errors ~~which~~ that affect the historic geodetic mass balance.

3.3.1 Elevation change uncertainty

After co-registering DEMs, elevation error on the geodetic mass balance was estimated by analyzing elevation differences over stable bedrock terrain. ~~Since~~ Because error tends to be greater over steep terrain at high elevations, we analyzed error by 50-m elevation band, rather than in bulk across the entire DEM. The quantity of stable bedrock points varied from 14,472 in the lowest elevation band to 1,825 points in the highest elevation band. We used standard error propagation, as applied in previous geodetic mass balance studies (Ruiz et al., 2017; Thomson et al., 2017), given by:

$$E\Delta h_i = \frac{\sigma_{dh}}{\sqrt{N_{eff}}}, \quad (2)$$

where $E\Delta h_i$ is the mean elevation error for a 50-m elevation band (i) that spans the glacier, σ_{dh} is the standard deviation of elevation differences over stable bedrock for the elevation band, and N_{eff} is the number of independent values within the elevation band. This in turn is given by:

$$N_{eff} = \frac{N_{tot} \cdot P}{2 \cdot d} \quad (3)$$

where N_{tot} is the total number of pixels (grid cells), P is pixel size, and d is the distance of spatial autocorrelation (100 m), estimated from variogram analysis. We then summed elevation error across the glacier surface, weighting the error by the ratio of the glacier surface covering that elevation band.

3.3.2 Density uncertainty

We followed the convention outlined by Huss (2013) and used a constant density of ρ_i= 850±60 kg m^{-3} to convert glacier volume change to mass, which was derived from a suite of empirical firn densification experiments, and is appropriate for geodetic mass balance calculations where the time intervals considered are longer than 5 years, the volume change is nonzero, and the mass balance gradient is stable. These conditions are satisfied for Sperry Glacier ~~since~~ because (a) geodetic mass balance periods are 10 years (1950-1960), 45 years (1960-2005), and 9 years (2005-2014) long, (b) glacier volume changes were nonzero, and (c) glaciological measurements show that mass balance gradients were relatively constant during 2005-2014, i.e. 0.004-0.019 m w.e. m^{-1} for winter and 0.003-0.011 m w.e. m^{-1} for summer (Clark et al., 2017). The ±60 kg m^{-3} density error amounted to <8% error on geodetic mass balances.

We assumed that elevation and density errors were independent, and therefore summed them quadratically to solve for the total error on the geodetic mass balance, given by:

$$E_t = \sqrt{E\Delta h^2 + E\rho^2} \quad (4)$$

where $\boldsymbol{E\Delta h}$ is elevation error, $\boldsymbol{E\rho}$ is density error, and $\boldsymbol{E_t}$ is the total error in m w.e. on the geodetic mass balance.

3.3.3 Map coverage errors

The historic maps used to derive 1950 and 1960 DEMs are missing the upper section of the glacier. Historic photos verify that in the mid-20th century Sperry Glacier extended to the top of Gunsight Peak, as it does today. To enable consistent geodetic mass balance calculation for the entirety of Sperry Glacier, we filled in elevation change over this missing section (Fig. 3) using modern 2005-2014 results. We opted for this remedy, rather than the alternative of truncating 2005-2014 data, in order to be consistent with glaciological data, which were generated for the entire glacier surface including the upper section. By using modern elevation change rate results to infill missing historic data, we assumed that the rate of mass change in that area near the cirque headwall was the same through the study interval (1950-2014). Given that we had no way to test the validity of this assumption, and to ensure it did not fundamentally alter geodetic mass balance results, we also computed results for the truncated glacier (Table S1, Supplement). The difference between the truncated and infilled geodetic mass balance was ≤0.04 m w.e. yr^{-1} for both 1950-1960 and 1960-2005 (Table S2, Supplement), which is less than the accounted geodetic mass balance error (0.05 m w.e. yr^{-1} for 1950-1960, 0.12 m w.e. yr^{-1} for 1960-2005) (see section 4.1). Infilling data for the missing upper section therefore does not alter geodetic mass balance results beyond the reported uncertainty bounds.

3.4 Glaciological mass balance

Sperry Glacier has been the focus of a ~~United States Geological Survey (~~USGS~~)~~ intensive glacier mass balance monitoring program since 2005. Therefore, glaciological mass balance measurements of seasonal mass gains and losses at Sperry Glacier are available from the year 2005 onward (Clark et al., 2017). We used these data, measured in the field according to standard mass balance protocols (Kaser et al., 2003; Ostrem and Brugman, 1991) to define specific, conventional (Cogley et al., 2011) winter and summer glacier mass balance from 2005-2014. We also analyzed point balance data collected along a longitudinal transect (stakes in Figure 1; data from Clark et al., 2017) to inspect mass balance gradients at Sperry Glacier. To correct for bias in the raw, specific ~~-~~glaciological balances reported by Clark et al. (2017), we performed calibration as outlined by Zemp et al. (2013). The results of this calibration, which utilized the 2005-2014 geodetic mass balance calculated in this study~~,which~~ to correct~~ed~~ the absolute magnitude of annual and summer glaciological balances without losing seasonal/annual variability (Zemp et al., 2013), are reported in Table 1. Such calibration ensures that systematic errors in the glaciological method are rectified and englacial and subglacial mass changes not measured at surface stakes are accounted. Details on this calibration are provided in the Supplement.

3.5 Mass balance and climate regressions

Employing annual glaciological measurements (Clark et al., 2017), we defined a functional relationship (i.e. linear regression) between 2005-2014 specific surface mass balance and regional climate. Regional climate was defined by

~~meteorological~~ data on winter peak snow water equivalent (SWE) and summer positive degree days (PDD). ~~Meteorological~~ Climate data from 2005-2014 were used to define the regressions, and ~~meteorological~~ climate data from 1950-2005 were used to apply the regressions back in time.

3.5.1 Meteorological and snow data

The Global Historical Climatology Network ~~(HCN)~~ provides historic temperature data for Kalispell, Montana located approximately 50 km southwest of Sperry Glacier. There are closer meteorological stations, but these had short and incomplete records. For example, average daily temperatures were recorded at Sperry Glacier for most (83%) summer days from 2005-2013 (Baker et al., 2018). To ~~vet~~ assess the representativeness of Kalispell temperature ~~record~~data relative to the glacier site, ~~We used~~ we compared this shorter, discontinuous record ~~to vet~~ with the longer, continuous Kalispell record. Temperatures measured at Kalispell are highly representative of regional climate as reflected by gridded values from North American Regional Reanalysis output (Supplement, Fig. S3). Kalispell is located at an elevation of 901 m, which is 1554 m lower than the average elevation across Sperry Glacier in 2005-2014. We therefore applied a lapse rate correction of -5.57 °C km^{-1}, calculated using 7 years of temperature measurements from a ~~recently installed~~ meteorological station at Sperry Glacier (Figure 1b), to correct for the elevation difference. Comparison of lapse-rate-corrected temperatures derived from the Kalispell ~~HCN~~ meteorological station with ~~this~~ the 7-~~-~~year record of in situ July, August, September temperatures measured at the Sperry Glacier meteorological station (Fig. 1b) yielded no statistically significant difference at the 99% confidence interval ($p<0.01$), and the distribution of residuals was normal.

