The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-30-AC1, 2019

The Cryosphere
Discussions
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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 RC1 on "Multi-year Evaluation of Airborne Geodetic Surveys to Estimate Seasonal Mass Balance, Columbia and Rocky Mountains, Canada" by Ben M. Pelto et al.

Anonymous Referee #1

We thank the referee for providing valuable feedback on our manuscript.

RC1: Specific comments The meaning of 'Glacier-wise' is unclear, but unfortunately used quite oftern throughout the paper. Please change to a 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 ± 48 kg m-3. . .".

RC1: Use 'our glaciers' should be changed to something less possessive like, 'glaciers in this study'.

We agree with this suggestion and have changed instances of 'our study glaciers' and 'our glaciers' to more appropriate phrasing such as: 'glaciers in this study', 'studied glaciers', and 'these glaciers'.

RC1: 279: Assuming that the exposed old firn occurs in the ablation zone, can you please provide an explanation as to how the overlying snow/firn/ice has ablated away without filling up the available pore space of the 'old firn' and leading to more internal accumulation than is accounted for in this study? this needs to be addressed as it also applies to your discussion on internal accumulation (L415-419) where it is similarly dismissed as insignificant.

This is a fair criticism. We now state in section 2.2.3:

"Firn meltwater retention and densification are neglected in our study."

We also added a discussion of meltwater retention renaming our section 4.1.2 Firn compaction, to 'Firn and internal processes'

"Internal accumulation within firn is not not incorporated into our annual balance estimates as it is not component of surface mass balance and is not measured within geodetic or glaciological surface mass balance studies. At Haig Glacier, firn meltwater retention has not been measured, but meltwater retention in the supraglacial snowpack is a negligible contributor to mass balance, though it does create an effective "energy sink", that should be accounted for in mass balance modeling (Samimi and Marshall, 2017). For glaciers in Svalbard, coupled energy balance and snow/hydrology models have been used to quantify the effects of meltwater freezing and retention on glacier mass balance (Van Pelt et al., 2012; Van Pelt and Kohler, 2015). Rates of meltwater retention are decreasing for Svalbard glaciers (Van Pelt and Kohler, 2015), and on the Devon Ice Cap (Bezeau et al., 2013), due to decreasing firn area and in particular, warmer temperature. Like at our glaciers, melt-freeze cycles form thick 'summer surface' layers on these Svalbard glaciers and Devon Ice Cap, which could act as a barrier for vertical water transport and is likely to promote near-surface lateral water flow, limiting deep firn water storage (Gascon et al., 2013; Van Pelt and Kohler, 2015)." L417-426.

RC1: Introduction doesn't justify this work well enough. Need to elaborate on the recent trends experienced by glaciers in western Canada as per menounous et al, 2018., and the potential impacts of declining contributions to stream flow post 2040ish as per Clarke et al, 2015. Contributions from glacier melt to sea level rise are of secondary importance from this region as it is poorly quantified as to how much actually makes it to tidewater and how much is taken up enroute through groundwater storage and human usage.

We agree with the reviewer that the importance of glacier mass change is more about water resources and much less about sea level rise. We revised the introduction to emphasize the importance of mass change on water resources.

RC1: L28-29 re: 'Measurement of seasonal mass change provides...' - I assume your talking about in situ mass balance measurements? if so, then should be specific about it - seasonal balances can be derived from more than just in situ meausrmeents –as you indicate below.

A fair point. Sentence is now modified to, "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.

RC1: L37-41: poorly written paragraph.

We refined this poorly written paragraph.

L50-51. "The climate of the Columbia Mountains is transitional between maritime and continental (Demarchi, 2011), with a strong maritime influence (Hägeli and Mc-Clung, 2003)." - So its more maritime then than continental? Would inner montane better describe the climate type here?

We have changed the sentence to: "The climate of the Columbia Mountains is transitional between maritime and continental (Demarchi, 2011). L72.

RC1: L55-56: Please give average snowfall rates and specify the source and what elevations they were measured at. This is probably the aspect of the climate that is the most important for this study.

An excellent suggestion. Please see the next comment response for average winter precipitation.

RC1: L64-65: please quantify differences - ie. average temp, snow precip, total precip, etc. describing the differences between climate regimes as "colder and drier.." is not very informative.

We now refer to climate normals from 1981-2010 for two nearby weather stations in the Columbia and Rocky Mountains. The text now states:

"From 1981-2010, Rodgers Pass, located in the center of the Columbia Mountains (Figure 1), at an elevation of 1330 m, has an average annual temperature of +1.9C, and an average winter (December-February) temperature of -8.0C, and experiences 1056 $\pm$ 49 mm w.e. of precipitation through the accumulation season (October-April) (Environment Canada, 2019)". L77-80.

"From 1981-2010, Lake Louise, located in the center of the southern Canadian Rockies (Figure 1), at an elevation of 1524 m, had an average annual temperature of +0.2C, an average winter temperature of -11.6C, and experienced 298 $\pm$ 9 mm w.e. of precipitation through the accumulation season. As evidenced by comparing Lake Louise and

Rodgers Pass, the Canadian Rockies are drier and colder in winter than the Columbia Mountains." L88-92.

While these two stations alone are not representative of their entire respective mountain ranges, they do quantitatively demonstrate the meteorological differences between the two climate regimes.

RC1: L68-71: please link glaciers to the Columbia and Rocky mountain ranges (described above) more clearly. An outline or some indication of the extent of each of the major mountain ranges in Figure 1 would be useful

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

"Haig Glacier is in the Rocky Mountains, whereas the other five glaciers lie in the Columbia Mountains". L99-100.

