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Interactive comment on "How unusual was 2015 in the 1984–2015 period of North Cascade Glacier Annual Mass Balance?" *by* Mauri S. Pelto

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I appreciate the reviewer detailed comments that will help guide development of what should be a simple and compelling story, if well told. The minor specific comments are nearly all appropriate and the paper will be adjusted as suggested. Below is the response to the broader comments of RC1 and the significant comments of both RC1 and RC2 with indicated location.

Specific comments: RC1 The results show that 2015 was the most negative year during the period of record, but there is no statistical analysis to quantify the "How unusual" part of the title.

AR: This is a crucial piece of new analysis needed.

Section 2.0 Climate should be some sort of site introduction that tells us about the North Cascades (and includes but is not limited to regional climate). It should also include something about total area, total glaciated area, elevation range, etc. All of section 2.1 Climate in 2015 should be moved to the discussion (prior to or combined with section 5.0 Climate correlations).

AR: This section 2.0 will be broadened as suggested, with particular care given to separating overview from actual discussion of climate data as in Section 2.1. The goal had been to discuss the overall climate record separate from 2015 and then later compare. The reviewers have made clear this was not the right approach.

Section 3.0 Methods, this section needs to include more details. At the very least, include what kinds of measurements are made, and what the AAR is calculated from. Describe the uncertainties better. it does not incorporate any geodetic check to assess for bias. Even a very small bias can create large errors in cumulative balances over time (e.g. Fischer 2011), which would have an impact on the % volume change.

AR: This is one section where I disagree to an extent with RC1. The point of the paper is to tell the story simply. There have been nine previous papers that have discussed the methods in detail, the methods remain the same and discussing again here blurs the focus. The uncertainty can be better defined, but again cannot become a focus. The geodetic balance is a separate topic that is completed as part of a reanalysis periodically for the WGMS. There certainly can be errors that lead to a cumulative balance error, which is not the focus either. Here we are focused on annual balance that has been measured using the same methods for all years, and an error on a particular glacier would be consistent. There was a geodetic comparison published in 2002. I am not presenting volume change as a data point, I can move away from the broader % volume change statement if that is deemed important.

Section 4.0 Results, If the glaciological balances are robust in part due to the large sample numbers, then add a table with the number and type of measurements at each

glacier. Add uncertainties to all of the reported numbers.

AR: This could be done and I will trust the suggestions of the editor. The downside of a separate table is space. The number of measurements and error are provided each year to the WGMS as part of the data submission so this information is available.

Section 5.0 Climate Correlations, it would be useful to evaluate the direct correlation between mass balances, snowpack at the SNOTEL sites mentioned previously, and the average ablation-season temperatures. All of this data is mentioned in the manuscript, yet no formal analysis was made. That is the intermediate step linking broad-scale regional forcing mechanisms to the actual climate at the scale of the North Cascades region.

AR: This analysis with SNOTEL and ablation season temperature was completed in detail in previous papers, and can be better referenced here, updating the record by a few years does not add significant value, but can be readily completed (Pelto, 2011).

Section 6.0 Conclusions The conclusions do not mention 2015. Based on the title I expected that to be the core of the paper. After the first two sentences, the entire paragraph reads like a part of the discussion, citing other papers on the potential impacts of continued mass loss from the North Cascades Glaciers. Move this to the discussion and replace it with conclusions about 2015, the correlations with climate, and the correlations with regional forcing mechanisms.

AR: Well said these suggestions will be adopted.

P1L12: RC1, This statement is only partially correct as the paper uses glacier mass balance data from NCGCP, NPS, and USGS to compare to regional climate. Please reword to be precise. AR: Data is not used from the NPS studies which are shorter term. Data from South Cascade is used for comparison, but is not part of the analysis.