The Kalispell record reports continuous daily average air temperatures back to 1950 for the melt season summer months. We follow the convention defined by previous GNP melt modelling (Clark et al., 2017) and confine the Sperry Glacier melt season to July, August, and September. Glaciological observations suggest that although May and June can be warm enough to generate melt at Sperry Glacier, the deep snowpack is not necessarily warmed with pore space filled to saturation, ~~saturated~~ripe and therefore melt does not necessarily run off the glacier.

Because the glacier terminus increased in elevation from 1950-2014, the surface of Sperry Glacier was on average 35 m lower in elevation during 1950-1960, and 21 m lower in elevation during 1960-2005. We accounted for these changes in elevation by adjusting the lapse rate correction accordingly for each time period. The effect of this accounting was small, resulting in -0.16°C and -0.12°C changes to average summer temperature, and cumulatively -24 °C day and -14 °C day changes to PDD. Ultimately, correcting for elevation changes at Sperry Glacier corresponded to cm-scale changes to the mass balance regression ~~(Fig. S2, Supplement).~~.

Data from the Natural Resources Conservation Service at five nearby snow course sites (Desert Mountain, 1707 m; Piegan Pass, 1676 m; Marias Pass, 1600 m; Mount Allen, 1737 m; and Mineral Creek, 1219 m) and one adjacent Snow Telemetry (SNOTEL) site (Flattop Mountain, 1921 m) provide SWE data for locations within a 50-~~-~~km radius of Sperry Glacier

(Fig.1a). Temperature data are also recorded at the Flattop Mountain site. SWE is recorded monthly at snow course sites, via manual measurement, whereas SWE is recorded daily at SNOTEL sites via transducer measurements from a snow pillow. The 1950-2014 period is long enough to encompass meso-scale changes in atmospheric flow patterns, which elsewhere have been shown to have an important impact on winter accumulation and glacier mass balance (e.g. Huss et al., 2010), The peak SWE data we analysed have been shown to reflect such meso-scale, decadal shifts in snow (McCabe and Dettinger, 2002; Pederson et al., 2011; Selkowitz et al., 2002).

Based on an analysis of the historical snow data from the region against observations from Sperry Glacier, we chose to use Mount Allen snow data for our mass balance regression.~~,~~ ~~and~~ We found high correlation coefficients ($r^2 \geq 0.939$) for each of the seven datasets analyzed (Table S3, Supplement). The highest correlation was with Flattop Mountain SNOTEL ($r^2 = 0.990$), but at this station consistent snow data only go back to 1970. The second highest correlation ($r^2 = 0.973$), for a snow record that started prior to 1950 and so encompassed the geodetic record, was Mount Allen. ~~We therefore used Mount Allen snow data for our mass balance regression.~~

3.5.2 Regression analysis

To quantify the glacier-climate relationship for 2005-2014, we fit a linear regression between 2005-2014 ~~meteorological~~ climate data (x: PDD, SWE) and glaciological mass balance (y: b_s, b_w) data. We forced the best-fit line through the origin so that zero PDD and zero SWE equated to zero melt and zero accumulation, respectively. The linear combination of the two seasonal linear equations was thus:

$$B_a = m_s\,(PDD) + m_w(SWE) \tag{5}$$

where B_a is the specific annual balance, m_s is the summer proportionality factor, m_w is the winter proportionality factor, PDD is summer positive degree days, i.e. the sum of the average temperatures of days above 0 °C during the melt season, and SWE is peak winter snow water equivalent. We solved for the proportionality factors using an ordinary least squares, one parameter linear regression.

The linear regression only provides a best estimate of the mass balance of Sperry Glacier. To discern how dependable this estimate was, we considered the 95% confidence interval on each seasonal linear regression. Knowing that the true proportionality factor (i.e. slope of the best fit line) fell somewhere within the upper and lower bounds, we used the upper and lower confidence intervals to compute maximum and minimum possible mass balances. This accounting accommodated uncertainty due to (a) the discrepancy between snow and meteorological station locations and Sperry Glacier, (b) assuming that seasonal melt is largely driven by net available shortwave radiation and that PDD is a reasonable proxy for this, and (c) assuming that the summer melt season is limited to July, August, and September (JAS). To test the sensitivity of our results to this last assumption, we computed a summer linear regression using May, June, July, August, September (MJJAS) PDD.

Ultimately, the median difference between mass balance values produced by the MJJAS versus JAS regressions was just 0.04 m w.e. yr $^{-1}$~~.~~

The linear regression quantifies the 2005-2014 relationship between Sperry Glacier and regional climate, and is fixed with respect to this time. Yet ~~in reality,~~ we have hypothesized that this relationship ~~likely~~ changed as the glacier retreated. By fixing the proportionality factors m_s and m_w to the modern (1950-2014) glacier-climate relationship, and then forcing this modern regression with historic climate data, we test our hypothesis that the glacier-climate relationship changed as the glacier retreated.

3.6 Shading, avalanching, and wind-drifting

Attributing the hypothesized change in the glacier-climate relationship to the increasing influence of local topographic effects requires inspection of topographically influenced processes at Sperry Glacier. To assess topographic shading, we used the Solar Area Radiation tool (ESRI, 2014) to calculate cumulative insolation received across Sperry Glacier during the melt season months of July, August, and September in 2014, when the glacier was smaller, steeper, and more shaded, versus 1950, when the glacier was larger, flatter, and less shaded. This hemispherical viewshed algorithm (Fu and Rich, 2002) calculated ~~insolation~~ radiation based on an upward-looking sky map for every grid cell within our 2014 DEM, the seasonal progression of the position of the sun relative to Earth, a fixed atmospheric transmissivity, topographic shading, latitude, elevation, slope, and aspect. To qualitatively assess avalanching and wind-drifting snow processes, we examined field observations, historic photographs, and field-measured mass balance data collected by Clark et al. (2017).

4 Results

4.1 Retreat, thinning, and negative mass balance

Sperry Glacier has decreased from 1.30 km^2 in 1950, to 1.23 km^2 in 1960, to 0.86 km^2 in 2005, to 0.80 km^2 in 2014 (Table 2~~1~~). During the mid-20th century the glacier extended onto relatively flat (<15° slope) bedrock terrain, therefore the lower portion of the glacier was relatively low angle. As a result, between 1950 and 2014, despite nearly 0.5 km of retreat, the glacier terminus only receded upward by 56 m in elevation. The loss of this northeast-oriented, low-sloping terminus resulted in a steepening of the glacier's average slope by ~~7~~ 9^0, and a rotation of the glacier's average aspect toward the north by ~~24~~ 11^0.

