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 ± 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/m^2 (≡ 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.