P2L5: RC2 Sperry Glacier, MT and the National Park Service glaciers in North Cascades have joined this group. AR: The aforementioned glaciers are submitting their

data to the WGMS, but are not part of the reference glacier network, and will not be until they have 30 years of continuous data. Since this draft was submitted Rainbow Glacier from the NCGCP network has been added as a WGMS reference glacier and Easton Glacier is expected to be added in 2019. Inclusion of Rainbow Glacier will be corrected in the manuscript. Data was submitted in June 2017 for South Cascade Glacier from 2015 that will now be incorporated in this study. There still are issues with South Cascade Glacier 2013 and 2014 data and is still not reported. If the South Cascade Glacier data is submitted to WGMS soon, this data will be incorporated. As the WGMS representative for the United States I will have the chance to review this data as soon as it is ready.

P2L16: RC2, Why suspend measurements on Foss Glacier? AR: Increasingly difficult access to the glacier and time spent is not of sufficient value given the rapid recent demise and imminent loss. I will expand description of ongoing mass balance at NPS and SC glacier.

P2L22: RC1, Reword. Perhaps: "Combined with South Cascade Glacier, this network represents the best distribution and density of direct measurements of glacier mass balance over a given mountain range. This allows us to separate the impacts of geographic characteristics and climate on glacier mass balance, and place the exceptional 2015 mass balance year in context." Thanks for the good suggestion.

P3L16: RC1, Why examine May-September and June-September? I suspect it has to do with the fact that most of the ablation measurements are made June-September, yet May is also part of the ablation season? Explain. AR: Just to illustrate that the temperature trend for both periods is the same, hence examination of climate records from one or the other is representative of the entire melt season.

P3L25: RC2, AR: Will reorganize this section following suggestions of RC2. The glacier balance forecast model utilizes PDO and ENSO actual values from the winter for predicting the end of the hydrologic year balance, no reliance is made on forecasted values

of PDO or ENSO. The degree to which this is successful is not the focus of the current paper.

P4L13: RC2, AR: Will clarify accumulation season years.

P4L17: RC2, (Abatzoglou, 2011) AR: This reference is for derivation of the freezing level product, which can be completed for any location in North America using the online application. This reference is not for a result reported.

P4L18: RC1, Figure 2. Directly contradicts this statement, showing 3 years with freezing levels above 1500 m. Revise the statement or revise the figure if there is an error in the figure. AR: Statement will be revised. The freezing level was highest in 2015 of any year, with 2016 in second place.

P5L7: RC2, AR: The reference used the term largest marine heatwave, will better constrain this with respect to spatial and temporal context.

P5L10: RC2, AR: Not attempting to indicate PDO or ENSO as cause of higher air temperatures or lower winter accumulation. I am treating the climate indices, temperature and precipitation and ocean temperature as separate measures indicating uniqueness of climate in 2015.

P5L25: RC1, You have already defined Ba, however for most readers it would be easier to read if it was written as annual balance rather than abbreviated. AR: This may be true, but I would suggest in terms of space Ba is entirely appropriate.

P5L28: RC1,This is the third time this description shows up in this paper. It should be presented once, either here on in a site introduction. AR: This suggests the third time was not the charm.

P5L31: RC1, Why bring up key geographic variables? Either give us data on what those variables are, and use that data in the analysis, or make a more useful statement. AR: In this case the point is there are a range of variables; however, this does not lead to a significantly different mass balance history as shown by correlation coefficients

and overall trend.

P6L20: RC2, AR: The maximum and minimum is for the range in annual balance in any given year between the most positive and most negative of this group of glaciers.

P6L23: RC2, AR: Data source is WGMS not Bidlake et al. (2010). Bidlake et al., (2010) merely most recent reference on this glacier providing program details.

P6L30: RC1, These citations have measured thicknesses for a couple of glaciers in this study, most of the glaciers have not been measured directly, and it should be pointed out that most of the thicknesses come from Post et al., (1971) which are qualitative estimates based on measured thicknesses of a couple of glaciers. Either present measured thicknesses or be more precise in describing the given data. Strengthen your argument by showing that even with maximum plausible ice thicknesses the % volume change is.

AR: I will focus on the results from Easton and Rainbow Glacier where thickness has been measured and volume loss is better constrained. Most of the thickness information here is not from Post et al (1971).

P7L4: RC1, Most of section 4.3 is giving an introduction to what AAR is and what it means. It does not belong in the results. The actual results here could be combined with the previous section as it should only be 1-2 sentences. AR: This will be done.

