Referee Responses

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Anonymous Referee #1 Received and published: 16 June 2020 Review of: Seasonal and Interannual Variability of Melt-Season Albedo at Haig Glacier, Canadian Rocky Mountains Submitted to The Cryosphere by Marshall and Miller.

Jing Ming (Referee) petermingjing@hotmail.com Received and published: 7 May 2020 Jing Ming Beacon Science & Consulting Melbourne, Australia Email address petermingjing@hotmail.com

The paper uses a long-term observation dataset of surface albedo in the Haig Glacier during the period 2002-2017 to depict the seasonal and Interannual Variability of Melt Season Albedo at Haig Glacier, Canadian Rocky Mountains. It is important to present this valuable dataset for developing any energy or mass balance model to project the evolution of the glacier. The tuning of the MB model is also a nice try. The paper is promising to be finally accepted by the Cryosphere from my point of view. However, before its formal acceptance, I want to address a few concerns here.

Thank you for your time and suggestions. We appreciate your thoughts on how to improve this manuscript. Please see below for our responses, in blue. Page and line numbers refer to the attached track-changes revised manuscript, not the TCD-formatted line numbering.

Specific comments:

1. The first paragraph of the Introduction part seems to describe the target of the work, which is more proper to be moved to the end of this part.

We rewrote this as suggested, and moved some of the specifics of this study (location, objectives) to later in the introduction.

2. Line 3-4. The sentence, "Variations in surface albedo, therefore, exert a strong control on the surface energy balance and available melt energy", needs a reference. Here is one by Ming et al. (2015) for your information. - Ming, J., et al. (2015). Widespread albedo decreasing and induced melting of Himalayan snow and ice in the early 21st century. PLoS One. 10: e0126235.

This and another reference from Oerlemans have been added here, p.2, l.14.

3. Line 4. "manuscript" -> "work" or "study".

Changed to "study" as suggested, p.3, l.23.

4. Line 44-51. This paragraph reads to be wordy and not well organized and needs to be rephrased.

We rewrote this to shorten some sentences and moved a bit of content to later in the introduction.

5. Line 44. The word "this" is not clear. Please clarify it.

"this" was deleted and we added "therefore", p.2, l.24.

6. Line 45-51. These two sentences are too long to read. Please rephrase them to several shorter sentences.

Rewritten; these sentences are now simplified, p.2, ll.25-30.

7. Line 97. Figure 1 had better incorporate a smaller map of the study area from a global perspective so that the readers could know where the study area is in the first sight. It is also beneficial to include the conditions of climatology for this area in the figure.

Sorry for the geographic assumption – we have added a larger map to indicate the area. We did not included climatology though – partly it is not known in the Rocky Mountains (e.g. monthly precipitation data is not really available, except in the valley bottoms where it is about 20% of what we measure on the glacier, based on the depth of the spring snowpack. Figure 1 has been revised to better indicate our study region within North America.

8. Line 97. “Albeta” -> “the Albeta province” or “the Albeta state” or “the Albeta city”?

Clarified: “provinces of British Columbia and Alberta”, p.4, l.8.

9. Line 101-102. “Snow surveys conducted on the glacier each May indicate a mean winter snowpack of 1.35 m water equivalent (w.e.) on the glacier from 2002-2017, with a standard deviation (σ) of 0.24 m w.e. (Table 1).” Is this original from this study or cited from other studies? If it is in the latter case, it needs a reference. I suggest using a simpler expression of 1.35 ± 0.24 m w.e. to replace the long one in the previous form.

Revised as suggested, for the standard deviation, p.4, l.16. We needed to introduce/define this here, so it is a bit wordy. These numbers are newly reported in this study, a slight update from Marshall (2014).

10. Line 105. Could you also add a standard error of the mean of the temperature after the number 5.3 âD˘ C?

Added as suggested, p.4, l.19. Although it is not standard error, but rather the standard deviation (i.e., the interannual variability).

11. Line 111-115. This paragraph ˘ could be incorporated into the measurement section, and the next as well, because two paragraphs are more like introducing the measurement and data collection.

Shifted into Section 2.2 as suggested.

12. Line 116. “The forefield AWS” -> “The AWS in the forefield”? This phrase appears a few times throughout the text.

We think it is permitted to use “forefield” as an adjective, similar to “glacier AWS” or “forefield environment”, but for clarity we have reworded this throughout the manuscript, e.g. p5, l.6.

13. Line 123. Please clarify what “the set of available in situ data” is.

We reworded this as well. We just mean the available data – the 79% of days from 2002-2015 with valid data (N = 1018), p.5, l.13.

14. Line 133-134. Here needs a more detailed description of how to do manual quality control and remove the questionable data, although the authors claimed that the data control had been introduced in Marshall (2014). The current is too simple to understand the method.

We added a few sentences to make this more self-contained, so that readers don't need to look this up elsewhere – thanks for this suggestion and we hope that it is now more clear, p.5, ll.3-8.

15. Line 135. "concentrates" -> "focuses" or "zooms in"? The usage of "concentrate" here seems to be strange.

Revised to "focuses on", p.5, l.29.

16. Line 135-136. The intent of the sentence is unclear, and please rephrase it.

Rewritten – we mean simply to define the variables and our notation here, p.5, l.30.

17. Line 136. "pragmatic" -> "virtual"?

Apologies, we have removed this word – it was unnecessary, p.5, l.31.

18. Line 137. "evolution" -> "variation"?

Clarified: seasonal evolution and interannual variation, p.5, l.31.

19. Line 142. "than" -> "from" or put "other" before it.

Revised to "from", p.5, l.38.

20. Line 150. Please clarify how you calculated out 7%.

Apologies, just from standard propagation of errors, and assuming 5% uncertainty in each of the incoming and outgoing radiation values: for z = x/y and uncertainties (dx, dy, dz),

dz/z = sqrt((dx/x)^2+(dy/y)^2) = sqrt(2*0.05^2) = 0.07

We add a short explanation, p.6, l.8, but don't include the equation in the text, as it is standard error analysis.

21. Line 157. The last sentence "modelling of potential reflected radiation from valleys walls indicates that this is negligible at our AWS site". Could you please present evidence of your claim?

This is a fair request. We have done the modelling as part of previous studies (Marshall, 2014; Ebrahimi and Marshall, 2016), but this specific result is not published and is ancillary to the focus of this study, so rather than include a Figure and the equations to explain this point, we have removed this sentence.

22. Line 159. "paper" -> "work". "repeat" -> "repetitive" or "repeated".

Revised to "study"; "repeat" deleted, p.6, l.20.

23. Line 161. "Haig Glacier albedo" -> "The albedo of the Haig Glacier".

Revised as suggested, p.6, ll.22-23.

24. Line 162. "points" (geometric concept) -> "sites" (geographic concept). Check that throughout the context.

Revised to "sites" as suggested. We consider it point data but it's true, we made multiple measurements over a few m^2, p.6, l.24.

25. Line 166. Was the sensor held manually? If so, how did you avoid the shadow of the body when measuring? Please clarify.

Yes, held manually, at arms length and pointed to the south to avoid shadows, p.6, l.33.

26. Line 167. Please give the detail of presuming a 10% uncertainty.

We added more detail on this. The manufacturer reported 5% accuracy, but we also observed fluctuations of a few 10s of W/m^2 while taking the readings of incoming shortwave radiation. e.g. for a value of 800 W/m^2, the instrument readings would bounce around between values of ~770 to 830 W/m^2. Readings of reflected shortwave radiation were much more stable. We therefore assign an additional 5% uncertainty in the observation itself, and add this to the instrumental accuracy to get what we consider to be a conservative estimate of 10%. Discussed on p.6, ll.34-38.

27. Line 169. "for melting and major ion and organic carbon analyses" -> "for the analysis of major ions and organic carbon". Please provide the source or references of the impurities used in this work.

These are detailed in Miller (2018), as cited. We are preparing a separate manuscript examining the impurities in detail, but with much of this beyond the focus of this study. That said, we recognize the importance of having the essential data that we refer to presented within this study, so we have added these results (Table 5) as well as essential details on the sampling and analysis, p.7, ll.4-14.

28. Line 176. "data" -> "temperature" and "precipitation"? Please specify them.

It is an energy balance model, so the full suite of meteorological data as described earlier. We now list this explicitly, p.4, ll.31-33.

29. Line 177. Please check the use of articles throughout the context. "forefield AWS data" -> "the data from the AWS in the forefield".

We deleted this part as it was redundant from the QC and gap-filling explanation in Section 2.2.

30. Line 191. What do you mean "the net energy goes to melting"? Please rephrase it.

We rephrased this as requested, p.7, l.35 – we mean that the energy is directed to melting.

31. Line 195. Give out the exact value of Lf (334 J g−1).

We don't systematically note the values of all of the established constants that are used in the energy balance model, but for clarity we added this here, as well as the density of water, p.7, l.39. Both values are standard but this does not distract too much from the flow of the narrative.

32. Line 240. Please clarify the definitions of a and b, respectively.

Regression coefficients – now defined, p.9, l.9.

33. Line 430. The first sentence needs to be rephrased. Do you mean "the impact of fresh snow on albedo"?

Rephrased for clarity, p.15, ll.18-20.

34. Line 450. "forced" –> "driven".

We see these as interchangeable in common usage, but revised to “driven” as suggested, p.16, l.7.

35. Table 1. Please clarify the definitions of summer and winter for this study in the caption or context.

This is now added to the text in Section 3.1, as the caption is already long and wordy. Our definitions are conventional for mid-latitude glaciers: winter accumulation is from the end of the previous melt season to the subsequent spring (i.e. the start of the next melt season), so roughly October to May at our site. Summer, glaciologically, refers to the melt season, roughly May to September at our site. The exact days vary from year-to-year and over the glacier.

36. Figure 2. Why didn’t the authors use the lines of means with shaded area indicating the error?

We think the reviewer is asking for a plot that includes the standard deviation of the measurements? We have added this in Figure 2a, but will leave Figure 2b as is to avoid clutter. Our intent with this plot was not to show the errors but rather then mean and minimum values associated with the 14-year observational record. i.e. the minimum here is not an error, but the lowest daily mean value recorded for that day over the 14 years. We have retained that, as it gives a clear indication of the “bare ice” season. But the inclusion of a shaded region for $\pm 1\sigma$ is useful additional information. Note that if the reviewer was actually requesting error bars, this is not what we have added here. These are very small for the average daily values: with an uncertainty of 7% in the mean daily albedo, the average over 14 years has an associated uncertainty of about 2%. (i.e. Or to be explicit from the quadrature rule for error propagation, for an example with $\alpha_s = 0.60 \pm 0.04$, we have $d\alpha_s = 0.04$ and N = 14. The error in the mean is $d\alpha_s/\sqrt{N} = 0.01$.)

37. Figure 7. The blue points denoting the snowpits are blur.

Thank you – we revised this to make them clear.

38. Figure 8. What about the significances between the observed and modelled?

It is inappropriate to compare the daily modelled vs. observed time series statistically, e.g. for correlation or R^2, as the stochastic model does not attempt to resolve the exact timing of specific snow events. This is a bit like weather vs. climate modelling. Our aim is not to represent a specific day, but rather the mean summer albedo value and the general seasonal evolution. The mean values can be compared through a standard t-test, and the observed vs. modelled variance can be compared with Bartlett’s test. The statistical tests indicate that the mean and variance are statistically equivalent ($p > 0.001$). We now report this, p.16, ll.21-25.

39. Figure 9. The same issue as that in Figure 8. Significance?

We now add the R^2 value and note the significance of the linear relation, p.17, ll.23-25. Good suggestion, thank you.

40. The language of the context needs a thorough check for grammar and misused words, such as articles, the function word “of”, ambiguous statements, etc.

We have read and edited carefully and believe that the text is in proper and clear English, but we welcome any additional specific comments where our writing is ambiguous.

Anonymous Referee #2 Received and published: 16 June 2020

Review of: Seasonal and Interannual Variability of Melt-Season Albedo at Haig Glacier, Canadian Rocky Mountains Submitted to The Crysphere by Marshall and Miller.

Major Revisions required.

Albedo measurements from in-situ weather stations are used to identify melt season albedo dynamics for Haig Glacier. The results are used to comment on the conventional application of degree-day melt rates and on how albedo describes glacier mass balance. C1 TCD Interactive comment Printer-friendly version Discussion paper These types of in-situ data driven papers are very important to the understanding of glacier dynamics and glacier mass balance, especially for mountain glaciers.

AU: We thank you for the time spent reviewing the manuscript and providing constructive suggestions for improvement. These are all helpful suggestions and we believe that we have been able to respond to these, leading to a better-organized and more clear contribution. Please see below for our point-by-point response, in blue. Page and line numbers refer to the track-changes copy of the manuscript.

The manuscript is well written with a logical presentation of material. I would suggest a minor re-organisation of the Introduction section to separate the literature review from specific mention of the study on Haig Glacier, as the sporadic reference to the study on Haig Glacier comes across as a bit disjointed. The final paragraph of the Introduction should be devoted to specific details regarding Haig Glacier. Specifically, how the study on Haig Glacier addresses the limitations related to glacier albedo and modelling.

We agree, we were jumping around far too much in an attempt to state the objectives of the paper in the opening paragraph. We have now reorganized as suggested, with the specific details of the study site and the aim(s) of the study in the final two paragraphs.

Abstract: The improvements related to the stochastic model on mass balance and the modification of the degree day model should be provided in more detail.

This is difficult with the limited space, but we have revised and added more detail here. This may need to be trimmed in the next round of revisions, as we are at 389 words for the abstract.

Line 11: Summer should be defined in the abstract (e.g., June 1 to August 31). Summer is defined on Line 104.

Thanks – JJA is now defined in the abstract.

Body of text:

Line 28: It is true that albedo is involved in the control of surface energy balance, but it is the net radiation (short wave and long wave) that mostly controls melt. Net radiation was previously mentioned, but a better description of how net radiation is related to albedo and what the proportion of shortwave to longwave radiation is, would be very useful.

This is true – it is net radiation that really matters, but with albedo as the main influence on melt-season variations in net radiation on mid-latitude mountain glaciers. It is a bit hard to compare the importance of net SW and net LW balances, as the latter is an energy sink. Hence we cannot say that X% of the melt energy is due to absorbed shortwave radiation and Y% from the net longwave. As a measure of this, we now report the correlation of each to the net energy that is available for melt, based on previously published data at our study site (Marshall, 2014). This interferes with the attempt to move all mention of Haig Glacier to the end of the introduction (per below), but it is relevant here and addresses this request to articulate the importance of albedo. Other references to Haig Glacier have been moved to the end of the introduction, as suggested.

We calculate the mean daily surface energy fluxes for the set of all summer (JJA) days reported in Marshall (2014), $N = 1012$. The average net energy, Q_N, is 101 W/m^2, with 79 W/m^2 from the net radiation, Q*, and 22 W/m^2 from the turbulent fluxes (26 W/m^2 from the sensible heat flux, Q_H, and –4 W/m^2 for the latent heat flux, Q_E). Net radiation accounts for 79% of the net energy that is available for melt. Within this, net radiation is dominated by net shortwave radiation in the summer months: 107 W/m^2, vs. –28 W/m^2 for the net longwave radiation. We also calculate Pearson's linear correlation coefficients, r, for net energy against each of the radiative fluxes and the albedo ($N = 1012$):

r (Q_N, SW in) = 0.39
r (Q_N, net SW) = **0.84**
r (Q_N, albedo) = **–0.81**
r (Q_N, LW in) = –0.09
r (Q_N, net LW) = –0.20
r (Q_N, net radiation) = **0.94** r (net radiation, albedo) = **–0.83**

These values are summarized in the introduction, although we tried not to get too bogged down in what feels like results (albeit from previously published data), p.2, ll.6-12. We also rewrote this to clarify that net radiation dominates net energy, but net shortwave radiation dominates net radiation in the summer melt season (with albedo being the main control of daily mean net shortwave radiation).

Line 29-30: Reference to Haig Glacier should probably come at the end of the introduction.

This sentence has been moved to the end as suggested.

Line 48-51: This sentence seems to be a bit misplaced and should be moved to the end of the introduction as a bridge between the literature review and the methods section.

True, our apologies. This was definitely out of place. Now moved to later in the introduction.

Line 64: Please define what a melt-albedo feedback is.

We added a sentence to explain this positive feedback, p.3, ll.8-9.

Line 69-71: Snow algae can be of many species (up to 4 or 5). Is there a reference for this material, or is it an observation from Haig Glacier? If it is an observation it would find a better home in the Results section.

This is just an observation from Haig Glacier, a common spring occurrence. In fact we don't know the species for certain, though I have been told it was *Chlamydomonas nivalis.* This comment was meant to make the reading more interesting but is not needed, so we have removed it in the event that we have the wrong species of 'pink algae'.

