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Interactive comment on "Glacier change in the Cariboo Mountains, British Columbia, Canada (1952–2005)" *by* M. J. Beedle et al.

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Final Author Comments

TC-2014-87 "Glacier change in the Cariboo Mountains, British Columbia, Canada (1952–2005)" by M. J. Beedle et al.

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November 2, 2014

Response to Referee #1: Heidi Escher-Vetter

Thank you for your timely and detailed comments on our manuscript, Heidi. We appreciate your detailed reading leading to the revision of errors on our part.

Comment from referee: Page 14, line 25: do you give average numbers here? It is a little bit hard to find them in Table 6.

Author′s response: Yes these are mean numbers here, with total volume change averaged over the total surface area of the seven glaciers.

Author′s changes in manuscript: To clarify we have added "mean" to this sentence and added the mean values to Table 6.

Comment from referee: Page 17, line 25: Could you comment a little bit more detailed on the statement and its relation to Fig. 7?

Author′s response: Our comments about the acceleration of glacier shrinkage in this sentence are in terms of mean relative area change per annum. We reference Fig. 7 here as it visually displays these increased rates of glacier contraction and also the variability within the glacier subsets

Author′s changes in manuscript: We have added "(mean relative area change per annum)" to this sentence to help clarify this statement and retained reference to Fig. 7.

Comment from referee: Table 3: Could you explain a little bit more on the numbers (18, 5, 2, : : :) given in the last statement below the table ('Summed extents and area change may omit some individual glaciers: All 18, C 5 and 18, : : :'). If these numbers refer to the numbering of glaciers in the table, e.g. glacier #18 is not in the Castle, but in the Quanstrom region?

Author′s response: We made an error in the last statement below the table: 18 should be 14 and 5 should be 1.

Author′s changes in manuscript: The last statement below table 3 so that reference to glacier 18 is now to glacier 14, and reference to glacier 5 is now to glacier 1.

Comment from referee: Page 10, line 11: 2000 m (not 2,000 m)

Author′s response:

Author′s changes in manuscript: We have changed 2,000 m to 2000 m.

Comment from referee: Page 20, line 6: Figs. 10 and 11, not 9 and 10.

Author′s response: Yes, this is an incorrect figure reference in the original manuscript.

Author′s changes in manuscript: We have changed the manuscript to “Figs. 10 and 11”

Comment from referee: Page 27, line 21: Citation of Schiefer et al., 2008 is probably missing in the text, I could only find citations of Schiefer et al, 2007.

Author′s response: Correct, we did not cite Schiefer et al., 2008 in the manuscript.

Author′s changes in manuscript: We have removed the reference to Schiefer et al., 2008.

Comment from referee: Figure 2, caption, last line: . . . corresponds to that of Tables 2 and 3 (not 2 and 4).

Author′s response: Yes, our original manuscript is in error here.

Author′s changes in manuscript: We have changed the Figure 2 caption to “. . . corresponds to that of Tables 2 and 3.”

Response to Referee #2: Chris DeBeer

Thank you for your in depth review of our manuscript, Chris. We greatly appreciate the time you dedicated to this review and feel your efforts have significantly improved the paper.

Comment from referee: The climatic analysis in this paper, although interesting and informative, does not explain the observed pattern of glacier changes as suggested on page 3388, lines 14–17. Rather, it provides a fairly general assessment of the regional climatic variations that have occurred, giving some context for the glacier changes that have been observed over the same period. In this regard, the analysis and discussion

seems oversold.

Author′s response: Yes, we agree that the use of the word “explain” was too strong here.

Author′s changes in manuscript: We have omitted “explain” and added ÂÍplayed important roles in forcing” to this sentence. Also, please see how we addressed this issue in our response to the next comment.

Comment from referee: The paper shows that the patterns of glacier changes, both collectively and individually, have been complex and continuously changing over time. Resolving the role of regional and local climate variations in influencing these patterns would be of high scientific value, but requires a considerable amount of further, more detailed analysis that is likely beyond the scope of this study.