P7L9: RC2, AR: AAR can be independent measure from ELA based on direct observations. The ELA cannot be identified directly on glaciers with a patchwork of accumulation and ablation zones, whereas AAR can be. ELA can be derived from the average balance gradient still, but that is not a direct measure and hence not as accurate. Similarly AAR can be derived from the ELA but again that would be an indirect calculation. It is important for our program to map the AAR repeatedly during the melt season, given the different melt rate of glacier ice versus glacier snow cover for a given temperature.

P7L20: RC2, AR: Misinterprets the use of AAR0 by the WGMS and here. The AAR0

reported to the WGMS is not the annual ELA it is the theoretical ELA0 for an equilibrium annual balance. Hence, the reported ELA0 to WGMS of 0.67 is not a subset, but the entire set of those reported. Here the AAR0 is determined from Figure 4, which is standard WGMS practice to use the regression line of mass balance and AAR. This is one reason WGMS has determined it is crucial to report AAR and ELA every year possible.

P8L13: RC2, bad analysis. AR: Point taken will redo based on Rainbow Glacier and Easton Glacier only where thickness data exists.

P8L23-25: RC1, AR: Section will be moved earlier as suggested.

P8L26: RC2, Why these time periods? AR: There was a shift in the PDO phase from positive to negative at this time and a change in correlation between annual balance and seasonal climate data.

P8L30: RC2, AR: The PDO relationship being stronger for winter is for any time period, a reference for this will be added.

P8L32: RC1, This sentence about "the global climate signal is the dominant driver of mass balance losses" is not well developed. What correlation are you talking about? AR: This is an important statement to make that is supported by the similar patterns of regional annual balance data. I have not done separate analysis so will look to other references to support. If the support remains too thin I can remove.

P15 Table 1: RC1. Accumulation seems to be unused in the analysis. The area and elevation values do not have any context. Mention the range of glacier areas and something about the elevation ranges within the North Cascades in a site description. AR: Good point, I will change this section to offer more value. The accumulation area and its elevation range can be better reported. However, given the very limited area of accumulation on all but Easton Glacier, the comparison will be an annual point balance comparison instead of accumulation comparison.

P18 Table 4: RC1 Table 4 seems like a little bit of a waste, as all it does is compare 2015 to the mean value. Why not do a multi-variable regression between the annual values of April-1 SWE., Summer temperature, and mass balance values? AR: The change from the mean I believe is more compelling in illustrating 2015 deviation from the mean, than a multiple regression. I will better incorporate the standard deviation for this purpose. However, multiple regression values can be reported as well.

P20 Figure 1: RC1, The resolution of this figure is very low. Consider using a hillshade AR: This is a map that has been used successfully in other publications, alteration would be quite difficult. I will provide a better resolution version for publication

P21 Figure 2: RC1 Why is there such a difference between these freezing levels and those in table 4? What do you use these freezing levels for? AR: Purple arrow indicates 2015. The table has the correct data and the figure is incorrect, I will replace figure and remove purple arrow. I can also expand caption to better explain. I do not use the freezing level in mass balance work, but is a useful measure of climate conditions above the elevation of local weather stations.

P22 Figure 3: RC1, This figure is incredibly hard to read. Please use thinner lines and higher resolution. AR: I can improve resolution, but thinner lines will just be hard to read. Part of the issue you identify is the point of the figure, the overlapping and similar nature of the annual balance records.

P23 Figure 4: RC1 and RC2, Again, there is too much data on one plot with heavy lines and symbols. AR: Thinner lines would also be hard to read, maybe the mean line and different symbols for the glaciers is the best approach. Maximum value on Y-axis will be changed to 100.

P24 Figure 5: RC1, Again, the resolution is too low. What is the purpose of figure 5, Mt. Baker? AR: This figure illustrates patchiness of accumulation zone, but could be removed as most of the glaciers shown not measured for mass balance.

Page 25 Figure 6: RC2, AR: Y-axis units will be corrected.

P26-28 Figure 7-9: RC2 and RC1 agree that all three picture are not needed. AR: I will focus on one picture with the best angle and report the percent of the accumulation area visible.

C9