Line 76: A recent article in Remote Sensing of Environment might be of interest here: Williamson et al., 2020 - Comparing simple albedo scaling methods for estimating Arctic glacier mass balance.

Thank you – now cited, p.3, l.21. Happy to have this paper brought to our attention.

Line 78-79: This material might be better suited in the final paragraph of the Introduction.

Thanks, also moved in the rewrite.

Line 82: Can you provide more detail on what the "simplified parameterizations" entails?

We now refer to these explicitly as temperature index melt models, described in more detail in the abstract and in the lines above and below the sentence that was flagged, p.3, ll.33-41.

Line 111: Campbell does not make many instruments. The details for the instruments should be included (manufacturer and instrument), at the very least for the radiometric instruments, as different instruments are sensitive to different range of the EM spectrum.

This is a good request, for a paper focused on albedo. This information has been added, p.4, ll.36-42.

Line 119-120: Data collection ongoing has previously been mentioned.

Thanks, now deleted.

Line 124: If only one station is collecting data how was the lapse rate estimated? Please provide details.

Details now provided, p.5, ll.16-26. This is based on the 'climatological' mean lapse rates at this site (or really just offsets, with two points), calculated from the multi-year record for all days when both stations were working. This gives daily and monthly mean values for the offset, or one can calculate lapse rates from this for glacier-wide application.

Line 126: How much error is related to the estimation?

This is a good question. Where forefield data are available, which covers about 70% of the data gaps, error is small because we understand the relation well between the forefield and glacier AWS records. The stations are 2.5 km apart, although there are systematic (and seasonally-varying) offsets associated with the different environments: snow/ice vs. rock. Where both stations are missing data, we fill in with the average value for that day from the 'climatological' (historical) data for that day, the mean of available data from 2002-2015. The error can be quantified by applying the gap-filling procedure to estimate data for times with valid data. For interest: comparing observed temperature at the AWS site (as an example) to adjusted AWS data from the forefield gives an average error of –0.13°C (a small cold bias), while using the 'climatological' mean value gives an average error of –0.11°C. A similar analysis for specific humidity gives values of 0.15 g/kg and 0.16 g/kg, compared with a mean value of 3.3 g/kg: hence an error of 5%. These values are for the 30-minute data.

We don't present this because we don't use gap-filled data for the albedo values that are reported here (cf. p.5, ll.9-10) – only the days with quality-controlled in situ data are used for the albedo statistics and plots. That is the primary focus of this study. We do use the gap-filled data to drive the surface energy balance model, e.g., to evaluate the sensitivity of modelled melt to albedo. This is secondary to the main results and discussion, however. A formal error analysis could be done to propagate the error in temperature, wind speed, etc. through the surface energy balance equations, but this would be a tangent to the main points of the manuscript. Interestingly, I seldom see this in surface energy balance studies, i.e. assessment of uncertainty in the meteorological forcing and how this propagates through to errors in the surface energy fluxes.

Line 132: Define “questionable data”.

We expand on this now, p.5, ll.4-6 – physically impossible values, off-scale readings (-6999), and ‘flat-lining’ that we sometimes see if a sensor gets buried by snow in the winter.

Line 154: There is a recursive reflection from the bottom of optically thin clouds or from scattered clouds and a high albedo snow covered surface.

Yes, interesting, but this should be implicitly accounted for in the radiation measurements. The incoming radiation sensor would measure this reflection from the clouds and it would be twice-reflected from the glacier surface. This can lead to overestimates of both the incoming and outgoing shortwave radiation, but this should scale without major effects on the albedo. Small effects are possible by changes in the composition of diffuse vs. direct radiation, but we do not separate these in this study. As a side note, we did examine subsets of overcast vs. clear-sky days, and found no statistically significant differences in average snow or ice albedo on the glacier on these days.

Line 165: Please define Jaycar QM1582. What is the spectral range of this instrument?

This is just the brand name of the specific handheld pyranometer we used. Thanks – we now report the spectral range, which does differ from the Kipp and Zonen instruments. Caution is therefore needed in comparing these values with the AWS albedo records, but within the particular spatial surveys conducted in 2017, we can compare these values in space and in time (i.e. for the four repeat surveys). We add a note of caution on comparing with the AWS-measured broadband albedo, p.6, l.31 to p.7, l.2.

Line 221: “this” should be these.

Revised as suggested, p.8, l.27.

Line 245: The introduction mentions two AWS. It is not clear which station these results refer to. I assume from the data period this is the on ice station (upper ablation zone).

Sorry yes, all of the albedo results are from the glacier AWS – the off-glacier AWS is not helpful here, but is just used in this study for gap-filling of missing meteorological data for the energy balance modelling. We clarify here, p.9, l.17.

Line 284: “jump” might not be the best descriptor here.

We revised this to “increase”, p.10, l.29.

In Table 2 why is Em larger for August than July? Cloud cover – because Em is using only shortwave radiation?

No, Em also includes longwave radiation. All of the terms in the energy balance, per equation (1). Cloud cover is not the cause - it is in fact directly due to the lower surface albedo in August. Much more shortwave radiation is absorbed in August than in June or July.

Line 289: What type of regressions are these? Linear, least-square regressions, Pearson's? Are the correlations statistically significant? If so, which ones?

These are simple linear Pearson's correlation coefficients. Now stated. We also now indicate in the Table which values are statistically insignificant ($p > 0.05$).

Line 291: What does "correlated" mean in this instance?

Here we mean to say there is a statistically significant negative or positive correlation. This should now be clear from the explicit indication of this in Table 3. The discussion on pp.10-11, Section 3.2, has been revised accordingly.

Line 297: Define "fewer samples".

We specified the numbers but have rewritten through here: we have 14 years of data, 2002-2015, so N=14 for the mean summer conditions and their relation to the annual mass balance conditions. Within each year we analyze data from May through September, giving us 70 months. This sentence has been removed in place of a more clear discussion of sample size, p.10, ll.40-43.

Line 300: Define "melt out" or replace with better descriptor.

Revised to the more specific/technical term "ablate", p.11, l.13.

Line 309: Define "ripened and saturated"?

Revised to "wet, temperate" (at 0°C, with liquid water content), p.11, l.28.

Line 315: Some other citations that might be useful here, especially in the context of spatial variability of albedo. 1. B.W. Brock, I.C. Willis, M.J. Sharp. Measurements and parameterization of albedo variations at Haut Glacier d'Arolla Switz. J. Glaciol., 46 (2000), pp. 675-688 2. S.N. Williamson, L. Copland, D.S. Hik. The accuracy of satellite-derived albedo for northern alpine and glaciated land covers Polar Sci., 10 (2016), pp. 262-269

We were already citing the Brock et al. (2000) paper here, p.11, l.37. We prefer to stay with comparisons to direct/in situ, broadband albedo measurements here, but the Williamson et al. (2016) paper is very relevant to later sections where we discuss spatial variations and satellite measurements of albedo, so we have added this there, p.17, l.12.

Line 323: Describe the film, thickness composition, etc. Is there liquid water in the surface matrix? If so, what effect does this have on albedo? O.k., I see this is addressed on Line 335.

It's about a 1 mm film, with examples in Figure 4, although it is not a continuous film everywhere – in many places impurities are discrete particles, with varying density. Now noted, p.12, l.4. Like most mid-latitude mountain glaciers, the glacier surface is wetted during the summer melt season, but well-drained. Certainly these two effects – the impurities and wetness – contribute to the low values of ice albedo, as discussed, and the generally lower albedo of mountain glaciers compared to polar ice.

Line 325: Not clear where the values for Figure 5 are coming from, and provide how N=224 was derived.

This is for all bare-ice days in the 14-year record (i.e. when there was snow cover at the AWS site). N=224 is the number of days, derived by counting all days with albedo values less than 0.4 after the initial rapid drop in albedo (the snow to ice transition) that is clearly evident each summer (e.g., Figure 3b). We have edited to clarify this, p.11, l.31. The caption of Figure 5 is also revised.

Line 343: Adding year to the dates will reduce confusion.

We note the year now in introducing this discussion, p.12, l.27.

Figure 6: Mean values should have standard error included on the figure.

We added this for plot 6a. The mean multi-year values have very low standard errors: for a mean daily error of 7% and for 14 years, averaging reduces this to about 2%. Standard error (the uncertainty envelope, really), is higher for individual years, as plotted for the data from 2003 in Figure 6a. For Figure 6b, the mean daily value for each year, we don't plot this because errors are vanishingly small – these values are calculated from a mean over either 92 days (JJA) or 152 days (MJJAS) for each year. On averaging, the uncertainty in an error $d\alpha$ (7% for a mean daily value) is calculated from $d\alpha/\mathrm{sqrt}(N)$, so for JJA this is 0.7%, or 0.004 for an albedo value of 0.6. This is not easily visible on the plot. Note that we have interpreted this request as the reviewer's suggestion to plot the standard error where possible and relevant – we assume that the reviewer is referring to standard error, not standard deviation.

Line 376: "dropping" should be decreasing.

Revised as suggested, p.13, l.29.

Line 385: The values of ~0.1 and 0.07 are close enough that instrument error might render these inseparable?

We conservatively estimate the instrument error to be 10%, double that of the manufacturer-specified accuracy. By taking the average of three measurements, this is further reduced, to 8%. But even at 10%, this means 0.10 ± 0.01 and 0.07 ± 0.007: 0.10 and 0.07 are statistically distinct. We also measured the 7% albedo at 3 different sites (the lowest three points) on the centreline transect.

Line 395: Can evidence be presented that Haig glacier was indeed downwind of the forest fire smoke? For example, can specific fire events be linked to specific albedo declines for 2017? Without this link the material presented here is speculation.

In fact we also consider this to be speculation here, and tried to phrase it that way. That said, we were up on the glacier in thick smoke for many days (smelling of smoke, hazy skies with limited visibility, direct observations of it blowing in from the southwest). Winds on the glacier systematically blow in from the southwest (B.C.), funneled by the valley geometry. We also have wind direction data to support this. However, a thorough analysis of specific forest fire events, black/organic carbon provenance, and plume modelling is beyond the scope and focus of this study. We comment on this explicitly now, and make it more explicit that "we speculate…", p.14, l.9, and subsequent lines. We also note our direct observations of forest fire impacts during this period, as well as the indirect evidence through the increase in particulate concentrations, now included in Table 5.

Line 399: Which year?

2017, per this entire section – now noted

Line 400: Please present pertinent details for the data. The reader can't evaluate the data from an unpublished source.

This is a valid request – apologies not to include this earlier. We had cited the MSc Thesis of Miller (2018), which is available online and contains all of the details, but agree that it is helpful if the manuscript stands alone. We now present the data that we refer to in Table 5. Interested readers can find more detailed data tables and analyses in Miller (2018), but we now include the referenced data in this study. Additional supraglacial and meltwater chemistry data in Miller (2018) will support a separate publication on the supraglacial chemistry of Haig Glacier and its evolution through a melt season. As much of this is not essential and is ancillary to the current study, we present only the data that shows the large increases in impurities and carbon concentrations through the period of regional forest-fire activity in summer 2017, coincident with the observed decrease in ice albedo through this period.

Line 401: How is this "consistent"? Provide details, references or rationale.

Consistent in that forest-fire fallout would be expected to be carbon-rich, so-called 'brown carbon' as well as black carbon and soot (e.g., C.J. Williamson et al., 2020). But as this is results and not discussion, we removed this comment and now just present the observations and data, without commentary.

Line 407: I assume that algae assimilate carbon that was on the glacier before, or during, its growth. If this is correct, then the algae are a carbon flux and not a source per se.

This is partially true – they assimilate available nutrients – but they are also autotrophic, prolifically photosynthesizing and engaging in atmospheric carbon fixation. See e.g. C.J. Williamson et al. (2019), cited in the manuscript, as well as Yallop et al. (2012), Cook et al. (2012).

Yallop, M.L. *et al, 2012.* Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet. ISME J., 6, 2302–2313.

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Cook, J. M., Hodson, A. J., Anesio, A. M., Hanna, E., Yallop, M., Stibal, M., et al. (2012). An improved estimate of microbially mediated carbon fluxes from the Greenland ice sheet. *J. Glaciol.* 58, 1098–1108. doi: 10.3189/2012JoG12J001

Line 420: What does "reasonable" mean? Is this fit presented by the authors?

Good point, this is imprecise language. We do present statistical fits below, after the introduction of stochastic snowfall events. But for this occurrence, we have revised this sentence to remove this statement, p.15, l.5.

Line 428: What about heterogeneity of albedo? Albedo increases on a glacier as elevation is gained. What is the amount of variability in albedo for a surface that appears to be homogeneous?

We consider variations with elevation in sections 3.4 and 4.3. The albedo increase with elevation is not generally observed when it is all snow-covered (i.e. for up to 9 months per year in the Rockies), but is true in the summer melt season when lower elevations have exposed ice (e.g., Figure 7b). Also, for the exposed glacier ice itself, albedo increases with elevation have been reported elsewhere and are seen on Haig Glacier as well. This is associated with increasing concentration of impurities at lower elevations, and could be incorporated in Eq. (7) through the value of *k* if one had an idea of the spatial variability of impurities and their influence on snow albedo. But Eq. (7) does not refer to glacier ice, which is where impurity-driven spatial heterogeneity has been documents. Applied across a glacier, Eq. (7) does capture differing rates of melt (i.e. greater PDD at lower elevations) and these effects on albedo decline (wetting, recrystallization, the timing of the transition from snow to ice).

Line 432: “brighten” should probably be changed to increases the albedo to that of fresh snow (~0.85), before declining to seasonal normal values (over a given time period on the order of days).

Revised to remove ’brighten’ and use the language ‘increase the surface albedo’, p.15, l.19

Line 446: What does “some” mean in this instance?

Some has been removed, p.16, l.2 – you are right, not meaningful here. We also added a sentence to explain this more clearly as well, p.16, ll. 2-3 (i.e. random sampling of a normal distribution to introduce realistic variability in this value, vs. assigning a single value).

Line 453: “reasonable” should be described. What is the difference between the two?

Thanks – this was imprecise language again. We have revised to “is in accord with the observations”, p.16, l.10. We also statistically assess this now, per the comments of both reviewers, p.16, ll.20-25.

Line 455: What is the temperature control on snow fall events? Snow does fall when the surface temperature is > 0.

Yes, recognized, as it the air temperature (the column) and not the surface temperature that matters. Rain also falls at near-surface temperatures below 0°C. Snow is increasingly unlikely as temperatures increase, however, so we parameterize this simply based on a linearly-decreasing snow fraction fs from 1 to 0 between near-surface air temperatures Ta of –2 to 2°C. This uses mean daily temperatures. Now explained, Eq. (8), p.15, l.34.

Line 458: What does “this year” mean?

The year being discussed and plotted here, 2007 – now stated again on p.16, l.19.

Line 465: Why were five realizations chosen?

This was arbitrary. In putting together our statistics we increased this to 10 realizations. Each one differs a bit (e.g. Figure 7b), so it is better to include several realizations in the mean, but the values after just a few realizations converge and are representative of model results for a given set of parameters.

Line 468: I don’t remember seeing any run-off data?

True, we don’t report that here. Like most mountain glaciers, all summer ablation runs off, based on past studies and discharge measurements at this site, so we commonly equate these. But to be careful here, we have removed the reference to runoff, p.16, l.38.

Line 471: Please describe how this is a positive feedback. A warming atmosphere produces more rainfall events (instead of snow) at the glacier’s elevation. Rain further melts the glacier causing more rainfall events?

Thank you, good catch. Indeed this is not a feedback, although it excited albedo-melt feedbacks on the glacier. Wording changed that this would accelerate the melting, but of course without feeding back on the precipitation, p.16, l.42.

Line 525: Are there no observations of this behaviour on Haig Glacier?

To our knowledge, glacier albedo trends have not been detected or reported on Haig Glacier or in the Canadian Rockies. Only anecdotal impressions. One of our objectives in this study was to analyze this from our long-term observations, to provide the first assessment of whether albedo is declining. Happily for the glacier, we don't see any evidence of albedo declines over the study period, so we have to reject our null hypothesis that the glacier is darkening due to an extended period of negative mass balance.

Line 529: From which transect date?

This is from late summer, when the seasonal snow is gone and we are comparing ice with ice. Now clarified, p.18, l.28.

Line 536: This paragraph is mostly results and should be presented in the Results section. It is a bit problematic that the authors are relying heavily on unpublished data to interpret the albedo results. Are the unpublished results necessary?