Elevation change across the glacier surface is generally similar in its spatial pattern, but not magnitude, during 1950-1960, 1960-2005, and 2005-2014 (Fig. 3a, c, e). Thinning occurred across the lower portion, but is most pronounced at the terminus. The upper elevations of the glacier thickened from 1960-2005 and 2005-2014, but at rates less than +1 m yr^{-1} (Fig. 3). The magnitude of thinning near the terminus is distinct for each period. ~~Terminal~~ Terminus thinning rates from 1950-

1960 were up to -2.5 m yr^{-1} (Fig. 3b), whereas ~~terminal~~ terminus thinning rates from 1960-2005 (Fig. 3d) and 2005-2014 (Fig. 3f) were smaller than -1.5 m yr^{-1}. No ~~change in~~development of debris cover at the glacier terminus that might explain this decreased thinning rate is evident. The magnitude of thickening was likewise distinct between periods, with 1950-1960 showing a bulge near the glacier's middle (approximately 2500 m), growing at nearly +1 m yr^{-1} (Fig. 3b).

Despite differences in the magnitude of elevation change, the hypsometry of the glacier remained similar in 1950, 1960, 2005, and 2014. Sperry Glacier lost 50 m of ice at the glacier terminus ~~-~~during the 1960-2005 interval which agrees with the average amount of thinning (52.4 m) reported for glaciers in the Canadian Rockies for the same period (Clarke et al., 2013). Commensurate with its area loss and thinning, the glacier also lost volume. Geodetic mass balance results show Sperry Glacier shrank by -3.33 $\times 10^6$ ~~*million*~~ m^3 from 1950-1960, -11.3 $\times 10^6$ ~~million~~ m^3 from 1960-2005, and -0.90 $\times 10^6$ ~~million~~ m^3 from 2005-2014. It lost -2.83 $\times 10^9$ ~~billion~~ kg of mass from 1950-1960, -9.68 $\times 10^9$ ~~billion~~ kg from 1960-2005, and -0.76 $\times 10^9$ ~~billion~~ kg from 2005-2014 (Table 1). The rate of mass ~~loss~~ change at Sperry Glacier was -0.22 ± 0.12 m w.e. yr^{-1} from 1950-1960, -0.18 ± 0.05 m w.e. yr^{-1} from 1960-2005, and -0.10 ± 0.03 m w.e. yr^{-1} from 2005-2014 (Table 3~~2~~). The glacier is near balance, but slightly losing mass.

4.2 Glacier-climate relationship

Linear regressions show strong ($r^2 > 0.97$), statistically significant ($p < 0.03$) correlation between ~~meteorological~~ climate and glaciological data (Fig. 4). The model therefore effectively defines a functional relationship between glacier mass balance and regional climate for 2005-2014. The regressions correlate warmer summers to more negative summer mass balance ($r^2 = 0.978$), and snowier winters to more positive winter mass balance ($r^2 = 0.973$). From the regression results, ~~T~~the proportionality factor for winter (m_w), which scales snow course data on peak SWE to winter glaciological measurements, is 2.99. The proportionality factor for summer (m_s), which scales meteorological data on PDD to summer glaciological measurements, is -0.004 m w.e. °C^{-1} · day^{-1}.

We used ~~meteorological~~ climate data time series data to apply the linear regression back in time to 1950 (Figure 5). Average PDD during 1950-1960 was 709 ± 53 °C ·day, which was virtually the same as average PDD during 1960-2005 (717 ± 86 °C · day). Summer PDD then showed a 41 °C · day increase to an average of 758 ± 75 °C · day during 2005-2014, although this increase was well within interannual variability. Snow data show that on average, SWE decreased from 1.31 ± 0.26 m w.e. in 1950-1960, to 1.08 ± 0.32 m w.e. in 1960-2005, to 0.95 ± 0.25 m w.e. in 2005-2014, although these step decreases are likewise within the range of interannual variability. The step change in peak SWE during the mid-1970s is consistent with other regional SWE records (Fig. S3, Supplement), and has been interpreted as a result of a modal change in the Pacific decadal oscillation, a pattern of ocean climate variability which is closely tied to peak SWE in this region (McCabe and Dettinger, 2002; Pederson et al., 2011; Selkowitz et al., 2002). Generally, PDD and SWE in 1950-1960 compared to 2005-2014 seem to differ. To quantitatively assess the difference, we performed simple t-tests. T-test results showed that the lower average SWE during 2005-2014 differed statistically from 1950-1960 SWE with ($p < 0.01$, $\alpha = 0.99$), and higher PDD ($p < 0.15$, $\alpha = 0.85$). This evidence supports the notion that 2005-2014 had relatively warm summers and dry winters compared to 1950-1960.

Nevertheless, geodetic results show that average mass change rates at Sperry Glacier for 2005-2014 (-0.10 ± 0.03 m w.e. yr^{-1}) and 1950-1960 (-0.22 ± 0.12 m w.e. yr^{-1}) were comparable, i.e. within error bounds, ~~,~~ ~~(Table 3),~~ ~~both showing mass loss rates at less than 0.25 m w.e. yr^{-1}~~. This differs drastically from mass balance results derived from the regression, which include many years of net mass gain during the mid-20th century (Fig. 6). ~~Enough~~ Sufficient individual years are positive ~~that the~~during the mid-20th century to yield positive averages from 1950-1960 and 1960-2005 ~~are positive~~, at +0.98 ± 0.83 m w.e. yr^{-1} and +0.34 ± 0.75 m w.e. yr^{-1} respectively. However, confidence intervals from the linear regression model suggest the possibility of a negative average during 1960-2005. Conversely, error on the 1950-1960 mass balance include only positive averages, i.e. glacier thickening and mass gain. The 1950-1960 mass gain predicted by the regression (+0.98 ± 0.83 m w.e. yr^{-1}) is distinctly at odds with the 1950-1960 geodetic mass balance of -0.22 ± 0.12 m w.e. yr^{-1}.

4.3 Local controls on surface mass balance

The amount of potential clear sky radiation available for specific summer melt at Sperry Glacier decreased by 118,605 kJ m^{-2} (approximately ~~30%~~15 W m^{-2} ~~day^{-1}~~) from 1950-2014, likely due to steepening of the glacier surface, and a greater proportion of the glacier becoming shaded. Given the heat of fusion for ice (334 kJ m^{-2}), this energy deficit translates to 0.36 m w.e. less potential melt for the summer melt season averaged over the entire glacier, driven only by changes in the relative influence of local effects (i.e. shading, steepening), independent of climate. Field observations show that the rock headwall extending above Sperry Glacier (Fig. 2) contributes high frequency, low volume, loose avalanches (Fig. 7a), and that the cornice above the bergschrund often breaks in the spring, subsequently triggering localized slab avalanches ~~which~~ that extend~~s~~ 500 m down from the crest of the ridge to an elevation of 2460 m. (Fig. 7b). Historic aerial photographs show that a prominent ridge of wind-drifted snow consistently develops at lower elevations in the basin (Fig. 8). Field-measured mass balance data ~~also~~ showing highly variable snow accumulation provide evidence of wind effects ~~on accumulation in the winter is highly variable~~. Accumulation ranges from 0.00 m w.e. in wind scoured areas, where seasonal snowpack had been stripped down to bare ice, up to more than 5 m w.e. in wind loaded areas (Clark et al., 2017).

