The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-30-AC2, 2019

The Cryosphere Discussions
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EGU

Interactive comment on "Multi-year Evaluation of Airborne Geodetic Surveys to Estimate Seasonal Mass Balance, Columbia and Rocky Mountains, Canada" *by* Ben M. Pelto et al.

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Received and published: 14 May 2019

Author Response to RC2

Anonymous Referee #2

We thank the referee for their valuable comments and time spent on evaluating our manuscript.

RC2: DTM-related uncertainties:

RC2: Which interpolation algorithms have been used for DTM production? Please state in one paragraph!

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Discussion paper

Laser survey point density has been added to Table 2 for all ALS surveys. We added the following lines: “We post-processed point clouds and exported finished LAS files into LAStools (https://rapidlasso.com/lastools/) from which we used las2DEM to create 1 m resolution DEMs. Las2dem triangulates ground classified ALS points from las/laz files into a temporary triangulated irregular network (TIN). A DEM is then created from this using nearest neighbor interpolation. Given an average point density of greater than 2 points m-2 (Table 2), little interpolation was required.” L111-115.

RC2: The authors use the mean, median and normalized median absolute deviation (NMAD) of the DTM-differencing over selected stable terrain as “systematic” uncertainty (Biash). It is unclear through the manuscript, how overall hdDEM was determined? Please describe in more detail! Furthermore, is hdDEM the same as Biash? If so, please streamline through the manuscript!

hdDEM is the same as BiasΔh and should not have been included. We have removed all references to hdDEM. BiasΔh is “. . .the mean height difference over stable terrain between two DEMs after coregistration”. L129.

Elevation change uncertainty (σhΔDEM) was calculated as a 2σ uncertainty using Supplemental eqns. 1 and 2: “Elevation change uncertainty is derived from the σ of height change over stable terrain (σh) after correction for effective sample size (Neff)”. Lines 29-35 in S2.

Values of σhΔDEM for both Ba and Bw can now be found in Table S3.

RC2: The authors have stated not to use their gridded data for correction of their sample sizes for spatial autocorrelation (L103-104). Please state what was used instead (point cloud data?) and, if so, have the point cloud datasets also been co-registered beforehand? To calculate uncertainty in ALS-derived height change, the authors account for spatial correlation, assessed over stable terrain based on semi-variogram analysis as described in Rolstad et al. (2009). How did the authors determine h and what are the values of hdDEM Please describe in more detail and present the values in a Table

(also possible in Supplement).

Our wording was not clear. We use our gridded data to calculate effective sample size while accounting for spatial autocorrelation. The lines detailing this are in the supplemental information (S2), lines 28-37:

“Stable terrain generally covered 10-20 km2. We determined L by plotting semivariance (Figure S3) for randomly selected coordinate pairs (n=10,000) against distance for ten separate simulations and defined L as the distance at which semivariance becomes asymptotic (5% change threshold). Decorrelation length averaged 0.75 km and varied from 0.5 to 1.3 km”.

We have also further clarified our treatment of spatial autocorrelation directly in the manuscript: “To calculate uncertainty in ALS-derived height change, we also account for spatial correlation as assessed over stable terrain based on semivariogram analysis (Figure S3) as described in Rolstad et al. (2009).” L246-247.

Values of σhΔDEM for both Ba and Bw can now be found in Table S3.

RC2: Specific comments

RC2: L19: delete aiborne, redundant to ALS

Removed

RC2: L26ff: I recommend to align the references based on the date of appearance. Streamline through the manuscript.

The standard for The Cryosphere (Copernicus Publications) is alphabetical, as reflected throughout the manuscript.

RC2: L28: “‘Measurement of seasonal mass change provides: : :” , you mean in situ measurements or do you refer to all methods?

This was also pointed out by referee #1. We refer to both methods as either produces

results relevant to assessing meteorological drivers of glacier nourishment and melt. Revised:

RC2: “Measurement of seasonal mass change via in situ and geodetic methods provides a means to assess the importance of meteorological drivers of glacier nourishment and melt”. L36-38.

L35: Please rephrase sentence!

Corrected.

RC2: L37-41: This paragraph could be improved, giving a bit more substance!

Similar to the concerns raised by Referee #1, we substantially revised the introduction of our paper.

RC2: L51: abbreviation CBR has to be introduced earlier

This acronym is now omitted since we only used it once in the paper.

RC2: L68-71: Please indicate the extent of the major mountain ranges in Figure 1.

The major mountain ranges, the Columbia and Rocky Mountains are now labeled in Figure 1 and described in the figure caption: “The Columbia and Rocky mountains are separated by the Rocky Mountain Trench (RMT).

RC2: L69: try to omit redundant information, which improves readability: eg. rephrase sentence to (1) Zillmer Glacier (5.4 km2) in the Cariboo Mountains, (2) Nordic Glacier (3.4 km2) and (3) Illecillewaet Glacier (7.7 km2) in the Selkirk Mountains, (4) Conrad Glacier (11.5 km2) and (5) Kokanee Glacier (1.8 km2) in the Purcell Mountains, and (6) Haig Glacier (2.6 km2), which straddles the continental divide in the Rocky Mountains.

