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The Cryosphere Discussions

Interactive comment on "Area change of glaciers in the Canadian Rocky Mountains, 1919 to 2006" *by* C. Tennant et al.

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This paper by Tennant et al. presents the area change of many glaciers in the Canadian Rocky Mountains between 1919 and 2006, using a novel approach whereby the glacier extents were digitized from georeferenced historical maps. The research is original, the error analysis rigorous, the paper generally well-written and the presentation concise. The figures and tables are overall of good quality and appropriate, but some need improvement and some can be removed. I agree with the comments and suggestions made by Mauri Pelto and Reviewer #1, and will not repeat their remarks, but may expand on some major issues.

Most of my comments are minor corrections and requests for more clarity. The more substantial issues concern the statistical analysis of the correlation between glacier

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properties, climate, and retreat rates; the extrapolation of area losses over the entire Canadian Rocky Mountains region; and the potential bias in glacier characteristics and spatial distribution introduced by the location of the historical maps and by the removal of ‘problematic’ glaciers. I suggest that once the authors have address these concerns, the revised paper will be suitable for publication in The Cryosphere. The results will contribute to increasing the understanding of regional scale response of different types of glaciers to climate change, and the methodology to refining the use of historical map and photographic data to extend the study of regional glacier changes beyond the era of satellite remote sensing (e.g. Andreassen et al., 2002; Bjørk et al. 2012).

SPECIFIC COMMENTS:

Title and abstract: Both need to be clear about the fact that area change was not measured for all glaciers in the Canadian Rockies: just 56% of the total number of glaciers on the IBCS maps were measured, and the maps were already a subset of the total glacierized area. Terminology such as “Total glacierized area decreased by 590$\pm$100 km2 (40$\pm$7 %)...” is somewhat misleading, as this is reduction of only a portion of the total glacierized area in the Canadian Rockies. Further, the extrapolation of the area loss rates through reconstruction of the 1919 area using the linear regressions should be clearly separated here and throughout the paper.

P2328-L13: “Absolute area loss negatively correlates with slope and minimum elevation, and relative area change negatively correlates with mean and median elevations.” This is confusing if we don’t know that an area loss is measured with a negative sign (see also P2338-L5-15). Clarify by restating: “Absolute area loss is larger for glaciers with low slopes and minimum elevation, while relative area change is larger for small glaciers with lower mean and median elevations.

P2328-L21: change ‘form’ to ‘morphology’

P2329-L10 Add a line including runoff contribution: e.g. Marshall et al (2011) quantify contribution from the eastern slopes glaciers, and Jost et al. (2011) and Jiskoot and

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Mueller (2012)from western slopes glaciers to the Upper Columbia River basin (∼25% the late melt season).

P2329-L15 Perhaps also add Moore & Demuth (2001) and Kienzle et al. (2012), as they present measurements.

P2330-L16-17: Delete: at least some spatial variation should be given as the study region is large and contains both windward and leeward aspects of a continental divide. See also comments on figure 2.

P2330-L25 Add Ommanney (2002) and Jiskoot et al (2009) here.

P2331-L2: Reference Ommanney (2002), as this is the only comprehensive review of the region's glaciers. Also, check the relative sizes of Columbia and Clemenceau icefields in the Bolch dataset: they may be very close in total area.

P2331-L7: Add a URL for Library and Archives Canada.

P2331-L22: Also report the error/accuracy of the source datasets?

P2331-L23: ..the features on the maps... This is rather vague. List some examples in brackets.

P2332-L2: Change 'We digitized..' to 'We manually digitized...'

P2332-L25:' .....missing terminus of a large glacier.' This is Wales Glacier, an important glacier as it is fed by 3 icefields: Columbia, Chaba and Clemenceau (see also Jiskoot et al., 2009: Fig 1)

P2332-L27: beyond the limits (plural)

P2333-L16-18: Only 56% of the original 937 flowsheds could be analysed for area change. Mention what the removal of the 'problematic' glaciers meant for the potential bias in glacier size and spatial distribution? Also add what percentage of original area was removed (e.g. on the basis of the available post 1919 areas)? More problematic is

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perhaps that the original coverage of the 1919 maps was mostly limited to the crown of the BC-AB border and the eastern slopes of the Rockies. Report what the glacierized area NOT covered by the 1919 maps was: looking at Fig 1 it could be > 25%. Most of the glacierized regions missed by the 1919 maps are on the west to southwestern slopes (e.g. the entire Clemenceau Icefield (∼300 km2: Jiskoot et al., 2009), which will certainly produce a bias in aspect and perhaps other glacier and climate properties (i.e. a more maritime climate). This makes the extrapolation of area loss (P2337-L8-29) problematic.

P2334-L5: I assume you calculated the arithmetic mean based on the DEM. Give a reference for the techniques used for elevation, slope and (mean) aspect, as especially the last two can have different approaches (e.g. Schiefer et al., 2008; Paul et al., 2009).

P2334-L21: What lapse rate was used? If this was not a monthly variable lapse rate (which generally takes into account winter inversions, which may occur about 25% of the time on the Eastern slopes of the Southern Canadian Rockies: Pigeon and Jiskoot, 2008) then this can result in large errors. See Shea et al. (2004) and Minder et al. (2010).