Field-measured point data (n=551), taken along stakes from the terminus toward the headwall of the glacier (Clark et al., 2017), show the impact of these local effects (shading, avalanching, wind drifting) on the mass balance elevation gradient (Fig. 9). Toward the glacier terminus, at elevations lower than 2475 m, the ~~lapse~~ mass balance gradient ~~rate~~ of winter accumulation is 10×10^{-4} m w.e. (m)$^{-1}$. Toward the glacier head, at elevations above 2475 m, the ~~lapse rate~~mass balance gradient of winter accumulation is an order of magnitude higher at 150×10^{-4} m w.e. (m)$^{-1}$. The elevation gradients shown by summer ablation measurements show a similar inflection (Fig. 6~~9~~). At elevations higher than 2475 m, where the glacier is steeper and more shaded, the melt ~~lapse~~ gradient rate increases eightfold from 6.6×10^{-4} m w.e. (m)$^{-1}$ to 53×10^{-4} m w.e. (m)$^{-1}$.

5 Discussion

Our results reveal that the drivers of mass balance at Sperry Glacier evolved as the glacier retreated. Specifically, the strong correlation between modern-era field and ~~geodetic mass balance~~climate data poorly predicts the 1950-1960 geodetically derived mass balance (Fig. 5c~~6~~) ~~suggesting~~ ~~points to~~and documents a change in the relationship between regional climate and rates of ice mass loss.

~~Viewed another way,~~ It seems that Sperry Glacier became less ~~sensitive to~~reflective of the regional climate as it retreated. G~~g~~eodetic results compared to regional climate data show that Sperry Glacier lost less area-averaged mass from 2005-2014 (-0.10 ± 0.03 m w.e. yr^{-1}) than from 1950-1960 (-0.22 ± 0.12 m w.e. yr^{-1}) despite the 2005-2014 period being characterized by warmer summers and lower precipitation winters. Glacier elevation changes reflect both surface mass balance and ice flow processes (Cuffey and Patterson, 2010). However, if we were to attribute geodetic results solely to surface mass balance, then our results (Fig. 3)~~eodetic results~~ suggest that the equilibrium line altitude remained relatively constant from 1950-2014 despite climate warming. Thus as Sperry Glacier retreated, its accumulation area ratio (Cogley et al., 2011) increased. With an increased fraction of the glacier remaining snow-covered throughout the melt season, average glacier albedo increases (Naegeli and Huss, 2017). Such time changes in glacier albedo must have affected the summer proportionality factor, i.e. the amount of area averaged melt relative to regional summer temperature, which in part explains the discrepancy between the linear regression and the 1950-1960 mass balance (Fig.5c).

We had hypothesized that the discrepancy between the regression and the historic mass balance would be attributable to avalanching, wind drifting, and shading becoming relatively more influential as the glacier retreated. Glaciological measurements provide direct evidence of these effects, as the mass balance gradient at Sperry Glacier has two distinct components reflecting regional and local drivers (Fig. 7c~~9~~). For example, the winter mass balance gradient at elevations below 2475 m, 10×10^{-4} m w.e. (m)$^{-1}$, falls within the range of regional SWE lapse rates, 6.2-10.4 $\times 10^{-4}$ m w.e. (m)$^{-1}$, reported in a study of snow accumulation in northwest Montana (Gillan et al., 2010). The stark increase (to 150×10^{-4} m w.e. (m)$^{-1}$) in winter mass balance gradient at higher elevations is consistent with enhanced snow accumulation reported for so-called "drift" glaciers located below the regional equilibrium line altitude in Colorado, where winter accumulation from local effects was four to eight times regional snow accumulation (Outcalt and MacPhail, 1965). Field-measured summer data at high elevations are sparse, but these summer point balances also show a sudden steepening of the summer mass balance gradient above 2475 m (Fig. 7), likely because these high reaches of the glacier are shaded by the headwall (Fig. 6~~9~~).

Our linear regression results fall short of elucidating what drove the change in the relationship between climate variables and Sperry Glacier. Therefore, we used these glaciological measurements (Fig.7c) in one final, complementary analysis ~~ran experiments~~ to assess the impact of the time-changing glacier hypsometry and the local and regional mass balance gradients on the glacier's total mass balance. We applied field-measured mass balance gradients to the hypsometry of Sperry Glacier in 2014 and 1950 (Fig. ~~10~~7a,b black bars), first using only the regional gradient (Fig. 7c dotted lines) and then using the regional plus local gradients (Fig. 7c solid lines). This demonstrates that without local effects, given the 1950 glacier hypsometry, specific surface mass balance would be -1.04 m w.e. Similarly, without local effects, given the 2014 glacier hypsometry, specific surface mass balance would be -0.96 m w.e. Thus, in theory, the hypothetical mass balance response of the 1950 and 2014 glaciers would be roughly similar when forced only by regionally determined ~~climate~~gradients. However, when the local mass balance gradients are applied, the balance for 1950 increased by 37% to -0.66 m w.e., and for 2014 by 57% to -0.41 m w.e. These results demonstrate that local mass balance processes~~, particularly relating to snow accumulation,~~ have apparently played a strong role at Sperry Glacier since 1950, and that role strengthened as the glacier retreated.

T~~t~~he ~~increase~~ impact of local topographic effects is not evenly partitioned between seasonal components.~~,~~ W~~w~~e find that ~~the~~ winter ~~local gradient~~ local effects (i.e. the surplus in winter accumulation due to avalanching and wind loading) account~~s~~ for 79% of the discrepancy between the mass balance defined by regional mass balance gradients alone versus that defined by both regional and local gradients, i.e. blue shaded area in Figure 7b,c ~~(Fig. 7b,c asterisks)~~. ~~and that~~ ~~the~~ S~~s~~ummer local ~~gradient~~ effects (i.e. the mediation in summer melt due to shading) ~~comprised~~ accounted for 21% of the discrepancy, i.e. red shaded area in Figure 7b,c. This ~~experiment~~ analysis supports the interpretation that the altered mass balance response we have documented, wherein the glacier had a less negative balance in 2005-2014 despite less favorable regional climate conditions, is driven by the increasing influence of local effects rather than just the changing glacier hypsometry. Here we have examined the time evolution of local ~~influences~~effects in bulk. To quantitatively partition the mass impact of discrete processes, future work could assess the evolution in geographic parameters for wind (e.g. Winstral et al., 2002) and avalanche (e.g. Carturan et al., 2013) effects.