Thank you, good comments. As discussed above, we had referenced Miller (2018) for the data, which is published on line and peer-reviewed, insofar as graduate theses have been vetted. But we agree that it is better to have the data presented here, so it is now included in Table 5 and discussed in the results. In the context here, we are going beyond results and talking about the potential for melt-induced concentration increases (vs. atmospheric deposition) – it is more discussion and interpretation than results. We have revised this paragraph though, to refer back to Table 5 rather than present new numbers/results here, p.18, l.37 to p.19, l.4.

Line 551: Upon what basis is this statement made? There is no observation station at lower station, yet the melt feedbacks are the strongest here. What exactly is the melt feedbacks and why is this plural?

Thanks, this was unclear as written. By "changes and melt feedbacks have been strongest here", we were referring to the mass balance and glacier thinning over the study period. The toe of the glacier has largely collapsed. But we don't have albedo data to comment on changes in albedo or whether the lower ablation zone is getting darker. We have rewritten this to specify that we mean "where glacier thinning and mass loss have been most extensive", p.19, ll14-15. We removed the discussion of melt feedbacks – plural because there are a few things happening, e.g. lower elevation = warmer and more melt; more exposed bedrock warms up and melts the glacier terminus more, though sensible and longwave fluxes; potential accumulation of dust and debris which warms up and melts the glacier more, etc. These are all known processes but we don't measure them or present data on these in this manuscript, so we have taken this out.

Line 578: Shouldn't start a new paragraph with "this".

Revised as suggested.

Line 582: Does water vapour pressure increase over the study period, or for that matter, any of the other environmental variables measured at the weather station?

We did not analyze this here, so won't introduce it in the conclusions and will keep the focus on the albedo measurements and modelling. There are increasing trends in summer temperature and melting/mass loss, though with a lot of interannual variability and so only weakly significant. There is no statistically significant trend in vapour pressure. This question concerns the glacier mass balance and weather trends, which are not the subject of this study, so we don't add this to the manuscript in the interests of keeping our focus. At this particular line, we are discussing how summer snowfalls (in general) impact the mass balance, not the trends in such events or in mass balance.

Line 590: What are the "ways" that you suggest?

Apologies, this would only be clear for those that read the results and discussion – it should be explicit in the conclusion (monthly factors or as a function of albedo), now stated, p.20, ll.21-23.

Figure 4: Including dates for the photos would be helpful.

To be honest, we don't know the exact dates, but also that is not important to the visual context that we wish to convey.

Figure 7a: No snow pits appear on the figure. The figure leads me to believe there are additional temperature measurements available.

We have revised the figure to better show the snowpits. It's true, there were three additional weather stations on the glacier this summer (Veriteq/Vaisala temperature-humidity stations), but we don't refer to these data so we have removed this from the plot.

Figure 8: The modelled values seem to reach a maximum at ~0.85. What is the reason for this? The observed data clearly achieves higher albedo values.

This is true – we set a maximum fresh-snow albedo of 0.85 in the summer snowfall model (as defined on p.15, l.10), but this is a free parameter that could be between ~0.75 and 0.9, looking at the data from Figure 8 as pointed out. Most of the fresh-snow events in August and the first two weeks of September that year are experienced by a rapid increase in albedo to values close to 0.8, whereas May snow events come in closer to 0.9. Our value, 0.85, is taken as an average fresh-snow value, not the maximum.

Figure 9: There are ~seven points in the above the trend line (f~7; albedo~0.7) that if removed would greatly improve the correlation. Can the author identify the origin of these points (i.e., a specific year, or month)?

This is interesting and we had thought about this, but cannot justify removing these points. Four of these occur in May, of various years. One is from June, two are from September. We don't observe anything special about these specific months, in terms of the temperature or other aspects of the meteorological conditions. These datapoints imply that there are certain times where there are high rates of melting per PDD even with high-albedo snow cover – degree-day factors of 7 are more typical of ice. A plot of just JJA conditions would give a stronger regression, but melt modelling needs to be inclusive of the shoulder season, May and September (e.g. melt totals in Table 2), so we retain these points, but can't explain what was different about these specific months. There is a fair amount of scatter at all albedo values in Figure 9 – the relation is significant but not as strong as we had hypothesized it would be ($R^2 = 44$, i.e. albedo explains only 44% of the variance in the melt factor, as discussed on p.17, ll.22-25).

Seasonal and Interannual Variability of Melt-Season Albedo at Haig Glacier, Canadian Rocky Mountains

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Abstract

In situ observations of ~~summer~~ summer (June through August, or JJA) albedo are presented for the period 2002-2017 from Haig Glacier in the Canadian Rocky Mountains. The observations provide insight into the seasonal evolution and interannual variability of snow and ice albedo, including the effects of summer snowfall, the decay of snow albedo through the melt season, and the potential short-term impacts of regional wildfire activity on glacier albedo reductions. Mean ~~summer~~ JJA albedo ($\pm 1\sigma$) recorded at an automatic weather station in the upper ablation zone of the glacier was $\alpha_S = 0.55 \pm 0.07$ over this period, with no evidence of long-term trends in surface albedo. Each summer the surface conditions at the weather station undergo a transition from a dry, reflective spring snowpack ($\alpha_S \sim 0.8$), to a wet, homogeneous mid-summer snowpack ($\alpha_S \sim 0.5$), to exposed, impurity-rich glacier ice, with a measured albedo of 0.21 ± 0.06 over the study period. The ice albedo drops to ~0.12 during years of intense regional wildfire activity such as 2003 and 2017, but it recovers from this in subsequent years. This seasonal albedo ~~evolution~~ decline is well-~~captured~~ simulated through a parameterization of snow-albedo decay based on cumulative positive degree days, but the parameterization does not capture the impact of summer snowfall events, which cause transient increases in albedo and significantly reduce glacier melt. We introduce this effect through~~, along with a melt model to estimate the timing of the snow-to-ice transition~~ a stochastic parameterization of s~~. S~~ummer ~~snowfall~~ precipitation events within a surface energy balance model. The amount of precipitation (from 1 to 10 mm) and the date of snowfall are randomly selected for each model realization, based on a pre-defined number of summer events, and precipitation phase (rain vs. snow) is determined from the mean daily temperature. This stochastic parameterization provides an improved representation of the mean summer albedo and mass balance at Haig Glacier. In addition, w~~ have a significant influence on albedo, and a stochastic parameterization of these events is shown to improve modelled estimates of summer albedo and mass balance.~~ e suggest m~~M~~odifications to conventional degree-day melt factors~~ are also suggested, ~~ to better capture the effects of seasonal albedo evolution in ~~climate, hydrology, and glacier mass balance models that use~~ temperature index or positive-degree day melt ~~methods~~models on mountain glaciers. Climate, hydrology, or glacier mass balance models that use these methods typically use a binary rather than continuum approach to prescribing melt factors, with one melt factor for snow and one for ice. As an alternative, melt factors can be based on the albedo, where this data is available from remote sensing, or monthly melt factors effectively capture the seasonal albedo evolution.

1

1. Introduction and Aims

Melting of snow and ice is driven by the net radiative, turbulent, and conductive energy fluxes at the surface. Observations indicate the primary role of ~~absorbed shortwave~~net radiation in driving snow and ice melt on mid-latitude glaciers (Greuell and Smeets 2001; Klok and Oerlemans 2002; Hock 2005; Marshall 2014). At Haig Glacier in the Canadian Rocky Mountains, net radiation provided ~80% of the net energy that was available for melt in the summer months (June through August, or JJA) from 2002-2012 (Marshall, 2014). Net radiation is dominated by net shortwave radiation in the summer melt season. ~~Variations in surface albedo therefore exert a strong control on the surface energy balance and available melt energy (e.g., Reijmer et al., 1999; Ming et al., 2015; Ebrahimi and Marshall, 2016).~~ For instance, in the Haig Glacier study noted above (Marshall, 2014), the linear correlation coefficient between daily mean values of net energy, Q_N, and net shortwave radiation is 0.84, compared with –0.20 for the net longwave radiation. The correlation coefficient between daily values of Q_N and albedo is –0.81 in this dataset ($N = 1012$). Variations in surface albedo therefore exert a strong control on the surface energy balance and available melt energy (e.g., Reijmer et al., 1999; Ming et al., 2015; Ebrahimi and Marshall, 2016).

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Mountain glaciers experience strong seasonal albedo variations, from ~0.9 for fresh, dry snow (i.e., the spring snowpack, at the start of the melt season), to ~0.5 for aged, wet snow or firn in mid-summer, to as low as 0.1 for impurity-rich glacier ice that is exposed after the seasonal snow has melted (Cuffey and Paterson, 2010). Albedo reductions through the melt season are due to recrystallization to larger, rounded grains, liquid water content in the snow, and increasing concentrations of impurities (Warren and Wiscombe 1980; Wiscombe and Warren, 1980; Marshall and Oglesby 1992; Conway et al., 1996; Gardner and Sharp, 2010).

A representation of seasonal albedo evolution is therefore important to accurate modelling of glacier melt (e.g., Brock et al., 2000; Klok and Oerlemans 2004). Where direct measurements of albedo are not available, the decrease in supraglacial snow albedo through the melt season is commonly parameterized as a function of snow depth and age (Wigmosta et al., 1994; Oerlemans and Knap, 1998; Klok and Oerlemans 2004). Alternatively, seasonal albedo decline can be ~~or~~ based on a proxy for cumulative melting, such as cumulative positive degree days (*PDD*) or temperatures above 0°C (e.g., Brock et al., 2000; Bougamont et al., 2005; Hirose and Marshall, 2013). ~~We consider the additional effects of summer snow events on mean melt-season albedo and introduce a simple stochastical method to represent their impact within an empirical albedo parameterization, based on a 14-year record of surface albedo observations at Haig Glacier in the Canadian Rocky Mountains.~~

Seasonal snow typically melts away by mid- to late-summer on mid-latitude glaciers, exposing low-albedo ice or firn ~~or glacier ice~~. The general trend of declining albedo through the summer melt season can be interrupted by snowfall events that temporarily increase surface albedo to fresh-snow values of ~0.9 (Oerlemans and Klok, 2003). High albedo values typically persist for a few hours to a few days, before the fresh snow melts away and the darker underlying-surface is re-exposed (Marshall, 2014).

A wide range of values for glacier ice albedo ~~values ~~is reported in the literature, from ~0.1 to 0.6 (Bøggild et al., 2010; Cuffey and Paterson, 2010). ~~ A wide range of ice albedo values is reported in the literature, from ~0.1 to 0.6 (Bøggild et al., 2010; Cuffey and Paterson, 2010). ~~Lower albedo values are mainly associated with high concentrations of particulate matter on the ice, which can accumulate over many melt seasons. Impurities on mountain glaciers are generally dominated by mineral dust (e.g., Oerlemans et al., 2009; Bühlmann, 2011; Nagorski et al., 2019), but include algae and cyanobacteria (e.g., Takeuchi et al., 2001, 2006; di Mauro et al., 2020; Williamson et al., 2019, 2020a), black carbon (soot) and other aerosols from incomplete combustion of fossil fuels, biomass burning, and forest fires (Ming et al., 2009; Keegan et al., 2014; de Magalhães Neto et al., 2019; Nagorski et al., 2019), and other long-range contaminants, such as volcanic dust and heavy metals (e.g., Zdanowicz et al., 2014).

Elevated concentrations of black carbon on glacier surfaces due to increased industrial and wildfire activity have been raised as a concern for glacier mass balance, due to their direct impact on albedo and through melt-albedo feedbacks (Ming et al., 2009; Dumont et al., 2014; Keegan et al., 2014; Mernild et al., 2015; Tedesco et al., 2016; de Magalhães Neto et al., 2019). This is a positive feedback because melting concentrates impurities, further lowering the albedo and increasing melt rates. Similar concerns have been raised about melt-albedo~~ and melt~~ feedbacks associated with algal activity on glaciers (Wientjes and Oerlemans, 2010; Stibal et al., 2017; Williamson et al., 2019; di Mauro et al., 2020~~)~~)). These processes are coupled, as microbial and algal activity require nutrients and meltwater, which increase in association with greater deposition and concentration of impurities, lower albedo, and longer melt seasons. ~~As an example of nutrient delivery, a classical ‘spring bloom’ of pink algae (*Chlamydomonas nivalis*) on a glacier can be triggered by walking on a clean, supraglacial snowpack with dirty boots.~~

In addition, mineral dust deposition on glaciers can increase in association with glacier retreat (Oerlemans et al., 2009), due to exposure of fresh sources of material on the glacier margin as well as melt-concentration effects. Impurities on glacier surfaces are also transported and removed by rainfall and meltwater runoff, as both dissolved and suspended sediment. ~~There is great interest~~It is important to understand and separate these influences on glacier albedo, to document whether albedo is changing in recent decades, and to quantify the potential impact on glacier mass loss (~~e.g., ~~Oerlemans et al., 2009; Dumont et al., 2014; Mernild et al., 2015; Williamson et al., 2020b).

This study examines the seasonal variability and multi-year trends in mean melt-season and glacier ice albedo from 14 years of surface albedo observations at Haig Glacier in the Canadian Rocky Mountains. ~~at Haig Glacier in the Canadian Rocky Mountains. ~~We discuss the processes governing albedo fluctuations, including the potential impact of regional wildfire on surface darkening at our site and the ~~Our particular focus is the impact~~nfluence of summer snowfall events, which ~~significantly reduce summer runoff at this site through~~introduce abrupt, transient increases in albedo~~. We~~. We quantify the ~~average frequency of these events ~~impact of summer snowfall events on albedo and mass balance at Haig Glacier and introduce a~~and their impacts on albedo and mass balance at Haig Glacier.~~ simple stochastic parameterization of summer snowfalls to effectively capture their influence in ~~ We introduce parameterizations of this process for ~~models of glacier energy and mass balance.

A final aim of our study is to examine ways in which the seasonal albedo evolution on mountain glaciers can be implicitly included in temperature-index melt models~~, and also suggest ways that the net effect of seasonal albedo evolution can be captured in simplified temperature-index melt models~~, which remain widely used in glaciology (e.g., Marzeion et al., 2014; Clarke et al., 2015; Maussion et al., 2019; Jury et al., 2020).

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~~We examine trends in melt-season and ice albedo at Haig Glacier and discuss the processes governing observed intra- and interannual variations.~~

~~This study examines the seasonal variability and multi-year trends in mean melt-season and glacier ice albedo at Haig Glacier in the Canadian Rocky Mountains. Our particular focus is the impact of summer snowfall events, which significantly reduce summer runoff at this site through abrupt, transient increases in albedo. We quantify the average frequency of these events and their impacts on albedo and mass balance at Haig Glacier. We introduce parameterizations of this process for models of glacier energy and mass balance, and also suggest ways that the net effect of seasonal albedo evolution can be captured in simplified temperature-index melt models, which remain widely used in glaciology (e.g., Marzeion et al., 2014; Clarke et al., 2015; Maussion et al., 2019; Jury et al., 2020).~~

~~We consider the additional effects of summer snow events on mean melt-season albedo and introduce a simple stochastical method to represent their impact within an empirical albedo parameterization, based on a 14-year record of surface albedo observations at Haig Glacier in the Canadian Rocky Mountains.~~

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~~A final aim of our study is to examine ways in which the seasonal albedo evolution of mountain glaciers can be implicitly included in temperature-index melt models. Models~~ Temperature-index models of snow and ice melt ~~frequently employ simplified parameterizations of melt~~can be necessary in mountain and polar environments where~~, where~~ essential meteorological data are neither readily available nor easily modelled (Hock 2005; Fausto et al., 2009). ~~Temperature-index or positive-degree-day methods are the most common approach, with melt parameterized as a function of temperature (e.g., Braithwaite 1984) or from a combination of temperature and potential direct shortwave radiation (Cazorzi and Dalla Fontana 1996; Hock 1999).~~ Snow and ice melt are calculated using a melt factor which linearly relates the amount of melt to cumulative positive degree days (Braithwaite 1984) and potentially other influences, such as incoming shortwave radiation (Cazorzi and Dalla Fontana 1996; Hock, 1999). Melt factors are generally taken as constants for snow and for ice, with a higher value for ice due to its lower albedo. This binary treatment of the melt factor does not realistically represent the continuous nature of surface albedo values or the systematic ~~seasonal~~ evolution of albedo ~~and melt rates on a glacier~~through the summer melt season. We ~~therefore~~ explore parameterizations of the melt factor that better capture the effects of the seasonal albedo evolution on ~~modelled~~ surface melt.

