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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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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

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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.

Abstract ——— P1.L17 “. . .closely predicts the geodetically measured mass loss from

2005-2014." Please quantify 'close'.

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.

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.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.

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? 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.

P2.L8-10 I think a reference here would be suitable

P2.L10-14 Again some more reflection on Hoffman's findings would be good for this introduction. Is Andrews Glacier facing south? Are the radiation loads or some other

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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).

Study site ——— P2.L24 Please give coordinates centred on the glacier

P3.L3 Historical photographs from which year?

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.

P4.L3 What aerial imagery?

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.L25 How does the quantity of stable bedrock, to provide more certainty in elevation differences, vary with elevation in your study site?

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? Also, including the eleva-

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tions 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.

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.

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

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).

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.

P7.L11 State which observations specifically were used for this analysis.

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?

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.

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.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?

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?

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. 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

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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.

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.

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.

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.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

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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.

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.

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.

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

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

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.

As mentioned in the review, Figure 7 and Figure 8 provide some potentially useful in-

formation, 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 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 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?

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.

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