Sperry Glacier's increasing sensitivity to local mass balance drivers is consistent with studies of 20th century glacier change elsewhere in the Rocky Mountains (DeBeer and Sharp, 2009), and is commensurate with modeled projections of future changes to cirque glaciers in the Swiss Alps. For example, although 25% of 1133 individual very small (<0.5 km^2) glaciers are projected to disappear as soon as the next 25 years, 67 glaciers (6%) are projected to maintain more than half of their area through at least 2050 (Huss and Fischer, 2016). The persistence of these select glaciers, which are located at lower elevation than the regional equilibrium line altitude~~ELA~~, signals the sometimes strong influence of local mass balance drivers. Despite local effects allowing some glaciers to persist for a few more decades, categorical evidence of world-wide glacier retreat in response to 20th century warming (Roe et al., 2016) suggests that local mass balance drivers do not interrupt the synchronicity of glacier response to climate change on global, century-long scales. Indeed, very small (<0.2 km^2) glaciers in

Colorado showed a strong annual mass balance response to 20th century summer temperatures despite being heavily influenced by winter topographic effects (Hoffman et al., 2007). Thus, the evolving relationship between climate and mass balance demonstrated by Sperry Glacier reveals the complexity in interpreting glacier changes in Glacier National Park and at small cirque glaciers elsewhere on Earth, but does not preclude the reality of a climate that is trending toward conditions that mandate glacier disappearance.

6 Conclusion

Analysis of a 64-~~-~~year record of glacier mass change against ~~climate~~ meteorological and snow data demonstrates that the ~~climate representativeness~~ relationship between regional climate variables and ~~of~~ Sperry Glacier is evolving through time. By assessing geodetic mass measurements, regional climate data, and field measured mass balance, we deduced that this shift ~~in representativeness~~ was caused by local drivers related to topography becoming increasingly influential as the cirque glacier retreated. Our results therefore emphasize the importance of accounting for spatially complex, local topographic processes in projections of 21st century mountain glacier change. These effects can exert ~~significant~~ substantial and time-changing control on the mass balance of retreating cirque glaciers, are likely highly variable from glacier to glacier, and must therefore be carefully considered and treated in interpretations and projections of cirque glacier change.

7 Disclaimer

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Data Availability. ~~Data and python code used for the analyses reported in this paper are available at xxx.~~ Temperature data from the Kalispell Historical Climate Network site are available at https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-historical-climatology-network-ushcn. Temperature data from the Sperry Glacier meteorological station are available at https://doi.org/10.5066/F7BG2N8R in version 2.1. Snow data analysed in this study are available at https://www.wcc.nrcs.usda.gov/snow/. North American Regional Reanalysis data analysed in this study were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA from their Web site at https://www.esrl.noaa.gov/psd/.

The Supplement related to this article is available online at doi: xxx-supplement.

Competing interests. The authors declare that they have no conflict of interest.

Author contributions. CF and JH designed the analytical approach, which CF then carried out with input from DF, JM, and EP. CF prepared the manuscript with contributions from all co-authors.

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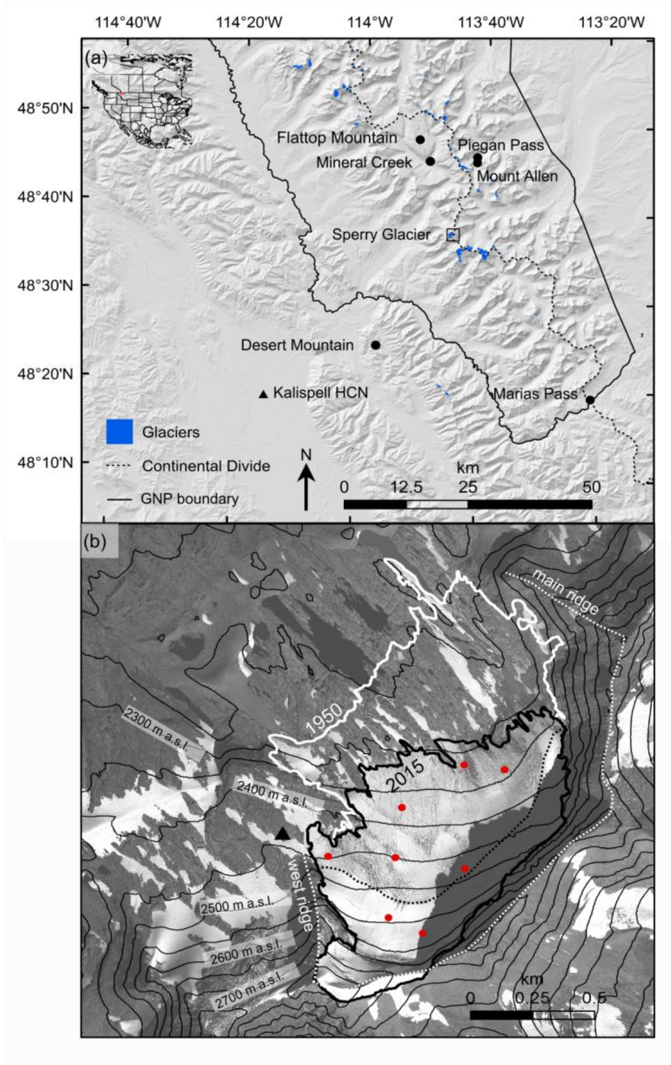

Figure 1: (a) Study area in the U.S. Northern Rocky Mountains, located just south of the USA-Canada border, as indicated by the red box on the inset map. The 39 named glaciers within and near Glacier National Park (GNP) are shown (blue). The continental divide (dashed black line), GNP boundaries (solid black line), the location of Sperry Glacier (small box), Kalispell Historical Climate Network (HCN) meteorological station (black triangle), and snow measurement sites (black circles), are also shown. (b) ~~Aerial image~~Worldview imagery from 07 September 2014 depicts Sperry Glacier ~~in 2015~~ with the 1950 (white line) and 2014 (black line) glacier margins shown. The approximate seasonal snow line (dotted black line) and the main ridge that defines the crest of the cirque headwall above Sperry Glacier, as well as the west ridge which bounds Sperry Glacier (dotted white line), are also depicted. Elevation (m) above sea level (a.s.l.) is represented by thin black

contour lines. Stakes where glaciological measurements were made are shown (red dots) as is the Sperry Glacier meteorological station (black triangle).

Figure 2: Sperry Glacier on 01 September 2009. Arrow points to the north. Note low-sloping proglacial terrain. In 1950 and 1960, the glacier extended onto this relatively flat ground. Gunsight Peak is indicated by the black star. The west ridge, headwall, cornice, bergschrund, and moraines discussed in the text are labeled. Photograph credit: USGS Climate Change in Mountain Ecosystem photograph archives. ~~Jon Scurlock~~.