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2 Study Site and Methods

2.1 Haig Glacier study site

Glaciological and meteorological measurements at Haig Glacier in the Canadian Rocky Mountains were initiated in August 2000 and are ongoing. Surface energy and mass balance characteristics of this site are summarized in Marshall (2014). Haig Glacier is the main outlet ~~a moderate-sized (2.62 km^2) outlet~~ of a small icefield that straddles the North American continental divide between the provinces of British Columbia and Alberta (Figure 1). It flows southeastwards into Alberta, covering 2.62 km^2 and ~~and~~ span~~s~~ning an elevation range from about 2520 m at the terminus to ~~2750 m at the continental divide. Slopes reaching to~~ 2950 m ~~elevation feed into~~in the upper accumulation area. Local geology is dominated by steeply dipping beds of limestone ($CaCO_3$) and dolostone ($MgCO_3$).

The region has mixed continental and maritime influences, being fed by Pacific air masses that transport moisture to the Canadian Rockies (Sinclair and Marshall, 2009). Snow surveys conducted on the glacier each May indicate a mean winter snowpack (± 1σ) of 1.35 ± 0.24 m ~~m~~ water equivalent (w.e.) on the glacier from 2002-2017 (Table 1). The standard deviation~~, with a standard deviation (σ) of 0.24 m w.e. (Table 1). The latter provides~~ provides a measure of the interannual variability. Summer (June through August (JJA)) temperature on the glacier over the period of study averaged 5.3~~°~~ ± 0.8°C from 2002-2017. The site has warm, sunny conditions in the summer months, driving average summer melt totals ~~(± 1σ)~~ of 2.60 ± 0.62 m w.e over ~~this~~ the study period. Annual mass balance at the site has been negative in every year of the study (Marshall, 2014; Pelto et al., 2019), with the glacier losing all of its winter snow in 9 of 16 years. Mean annual mass balance over the glacier from 2001-2017 was –1.35 ± 0.24 m w.e., giving a cumulative mean thinning of about 24 m of ice over this period.

2.2 Field Measurements

Glacier albedo data and meteorological conditions are available from a Campbell Scientific automatic weather station (AWS) installed in the upper ablation zone of the glacier from the period 2001 to 2015. A second AWS was ~~also~~ installed in the glacier forefield in 2001, and remains operational (Figure 1). ~~The stations are maintained through an average of six visits per year, with sensors and dataloggers swapped out four times over the period 2001-2017, to be returned to the University of Calgary weather research station for calibration.~~ Each AWS was equipped with sensors to measure temperature, humidity, wind speed and direction, incoming and outgoing longwave and shortwave radiation, rainfall, barometric pressure, and snow/ice surface height. AWS data were stored at 30-minute intervals, calculated from the average of 10-second measurements. The instrumentation is described in more detail in Marshall (2014). This study focuses on the albedo data, which were measured with two different radiation sensors over the study period. From 2001 to 2003, each AWS was deployed with upward- and downward-facing Kipp and Zonen CM6B pyranometers, integrating over the spectral range 0.31 to 2.80 µm, with a manufacturer-reported accuracy of within 5% for mean daily measurements (first class rating from the World Meteorological Organization). From July, 2003 to present we shifted to Kipp and Zonen CNR1 four-component radiometers, with a spectral range of 0.35-2.50 µm for the shortwave radiation. The manufacturer-reported accuracy of the CNR1 is 10% for mean daily net radiation.

The ~~station~~AWSs ~~a~~were maintained through an average of six visits per year, with sensors and dataloggers swapped out four times over the period 2001-2017, to be returned to the University of Calgary weather research station for calibration.

~~AWS data are stored at 30-minute intervals, based on the average of 10-second measurements of temperature, humidity, wind speed and direction, incoming and outgoing longwave and shortwave radiation, rainfall, barometric pressure, and snow/ice surface height.~~ The AWS observations are subject to~~ a~~ manual quality control~~,~~ and any ~~and any questionable~~physically implausible data ~~a~~were removed from the analysis (i.e., values outside the normal range of conditions or a lack of variability, which occurs when a sensor is covered by snow). ~~The instrumentation and data are described in more detail in Marshall (2014).~~
~~The~~ The~~forefield~~ AWS in the glacier forefield has been in place continuously~~,~~ but ~~but~~ sensors can fail, the station was blown down once, and on two other occasions the station was buried by snow from the late spring through early summer. Hence there are occasional data gaps, but there is 92% data coverage for the summer period (~~June through August,~~ JJA) from 2002-2017. ~~Data collection is ongoing at this site.~~ The glacier AWS is more intermittent, due to the more difficult environment. It was maintained year-round from 2001 to 2008, but from 2009 to 2015 the station was set up only in the summer months. It ~~is~~ was established at the same site each year. Quality-controlled data represent 79% of JJA days from 2002-2015 ($N_{JJA} = 1018$).

~~Where~~ ~~G~~glacier albedo values ~~are~~ presented in this ~~manuscript~~study~~, they~~ are restricted to ~~the set of available in situ data~~the days with direct *in situ* values measured at the glacier AWS. For energy balance and melt modelling, missing ~~glacier~~ meteorological data on the glacier are estimated from ~~the forefield~~ the off-glacier AWS, adjusted ~~with transfer functions (i.e., lapse rates and regression equations)~~using monthly offsets ~~based on~~calculated from the set of observations that are available from both sites, as explained in detail in~~(~~ Marshall~~,~~ (2014). As an example, for mean monthly temperatures $T_G(m)$ and $T_{FF}(m)$ on the glacier and in the glacier forefield, the mean monthly temperature offset is $\Delta T(m) = T_G(m) - T_{FF}(m)$. Where there is missing temperature data at the glacier AWS at time t during month m, it is gap-filled following $T_G(t) = T_{FF}(t) + \Delta T(m)$. For wind speed, incoming solar radiation, and specific humidity, the offset is applied through a ratio rather than a difference. For instance, missing wind-speed data are gap-filled following $v_G(t) = v_{FF}(t) \cdot v_G(m)/v_{FF}(m)$. If data are missing from both weather stations, gap-filling is based on the mean multi-year value recorded at the glacier AWS for a given day. This ~~enables~~ provides a complete ~~estimate of~~meteorological forcing dataset for estimation of the summer energy and mass balance.

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This manuscript focuses on the long-term albedo record at the glacier AWS site. We define the incoming and reflected shortwave radiation to be $Q_S^{\downarrow}$ and $Q_S^{\uparrow}$, respectively, with albedo $\alpha_s = Q_S^{\uparrow}/Q_S^{\downarrow}$~~,~~. ~~**2.2 Field Measurements**~~

~~AWS data are stored at 30-minute intervals, based on the average of 10-second measurements of temperature, humidity, wind speed and direction, incoming and outgoing longwave and shortwave radiation, rainfall, barometric pressure, and snow/ice surface height. The AWS observations are subject to a manual quality control, and any questionable data are removed from the analysis. The instrumentation and data are described in more detail in Marshall (2014).~~

~~This manuscript concentrates on the long-term albedo record at the glacier AWS site, $\alpha_s = Q_S^{\uparrow}/Q_S^{\downarrow}$, for reflected and incoming shortwave radiation $Q_S^{\uparrow}$ and $Q_S^{\downarrow}$.~~ We ~~have 30-minute values for this, but our pragmatic interest in this study is~~ are interested in the seasonal evolution and interannual ~~evolution~~ variation of surface albedo and its influence on ~~and its influence on~~ glacier mass balance, so we restrict our analysis to daily and longer timescales. M~~, so we consider just m~~ean daily albedo~~,~~ is calculated from the integrated daily sum of incoming and outgoing shortwave radiation,

$$\alpha_{sd} = \frac{\int Q_S^{\uparrow} dt}{\int Q_S^{\downarrow} dt}. \tag{1}$$

Note that this gives different values ~~than~~ from the average of instantaneous albedo measurements, as it weighs the albedo calculation to the middle of the day, when insolation is highest. This accurately reflects the amount of shortwave energy that is available for glacier melt. It also means that we do not consider zenith angle effects on surface albedo in this study~~, and~~.

M ~~m~~easurement uncertainty is reduced through daily averaging. The CM6B and CNR1 radiation sensors ~~(Kipp and Zonen CM6B) integrates over the~~deployed at the glacier AWS have similar spectral ranges ~~0.31 to 2.80 µm, with a manufacturer-reported accuracy of within~~ and manufacturer-reported accuracies of 5 to 10% for mean daily measurements ~~(first class rating from the World Meteorological Organization), although~~. These values are conservative based on c ~~c~~alibration studies ~~-~~indicat~~e~~ing mean biases of ~~less than~~1 to 2~~1~~% for total daily radiation measurements with th~~is instrument~~ese two sensors (Myers and Wilcox, 2009~~)~~;~~.~~ Blonquist et al., 2009). ~~Given that o~~Our ~~installation is~~sensors are not maintained on a daily basis, however, and are~~is~~ ~~difficult to maintain an ideal horizontal platform~~not respirated or heated, so we~~, we~~ ~~take the conservative~~adopt an ~~estimate of an~~ uncertainty of 5% for the~~the~~ mean daily incoming and outgoing ~~daily~~ radiation. Propagation of errors for division gives an~~The~~ uncertainty ~~in~~ of 7% for the mean daily albedo ~~is then 7%~~ (e.g., 0.~~55~~ 60 ± 0.04 or 0.20 ± 0.01).

~~Other s~~Sources of uncertainty in the albedo measurements include deviations from horizontality for measurements of incoming shortwave radiation, multiple reflections from the undulating glacier surface, reflected radiation from valley walls, and potential covering of upward-looking sensors during snow events, among other effects. The quality control measures identify obvious environmental corruption such as times when fresh snow is covering the sensors or excessive station leaning, and data from these days are omitted from the analysis. The glacier AWS is located near the glacier centreline, more than 400 m from the valley walls, with minimal impact from reflected radiation. The station experiences topographic shading within one hour of local sunrise and sunset during the summer melt season, but none through the day.~~The valley walls are steep and free of snow from July through September; modelling of potential reflected radiation from valleys walls indicates that this is negligible at our AWS site.~~

Additional data are included in this ~~paper~~ study from summer 2017, based on ~~repeat~~ centreline surveys of albedo and chemical ~~analysis~~ analyses of supraglacial snow and ice. These data, described in detail in Miller (2018), provide an additional spatial perspective on albedo variation~~Haig Glacier~~, ~~albedo~~ as well as insights about the provenance and concentration of impurities on the ~~glacier~~ surface of Haig Glacier ~~and their association with albedo~~. Four surveys were conducted in July and August, 2017, at 33 ~~points~~ sites on an altitude transect that ~~approximating~~ approximates the glacier centreline (~~see~~ cf. Section 3 and Figure 7a). These measurements provide an indication of the variation in albedo with elevation on the glacier, its evolution over four different times through summer 2017, and the relation to supraglacial impurities.

For the spatial albedo surveys, measurements were only taken under clear-sky conditions and within three hours of local solar noon, to minimize the effects of diffuse radiation and high zenith angles. We used a Jaycar QM1582 portable pyranometer for these measurements, taking the average of three upward and three downward shortwave radiation measurements at each point. The sensor was held to the south at arms-length, at a height of ~1.1 m above the glacier surface for all measurements. The manufacturer-reported accuracy is 5%, but when measuring incoming shortwave radiation we observed considerable fluctuation in the reading, of order 10s of W m^{-2}. Fluctuations were within ±5% of the reading, but we take this as additive to the 5% error associated with instrumental accuracy, giving a total uncertainty of 10% for individual radiation measurements. With three measurements at each site, error propagation gives an uncertainty of 8% for the point albedo measurements. The spectral range of the handheld pyranometer is 0.3 to 4.0 µm. This extends further into the near infrared than the Kipp and Zonen instruments, and could bias the albedo to lower values. Caution is therefore needed in comparing values from this sensor with the AWS albedo data, although values are consistent at the AWS site. We only intercompare data from this specific sensor, and not against the AWS-measured albedo values, to avoid the problem of differing spectral windows.

Surface snow and ice samples were collected at every third point and were ~~bagged for~~ melt~~ing~~ed, bottled, and analyzed for major ion and ~~organic~~ carbon ~~analyses~~concentrations. ~~The impurity concentrations are referenced here but will be analyzed in detail elsewhere~~Samples were collected and melted in freezer bags and then transferred to 20-mL vials for transport to the University of Calgary, where they were analyzed in the Environmental Sciences program laboratory. For the ion analyses, 5 mL subsamples were run on a Metrohn 930 Compact Iron

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Chromatography (IC) Flex system, connected to Metrohm 858 autosampler. Concentrations are reported in mg L^{-1}, with precision and accuracy of 5% and a detection limit of 0.10 mg L^{-1}. Carbon concentrations of unfiltered glacier surface samples were analyzed on a Shimadzu TOC-V total organic carbon analyzer. For each sample, the machine measures the concentrations of total carbon and inorganic carbon (mg L^{-1}). The difference in these two values gives the concentration of organic carbon in the sample. Miller (2018) provides a complete summary of the chemical analyses.

~~; Miller (2018) provides a complete summary of the chemical analyses.~~

~~Albedo was only measured under clear-sky conditions and within three hours of local solar noon, to minimize the effects of diffuse radiation and high zenith angles. We used a portable pyranometer (Jaycar QM1582) for these measurements, taking the average of three upward and three downward shortwave radiation measurements at each point. The sensor was held at a height of ~1.1 m above the glacier surface for all measurements. Based on instrumental fluctuation and repeatability, we assign an uncertainty of 10% to individual radiation measurements. This giving an estimated uncertainty of 8% for the point albedo measurements.~~

~~Surface snow and ice samples were collected at every third point and were bagged for melting and major ion and organic carbon analyses. The impurity concentrations are referenced here but will be analyzed in detail elsewhere; Miller (2018) provides a complete summary of the chemical analyses.~~

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2.3 Energy Balance Model

We use a distributed surface energy balance model to examine the influence of seasonal and interannual albedo variations on glacier mass balance and summer runoff for the period 2002-2017 (Ebrahimi and Marshall, 2016). The summer melt model is driven by 30-minute meteorological data from the glacier AWS. We carry out a survey of the winter snowpack each spring, typically in the second week of May, and use ~~this~~ the winter mass balance data as an initial condition for the simulation of summer mass balance. ~~The summer melt model is driven by 30-minute data from the glacier AWS; where these data are lacking we drive the melt model with forefield AWS data, mapped onto the glacier through transfer functions that are well-calibrated from the overlapping data records (Marshall, 2014). Four-component radiation measurements,~~Following Ebrahimi and Marshall (2016), the radiation data, ~~-~~parameterizations of the turbulent fluxes,~~,~~ and a subsurface model of snow/ice temperature and heat conduction ~~(Ebrahimi and Marshall, 2016) are combined to~~provide~~ calculate~~ the net surface energy flux, Q_N:

$$Q_N = Q_S^{\downarrow}(1 - \alpha_S) + Q_L^{\downarrow} - Q_L^{\uparrow} + Q_H + Q_E + Q_C, \tag{2}$$

where $Q_L{}^{\downarrow}$, $Q_L{}^{\uparrow}$, Q_H, Q_E, and Q_C represent incoming and outgoing longwave radiation, sensible and latent heat flux, and subsurface conductive energy flux, respectively. All energy fluxes have units of W m^{-2} and are defined to be positive when they are sources of energy to the surface.

Turbulent fluxes of sensible and latent energy are parameterized from a bulk aerodynamic method (Andreas, 2002~~; Ebrahimi and Marshall, 2016~~) and surface temperature and conductive

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heat flux are ~~internally~~ modelled within a subsurface snow model that includes meltwater refreezing ~~, which includes calculations of meltwater percolation and refreezing~~ (Samimi and Marshall, 2017). When Q_N is positive and T_s = 0°C, ~~the~~ net energy ~~goes~~ is directed to melting, with melt rate

$$\dot{m} = \frac{Q_N}{\rho_w L_f}\,, \qquad (3)$$

where ρ_w = 1000 kg m^{-3} and L_f = 3.35 × 10^{5} J kg^{-1} are the density and latent heat of fusion of water. Melt rates have units m w.e. s^{-1}. By integrating over the times when melt occurs (i.e., when $Q_N > 0$ and T_s = 0°C), one can calculate the total melt energy, E_m, over a period of time τ, with units J m^{-2}. Melt over time τ is then calculated from

$$m(\tau) = \frac{E_m}{\rho_w L_f}\,. \qquad (4)$$

This can be directly related to the classical positive degree day method (e.g., Braithwaite 1984), where snow or ice melt m over a period of time τ is calculated from

$$m(\tau) = \cancel{f}d_{s/i}\int_0^{\tau} \max(T, 0)\, dt\,, \qquad (5)$$

where ~~f~~$d_{s/i}$ is the degree-day melt factor for snow or ice. This linearly relates the amount of melt to cumulative positive degree days (*PDD*) over time τ. The integrand can also be modified to include other influences, such as the potential direct incoming shortwave radiation (Hock, 1999).