Author′s response: The point of our climatic analysis is an attempt to better understand the broad-scale changes in precipitation and temperature that likely drove the mass and area change that we observed in the study area during the latter half of the Twentieth Century. We concur with the reviewer that resolving the role of regional and local climate variations would be of high scientific value, and also that more detailed analysis is beyond the scope of this study. Unfortunately we lack additional data sets with which to complete this detailed assessment. In addition, a proper analysis would also need to assess the response time of these glaciers to assess how changes in precipitation and temperature affected area and volume change of the study glaciers.

Author′s changes in manuscript: We have revised the first two paragraphs of section 4.5 (Relations to climate) to address the referees concerns regarding our discussion and conclusions about climatic forcing of glacier change. Additionally we have revised paragraph four in this section on the relation between ClimateWNA records and synoptic climatology.

o We have noted that observed climatic patterns “coincide with” instead of “likely re-

sulted in" observed glacier change

o We have used wording that better reflects the non-conclusive nature of the relations between ClimateWNA records and synoptic climatology, omitting "aligns with" and "agree" in favor of "coincide", "associated with" and "broadly accord". Please see paragraph four of this section for these changes.

Comment from referee: In particular, it currently does not come across as clearly as it could what the actual new scientific contributions are (although there are several noted above). It is important to distinguish, up front, what is new about this paper that sets it apart from previous studies of glacier change in the region.

Author′s response: We have added content to the introduction to more clearly state the new scientific contributions of the paper. In particular we have drawn further attention to the valuable role of decadal aerial photogrammetry can play in more detailed assessment of glacier response to climate forcing.

Author′s changes in manuscript: The following paragraph has been expanded to address the referee′s concern: "Aerial photography can be used to extend glacier change documentation by up to three decades prior to the beginning of the satellite era. In British Columbia, repeat aerial surveys have been approximately decadal and thus an opportunity exists to assess multi-decadal changes in the area and volume of alpine glaciers. Debeer and Sharp (2007), for example, combined aerial photography and satellite imagery to assess changes in glacier cover in the southern Canadian Cordillera over the second half of the twentieth century. In particular, they noted negligible change of small glaciers in their study. Our study builds on Debeer and Sharp (2007) by expanding the spatial domain over which glacier change is evaluated and by increasing the number of epochs over which these changes can be compared to the instrumental record."

Comment from referee: The figures and tables are useful and clear, but it is worth considering adding another one or two figures to show relationships between relative

changes and initial glacier area, since this would enable better comparison with the results of other studies and because these relationships are explicitly mentioned (but not shown) in the paper.

Author′s response: We feel that the manuscript is already figure-heavy, and that all relative changes and initial glacier areas in the study are presented in Table 3 for comparison with other studies.

Author′s changes in manuscript: No changes made.

Comment from referee: Abstract (page 3368, lines 1–13): The abstract could be improved by including some context as to why the study was done (the introduction would also benefit from this), some more specific detail on how the study advances understanding of recent glacier changes in this region, and some more information on what was actually measured and over what periods (see, for instance, the first paragraph in the general comments above).

Author′s response: We have added content to the abstract to provide further insight into the motivation for our study, as well as additional details on the primary advances made in understanding of regional glacier changes and details on the periods of study.

Author′s changes in manuscript:

o The following content has been added to the first sentence of the abstract in order to add clarity regarding our methods and the periods of study ". . . applied photogrammetric methods with aerial photography from 11 different years between 1946 and 2005 to assess . . ."

o A new sentence (now sentence #2) has been added to the abstract: "These are used to identify changes in extent and elevation primarily for the periods 1952-1985, 1985-2005 and 1952-2005."

o We have added the following to the end of the abstract to further clarify a primary finding of our study: "Our results also indicate that the 1985 glacier extent for the study

area, reported previously by other studies, may be slightly overestimated due to errant mapping of late-lying snow cover."