P2335-L22-25: Confusing phrasing "glaciers <1.0 km2 contained 49%", in the context of glacier numbers (previous line) and area (next line). Mention that this contains 3 bins of glacier sizes <1.0km2, and state if this is numbers or area.

P2336-L2: Report that this is in part the result of the location of the removed glaciers, which were mostly on the (south)western slopes.

P2337-L8-29: I concur with Mauri Pelto and Referee #1 (C1195) that the regression analysis to extrapolate area losses to the entire region is problematic, especially since each term is considered separately and interaction terms are not considered. Moreover, the explanatory and response variables are not independent (e.g. area-slope, area- minimum elevation). Interaction terms between the explanatory variables should be considered: e.g. mean slope and lowest elevation are generally correlated because longer glaciers have lower slopes and descend further. Considering interactions may lead to better understanding of the sensitivity of particular glaciers to climate change. Additionally, there is a clear aspect bias in the omitted glaciers (many omitted glaciers are W and SW-facing: Fig. 1), and perhaps size/other biases, so the extrapolation of area loss may not be valid for these regions. Mauri Pelto's comment of comparing your 1985-2001 Chaba Icefield region with Jiskoot et al. (2009), and then comparing this with the Clemenceau Icefield region rates (omitted in yours) may provide an additional error estimate of this regional extrapolation through linear regression.

P2338-L5-15: Write whether the correlations are positive or negative (additionally to strong/moderate, etc). Since you use the more negative rate as the larger loss I find this a little confusing to interpret. Also, I am a little surprised by the correlation of higher relative areal losses with lower median and average elevations. I would expect smaller glaciers to have higher mean and median elevations, but according to your results they are at lower elevations. Perhaps adding a scatterplot of glacier area versus the three elevations (Emin, Emean, Emed) may clarify this area-elevation distribution.

P2339-L14-15: Make clear that this loss is for 56% of the total glacier number. Also, change 'by' to 'in'.

P2340-L4-5: Jiskoot et al. (2009) is 1985-2001 so can be directly compared to your 1985-2000 and should be brought into the previous paragraph. Since their Chaba Icefield rates are comparable to yours, but not their Clemenceau Icefield group rates (not measured by you) this may be an argument for why your linear regression extrapolation of area losses into the unmeasured regions may not work as well as you argue (see also Mauri Pelto's 2337-13 comment).

P2340-L17-21: There are measurements of glacier retreat since the LIA maximum for some individual glaciers in the Rockies (e.g. Stutfield and Cavell Glaciers). These could be compared, almost directly, to your retreat rates, assuming there is not much retreat before 1919.

P2340-L29: Add reference that quantifies this effect from measurements or modelling (e.g. Jiskoot and Mueller (2012) on a Clemenceau Icefield outlet glacier).

P2341-Paragraph 5.2. This discussion is quite superficial and needs to be updated once a more thorough regression analysis is done. Clearly separate absolute and relative area changes (be clear for the referenced regions too).

P2342-L18: Figure 10 does not show how variable the climate was: See at Fig 10 below.

P2343-L1-24: This discussion is quite vague and could be improved in several ways once Fig 10 is updated. Further, the correlation between temperature and precipitation with PDO will need to include some more detail, with a cautionary note about the length of the last period (2001-2006). Line 20 should not be stated with such certainty since you have just argued that the 2000-01 area extent might have been overestimated. Estimated response times of the different glacier sizes/types may also help strengthening this discussion.

REFERENCES: Delete the page numbers of this manuscript after each reference.

TABLES AND FIGURES:

Table 3: I assume that the correlation was done with negative rate (the faster the change the more negative the rate). Mention this in the caption for clarity.

Fig 1: Change Fraser to ‘Fraser River Basin’ and Columbia to ‘Columbia River Basin’. Note in the caption or legend what year the blue glacier outlines are from. Are the parks (especially the provincial) really necessary? Especially the bright green takes away from the focus on the glacier outlines.

Fig 2: Not sure if this is such a useful/necessary figure in this paper. Taking the average over all glaciers does not say much over such a large area including both sides of a continental divide. Further, the snowfall amount frequency is not clear at all (snow pillow data may be better). Delete the figure, and the text does not depend on it.

Fig 5: It may be helpful to provide centrepoint latitude and longitudes and/or glacier names, for all 6 panel locations in the figure caption. Also, panels a, c, and e have black outlines, but b, d and f not.

Fig 7: I assume the disintegrated glaciers' area in 2006 are the sum of the fragmented parts. It may be interesting to do a statistical analysis of the difference in retreat rate between fragmented and non-fragmented glaciers (c.f. Jiskoot et al., 2009)

Fig 10: Update: this figure does not show how variable the climate was. It is also statistically confusing for the box plot periods to have different lengths. Instead, plot the seasonal accumulation/ablation season temperatures and precipitation as a line graph, and add a horizontal line for the average per studied period of area change.

Figs 6-10: This may be a personal preference, but I think it is clearer when the numbers on the y-axes read horizontally.

References used in review (excl. those in the Discussion paper):

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Interactive comment on The Cryosphere Discuss., 6, 2327, 2012.