Eq. (5) is an empirical alternative to the physically-based approach in Eq. (4). It is ~~sometimes helpful because~~useful because surface energy fluxes are uncertain in the absence of local AWS data, due to poorly-constrained meteorological input variables. Wind, humidity, cloud cover, and radiation fields are difficult to estimate in remote mountain terrain. Eq. (5) requires only temperature, which can be estimated via downscaling or interpolation of regional station data or climate model output. While appealing, it is recognized that this parameterization is over-simplified with respect to its transferability to other locations or times. For instance, there is no direct way to incorporate influences from meteorological variables other than temperature, and melt-albedo feedbacks are not physically represented where ~~f~~d_s and ~~f~~d_i are taken as constants.

~~Most t~~Temperature-index models commonly approximate ~~this seasonal evolution~~albedo effects ~~to first order~~ by using different melt factors for ice and snow~~; ~~. T~~t~~ypical values are ~~f~~d_i ~ 6-9 mm of water equivalent melt per degree day (mm w.e. °C^{-1} d^{-1}) ~~, while~~and ~~f~~d_s ~ 3-5 mm w.e. °C^{-1} d^{-1} (Braithwaite, 1995; Jóhannesson, 1997; Hock, 2003; Casal et al., 2004; Shea et al., 2009). There is considerable local, regional, and temporal variability in the parameters chosen for different studies, with values sometimes twice as high as ~~this~~these, particularly for glacier ice (see Hock, 2003). Lefebre et al. (2002) also find a large spatial variation in melt factors, through modelling studies of melt patterns in Greenland. This variability is associated with differences in the energy balance and surface conditions that drive melt, much of which may be due to variations in surface albedo.

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For regions where melting is the dominant process in glacier ablation (cf. Lett et al., 2019), one relatively simple way to improve on temperature-index models is to permit melt factors to vary in space and time, consistent with spatial and temporal variations in net energy and glacier albedo (Schreider et al., 1997; Arendt and Sharp, 1999). For melting over time τ, one can combine Eqs. (4) and (5) to derive an expression for the melt factor at any location (*x*,*y*):

$$\cancel{f}d(x, y, \tau) = \frac{E_m\,(\tau)}{\rho_w L_f \int_0^\tau \max\,(T,0)\;dt}\,. \tag{6}$$

Eq. (6) implicitly includes the seasonal evolution of surface albedo, as an important control on the melt energy, but numerous other meteorological influences are embedded in E_m, so there is not a direct relation between d~~f~~(*t*) and $\alpha_S(t)$. Because absorbed shortwave radiation is the dominant term driving ablation of mountain glaciers (Greuell and Smeets, 2001; Klok and Oerlemans, 2002), including Haig Glacier (Marshall, 2014), one can expect that $E_m \propto 1/\alpha_S$. Moreover, melt energy is proportional to *PDD*, such that the numerator scales with the denominator in Eq. (6). Hence, it should be possible to develop a simple parameterization which includes the lead-order effects of surface albedo on the melt factor. We use Eq. (6) to calculate ~~the~~daily and monthly mean values ~~seasonal evolution~~ of the melt factor, ~~f~~d(*t*), at the Haig Glacier AWS site. A c~~A c~~ompilation of monthly mean values of ~~f~~ d and α_S ~~then~~ informs a relation ~~f~~ d = ~~a – bf~~ (α_S) which ~~can better~~ represents the seasonal ~~and spatial~~ evolution of melt factors, ~~where~~ if albedo is known or can be estimated (e.g., Williamson et al., 2020b). We consider different forms of this relation, but the simplest model is a linear parameterization $d(t) = a - b\alpha_S(t)$, for linear regression coefficients *a* and *b*.

3. Results and Analysis

3.1 AWS Albedo Measurements, 2002-2015

Table 1 gives summary statistics for the observed Haig Glacier mass balance, net energy, and mean summer albedo at the glacier AWS site from 2002-2015. The winter mass balance is measured from snow surveys each May, and represents the snow accumulation from the end of the previous melt season (typically mid-September) through to May, averaged over the glacier surface. The summer mass balance is defined as the average glacier-wide mass change over the summer melt season, which typically runs from mid-May to mid-September. The specific dates vary from year to year and across the glacier. Positive degree day and melt totals are presented for the complete summer melt season, May through September, and temperatures, energy fluxes, and albedo values are given for the core summer months, June through August (JJA), when more than 80% of the melt occurs.

Table 2 reports the mean monthly values at the glacier AWS site for the 14-year record.

The mean JJA surface albedo at ~~the AWS~~this site is 0.55, with a marked ~~decrease~~ decline through the summer months and a minimum of 0.38 in August (Figure 2a). ~~The~~ Because the

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AWS ~~site~~ is installed in the upper ablation zone of the glacier, ~~and~~ seasonal snow gives way to bare glacier ice at some point in late summer. This is attended by a sharp drop in albedo, to the bare-ice value of 0.21 ± 0.06. Mean August albedo values represent an average of aged, wet snow and bare ice, with year-to-year variability associated with the timing of seasonal snow depletion. The average date of seasonal snow depletion at the AWS site is August 3, but it ~~ranging~~ ranges from July 21 to August 20 over the study period. New snow accumulation at the AWS site (‘winter snow’) begins in September in most years, accounting for the albedo increase this month (Table 2). Persistent snow began to accumulate at the AWS site between August 30 and September 25 during our study period. On average, there are 25±10 days with glacier ice exposed at the AWS site during the melt season. The site was selected because it is near the equilibrium mass balance point of the glacier: the elevation at which annual snow accumulation is equal to summer melt, for the glacier to be in balance. The observations of bare ice exposure are consistent with the persistent negative mass balance of the glacier over the period of observations.

Intermittent summer snow events also temporarily refresh the glacier surface (*e.g*., Figure 2b), reducing the number of snow-free days on the glacier surface. The average melt-season albedo evolution at the site in Figure 2a averages out the impact of episodic summer snowfall events that refresh the snow or ice surface (*cf*. Figure 4d). As seen in Figure 2b, these cause an immediate increase in albedo to a fresh-snow value of ~0.9, followed by a decay back to the albedo of the underlying surface over the course of hours to a few days. Figure 3 provides a more detailed illustration of summer snowfall events over exposed glacier ice. This plot covers the period August 3-28, 2015, during which there were three distinct summer snow events, each of which increased the surface albedo for two to three days. The events can be predicted somewhat from the meteorological conditions, where temperature drops below 0°C and relative humidity reaches 100% (Figures 3a,b), but they are most clearly evident in the albedo record (Figure 3c). The accumulation of new snow is also apparent in the glacier surface height (SR50) data (Figure 3d), attended by an interruption in surface melting.

Even a modest amount of fresh snow has a strong albedo impact; there were roughly 4 cm of accumulation in the first two snow events and 8 cm for the third event in Figure 3. The latter event had a longer impact, roughly three days before the surface albedo returned to values typical of bare ice. Total surface ablation at the AWS site was 1.05 m over this 25-day period (Figure 3d), equivalent to about 0.95 m w.e. Based on the observed bare-ice vs. actual average albedo values over the 25-day period, 0.15 vs. 0.27, we calculate that the snow events reduced the average net energy by 24 W m^{-2}, equivalent to 0.16 m w.e. or a 17% reduction in melting over this period. Hence, the direct impact of summer snowfall on glacier mass balance is generally minor (estimated at ~0.03 m w.e. for the events in Figure 3), but the indirect impact through increased albedo and reduced melting is important.

Based on analysis of the SR50 and albedo data over the full study period, an average of 9.3 ± 2.6 ephemeral snowfall events per year occurred at the AWS site from May to September. This included 6.3 ± 2.2 summer (JJA) events. Our main criteria to identify summer snowfall events is a mean daily albedo ~~jump~~ increase of at least 0.15. This may not capture trace precipitation events that are too minor to be seen in either of the SR50 or albedo measurements (i.e., too ephemeral or not enough snow to mask the underlying surface), but these small events have limited impact on the mean summer albedo or mass balance.

3.2 Relation Between Summer Albedo and Mass Balance

The broader relations between glacier mass balance and albedo, summer snow events, and temperature at the Haig Glacier AWS site are summarized in Table 3. The bottom left portion of the table shows Pearson's linear correlation coefficients for monthly mean values of all variables (N=70~~0~~), while the ~~top right~~ section above the diagonal shows correlation coefficients for the mean ~~gives mean values for the~~ summer ~~melt-season~~(JJA) values and ~~and annual~~the winter and annual mass balances (N = 14). Values that are not statistically significant at the 95% confidence level are shown in brackets. With the small sample size for the mean summer/mean annual variables, statistical significance requires $|r| > 0.53$. The greater number of months that are sampled permits a lower threshold for significance, $|r| > 0.23$.

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Most variables in Table 3 are significantly correlated, with numerous interactions.~~, but the~~ The importance of albedo ~~is clear~~to melt and mass balance conditions is clear. Monthly mean albedo is highly correlated with monthly melt (r = –0.~~89~~88) and net energy (r = –0.84), in addition to strong negative correlations with other melt indicators such as mean monthly temperature and *PDD* (r = –0.73~~4~~). Monthly albedo values are also significantly correlated with the optimal monthly degree-day melt factor calculated from Eq. (6) (r = –0.66), which we discuss further in Section 4.2.

Correlation coefficients for the mean summer conditions are generally weaker~~, though there are fewer samples so these statistics are less robust~~. Mean melt-season albedo remains strongly correlated with summer and net mass balance ~~(melt)~~, net energy, and temperature, but is ~~only weakly~~on-ly weakly associated with winter mass balance and total melt-season *PDD*. ~~The influence of w~~Winter mass balance ~~is also evident through positive correlations with~~is expected to impact the summer -albedo, ~~and net mass balance;~~as deeper snowpacks take longer to ~~melt out~~ablate, delaying the transition to the low-albedo summer surface, but this is not as strong an influence as the summer melt conditions at Haig Glacier. In contrast, m~~M~~ean summer albedo is ~~also positive~~significantly correlated with the number of summer snow events (r = 0.66). Summer snow events have a significant overall influence on the summer and net mass balance (r = –0.73 and r = 0.70, respectively). Due to the~~se~~ compounding influences, mean summer albedo has a ~~strong~~ high association with net annual mass balance (r = 0.86). This is stronger than the correlation between mean summer temperature or *PDD* on net annual mass balance. ~~The influence of winter mass balance is also evident through positive correlations with albedo and net mass balance; deeper snowpacks take longer to melt out, delaying the transition to the low-albedo summer surface. Mean summer albedo is also positively correlated with the number of summer snow events (r = 0.66). Due to these compounding influences, mean summer albedo is highly correlated with net annual mass balance (r = 0.76). Summer snow events have a~~

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~~significant overall influence on the summer and net mass balance ($r = -0.73$ and $r = 0.70$, respectively).~~

3.3 Ice Albedo Values

The progressive decline in glacier surface albedo through the melt season has been reported in many previous studies (e.g., Brock et al., 2000, Klok and Oerlemans, 2002, 2004). Within the seasonal snow, this can generally be related to cumulative melting, with its associated effects on snow grain size, liquid water content, and increasing concentration of impurities (Warren and Wiscombe, 1980). We discuss modelling of this seasonal evolution in Section 5. At Haig Glacier~~,~~ the wet, ~~ripened~~ temperate ~~and saturated~~ July snowpack typically asymptotes ~~at~~ to an albedo value ~~values~~ of ~~about~~ ~0.5, before surface albedo drops sharply to a value of ~0.2 once bare ice is exposed. Figure 4a visually captures this transition. For a composite of ~~The mean glacier albedo value from a composite of 224~~ all bare-ice days in summer (JJA) in the 14-year record (i.e., days with no snow cover at the glacier AWS), the mean glacier albedo is 0.21 ± 0.06 ($N = 224$). Including the month of September, the number of bare-ice days increases to 272 and the mean ice albedo is 0.22 ± 0.07. Figure 5 plots the distribution of measured daily mean ice albedo values at the glacier AWS, ranging from 0.11 to 0.34.

~~Our~~ Observed values for glacier ice albedo are in line with other mid-latitude glacier observations (e.g., Brock et al., 2000; Gerbaux et al., 2005; Naegeli et al., 2019) and the value of 0.2 recommended by Cuffey and Paterson (2010) for impurity-rich ice. Particulate concentrations are high in the old snow and glacier ice on Haig Glacier, and include a combination of mineral dust, black carbon, and organic material (see Section 4.4). Ice albedo values of 0.07 have been measured on the lower glacier in multiple years, in association with high impurity loads (Figure 4b,c). Indeed, during spatial albedo surveys, measured albedo is generally higher on the proglacial limestone than in the lower ablation zone (e.g., ~~Figure 1c and~~ Figures 4b,c).

No part of Haig Glacier is considered to be debris-covered, where material covering the glacier is thick enough to insulate the ice surface from ablation; rather, supraglacial particulate matter takes the form of discrete particles or a thin (~1-mm) film, with considerable spatial heterogeneity and temporal variability in impurity concentrations. The heterogeneity ~~is presumably~~may be associated with variable patterns of atmospheric deposition, flushing (cleansing of the glacier surface through rain events or meltwater runoff), and microbial/algal activity. Temporal changes in these processes may also ~~underlie the range of ice albedo values measured at the AWS, from 0.11 to 0.34 (Figure 5)~~explain some of the variability in ice albedo at the AWS site.

We sorted all bare-ice days into subsets of clear-sky and overcast conditions, based on incoming shortwave radiation measurements at the AWS (specifically, the ratio of the total daily and potential direct incoming solar radiation). The spectral reflectance of snow is dependent on the solar incidence angle (Hubley, 1955; Wiscombe and Warren, 1980), hence differs for direct vs.

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diffuse radiation. As a result, mean daily albedo values can be expected to be higher on cloudy days, when diffuse radiation is dominant (Cutler and Munro, 1996; Brock, 2004; Abermann et al., 2014). However, we found no difference between the mean ice albedo values for clear-sky and overcast days in our dataset (a mean value of 0.21 for each subset). Glacier ice albedo is less sensitive to the zenith angle than snow (Cutler and Munro, 1996), and this ~~appears to~~may be particularly true for impurity-rich glacier ice, ~~possibly~~ due to isotropic absorption by impurities and liquid water on the glacier surface and in the intergranular interstices.

However, another phenomenon may contribute to some of the higher ice-albedo values recorded at our AWS site. Values above 0.3 are most common in September, after ephemeral snowfall events have melted away; these serve to increase albedo by 0.1 to 0.2 above the minimum seasonal values attained in August. We interpret this to be due to either residual, refrozen (i.e. superimposed) ice that is more reflective or because of meltwater flushing of some of the local impurities. The albedo record ~~-~~in Figure 3c, an example from summer 2015, illustrates this temporary increase in albedo in the days following fresh snowmelt, particularly for the third snow event on August 22. The storm snow was melted away by August 24 (Figure 3d), but the exposed ice albedo values remained above their early-August ‘baseline’ value of ~0.13 until August 28. Albedo values after this returned to the baseline, indicating that a potential crust of superimposed or flushed ice had been melted away. This pattern is typical of the albedo evolution following summer snow events.

Figure 6a plots mean daily ice albedo values through the summer melt season, based on the average of all available data from 2002 to 2015. There is no trend of ice albedo decrease through the summer melt season; hence, no evidence of increasing impurities that cause progressive darkening once the glacier surface ice is exposed. In contrast, ice albedo increases in late August and September, perhaps associated with the brightening influence of superimposed ice or meltwater flushing, as hypothesized above. ~~The s~~Summer 2003 was an interesting exception, plotted in red in Figure 6a. Ice albedo declined through July and the first week of August in 2003, reaching a minimum of 0.11 (the lowest mean daily value on record at the Haig AWS) and remaining at ~0.13 until strong melting caused the AWS to lean beyond a condition that ensures reliable data after August 22. Severe wildfire conditions in southwestern Canada that summer resulted in ~~a~~ an evacuation order for the region in mid-August, so we were forced to leave the site and could not maintain the AWS. These same wildfire conditions may have resulted in deposition of soot and black carbon that produced the extremely low albedo values that summer.

Figure 6b plots the 14-year record of mean and minimum summer albedo at the site for the period 2002-2015. Mean melt-season values are shown for both May through September and JJA. There is interannual variability but not temporal trend to these or to the minimum values over the study period. Notably, the 2003 ice albedo minimum noted above (Figure 6a) was tied for the lowest in the AWS record, matched again in 2015. The ice at the AWS site had a moderately higher albedo in intervening years. The lack of a trend either during the melt season (Figure 6a) or over multiple years (Figure 6b) implies that impurities must be flushed at a rate similar to their concentration through melting, at least in the upper ablation zone.

