

Interactive comment on “Glaciological Measurements and Mass Balances from Sperry Glacier, Montana, USA Years 2005–2015” by Adam M. Clark et al.

Adam M. Clark et al.

amclark@usgs.gov

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The reviewer's comments are repeated and then our responses are provided below.

Comment 1: Clark et al (2016) provide a valuable initial record of mass balance from Sperry Glacier. I congratulate the authors on their detailed report on both methods and results. The comments below are for further clarification of steps taken in achieving results. These are not suggestions to change approach, just to explain how something was accomplished more completely. The other main issue is that results were not placed in the regional context of other WGMS reference glaciers in the region, none are obviously in the same range, but several are close enough as to be valuable (WGMS, 2015, <http://wgms.ch/latest-glacier-mass-balance-data/>).

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Reply 1: Thank you for your work reviewing our manuscript. There are many excellent comments here that will improve this paper. We have addressed each specific comment below.

In response to the fact that we made no comparisons to others glaciers in the western United States and Canada, we'd like to clarify and state that this was done deliberately. This paper is meant to be a foundational work that describes the methods and reports the results from the Sperry Glacier mass balance program only. We refrained from discussions about regional comparisons because we believe that material better belongs in future publications. We also partly made that decision based on the scope of ESSD as a journal as well – mainly a journal for reporting on datasets. Thus, we chose not to examine what our results from Sperry Glacier may (or may not) mean, and simply stuck close to the data.

However some small amount of comparison to other North American glaciers would be appropriate and improve this paper. So we have added some of this to our revised manuscript. See detailed comments below.

Comment 2: 52: Reword sentence: “From 2005-2015, Sperry Glacier had a cumulative mean mass balance loss of 4.37 m w.e. (water equivalent).”

Reply 2: Thank you. We've agreed to this suggestion and made the change in a revised manuscript.

Comment 3: 57: New sentence “This data also allows determination of mass balance point values, and a time series of seasonal and annual glacier-wide mass balances for all eleven measurement years.”

Reply 3: Thanks. We've agreed to this suggestion and made the change in a revised manuscript.

Comment 4: 98: Must refer to other mass balance programs in the region including in Canada. Also the WGMS has 40 reference glaciers in the world, which are the

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benchmark glaciers for the global mass balance data set. the three USGS glaciers mentioned are part of this as are Columbia Glacier in the North Cascades, Lemon Creek Glacier in Southeast Alaska and Peyto Glacier in the Canadian Rockies. In this case the three most similar reference glaciers are Columbia, South Cascade and Peyto. Also could reference changes in Wind River Range Maloof et al (2014).

Reply 4: In this particular case this sentence is referring specifically to the USGS Glaciers and Climate Program, which only monitors four glaciers: Gulkana, Wolverine, South Cascade, and Sperry. It would not be appropriate to refer to the other glaciers mentioned in the above comment in this section of our manuscript given the context of this sentence. We have added a hyperlink to the USGS Glaciology Project website in the manuscript for further clarification.

Comment 5: 133-137: Expand on this discussion, what is the dominant weather source in the summer? Are the Pacific storms still important? What are some basic climate means from a nearby weather station? Reference any climate trends in the region already identified.

Reply 5: This is a good suggestion. We have added a couple paragraphs to our revised ms that better describe the climate in Glacier Natl. Park as well as reference papers highlighting some changes to climate and mountain snowpacks in the region.

Comment 6: 169: I cannot determine if an actual DEM is being used. More information is needed ie. 1.. Who developed the DEM from the images? 2. What methods/software and what information were used to take the aerial photographs from a raw image to DEMs? 3. What are the horizontal and vertical errors? The resolution of 5 m is noted but this is not error and does not denoted vertical vs horizontal. This can be very important as if you are off in position on a steep slope by a meter or few meters, then you are introducing large vertical errors, move a 5 m pixel a few pixels away on a steep slope and you've changed the elevation. These errors are best estimated by comparing off ice areas. 4. Were the DEMs co-registered?

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Reply 6: We have added more text in our revised manuscript that more completely describes how these DEMs were generated, the associated errors, and included two citations.

Comment 7: 187: Pelto (1996) has also noted the lack of superimposed ice in the North Cascades directly to the west.

Reply 7: OK, we noted this in our revised manuscript and added this reference. Thanks.

Comment 8: 246: Are all of these measurements made in the spring? What about snow density at the end of the melt season, which is critical for mass balance. It has been noted in the North Cascades density of snowpack is consistent after Aug.1 (Pelto and Riedel, 2001; Krimmel, 2001). You give a maximum snow density of 600 kg m⁻³ is this the end of summer density assumed?