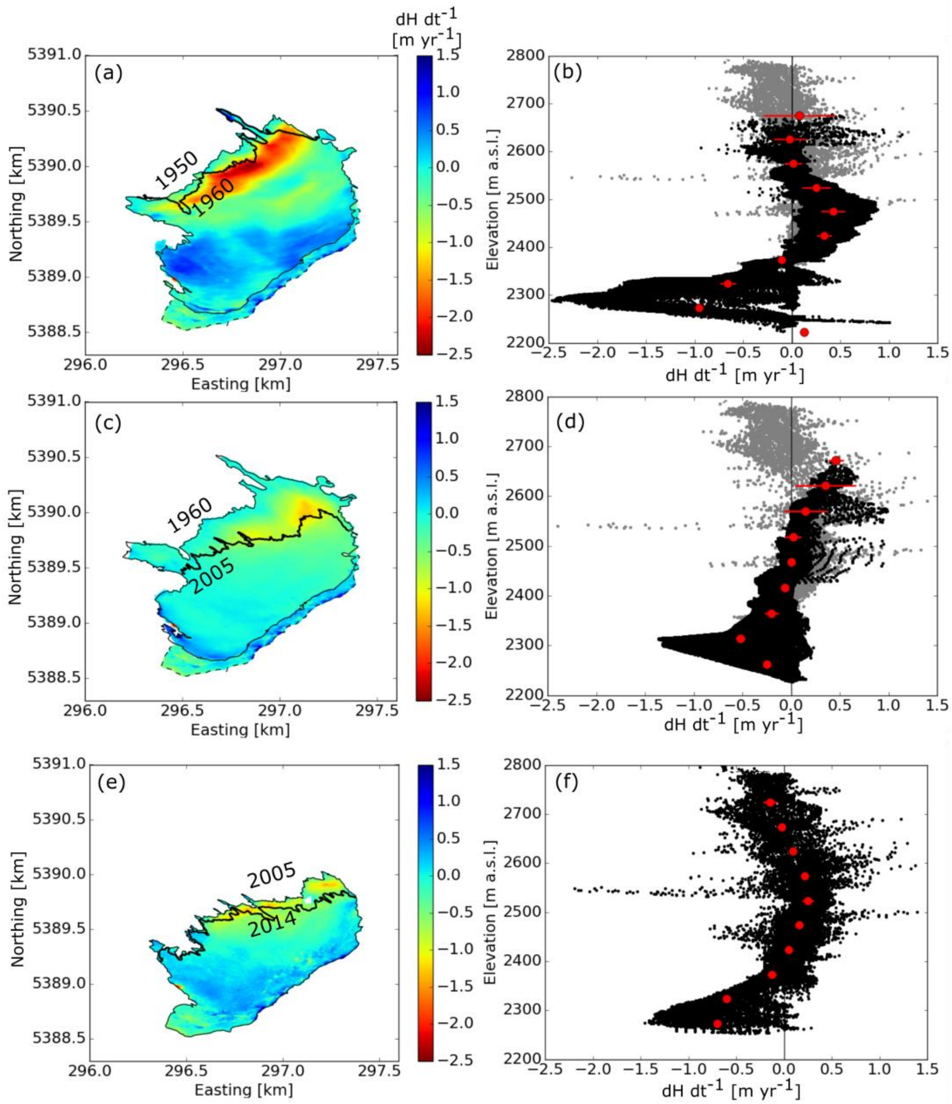

Figure 3: Elevation change over Sperry Glacier from (a,b) 1950-1960, (c,d) 1960-2005, and (e,f) 2005-2014. Left column shows elevation change across the glacier surface, and right column shows hypsometry of elevation change. Black dots on the hypsometry figures (b,d,f) indicate individual pixels, green dots indicate elevation band means, and horizontal green bars indicate elevation band mean errors. Error is mostly smaller than, and therefore obscured by, the green dot. The missing upper section is delineated by the dotted line in (a) and (c). Data from 2005-2014 were used to fill in this missing section. These 2005-2014 infill data are indicated by the gray dots in (b) and (d).

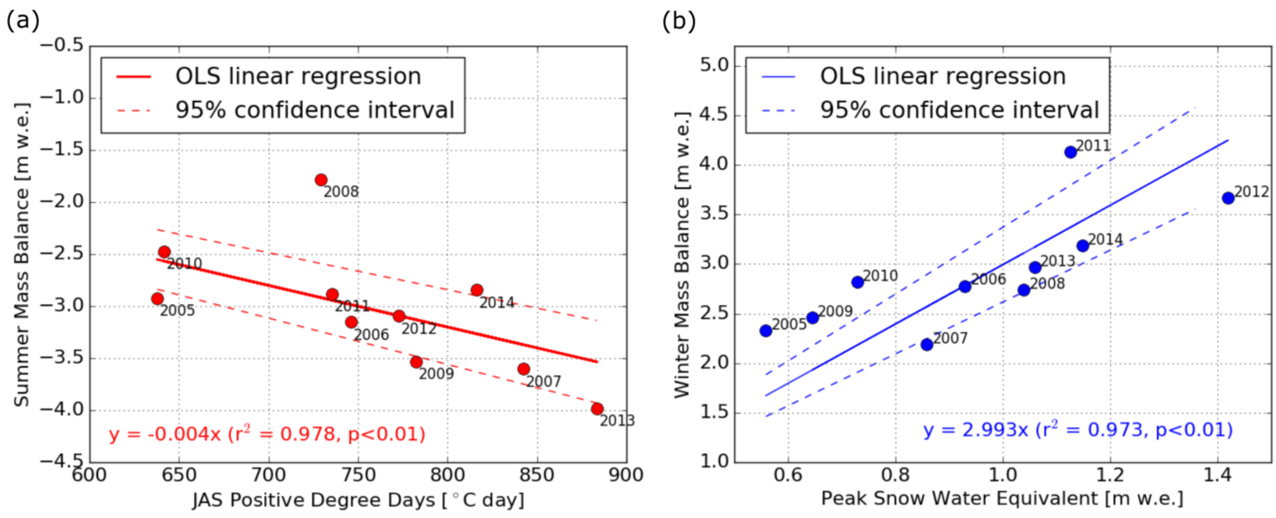

Figure 4: Ordinary least squares (OLS) linear regressions between ~~meteorological~~ climate data and glaciological mass balance for 2005-2014. (a) Summer, i.e. July, August, September (JAS), positive degree days versus summer mass balance. The linear regression is shown in red text (y = -0.004 x) and is plotted (solid red line). The 95% confidence interval on the regression is also shown (dotted red lines). ~~The one parameter regression explains 97.8% of the variability (r^2 = 0.978) and is statistically significant ($p < 0.01$) although the sample is small (n = 9).~~ (b) Peak snow water equivalent (SWE) versus winter mass balance. SWE data are from the Mount Allen snow course. The linear regression is shown in blue text (y = 2.99x) and is plotted (sold blue line). The 95% confidence interval on the regression is also shown (dotted blue lines). ~~The one parameter regression explains 97.3% of the variability (r^2=0.973) and is statistically significant ($p < 0.01$) although the sample is small (n = 9).~~