3.4 Albedo Transects and Snow/Ice Impurity Data

To supplement the AWS albedo record from a single point on the glacier, we conducted spatial albedo surveys across the glacier during different seasons. In summer 2017 we completed four centrelines albedo surveys through July and August, in conjunction with collection of snow and ice samples to analyze the chemistry and concentration of particulate matter on the glacier surface. Figure 7 plots the location of the survey sites and the centreline albedo data from these four surveys, with summary data provided in Table 4.

The characteristic decrease in surface albedo on Haig Glacier over the summer melt season is evident in Figure 7b. For the initial survey on July 13, the glacier surface was still completely snow-covered, with a relatively uniform albedo typical of old, wet snow. The average albedo value (± 1 standard deviation) on the July 13 survey was 0.48 ± 0.04, and albedo declined through each ~two-week period (Table 4). Glacier ice was exposed as the seasonal snowline moved upglacier in the following weeks, with albedo values ~~dropping~~ decreasing to 0.16 ± 0.11 on August 22. The toe of the glacier is a high-accumulation area due to wind-blown snow deposition in the lee of a convexity (Adhikari and Marshall, 2013); it retained seasonal snow through mid-August, but was snow-free by August 22. On this final day of sampling, only the uppermost sampling site retained seasonal snow cover, possibly refreshed by a snow event on August 13-14.

The seasonal albedo decline is partly associated with the transition from snow to bare ice and partly because the glacier ice albedo systematically decreased over the course of the melt season, from an average value of 0.21 ± 0.07 on July 25 to 0.13 ± 0.05 on August 22 (Table 4). The snow albedo at the glacier toe also decreased from July 13 to August 9 (Figure 7b), but a decline in snow albedo was not apparent on the upper glacier. Much of the glacier surface had an albedo of ~0.1 by the end of the melt season, and the lower glacier had values of 0.07. As reported in previous studies (Brock et al., 2000; Klok and Oerlemans, 2002), ice albedo generally increases with altitude on Haig Glacier.

These ice albedo values are unusually low compared to values reported in the research literature and in the context of the longer-term record at Haig Glacier. There is an inheritance of accumulated particulate matter on the glacier surface from previous summers, but the significant changes from July 26 to August 22 indicate a strong intra-seasonal change, which feeds back on intensified melting and mass loss through the month of August. Some of this may be due to increasing concentration of impurities, as melting snow and ice leave the particulate load behind while the meltwater runs off.

In addition, ~~similar to the summer of 2003~~we speculate that~~,~~ glacier darkening through the month of August ~~may~~ may be associated with deposition of soot and other particulate matter associated with regional wildfires. T~~T~~he summer of 2017 was a severe wildfire season in western Canada~~, with numerous wildfires in southern British Columbia, upwind of Haig Glacier. More than~~. More than 1.2 million hectares of land burned in the province of British Columbia in 2017, a record at the time (Government of British Columbia, 2020)~~, although this was eclipsed in 2018~~. During our August field work on the glacier, the air smelled of smoke and visibility was limited due to smoky skies. Impurity measurements from snow and ice samples collected during the glacier visits indicate a ~four-fold increase in total carbon on the glacier surface from July 26 to August 9, 2017, from average concentrations of 5.6 to 22.7 mg L^{-1}, respectively (Table 5). The increase in impurities is evident in both inorganic and organic carbon. Particulate matter from local terrigenous dust also increased over this period, but by a factor of ~2.3 (Table 5). The mineral dust load is dominated by calcium and magnesium carbonate, with the carbon concentration associated with carbonaceous dust, [C$_{dust}$], equal to 2.0 mg L^{-1} on August 9. This indicates that more than 90% of the carbon on the glacier had a source other than local, terrigenous dust at this time, although we recognize that Ca and Mg are highly soluble and may have been preferentially removed by meltwater.

We are not able to partition the non-dust carbon between algal, wildfire, or other potential sources such as British Columbia industrial activity. The marked increase in impurity and total carbon concentrations from mid-July to mid-August, 2017 is consistent with the potential impacts of wildfire fallout on surface albedo. Wind direction data at the AWS confirms the prevalence of westerly winds bringing air masses from southern British Columbia to the study site. A full analysis of air mass trajectories and the specific source(s) of forest-fire fallout at Haig Glacier is beyond the current scope, but is recommended for followup studies.

~~Impurity measurements from snow and ice samples collected during each glacier visit indicate a ~four-fold increase in total carbon on the glacier surface from July 26 to August 9, from average concentrations of 5.6 to 22.7 mg/L, respectively (Miller, 2018). These data will be described in detail elsewhere (Miller and Marshall, in preparation). The increase in impurities was evident in both inorganic and organic carbon, which are present in roughly equal proportions, and are consistent with the potential impacts of wildfire fallout on surface albedo. Particulate matter from local terrigenous dust also increased over this period, but by a factor of about two. The mineral dust load is dominated by calcium and magnesium carbonate, with an average summer carbon concentration associated with carbonaceous dust, [C$_{dust}$], of 2.2 mg/L. This compares with an average total carbon concentration of 14.5 mg/L, indicating that up to 85% of the carbon on the glacier has a source other than local, terrigenous dust, although we recognize that Ca and Mg are highly soluble and may have been preferentially removed by meltwater. We are not able to partition the non-dust carbon between algal, wildfire, or other potential sources such as British Columbia industrial activity.~~

4. Discussion

4.1 Albedo Modelling

Given the strong variation of surface albedo through the summer melt season – a typical decline from ~0.9 to ~0.2 from May to August – it is important to capture the seasonal albedo evolution

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in glacier hydrological and mass balance models. Numerous other researchers have tackled this problem, and physically-based snow albedo models have been proposed (e.g., Marshall and Oglesby, 1994; Flanner and Zender, 2006; Gardner and Sharp, 2010; Aoki et al., 2011).

In glacier modelling, the decrease in supraglacial snow albedo through the melt season can be approximated by a proxy for snow age or cumulative melting, to capture the systematic decline in albedo due to rounding and growth of snow grains, the effects of liquid water content in the snowpack, and increasing concentration of impurities (Brock et al., 2000). Following Hirose and Marshall (2013), we use a parameterization based on cumulative *PDD* ~~gives a reasonable~~ to approximate the~~fit to observed~~ melt-season albedo decline on~~albedo at~~ Haig Glacier,

$$\alpha_s = \alpha_0 \exp\left(-k \cdot PDD\right),$$

(7~~8~~)

where α_0 is the fresh-snow albedo (~0.85) and k is an albedo decay coefficient. The free parameter, k, can be tuned to fit a given observational record such as those plotted in Figure 2b. The ~~influence~~ effects of snow grain size ~~or~~ and impurity concentration can~~ould~~ also be incorporated in k in this type of model. Once the seasonal snow has melted, the albedo drops to that of the underlying firn or ice. Additional details can be added to the snow albedo model for thin snowpacks (e.g., less than ~10 cm), to capture the influence of the underlying firn or ice albedo when it begins to show through (Oerlemans and Knap, 1998).

This simple parameterization ~~works~~ represents the seasonal albedo decline reasonably well, with minimal inputs, but ~~fails~~ does not~~to~~ capture the ~~albedo impact~~effects of fresh snow events, which temporarily ~~brighten~~ increase the glacier surface albedo. The albedo impact of summer snowfall is ephemeral, but these events significantly increase the mean summer albedo and reduce the total summer melt, as discussed in Section 4.2. This is a difficult thing to model remotely or in future projections, as precipitation events can be extremely local in the mountains and the phase of precipitation (rain vs. snow) is difficult to predict. Rain and snow events are both are common on Haig Glacier in the summer months, often mixed on the glacier as a function of elevation.

As a simple approach to address this, we ~~recommend the~~ introduc~~tion of~~e summer snow events as a stochastic process. ~~A~~ We randomly sample a normal distribution characterized by the mean and standard deviation of the expected number of summer precipitation events (Table 1)~~ can be randomly sampled~~, with the phase of precipitation determined by ~~the current~~ local temperature ~~(e.g., $T < 2$°C for snowfall)~~. We prescribe a linearly-decreasing snow fraction, f_s, between the temperatures of –2 and +2°C, for mean daily air temperature T_a:

$$\begin{aligned} f_s &= 1, & T_a &< -2℃ \\ f_s &= 1 - (T_a + 2)/4, & T_a &\in [-2, 2℃] \\ f_s &= 0, & T_a &> 2℃ \end{aligned} \qquad (8)$$

Total event precipitation ~~can also be~~is also treated as a random variable. ~~Each s~~Summer snow events ~~then~~ reset~~s~~ the surface albedo to the fresh-snow value, α_0, and the albedo decay begins anew ~~with this~~for the fresh summer snow, until it is ablated and the underlying ~~, darker~~ surface re-emerges (old snow, firn, or ice).

The albedo of the underlying glacier firn or ice can be held constant or can be parameterized to decay with the amount of time exposed or as a function of impurity concentration. Lacking a good understanding or independent model of these processes, we assign the ice albedo to be equal to the observed longterm mean at the Haig Glacier AWS site, 0.21~~,~~ (Table 1). Temporal~~once again including some stochastic~~ variability can also be introduced, based on random sampling of a normal distribution that describes the~~the~~ observed distribution of ice albedo values (Table 1).

Figure 8 plots an example of this simple treatment for summer 2007, with $k = 0.0009$ (°C d)$^{-1}$. The albedo model is embedded in a ~~glacier~~ surface energy balance model (Ebrahimi and Marshall, 2016) that calculates *PDD* and melting, ~~forced~~ driven by the observed AWS data. The model is seeded with the observed winter snowpack, measured on April 13 of that year, and is run from May 1 to September 30. The timing of the transition from seasonal snow to ice is well-captured in Figure 8, and the number of fresh-snow events is ~~also reasonable~~in accord with the observations, but the timing is not correct (nor is it expected to be). Figures 8a and 8b show two different model realizations, illustrating the differences in timing of summer snow events.

The ~~se~~ modelled summer snow events in Figure 8 are not completely random, as a stochastic precipitation event will only register as a snowfall when temperatures are cold enough. Because of this, snow events are more common in early and late summer and are also correlated in different model realizations. This temperature control also helps ~~the model~~ to capture the end of the summer melt season (beginning of winter snow accumulation~~), although not always~~) in the model. For instance, the end of summer, which occurs around September 17 ~~this year~~in 2007, is well ~~captured~~ represented in Figure 8a but is ~one week late in Figure 8b. For the examples in Figure 8, the mean observed albedo values (± 1σ) in JJA and MJJAS are 0.53 ± 0.23 and 0.59 ± 0.24, compared with modelled values of 0.54 ± 0.24 and 0.60 ± 0.26. Modelled albedo values are calculated from the mean of 10 model realizations; the plots in Figure 8 are representative of this population. Based on a simple t-test for comparison of means and Bartlett's test for equal variance (Snedecor and Cochran, 1989), the observed and model results are statistically equivalent.

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4.2 Implications for Glacier Mass Balance

The seasonal albedo decline, summer snow events, and realistic values of firn and ice albedo are all important to resolve in models of glacier energy and mass balance. As an example, the energy balance model driven by the observed AWS meteorological data and surface albedo gives a total melt of 2.97 m w.e. for the 2007 melt season (May to September), the case study in Figure 8, corresponding to a mean melt-season surface albedo of 0.59. With the random snow events as illustrated in Figure 8, the mean of ~~five~~ ten model realizations gives a~~n estimated~~ summer melt of 2.82 ± 0.25 m w.e., corresponding to a mean melt-season albedo of 0.60. This slightly underestimates but is within the uncertainty of the observation-based estimate~~; the energy balance model is well-calibrated to this site~~.~~.~~ Without the summer snow events, however, modelled melt equals 3.61 m w.e., with a mean melt-season albedo of 0.48. This overestimates summer ~~ablation~~ melting and mass loss ~~and runoff~~ by 22%.

There are also important implications for modelling of glacier mass balance at remote sites or in future projections. As temperatures warm, summer precipitation events can be expected to shift to rain rather than snowfall, ~~with positive feedbacks on~~which would accelerate glacier melting. Without an explicit treatment of summer snow events and their impact on albedo, models calibrated to present-day conditions will not capture this feedback. Similar caveats can be raised about assignment of a constant, observationally-based ice albedo in mass balance models; conditions vary between glaciers and may change in the future as a function of changing particulate loads, and possibly other factors. Physically-based models of impurity deposition and washout and the relation to ice albedo are needed for more reliable regional models and future projections. Similar efforts are underway to improve mass balance models for debris-covered glaciers (e.g., Reid and Brock, 2010; Rowan et al., 2015), although the processes differ for transport and dispersal of coarse debris such as rockfall.

Most studies to date involving regional or future models of glacier mass balance employ degree-day or temperature-index melt models, since in situ meteorological data are unavailable (e.g., Marzeion et al., 2014; Clarke et al., 2015). A full surface energy balance requires a large suite of variables such as wind speed, humidity, and cloud conditions. These are difficult to downscale from climate models with fidelity, relative to temperature fields. In this case, albedo does not appear directly in most formulations of the melt parameterization, but is implicit in the assignment of different degree-day melt factors for snow and ice, fd_{snow} and fd_{ice}.

Observations of surface albedo evolution on mountain glaciers make it clear that a continuum approach is more appropriate, with changing degree-day melt factors that track the seasonal albedo evolution (e.g., Arendt and Sharp, 1999). The monthly melt factor ~~f~~ d was calculated from Eq. (6) using mean monthly values of melt energy and temperature at the Haig Glacier AWS from 2002-2015, giving a range of values that can be compared directly with mean monthly albedo (Figure 9). As expected, there is a relatively strong inverse relation, with a linear correlation coefficient of –0.66 and a coefficient of determination of $R^2 = 0.44$. A linear fit to the data gives ~~and~~ the regression equation $fd = 7.98 - 6.16\alpha_s$~~.~~, significant at $p < 0.0001$. This relation could be applied if one has independent estimates of the surface albedo, e.g., from remote sensing (e.g., Williamson et al., 2016) or ~~UAV~~ drone surveys. Alternatively, Table 2 includes mean monthly values of the melt factor for the full dataset, which would be preferable to using single values for snow and for ice. ~~Equivalent m~~Monthly factors could also be calculated for the radiation melt coefficient in enhanced temperature-index melt models which use potential direct solar radiation as an input (e.g., Hock, 1999; Clarke et al., 2015; Carenzo et al., 2016).

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The correlation matrix in Table 3 summarizes the broader relations between albedo, temperature, and mass balance conditions on Haig Glacier. The monthly net energy and melt are strongly correlated with temperature and *PDD* ($r \sim 0.9$), implying that temperature-index melt models could give good estimates of monthly melt at this site, given a judicious choice of melt factor, ~~*f*~~d. ~~This~~ The relation~~ship~~ between Q_N and melt is weaker but still significant for the total summer melt ($r \sim 0.7$). Annual mass balance is highly correlated the summer balance ($r = 0.94$), emphasizing the importance of the summer melt season, which in turn is highly sensitive to surface albedo. Mean summer albedo is highly correlated with net annual mass balance ($r = 0.76$). This is stronger than the correlation of net balance with mean summer temperature or *PDD* totals. Closely related to this, summer snow events have a significant association with the summer and net mass balance ($r = –0.73$ and $r = 0.70$, respectively). The amount of mass added to the glacier is small in summer relative to the winter snowpack (less than 5%), but net mass balance is more strongly correlated with the number of summer snow events than the winter balance, due to the albedo impact.

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4.3 Temporal Variability and Trends in Ice Albedo

Glacier ice albedo is low at this site, in association with high concentrations of supraglacial impurities. The impurities are a combination of mineral dust, primarily calcium and magnesium carbonate, other sources of inorganic carbon, and organic carbon, including active algal populations. The mean value of summer ice albedo at the AWS site is 0.21, but this dips to 0.11 in some years (2003, 2015, 2017), possibly in association with regional wildfire activity. The summers of 2003 and 2017 were particularly active wildfire seasons in southern British Columbia, upwind of our study site, and ice albedo declined through the summer melt season in these two summers. This was unusual, however; overall, there is no evidence of decreases in ice albedo over the melt season (Figure 6a). In contrast, bare-ice albedo increases slightly in the late summer and early autumn, perhaps in association with superimposed ice formation and/or meltwater rinsing of the glacier surface after transient summer snow events.