Reply 8: We have added more text and a figure to the revised manuscript that better describes the density measurements and exactly how they were used to calculate point balances.

Comment 9: 282: The most significant assumption made in this study is that each elevation bin has a representative mass balance value. On small glacier like Sperry this is usually not the case. There are zone of accumulation and ablation within the same bin, which is why AAR ends up being a more useful measure of mass balance than ELA. What is your evidence that particularly above 2500 m the measurements points used are representative of the bin? Figure 2 highlights this point with blue ice zone above the firn line and two disparate small retained snow patches at different elevations. I have also included here Fig. 1 image of the Sperry Glacier in 2009 from Bob Sihler illustrating the same point. This does not mean the calculations of mass balance here need to be adjusted at this time. The issue needs greater acknowledgement, how will it be addressed going forward and any steps you are already taking to address it should be mentioned. For example, the higher density of probing in the spring maybe what you have used. The sections on seasonal variation noted at 350 and 382. Also suggest

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this is needed.

Reply 9: The issue of point balances being representative of a certain areas on the glacier (elevation bins) is problematic. Certainly we acknowledge that there are instances when there are zones of ablation and accumulation in the same bin. To report this issue, we have measured AARs for selected years (2005, 2009, 2010, and 2013). Please see the supplement to the paper which contains the mass balance maps (with measurement points and AARs plotted as well). A reference to this supplement has been added in the revised manuscript to section 3.1.2. Glacier Mapping – Accumulation Area for clarification Future work on Sperry will address this problem and our network of measurement points may change due to the complicated patterns of accumulation and ablation on Sperry. We describe this more in our revised manuscript in the Conclusions section.

While a measure of AAR can be a useful metric, it is important to note that it comes with its own host of problems. Specifically, if no measurements of the depth and/or density of snow are taken inside the accumulation area at the end of the ablation season, then there will be considerable uncertainty about how much mass is actually contained there. From our dataset of snow depths taken in the spring on Sperry we know that the snow depths change rapidly with distance on the upper elevations of the glacier. This is discussed in the paper. However, our end of ablation season measurements are limited to the stake sites. This certainly introduces error and uncertainty in our balance calculations. But without having more data (point balances), we cannot know how much error in our balance estimates is attributable to these patches of accumulation within bands that contain both zones of accumulation and ablation. Again, we have addressed this problem more in our revised manuscript in our Conclusions section.

Comment 10: 324: Figure 3 provides no additional value to the Table.

Reply 10: Agreed. We replaced this with a different figure related to snow density.

Comment 11: 340: On this size of glacier with such a spatial variation of ba, how

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do you justify determining mass balance without knowing the AAR? The WGMS for its reference glaciers expect both ELA and/or AAR to be submitted (WGMS, 2015; Mernild et al 2013)

Reply 11: See Reply 9. But also, we question whether AAR or ELA is always a reliable way to justify a mass balance estimate obtained from glaciological methods, especially on a cirque glacier like Sperry.

Comment 12: 417: This similarity of ablation with elevation has also been noted at other alpine glaciers, provide a reference.

Reply 12: This is true, but we have elected to not make comparisons with other glaciers in this part of the text. This section was written to describe the general ablation pattern and resultant summer balance on Sperry specifically. In our Conclusions section, we discuss Sperry in the general context of small alpine cirque glaciers and their sensitivity to topographic effects in more detail. We have also added some relevant references to the Conclusion in our revised manuscript.

Comment 13: 482: Should reference changes on other glaciers in the region to put this glacier in context. What was the cumulative mass balance of Peyto and Columbia Glacier, WA during this period? This could include a comparison of area loss rate versus other GNP glaciers.

Reply 13: We agree and have added a new section in a revised manuscript about other glaciers in the region (western USA and Canada) and how those mass balance records compare to Sperry.

Comment 14: 484: How does this compare to area change from 1966-2005? Are there other GNP glaciers to compare this too?

Reply 14: This will be in a forthcoming paper. Some of the authors for this paper are also working on a project where changes in glacier area in GNP from the 1960s through the present will be quantified. Thus we have elected not to go into a discussion

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about glacier recession across GNP in this paper.

Comment 15: Figure 5-6: Would be ideal to combine these on one figure with two y-axes.

Reply 15: Agreed and combined as suggested.

Comment 16: Table 4-7: these provide excellent value.

Reply 16: Thank you. Also please see the additional tables in the paper's Supplement. These contain all the point balance data which we hope will be useful to other researchers.

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