Excellent suggestion. We have reorganized as suggested.

RC2: L77: swatch change to swath

Corrected.

RC2: L82: Please state in one paragraph, which interpolation algorithms you used!

Addressed in an earlier comment.

RC2: L117: It would be helpful to describe what ‘snow course’ data is.

We have changed ‘snow course’ to ‘snow survey’ throughout the document, as this is the official name of the BC snow survey program. We have also added a reference (Weber and Litke, 2018) that details the methodology for the BC snow survey program. The data can be found at: https://catalogue.data.gov.bc.ca/dataset/705df46f-e9d6-4124-bc4a-66f54c07b228. We now introduce the snow surveys as ‘manual snow survey measurements’ and have added further description of these surveys:

“These snow surveys are conducted as part of the BC snow survey program eight times per year, with most sites located between 1000 and 2000 m asl”. L147-149.

RC2: L256: ‘glacier-wise’ is an unclear term, but used quite often throughout the manuscript. Is it possible to change to another more intuitive term?

Good suggestion, this term is unclear. We have removed all instances of ‘glacier-wise’. See line 302 for an example of a revision:

“Glacier averaged snow density from snow pits and cores for spring is 457 $\pm$ 48 kg m-3. . .”.

RC2: L281: omit hyphen in lower-accumulation

Removed.

RC2: L282: Which unit does 0.06 have? Think km2? I thought Haig glacier is not in the Columbia Mountains?

The value 0.06 was unit-less as it is the ratio of firn area to total glacier area, but we now use 6% for clarity, and have switched all ratios in the paragraph to percent for consistency.

RC2: We have added the following sentence to clarify the glacier locations relative to the Columbia and Rocky Mountains:

"Located in the Rocky Mountains, Haig Glacier is the easternmost site in our study and is in a lower accumulation environment. It has lost nearly all its firn cover over the last 20 years, with firn area at 6% in 2015. The study glaciers that lie in the Columbia Mountains had an AAR of 45% with 15% exposed multi-year firn cover and 40% bare glacier ice." L312-315.

RC2: L331: hdDEM is not in Table 3, see comment above

hdDEM is the same as BiasΔh and has thus been removed from the manuscript. BiasΔh is in Table 3, and we have added Table S3 which contains elevation change uncertainty (σhΔDEM), calculated as a 2σ uncertainty using Supplemental eqns. 1 and 2.

RC2: L373: 'In western Canada, onset of snow melt is occurring earlier on average relative to 1970-2006'. For what period is the onset of earlier snow melt occurring? Please give detrails.

We have removed this sentence from the manuscript.

RC2: L407-411: 'Our field operations have been impacted by the melting out of crevasses: as strongly negative years are becoming the norm, and glacier flux is likely decreasing, crevasses are exposed for longer periods of time, and slower to close. This means that the total void area of crevasses is increasing due to ablation, which we have observed on Conrad, Zillmer, Nordic, and Haig glaciers, which could possibly increase their influence on Bw.' This part is a bit unclear! What is meant with melting out of crevasses, please clarify. Which flux decreases (surface velocity or mass balance or both)? Give references of the source your assumption is based on! How was the increase of the void area of crevasses due to ablation observed? Can you detail this?

These lines have been removed from the manuscript. The authors feel that these lines add confusion and are a distraction. We have now added to the sentence leading into these lines which now reads:

“Despite the small influence of crevassing on Ba_geod observed in this study, additional studies should quantify the magnitude of this bias in greater detail”. L457-458.

What we intended to convey was that our visual field observations indicate that crevasses are being exposed (snow cover melted off) for a greater duration of the melt season than previously experienced. This extended exposure, tends to melt the sidewalls of the crevasses, widening the crevasses. After several years or decades of increased melt, many crevasses are merging to form ice-falls or serac fields that are difficult or impossible to navigate. This has implications for the safety and feasibility of travel during field work, but also for geodetic studies, as this likely increases the void area of crevasse fields, if not crevasse field extent. Ablation within crevasses is typically not captured by field studies, and may not be adequately captured in geodetic studies, depending on resolution and other factors.

As the length of the above explanation demonstrates, including these lines is a distraction from the goals of the manuscript, and while of scientific interest, our study has not taken steps to quantify these observations. Our primary goal was to highlight an area of uncertainty that future studies should tackle in greater detail, which the revised line above now does, without introducing a speculative discussion that we can add little to.

RC2: L426: The statement “Our glaciological measurement densities ranged from 0.5 to 18.5 points km-2 (Table 2), whereas our ALS data had around one million points km-2” is a bit of comparing pears with apples. Please discuss in more detail or omit!

Complete agreement here. This statement is unfair and has been removed. To discuss the relative strengths and weaknesses of each method, which this statement fails to do, is not the purpose of this section.

RC2: Figures: text is of variable font and size within figures. Especially on figures 4 and 7 the text is hardly readable

We have standardized our figure text font and size, and now text in Figures 4 and 7 is legible.

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