Similarly, there is no multi-year trend for ice albedo at this site (Figure 6b), although this record is limited to a relatively short period (2002-2015) at just one location on the glacier. Based on the available data, however, there is no evidence of glacier ‘darkening’ over the period of study, despite years such as 2003 which experienced heavy deposition and accumulation of particulate matter. This stands in contrast to reported glacier albedo reductions over the last two decades in other regions (e.g., Mernild et al., 2015; Naegeli et al., 2019). These results imply that there is some degree of effective cleansing and refreshing of the glacier surface through rainfall and meltwater runoff, although the baseline albedo remains low and there is a multiyear accumulation of~~, in connection with a~~ ~~multiyear~~ supraglacial ~~accumulation of~~ impurities over much of the glacier.

The transect data from August 22, 2017 indicate lower albedo values and greater impurity loads near the glacier terminus (Figure 7b; Miller and Marshall, in preparation). This is consistent with increased concentration of residual particulate matter due to cumulative melting, within a given summer or over many years, as well as the possibility of greater mineral dust loading on the lower glacier (and associated nutrients to support algal activity), as reported by Oerlemans et al. (2009). We do not have the data to assess multiyear albedo or impurity trends on the lower glacier, to test whether the terminus zone is darkening as a feedback to negative mass balance trends, as has been reported elsewhere (Oerlemans et al., 2009; Naegeli et al., 2019).

At a given location on the glacier, increases in the concentration of impurities during the melt season ~~generally~~ exceed what would be expected from melt~~-induced concentration of ions~~ing. As an example, ~~at 2730 m altitude in the accumulation area, inorganic~~total carbon concentrations ~~in surface snow~~across the glacier ~~-~~increased ~~from 1.4 to 9.1 mg/L~~four-fold from July 26 to August 9, 2017 while ~~calcium~~ mineral dust concentrations more than ~~increased from 1.0 to 1.9 mg/L~~doubled (Table 5). Applying the surface energy balance at an elevation of 2730 m on the upper glacier, we estimate a total melt of 0.48 m w.e. over this two-week period~~Melt modelling at this point on the glacier gives an estimated 0.48 m w.e. melt~~. This is not enough to explain the observed increases in concentration, as~~, which should lead~~ ~~to leaching and removal of some dissolved ions in the meltwater runoff, but concentrations increased 2- to 6-fold.~~ ~~S~~subsurface snow samples ~~were essentially clean~~had ~~(~~ carbon and dissolved ion concentrations below the detection limit of 0.1 mg~~/~~ L^{-1}~~),~~ . Meltwater runoff should also lead to leaching and removal of some dissolved ions. T~~so t~~he increased particulate matter must have been due to deposition on the glacier. Further work is needed to quantify deposition and rinsing (leaching, washout) of particulates, to develop models for these processes, and to characterize their influence on temporal and spatial variations in albedo.

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5. Conclusions

Albedo measurements from the upper ablation area of Haig Glacier over the period 2002-2017 indicate significant interannual variability in mean melt-season and glacier ice albedo, but there is no temporal trend in surface albedo over this period. This runs counter to documented albedo reductions elsewhere (Oerlemans et al., 2009; Mernild et al., 2015; Williamson et al., 2019; di Mauro et al., 2020), and to anecdotal evidence of darkening glaciers in the Canadian Rockies. The result may just be specific to the Haig Glacier AWS site; we do not have data to constrain albedo trends ~~on~~ in the lower ~~glacier~~ablation zone, where the ice albedo is lowest and ~~changes and melt feedbacks~~glacier thinning has ~~have~~ been ~~strongest~~ most extensive over the observation period. ~~Moreover, the~~The observational record is also short for trend detection. ~~and~~ Haig Glacier mass balance has been negative through this whole period, and i~~. I~~t is ~~plausible~~ possible that ~~there have not been significant changes in albedo in the 2000s, but there may be~~ the ~~substantial~~ glacier has ~~darkening~~ darkened over a multi-decadal time frame (e.g., since the 1970s), but not since the early 2000s.

The baseline summer ice albedo at the Haig Glacier AWS site is 0.21 ± 0.06, so it has been relatively low for the whole period of study. It drops to values as low as 0.11 in ~~certain ~~some years ~~though ~~(2003, 2017), in association with strong wildfire seasons in southern British Columbia, upwind of our study site. Large increases in total and organic carbon concentrations measured on the glacier in August 2017 support this association. The glacier ice appears to recover from these low-albedo summers, however, returning to albedo values of ~0.2 in subsequent years. This is evidence of cleansing of the glacier surface by rainfall and meltwater runoff. Impurities at Haig Glacier are dominated by fine particulate matter, mineral dust in particular and much of this may be effectively leached as dissolved sediment load. The mass balance of supraglacial particulate matter is not well understood, and requires further study.

Other processes controlling the variability in ice albedo also require further study. We find no relation between mean daily ice albedo and cloud conditions in our data, as reported elsewhere (e.g., Brock, 2004; Abermann et al., 2014) and as theoretically expected. This may be because the albedo is relatively low, with a high concentration of impurities; particulate matter and liquid water content act as isotropic absorbers, reducing the sensitivity of specular reflection to zenith angle (hence, diffuse vs. direct radiation). We also see no evidence of ice albedo reductions through the melt season, unlike in seasonal snow, although the major wildfire years provide an exception to this. This further argues for effective rinsing of the glacier surface in most summers, save when dry deposition of particulate matter is unusually high.

We do see evidence of temporary increases in bare-ice albedo to values of ~0.3 following melting and runoff of fresh summer snow. The post-snowfall glacier ice albedo is commonly about 0.15 higher than before the snow event. This may be due to a reflective, superimposed ice crust that temporarily forms after snow events, or it could be a result of effective washing of the glacier surface from the melting of clean snow. The increase in ice albedo is transient, but the effect persists for two or more days after the new snow has melted away.

~~This effect is subtle, but~~O~~ o~~verall, summer snow events at Haig Glacier have a large impact on mean summer albedo and glacier mass balance. An average of 9.3 ± 2.6 such events were recorded each summer, resulting in a mean melt-season albedo increase of ~~about ~~0.12 (e.g., from 0.48 to 0.60 in 2007). Such events are particularly significant when they occur late in the summer, temporarily brightening the low-albedo ice. Based on both energy balance modelling and direct AWS observations, we estimate that summer snow events reduce summer melting and mass loss~~runoff~~ by about 20% at Haig Glacier. This is an important potential feedback and sensitivity to climate change, as warming is likely to cause more of these summer precipitation events to shift to rainfall rather than snow in the coming decades.

We introduce a stochastic model of summer snow events in a simple model that captures the typical melt-season albedo evolution on glaciers. This is necessary for realistic mass balance modelling at Haig Glacier, and could be adapted for use elsewhere, as long as there is some knowledge of precipitation frequency during the melt season. The seasonal albedo evolution on glaciers governs how effectively incoming shortwave radiation is converted to melt, and it is important to capture this influence in simplified melt and mass balance modelling applications where local meteorological data are not available. For temperature-index melt modelling, w~~W~~e suggest ~~ways in which~~that either ~~the~~ monthly melt factors or melt-factor ~~in temperature-index melt models can be~~ parameteriz~~ed~~ations as a function of albedo~~, to~~ can better capture the conversion of positive degree days to melt.

Haig Glacier albedo values and summer snow conditions may not be broadly applicable, particularly given regional differences in the provenance and concentration of impurities. Particulate loading is highly variable in space, even within a given glacier. The processes discussed in this contribution and the general pattern of melt-season albedo evolution are relevant to most mountain glaciers, however. These observations can help to inform regional models of glacier mass balance and assessments of glacier response to climate change. We emphasize the need for process studies of particulate mass balance (deposition, accumulation, transport, and removal) in supraglacial environments, including the potential effects of forest fire fallout on glacier albedo and mass balance.

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Code/Data Availability

The automatic weather station data from Haig Glacier and MATLAB code for the surface energy balance model used in this study are available from the authors on request.

Author Contributions

SM initiated the Haig Glacier field study, led the field effort and data collection, wrote the MATLAB code for the surface energy balance modelling, was responsible for the data analysis and wrote the manuscript. KM collected the summer 2017 surface albedo and supraglacial chemistry data as part of her Masters research at the University of Calgary.

The authors declare no competing interests and no conflict of interest with this research or its conclusions.

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Tables

Table 1. Mean summer albedo and mass balance conditions at Haig Glacier, 2002-2017, based on glacier-wide simulations driven by local AWS data. B_w, B_s, and B_n are the winter, summer and annual specific mass balance, N_m and N_{ss} are the number of melt days and summer snowfall days from May through September, *PDD* are the positive degree days over the summer melt season, *T* and Q_N are the mean June through August (JJA) air temperature and net energy flux, and E_m is the total summer melt energy. Albedo values are ~~as~~ measured at the glacier AWS~~, where~~: α_s is the mean JJA surface albedo and α_i is the measured ice albedo for the composite of snow-free days ($N = 224$).

	B_w (m w.e.)	B_s (m w.e.)	B_n (m w.e.)	N_m	N_{ss}	*PDD* (°C d)	*T* (°C)	Q_N (W m^{-2})	E_m (GJ m^{-2})	α_s	α_i
mean	1.35	–2.60	–1.25	137	9.3	671	5.3	107	1.113	0.55	0.21
std dev	0.24	0.62	0.68	8	2.6	92	0.8	17	0.177	0.07	0.06

Table 2. Mean monthly temperature, surface energy balance, and melt conditions at the Haig Glacier AWS, 2002-2015. Symbols are as in Table 1, with the addition of degree-day melt factors, f_E, calculated from Eq. (7), and the conventional version, f_{PDD}, calculated from Eq. (6).

Month	*T* (°C)	*PDD* (°C d)	Q_N (W m^{-2})	E_m (MJ m^{-2})	α_s	*melt* (m w.e.)	f_E (m w.e.	f_{PDD} (°C d)$^{-1}$)
May	–1.0	42	22	47	0.77	0.13	3.4	3.3
June	2.8	100	62	142	0.71	0.40	4.4	4.2
July	6.8	212	126	319	0.56	0.93	4.5	4.4
August	6.1	191	137	368	0.38	1.10	5.8	5.8
Sept	2.0	91	42	116	0.64	0.35	3.7	3.7

Table 3. ~~Correlations~~ Linear correlation coefficients for ~~of mean summer (top right) and mean monthly (bottom left)~~ albedo, ~~with mean summer and monthly~~ energy balance, ~~weather~~ and mass balance conditions at~~,~~ Haig Glacier, 2002-2015. Symbols are defined in Tables 1 and 2. The top right sector is for mean summer (JJA) and annual mass balance ~~Summer correlations are for the glacier-averaged, JJA~~ conditions ($N = 14$), and the bottom left sector (italicized) shows correlation coefficients for all available monthly mean values from May to September ($N = 71$). For the monthly data, B_s refers to the monthly summer balance (melting minus refreezing), defined as a negative for mass loss. B_n and B_w are not relevant for the monthly data. Correlations that are not significant at the 95% level [$p > 0.05$] are shown in brackets.

Annual (B_n, B_w) or summer (JJA, all other variables) means or totals

	α_s	B_w	B_s	B_n	N_{ss}	PDD	T	Q_N	E_m
α_s	—	[0.~~52~~39]	0.~~66~~74	0.8~~7~~6	0.67	[–0.30]~~5~~	–0.~~85~~68	–0.~~68~~81	–0.67~~0~~
B_w		—	[–0.04]~~15~~	[–0.47]	[–0.20]	~~–0~~[0.~~25~~18]	[0.12]~~09~~	[–0.12~~6~~]	[~~–~~0.01~~8~~]
B_s	*0.89*		—	0.93~~4~~	0.73	–0.68~~73~~	–0.~~69~~75	–0.93~~1~~	–0.98~~9~~
B_n				—	0.70	[–0.~~55~~43]	–0.64~~58~~	–0.87~~6~~	–0.82~~90~~
N_{ss}					—	–0.58	–0.58	–0.76	–0.73
PDD	*–0.74*		*–0.89*			—	0.63~~82~~	0.65~~4~~	0.~~80~~76
T	*–0.73*		*–0.88*			*0.97*	—	0.86~~0~~	0.73
Q_N	*–0.84*		*–0.97*			*0.92*	*0.91*	—	0.~~8~~92
E_m	*–0.87*		*–0.99*			*0.92*	*0.90*	*0.99*	—
df_E	*–0.66*		*–0.62*			*0.39~~6~~*	*0.~~38~~41*	*0.64~~3~~*	*0.65~~3~~*

Table 4. Mean albedo values (± 1σ) along the Haig centreline transect during four surveys in summer, 2017: glacier average, and for the subset of sites over seasonal snow and glacier ice. The number in brackets indicates the number of samples for each average. Snow values on the upper glacier are estimated on August 9.

Date	All sites	Snow	Ice
July 13	0.48 ± 0.04 (33)	0.48 ± 0.04 (33)	—
July 26	0.34 ± 0.15 (33)	0.48 ± 0.05 (16)	0.21 ± 0.07 (17)
August 9	*0.23* ± *0.11* (33)	*0.41* ± *0.03* (9)	0.17 ± 0.05 (24)
August 22	0.16 ± 0.11 (33)	0.47 ± 0.08 (3)	0.13 ± 0.05 (30)

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Table 5. Mean concentrations (±1σ) of major ions and carbon along the Haig centreline transect surveys on July 26 and August 9, 2017 (*N* = 11). All concentrations have units mg L^{-1}. TC is total carbon, TIC and OC are inorganic and organic carbon, [C_{dust}] is the inorganic carbon associated with carbonate mineral dust, and [dust] is the total mineral dust. Factor indicates the ratio of concentrations for August 9 over July 26.

Date	[Ca^{+2}]	[Mg^{+2}]	[TC]	[TOC]	[IC]	[C_{dust}]	[dust]
July 26	2.3 ± 2.9	0.3 ± 0.2	5.6 ± 5.7	3.7 ± 3.4	1.9 ± 2.3	0.9 ± 1.0	7.1 ± 7.8
August 9	5.1 ± 6.9	0.9 ± 1.5	22.7 ± 13.6	11.3 ± 8.4	11.4 ± 6.3	2.0 ± 2.7	16.4 ± 21.4
Factor	2.2	2.7	4.0	3.0	6.0	2.3	2.3

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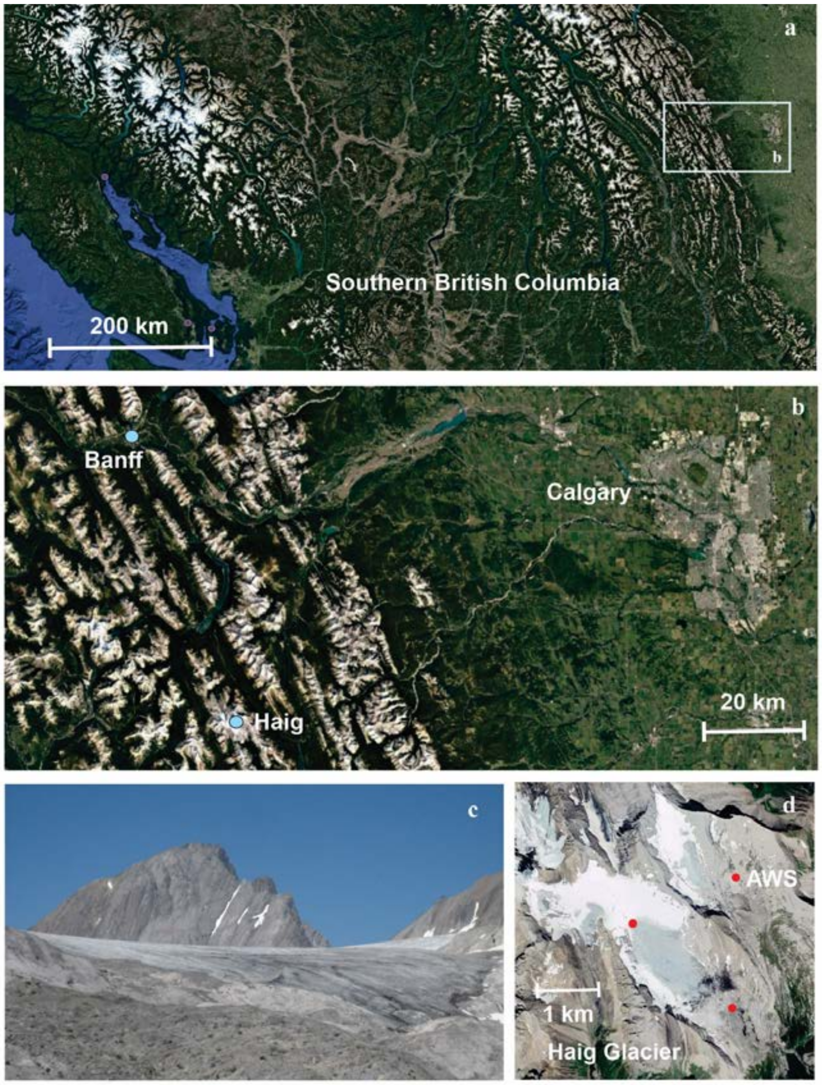
Figures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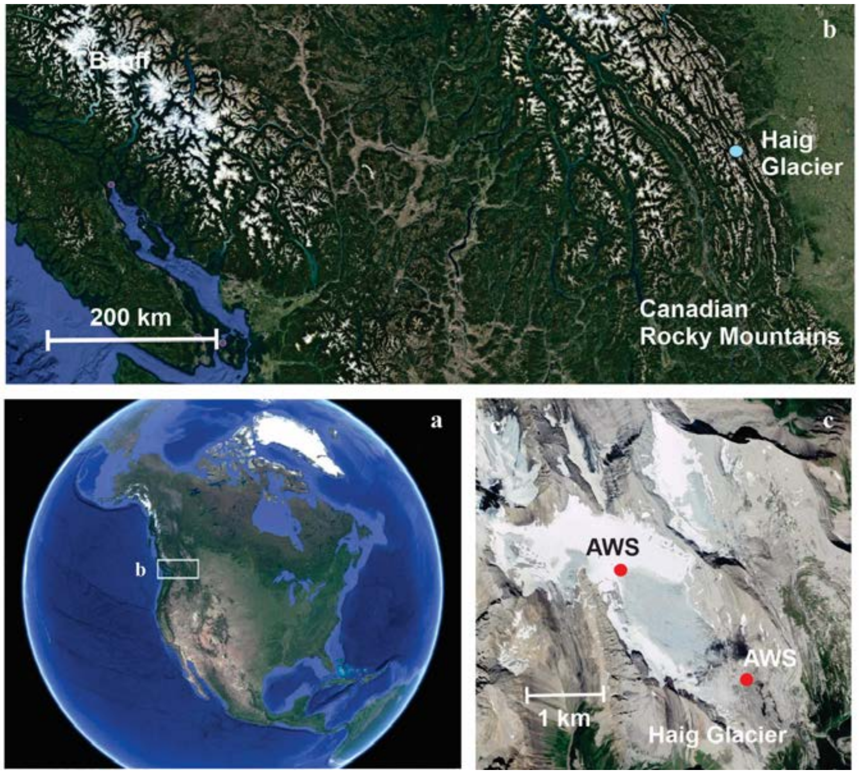