Comment from referee: As it reads now, it is somewhat misleading in that volume changes were only determined for seven of these 33 glaciers.

Author′s response: We agree that it was not clear at the outset of the manuscript that volume changes were only determined for a subset of seven glaciers.

Author′s changes in manuscript: We have changed the abstract to read ". . . Thinning rates of a subset of seven glaciers. . ."

Comment from referee: It would also be helpful to include the results for total glacier changes (km2 and % for area, and km3 for volume), in addition to the average annual rates of change.

Author′s response: We are confused as to whether this comment is in respect to just the abstract or the entire manuscript. We do mention total glacier changes (km2 and km3) in the results section. Average annual rates of change are the focus here as they are independent of initial glacier size. As our work is on a subset of glaciers and not a complete inventory, we feel that total glacier changes may be confused with change of the entire region, and also cannot be compared readily with other studies in terms of absolute glacier change.

Author′s changes in manuscript: No changes made.

Comment from referee: Page 3373, lines 3–5: Although glaciers in the largest size class are likely to play a dominant role in meltwater contributions to their respective watersheds, it would have been useful to also include a larger number of glaciers in the smaller classes since their behavior and dynamics are so different.

Author′s response: We agree that it would have been useful to include a larger number of glaciers in the smaller size classes. These glaciers, unfortunately, are most susceptible to being effectively "hidden" by seasonal snow cover, shadow, and poor contrast.

The smallest glaciers included in our study represent all of those that were included in avaialable imagery and that we felt could be reliably measured.

Author′s changes in manuscript: No changes made.

Comment from referee: Page 3373, lines 10–15: While this is likely a good approach to minimize error in change detection, care still needs to be taken to check for instances where obvious or even subtle changes have occurred above the transient snow line (TSL). Also, what about very small glaciers and niche glaciers that may exist entirely or mostly above the TSL?

Author′s response: Yes, care does need to be taken to check for instances where changes have occurred above the TSL. However, in our experience seasonal snow cover – particularly in older imagery of poorer quality – prohibits any reliable mapping of extent change and leads to more guess work than mapping of actual extent by the analyst. Indeed this, we contend, is the primary reason that the TRIM extents used in Bolch et al., 2010 are in error, with the analysts mapping large areas of seasonal snow cover as glacier. Reliable measurement of glacier extent depends on imagery in years and at times when the TSL is high, particularly for reliable measurement of the changes of very small glaciers.

Author′s changes in manuscript: No changes made.

Comment from referee: Page 3374, lines 14–19: There is an issue with using different densities for the accumulation and ablation zones (750 and 900 kg m-3 in this study, respectively) towards determining water equivalent volume change of glaciers. Thickness change is assumed to be the result of a change throughout the entire ice column (surface to bed), not simply a change in thickness of the upper firn and snow layers. Thus a density of 900 kg m-3 should be used for the entire glacier. Different densities have been applied in other studies (Schiefer et al., 2007; Tennant and Menounos, 2013) but no strong explanation and justification have been given, so perhaps the authors could comment on this here. Further, these other studies had used a density

of 550 kg m-3 for the accumulation zone and either used an accumulation area ratio (AAR) of 0.6 or the elevation of the mean late summer snow line on the glacier to define the boundary between the accumulation and ablation zones. Here, the glacier's median elevation is used. This introduces a dissimilarity in methodology that makes direct and meaningful comparison of the results among the studies difficult.

Author′s response: A density of 900 kg m-3 is only used when one assumes Sorge′s law. This assumption, arguably, is too simplistic. This issue has been discussed in detail in a recent paper that we cite in the revised manuscript (Huss, 2013). In the original manuscript, and retained in the revised one, we also cite Beedle et al., 2014, which goes into detail on this issue and also uses densities collected from one of the glaciers in the present study. We feel that strong explanations have been given in both of these previous studies, and that adding additional details here is not necessary.

