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Discussions

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

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General Comments

This manuscript presents an analysis of changes in area for a subset of 33 glaciers within the Cariboo Mountains, British Columbia, over the period 1952–2005 and several shorter sub-periods within (1952–1985 and 1985–2005, as well as the additional sub-periods of 1952–1970 and 1970–1985 for 26 of these glaciers). The analysis is based on a comparison of glacier extents derived manually from digital aerial photos, providing higher confidence in the assessment of changes in comparison to changes derived from lower resolution satellite imagery. Photogrammetric techniques are used to measure the surface elevation changes for a subset of seven of these glaciers over the periods 1952–1985, 1985–2005, and 1952–2005. A rigorous assessment of the er-

ror associated with both area and surface elevation changes is provided. Net changes are then scaled up to the entire population of Cariboo Mountains glaciers based on 2005 glacier inventory characteristics from the study by Bolch et al. (2010). An assessment of regional climatic variations over the entire period is provided and insights are drawn on how these variations may relate to the observed patterns of glacier changes.

The paper is interesting for several reasons and is methodologically sound (although there are some minor issues raised below). The results, for the most part, should be considered very reliable and as such they provide some important insights into recent glacier changes in this region. These include a clearer understanding of the temporal variations in changes (many previous similar studies have included only net changes, which overlook short-term behaviour and responses), and demonstration of how the relationship between individual glacier changes and various morphological characteristics has varied here over time. Also of importance, this study clearly highlights how the misclassification of high elevation seasonal snowcover as glacier ice can lead to large uncertainties and errors in quantifying glacier change, which is a potential problem when using spectral classification or manual delineation techniques with lower resolution imagery. Detailed manual oversight and use of additional sources of information are thus important towards reliable regional glacier inventories and assessments of change. A significant result of the study is the difference in net area change found here in comparison to that for the same subset of glaciers over the same period (1985–2005) by Bolch et al. (2010). On page 3379, lines 21–23, it is noted: "Errant mapping of late-lying snow thus led to 52% more surface area loss reported in the Bolch et al. (2010) inventory than we find for the 28 glaciers of this comparison". The glacier changes for all of British Columbia and Alberta reported by Bolch et al. (2010), which were based on potentially unreliable ca. 1985 glacier extents mapped by the B.C. Terrain Resource Inventory Management (TRIM) programme, are becoming widely cited and accepted, yet the present study casts significant doubt as to their accuracy. The results of Bolch et al. (2010) may therefore need to be carefully revisited.

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. This is explained further in the specific comments below. 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.

Overall, this is a good paper that is worthy of publication in this journal. The paper would benefit from some revision to more prominently highlight and address the issues mentioned above. 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. 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. Otherwise, I do not see any major changes as being necessary. A number of more specific points are raised below that may help to improve the manuscript and the authors should consider these.

Specific Comments

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

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.

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?

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. 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. 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.

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?

Page 3380, lines 1–3: This is a key statement that should probably appear in the abstract.

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.

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.

Page 3383, line 16: What is the meaning of "significant"? Should this be "statistically significant", or does this mean change beyond the measurement error bounds?

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.

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.

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.

Technical Issues

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

Figure 12 (Page 3411): The figure could be improved by using a consistent scale, thereby making it easier to compare the magnitude of mean anomalies.

References

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