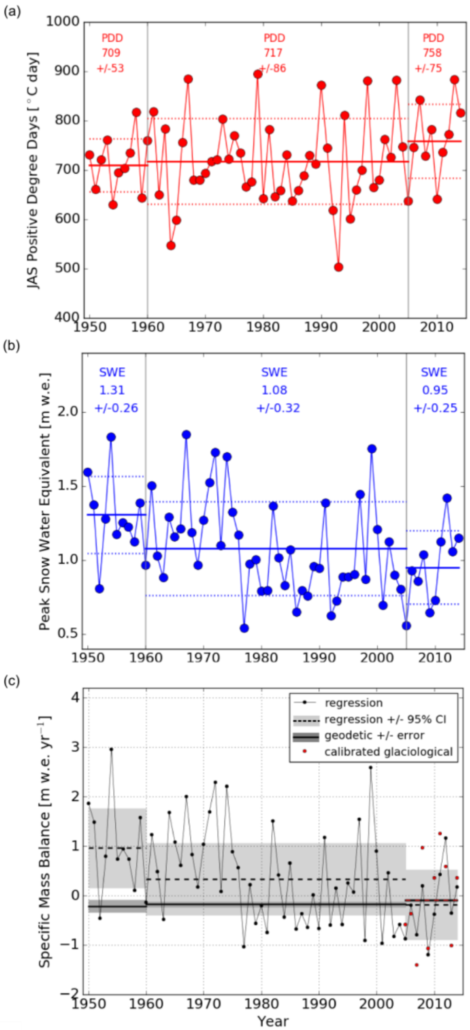

Figure 5: ~~Meteorological~~ Annual climate data for 1950-2014 and comparison of regression and geodetic mass balance results. (a) Positive degree days (PDD) calculated from the Kalispell Historical Climate Network summer, i.e. July, August, September (JAS), temperature data, adjusted for elevation by the standard lapse rate. (b) Peak snow water equivalent (SWE), calculated from Mount Allen snow course data. Mean (solid line) and one standard deviation (dashed line) of PDD and SWE for each geodetic mass balance interval (1950-1960, 1960-2005, 2005-2014) are plotted and reported in text with standard deviation. (c) Regression results for annual mass balance (black dots, thin black line) are shown, as are regression results for the average mass balance from 1950-1960, 1960-2005, 2005-2014 (black dotted lines). Calibrated, annual glaciological balances are shown (red dots), as is the average of this glaciological balance from 2005-2014 (red dotted line). Errors, set by confidence intervals on the linear regression, are also shown (light gray boxes). Geodetic mass balances for 1950-1960, 1960-2005, and 2005-2014 are plotted (horizontal black lines) with errors (dark gray boxes).

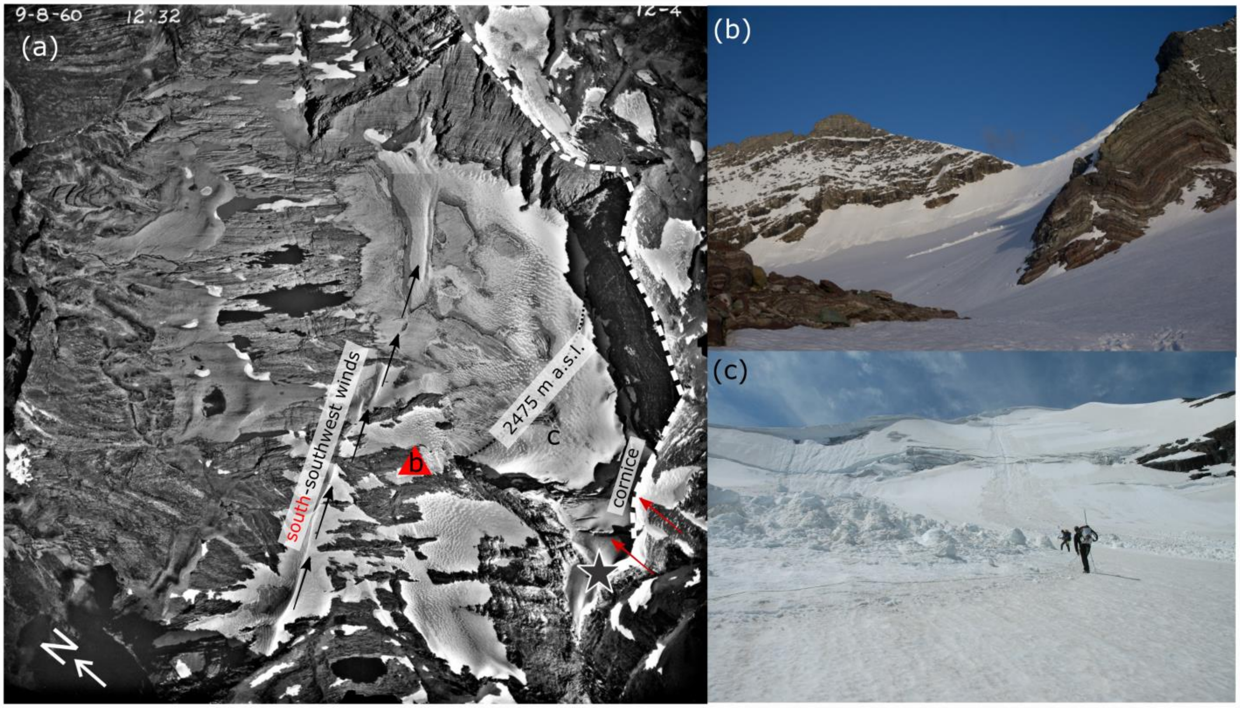

Figure 6~~7~~: Snow avalanches and wind drifted snow at Sperry Glacier. (a) Aerial photograph of Sperry Glacier taken on 8 September 1960 shows a prominent ridge of wind drifted snow that is evidence of southwest winds in the basin (black arrows), is shown. The cornice that is evidence of south winds (red arrows) is labeled. Sperry Glacier meteorological station is shown (red triangle) and the approximate elevation above which the winter and summer mass balance gradients change (Figure 7) is drawn (2450 m a.s.l.). The photograph also shows the glacier lapping over the top of Gunsight Peak (black star) at the highest elevation of the ridge (dotted white line). Photograph credit: USGS Climate Change in Mountain Ecosystem photograph archives. (b) Sperry Glacier in June, 2010. Snow sluffing and loose avalanches off the headwall are depicted. Photograph was taken from the Sperry Glacier meteorological station, labelled "b" in (a). Photograph ~~source~~credit: Joel Harper. (c~~b~~) Sperry Glacier in June, 2006. Cornice collapse (on the left) often causes a localized slab avalanche. Loose avalanche depicted on the right. Photograph credit: USGS Climate Change in Mountain Ecosystem photograph archives. Photograph location labelled "c" in (a).