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)".

RC1: L77: indicate swath widths for each instrument/altitude.

We added swath widths for each instrument:

"The VQ-580 and Q-780 were respectively flown at flying heights of around 500 and 2500 m above the terrain that yielded swath widths of 500-1000 m and 2000-3000 m". L105-106.

RC1: L81: is there a systematic bias in error of the laser shots as a function of off-nadir angle? Ie., does accuracy of z degrade towards the swath margins?

A good point raised by the referee. Yes, off-nadir laser shots do have larger positional

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errors than nadir ones. We designed flight lines to have 53% overlap, and this overlap would tend to reduce off-nadir bias. Any bias introduced by this sampling should be captured in the height uncertainty that we calculate for the stable terrain. We have expanded lines 106-108 to clarify this:

"We planned laser surveys with 53% overlap between flight lines, to yield return point densities that averaged 1-3 laser shots m -2 (Table 2) with an effective sampling diameter of 10-20 cm per laser shot.". Point density has been added to Table 2 for all laser surveys.

RC1: L119: It would be helpful to add a sentence or 2 here 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.

RC1: L282-283: 'Excluding this site, the remaining study glaciers in the Columbia Mountains had an AAR of 0.45 with 0.15 exposed multi-year firn cover and 0.40 bare glacier ice.' - The way this is written it implies Haig is in the Columbia mtns, it is not.

Sentence is now modified to: "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." L314-315.

RC1: L282: I presume you mean the average AAR of the remaining glaciers in the Columbia mtns? If so, please edit.

See the above comment for the clarified sentence.

Line 279-283: Line 279-280 indicates firn/glacier ice extents as percentages (13% and 49%) while the same are expressed as ratios on 281 – 282. Need to be consistent.

We have switched all ratios in the paragraph to percent for consistency.

RC1: L373: ‘In western Canada, onset of snow melt is occurring earlier on average relative to 1970-2006’. Please clarify for what period the onset of earlier snow melt is occurring.

We have removed this sentence from the manuscript.

RC1: L387-389: the statement ‘We also chose not to apply a firn correction since it requires glaciological measurements that we purposely withheld in order to evaluate the feasibility of measuring seasonal balance without surface observations from the glaciers.’ Is vague. Please be more specific.

This statement has been removed from the manuscript. We initially chose to produce geodetic winter balance estimates only using the snow survey density to evaluate the feasibility of measuring seasonal balance without surface observations from the glaciers. However, we then used our in-situ densities to produce a separate geodetic winter balance estimate for each glacier to assess the impact of using in-situ versus regional density values (Table 3). The statement was attempting to convey that firnification models require an estimate of accumulation zone balance, which geodetic measurements, without correcting for ice dynamics, cannot provide.

RC1: L407-409: Re: ‘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. RC1: L408: ’ Please define the ’melting out of crevasses’. RC1: L408: What are you basing the assumption that flux is decreasing? Decreasing velocity or surface mass balance? Or both? If these assumptions are based on velocity changes, please indicate the sources used. RC1: L409-411: re: '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.' Can you expand on how this was observed? Was it measured? If so, how was it measured and over what period of time?

The lines referenced in the above four referee comments 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".

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.

RC1: L415-419: Methods to measure internal accumulation include repeat shallow ice cores and ground penetrating radar (Bezeau et al., 2013; Gascon et al., 2013). As the issue of internal accumulation has not properly been addressed in western Canada, particularly over the larger icefields where this process has potential to be significant, it is worth highlighting as an important knowledge gap concerning glacier mass balance in this region.

We agree with this comment. We have now highlighted this important knowledge gap and added discussion of this process in section 4.1.2 as detailed in a previous comment. See lines 417–426 for the added material.

RC1: L426-427: re: 'Our glaciological measurement densities ranged from 0.5 to 18.5points km-2 (Table2), whereas our ALS data had around one million points km-2.' This is an unfair concluding statement as the datasets have different limitations that are not fully discussed.

We concur with the referee here and have removed this statement from the manuscript.

RC1: L433-434 specify, ' as the melt season progresses: : :' ice layers may form as internal storage 'within the snowpack'

Amended as suggested.

Technical corrections RC1: Questionable use of hyphens throughout the paper.

Thank you for highlighting this issue. We have double-checked (sorry for the pun) our use of hyphens and corrected as requested.

RC1: L281: lower accumulation, no hyphen.

Hyphen removed.

RC1: L282: 0.06 add ' km2'

This was a ratio, and now is expressed as a percent.

RC1: Figures: text is of variable font and size – this should be standardized for all figures. Text is so small it is unreadable on figures 7 and 4

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

RC1: References: Bezeau, P, Sharp M, Burgess D, and Gascon G (2013) Firn profile changes in response to extreme 21st century melting at Devon Ice Cap, Nunavut, Canada, J. Glaciol., 59(217), 981-991 (doi:10.3189/2013JoG12J208).

Gascon G, Sharp, M, Burgess D, Bezeau P, and Bush ABG (2013) Changes in accumulation-area firn stratigraphy and meltwater flow during a period of climate warming: Devon Ice Cap, Nunavut, Canada. J. Geophys. Res.-Earth, 118, 2380-2391

Thank you for these references, in addition to (Van Pelt et al., 2012; Van Pelt and Kohler, 2015), these were very informative to read and better discuss firn processes.

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