Author′s changes in manuscript: We have added a reference to Huss, 2013.

Comment from referee: This is overlooked on page 3384, lines 18–22 when comparing extrapolated volume changes over the Cariboo Mountains with those found by Schiefer et al. (2007), notwithstanding the other differences related to time period and initial glacier extent.

Author′s response: We did not mention this difference in methodology in the original manuscript, but do point out that the Schiefer et al, 2007 study is for a time period that is six years shorter. The main point here is to show that our results are similar – within our margin of error – to previous work.

Author′s changes in manuscript: We have added " . . . and using different density assumptions, . . ." to this sentence.

Comment from referee: One further point worth noting is that this density uncertainty is accounted for in the error analysis on page 3375, and so the actual water equivalent change should still fall within the error bounds given.

Author′s response: Yes, we do account for uncertainty in our density assumptions in our error analysis, and the results do fall within the error bounds given, hence are conclusion that the two are "comparable".

Author′s changes in manuscript: No changes made.

Comment from referee: Page 3379, lines 15–23: There is an issue here that could be clarified. If the ca. 1985 B.C. TRIM glacier extents average 5% larger than the 1985 glacier extents delineated here, and the Bolch et al. (2010) 2005 glacier extents average 2% larger than the 2005 glacier extents delineated here, then presumably the net difference in results between the two studies should be about 3%. But the difference is quoted to be 52% more area loss reported by Bolch et al. (2010). Can the authors offer some further insight? Is this due to clearly misclassified snow patches in the TRIM dataset not being included in the comparison reported on lines 15–17? Did the errors in the TRIM data affect small glaciers much more than larger glaciers?

Author′s response: For TRIM the total glacier areas are 139.062 km2 (Bolch) and 132.313 km2 (this study), yielding a difference of 6.749 km2 (5%). For 2005 the total glacier areas are 126.615 km2 (Bolch) and 124.118 km2 (this study), yielding a difference of 1.973 km2 (2%). The resulting changes in surface area over this period are -12.447 km2 (Bolch) and -8.196 km2 (this study), yielding a difference of 4.251 km2, a difference which is 52% of what we found for this study. Indeed, at least for these 28 glaciers, the Bolch analysis results in 52% more area loss than what we find here. This analysis, however, is not statistically significant given the error of margin in our measurements of surface area. A more detailed study is underway on the role of late-lying snow in the TRIM photography and its role in potentially errant measurements of glacier extent change.

Author′s changes in manuscript: We have omitted 52% and changed this discussion to be more general: "The TRIM mapping included some late-lying snow as glacier, resulting in overestimation of 1985 extents in the TRIM dataset, by approximately 5%,

and thus led to more surface-area loss reported in the Bolch et al. (2010) inventory than we find for the 28 glaciers of this comparison. However, the average change that we observe during the epoch 1985-2005 for our study and that of Bolch et al., (2010) is not statistically different." Our ongoing work will further clarify this important concern. In the conclusion we have also adjusted the text, adding: "When uncertainties are taken into account, however the average difference between our subset and that of Bolch et al. (2010) is not significant." Comment from referee: Page 3380, lines 1–3: This is a key statement that should probably appear in the abstract. Author′s response: Author′s changes in manuscript: We have added this sentence to the abstract: "Our results also indicate that the 1985 glacier extent for the study area, reported previously by other studies, may be slightly overestimated due to errant mapping of late-lying snow cover."

Comment from referee Page 3381, lines 14–16: It is unlikely that there are any statistically significant trends in the annual or seasonal precipitation series, and the (very small) reported reductions are overwhelmed by the large inter-annual variability that exists.

Author′s response: Yes, we agree. Author′s changes in manuscript: We have added this to the end of this sentence: ". . . minor changes that are overwhelmed by large inter-annual variability."