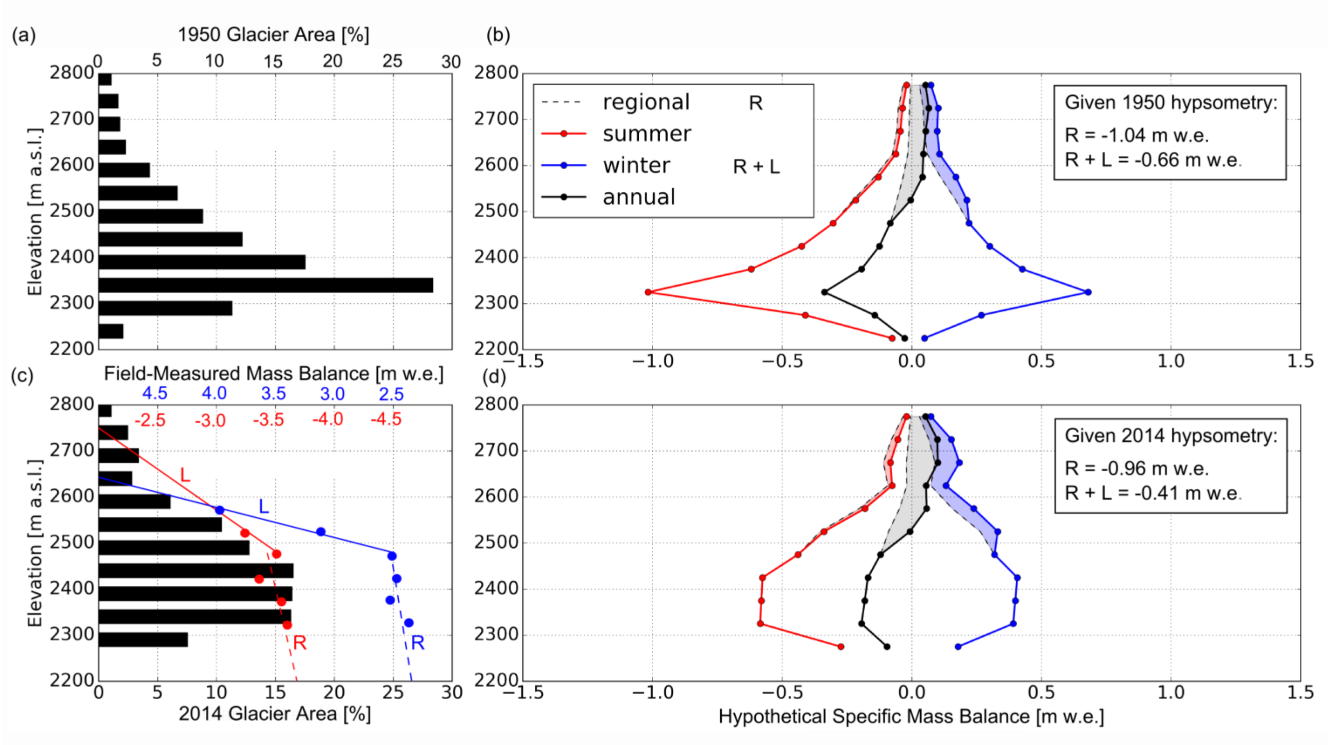

Figure 7~~9~~: Parsing local from regional mass balance drivers. (a) Hypsometry of the 1950 glacier, presented in 50~~-~~m elevation bands (black bars). (b) Sperry Glacier hypothetical mass balance, as it varies with elevation, given 1950 glacier hypsometry and ~~the~~ mass balance gradients ~~measured by 2005-2014 stake balance data (Clark et al, 2017).~~ Solid lines show the summer (red), winter (blue), and annual (black) balances calculated using field-measured local (L) and regional (R) mass balance gradients shown in (c). Dotted black lines show the same but excluding ~~local lapse rates~~L at high elevations, i.e. using ~~regional lapse rates~~R only. The difference between the solid and dotted lines highlights the effect of local controls on mass balance: suppression of summer melt (light red area), surplus in winter accumulation (light blue area), and net mass balance enhancement (light gray area). (c) Hypsometry of the 2014 glacier surface (black bars), and mass balance gradients measured at Sperry Glacier (red and blue dots and lines). The mean of 2005-2014 summer (red dots~~/solid red line~~) and winter (blue dots~~/solid blue line~~) point mass balances, measured at stakes sites, are plotted against the average elevation of the 50 m elevation band wherein the stake was located. ~~Linear gradients fit to these data are also plotted.~~ Lower elevation (< 2475 m) mass balance gradients reflect regional (R)~~lapse~~ mass balance ~~rates~~ gradients for melt (dashed red line) and snow water equivalent (SWE) (dashed blue line). Higher elevation (> 2475 m) mass balance gradients reflect local l~~apse rates~~ (L) mass balance gradients for melt (dotted red line) and SWE (dotted blue line)~~.~~. (d) Sperry Glacier hypothetical mass balance as shown in (b), but given 2014 glacier hypsometry.

Table 1: Area-averaged glaciological mass balance values used in this study. Winter balances are as reported by Clark et al. (2017). Summer and annual balances are the result of calibration against the 2005-2014 geodetic mass balance, accomplished following the ~~method~~ calibration steps outlined by Zemp et al. (2013). Accumulation area ratio (AAR) as reported by Clark et al. (2017) is listed for years when the seasonal snowline was mapped.

	Summer Balance (m w.e.)	Winter Balance (m w.e.)	Annual Balance (m w.e.)	AAR
2005	~~-3.01~~ -2.92	+2.33	~~-0.68~~ -0.59	34%
2006	~~-3.36~~ -3.15	+2.78	~~-0.58~~ -0.37	-
2007	~~-3.54~~ -3.60	+2.19	~~-1.35~~ -1.41	-
2008	~~-1.60~~ -1.78	+2.74	~~+1.14~~ +0.96	-
2009	~~-3.68~~ -3.53	+2.46	~~-1.22~~ -1.07	46%
2010	~~-2.50~~ -2.47	+2.82	~~+0.32~~ +0.35	48%
2011	~~-3.13~~ -2.88	+4.13	~~+1.00~~ +1.25	-
2012	~~-3.09~~ -3.09	+3.67	~~+0.58~~ +0.58	-
2013	~~-3.87~~ -3.98	+2.97	~~-0.90~~ -1.01	36%
2014	~~-2.95~~ -2.84	+3.19	~~+0.24~~ +0.35	-

Table 2: Digital elevation model (DEM) specifications and glacier elevation results. Acquisition dates for the original imagery used to derive elevation data are listed.

	DEM Source	Area (km^2)	~~Mean~~ Median Elevation (m)	Mean Slope (°)	Mean Aspect (°)
01 Sept 1950	USGS Topographic Map 1:6,000	1.30	~~2402~~ 2317	17	336 NNE
08 Sept 1960	USGS Topographic Map 1:6,000	1.23	~~2408~~ 2325	19	340 NNE
02 Sept 2005	National Technical Means Imagery	0.86	~~2445~~ 2425	22	313 NE
07 Sept 2014	National Technical Means Imagery	0.80	~~2466~~ 2444	24	312 NE

Table 3: Geodetic mass balance results. Net changes in volume (ΔV) and mass (ΔM) on Sperry Glacier from 1950-1960, 1960-2005, and 2005-2014 are listed. Uncertainties due to elevation error (EΔh) and density (Eρ) are listed, as are total errors (E_t). Geodetic mass balances (dH dt^{-1}) are listed with uncertainty defined by total error, expressed as a rate.

	Net Volume Change ΔV (m^3 x 10^6)	Net Mass Change ΔM (kg x 10^9)	Elevation Error EΔh (m w.e.)	Density Error Eρ (m w.e.)	Total Error E_t (m w.e.)	Geodetic Mass Balance dH dt^{-1} (m w.e. yr^{-1})
1950-1960	-3.33	-2.83	1.20	0.18	1.22	-0.22 ± 0.12
1960-2005	-11.3	-9.68	2.16	0.68	2.27	-0.18 ± 0.05
2005-2014	-0.90	-0.76	0.26	0.06	0.27	-0.10 ± 0.03