Figure 1. (a) Haig Glacier study area in ~~(a)~~ southwestern Canada (inset b). (b) Haig Glacier is about 100 km southwest of Calgary, AB, on the eastern slopes of the Canadian Rocky Mountains. (c) ~~Photograph of the terminus area of the glacier, July 2007, from S. Marshall. (d)~~ Map view of the glacier, indicating the locations of the two automatic weather stations (AWSs). All i~~I~~mages are ~~(a), (b) and (d) are~~courtesy of ~~©~~ Google Earth ©.

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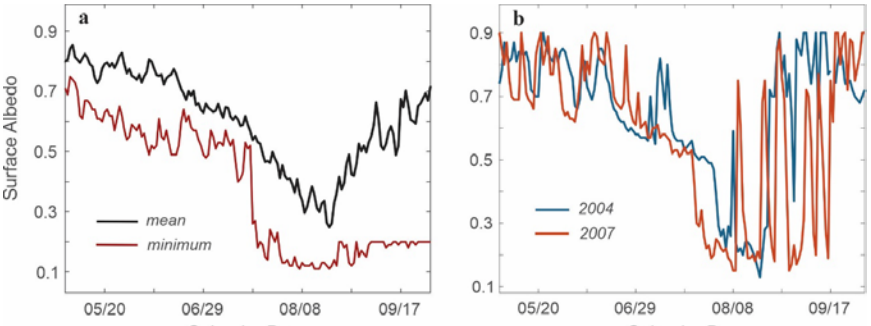

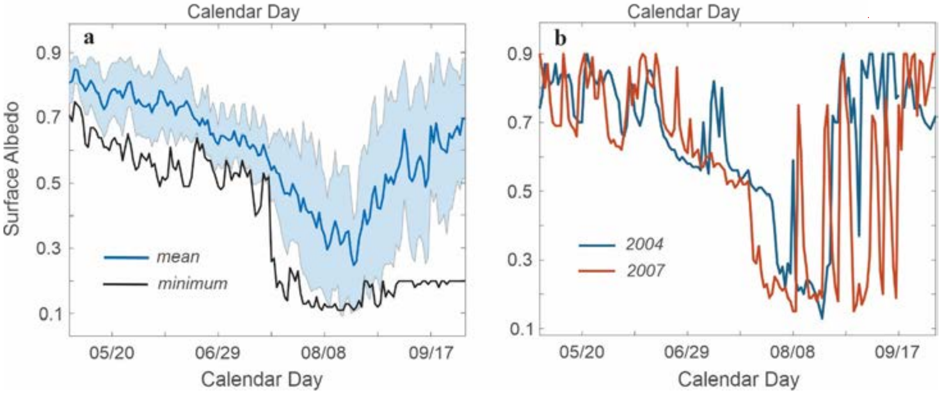

Figure 2. Daily albedo evolution at the Haig Glacier AWS site over the melt season, May to September. (a) Mean and minimum daily albedo from 2002-2016. Shaded area indicates the 1-standard deviation range about the mean. (b) Select individual years (2004 and 2007) to better illustrate the transition from seasonal snow to exposed glacier ice and the ~~impact of~~albedo spikes associated with summer snow events~~ (albedo spikes)~~.

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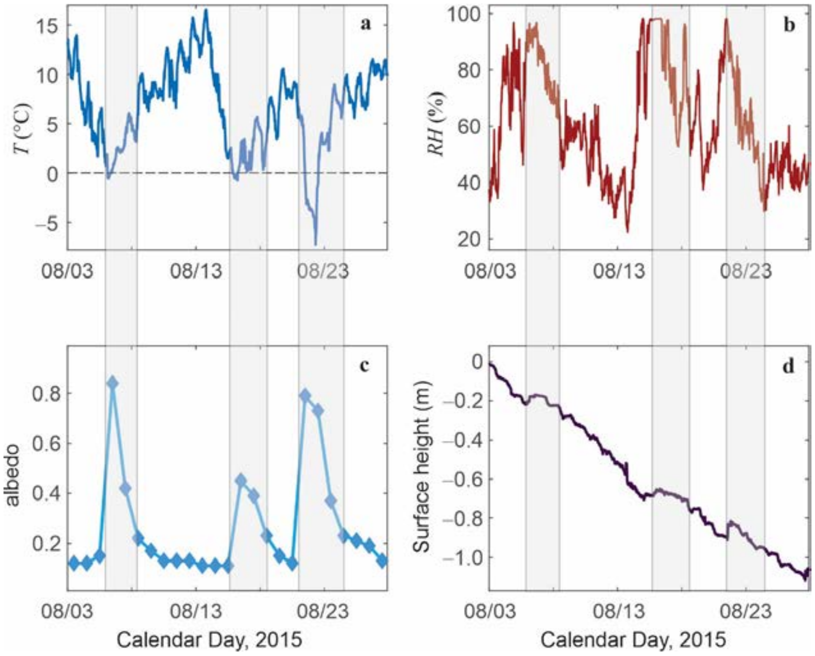


Figure 3. Examples of summer snow events recorded at the Haig Glacier AWS site from August 3-28, 2015. (a) Air temperature, (b) relative humidity, (c) mean daily albedo, and (d) surface height, as measured by the ultrasonic depth gauge (SR50).

Figure 4. Photographs of the Haig Glacier, illustrating the variability of summer surface cover. (a) The transition from seasonal snow to exposed glacier ice. (b) Meltwater runnels looking downslope in the ablation area, illustrating the heterogeneous but extensive concentration of surface impurities. (c) Dark ice at the glacier terminus. (d) Fresh snow covering the glacier after a heavy August snowfall. Photos by S. Marshall.

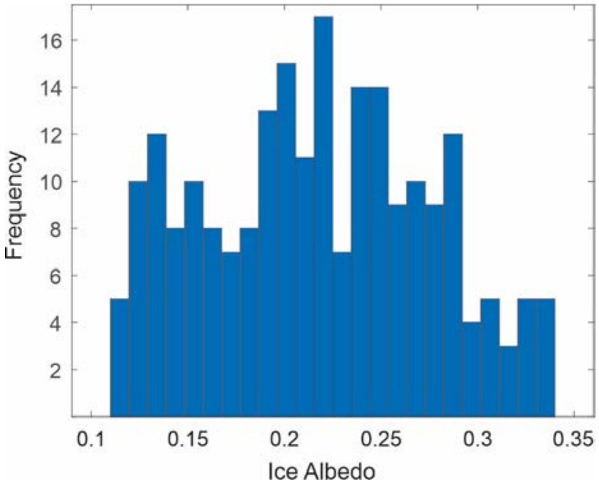
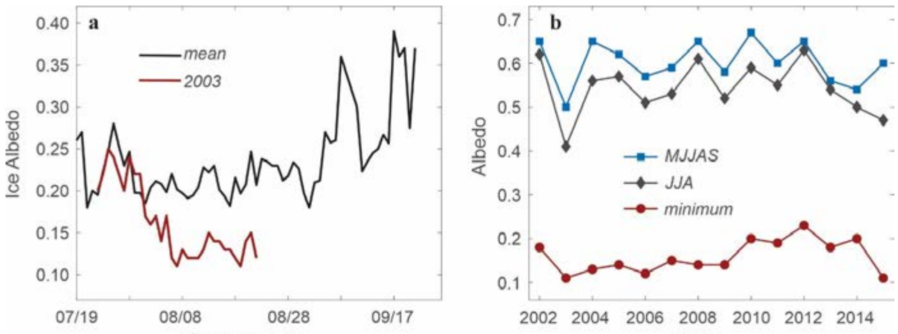


Figure 5. Distribution of daily mean ~~bare~~ ice ~~glacier~~ albedo values recorded at the Haig Glacier AWS from the summers (JJA) of 2002 to 2015, ~~(~~for all days that were snow-free at the AWS site (*N* = 224).



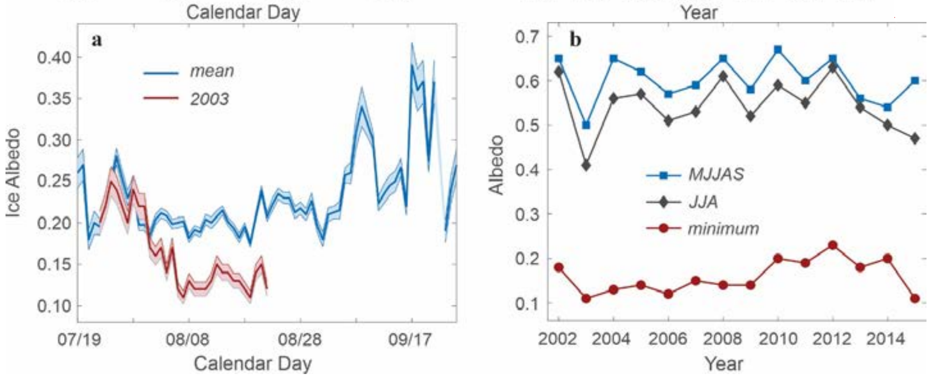
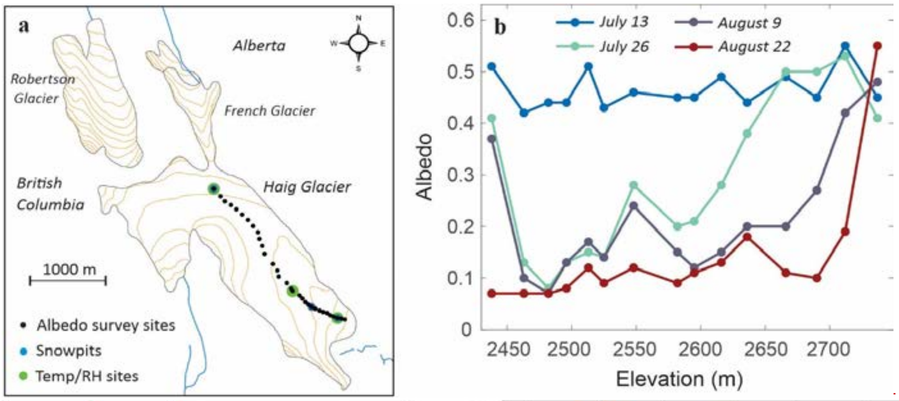


Figure 6. (a) Evolution of Haig Glacier ice albedo through the summer melt season. Mean values for 2002-2015 are shown in ~~black~~ blue and available data from summer 2003 is in red. In 2003, the station was leaning too much for reliable data after August 23. Shading indicates the uncertainty envelope of the measurements (one standard error). (b) Evolution of the mean melt-season albedo at Haig Glacier from 2002 to 2015, for May through September, ~~(blue) and JJA~~July through August, and ~~(black). The red line plots~~ the minimum daily value ~~for~~ of each year.



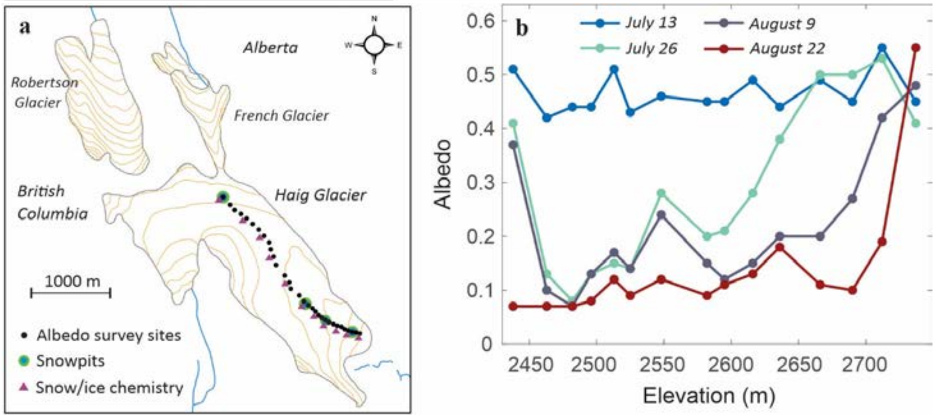


Figure 7. (a) Black circles show the 33 survey sites for winter mass balance and albedo measurements along the Haig Glacier 'centreline' transect. (b) Evolution of surface albedo along the centreline transect during four visits in July and August, 2017.

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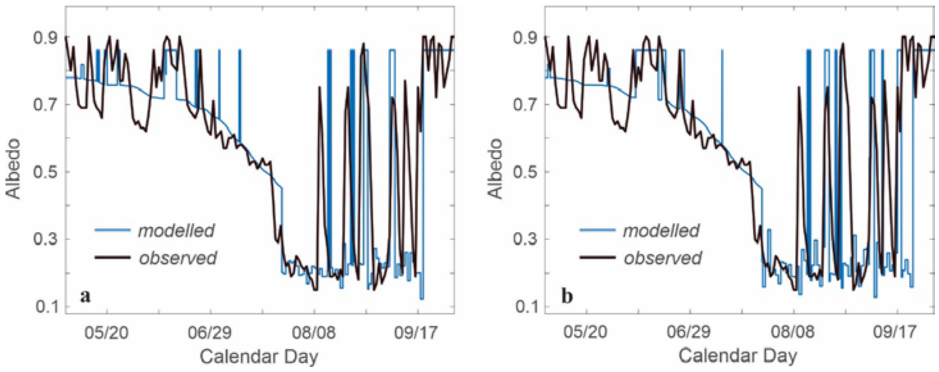

Figure 8. Two realizations of modelled vs. observed surface albedo at the Haig Glacier AWS site, May 1 to September 30, 2007. Summer snow events (albedo spikes) are modelled as random events in the albedo model.

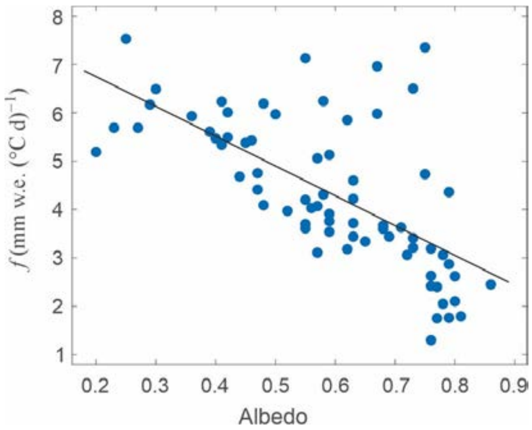

Figure 9. Degree-day melt factor, *f*, as a function of monthly mean albedo and melt energy at the Haig Glacier AWS site, for MJJAS from 2002- to 2015.