Comment from referee: Page 3382, lines 4–5: This is arguable, as the period 1971–1985 includes more years that coincide with the warm phase of the PDO that began in 1976.

Author′s response: Yes, this is arguable.

Author′s changes in manuscript: We have added this to this sentence to clarify: ". . . or partially . . ."

Comment from referee: Page 3383, line 16: What is the meaning of "significant"? Should this be "statistically significant", or does this mean change beyond the mea-

surement error bounds?

Author′s response: Significant here is meant to be change beyond the measurement error.

Author′s changes in manuscript: We′ve replaced "significant" with "did not exceed measurement error."

Comment from referee: Page 3385, lines 18: The reference to DeBeer and Sharp (2009) does not belong here. That study did not examine relationships between the amount of area change and morphometric parameters, but did show that very small glaciers that underwent no observable net area change tended to exhibit certain types of characteristics.

Author′s response:

Author′s changes in manuscript: We have removed reference to DeBeer and Sharp (2009) here.

Comment from referee: Page 3385, lines 22–25: The relation between glacier slope and area change is probably not spurious. It may actually be a dominant factor over area and length, and is indicative of underlying physical controls influencing the geometric response of glaciers to climatic changes. This is something to explore further in the future.

Author′s response: Yes, it may actually be a dominant factor over area and length. However, we still contend that it "may be spurious". We agree that this is a topic for future investigation, but here our purpose is to indicate that there may well be confounding factors in this relation.

Author′s changes in manuscript: No changes made.

Comment from referee: Section 4.5 - Relations to Climate (Pages 3386 and 3387): The changes in the Climate WNA precipitation records (i.e. linear trends over time or

means for certain periods) are not pronounced, but instead show large interannual variability that overwhelms any changes in the means. The discussion on page 3386, lines 22–27 about how these changes may have influenced glacier behavior is weakly or unsupported by the data, and for the most part this is speculative. Most of the discussion in the second paragraph of page 3387 consists of fairly broad assumptions, and the potential counteracting role of any future increases in winter precipitation is not considered. Anecdotally, however,there have been some recent years in the nearby Rocky Mountains where the end of summer snow line has moved to the highest reaches of many glaciers, leaving most of the glacier's surface exposed, and these are indeed the conditions under which widespread and sustained loss of glaciers are likely to continue. Still, much of this discussion seems oversold as the climate variations shown in the study can only be associated in a very general way to the glaciers changes that have been observed.

Author′s response: Yes, we agree that our discussion of precipitation on page 3386 is speculative, particularly in light of the lack of any dominant trend and large interannual variability. We contend, however, that neglecting any discussion, or indeed speculation of the role of precipitation on glacier change in the Cariboo Mountains would be negligent. We agree that much of the second paragraph on page 3387 is built on broad assumptions and does not build on the primary findings of the study.

Author′s changes in manuscript: We have omitted the second paragraph, and the associated references, on page 3387.

Comment from referee: Page 3380, line 21: "Over the period 1952–1985 : : :" Is this a mistake? Should it be 1952–2005?

Author′s response: Yes, this is a mistake and should be 1952-2005.

Author′s changes in manuscript: We have changed the period to 1952-2005.

Comment from referee: Figure 12 (Page 3411): The figure could be improved by us-

ing a consistent scale, thereby making it easier to compare the magnitude of mean anomalies.

Author′s response: Our analysis shows both anomalies from the mean (colors) and contours (black lines) that denote 95% confidence limits of these anomalies. In other words, the areas within the black contours denote statistically significant anomalies. Though we agree that standardized anomalies would allow comparison among plots, it would not allow us to highlight regions were those anomalies are significantly different from the mean.

Author′s changes in manuscript: No change made

References

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, The Cryosphere, 7, 877-887, doi:10.5194/tc-7-877-2013, 2013.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/8/C2212/2014/tcd-8-C2212-2014-supplement.pdf

Interactive comment on The Cryosphere Discuss., 8, 3367, 2014.