Author's response to Anonymous Referee #1

Referee comment

This paper gives a thorough account of April (2016 and 2017) field measurements conducted on the Alerce Glacier in the Northern Patagonian Andes. Combined with an updated Snow, Ice, and Aerosol Radiative (SNICAR) model that accounts for partly cloudy conditions, the measurements are used to estimate the glacier's April 2016 – April 2017 surface mass balance. Representing the first particulate matter concentration, albedo, and grain size measurements conducted on the Alerce Glacier, these results are a valuable contribution to the community and therefore warrant consideration for publication in *The Cryosphere*. Before acceptance, however, there are specific concerns, provided below, followed by a list of technical corrections that I recommend the authors consider in a minor revision.

Author's response

We deeply appreciate the referee for the thorough and useful comments to improve the manuscript.

Referee comment

Throughout the manuscript, the authors refer to an average snow grain radius value that they claim (in Sect. 2.2) to be precise. Average radii values were obtained using two methods: from visual inspection against a crystal grid, which is outdated, and from ImageJ software, which, to my knowledge, is not a standard method for obtaining snow grain radius. Although these methods provide one estimate of snow grain size (e.g., the length of maximum dimension), they will not yield a precise optically equivalent snow grain radius (nor specific surface area) that is the relevant quantity in two-stream snow radiative transfer algorithms like the SNICAR model. To reduce a potential source of error regarding the SNICAR modeling results, I suggest placing a greater emphasis on the other measured quantities used as inputs into the SNICAR model, especially the light absorbing particle (LAP) concentrations.

Author's response

We appreciate the referee's comment. Regarding the method in the first field campaign, we do agree is outdated, but it was the only method available for the first, exploratory campaign. Regarding the improved method we used in the second field campaign, which averages the maximum and minimum axes of equivalent ellipses that fit the snow grains in the pictures, we believe that it gives a reasonable estimate of the particles dimensions. We want to clarify that we do not claim that it is "precise", but only "more precise" than the previous method. The main evidence in support of our grain size results is that the differences among measured albedo values for fine and coarse snow can be explained using these grain size values in SNICARv2.1 model.

Nevertheless, we do agree that the snow grain size measurement method could be further improved. Pirazzini et al. (2015, cited in the manuscript) also use 2D photos, but with a different metric. They suggest that their metric is a proxy for "half the width of the shortest particle dimension", which they claim is a better approximation of the optically equivalent snow grain radius. If that is the case, our results would overestimate the optically equivalent snow grain radius. Pirazzini et al. determined 11% uncertainty in the 2D photos metrics (due to the subjectivity of the software operators). Although we did not determine such kind of uncertainty in our measurements, we report the estimated effect of the dispersion of the grain size for each sample, through sensitivity studies on SNICARv2.1 model. Even though the dispersions are large (probably larger than the uncertainty of the method), the effect on the modeled albedo are lower than 4.5% (for clean snow) or lower than 0.8% (for dirty snow). We believe that this explains the fact that we can reproduce the measured albedo using the estimated grain size together with other snow properties (especially LAP content), even though our grain size estimate might not be as accurate as that obtained by other methods. Spectral albedo (not available in our field campaigns) would be a complementary approach to validate separately the effect of snow grain size and LAP content on our albedo results. For instances, Carmagnola et al. (2013, cited in the manuscript) measured snow SSA (indirectly,

through an IR optical method) independently of LAP content, which mostly affects UV-vis albedo (lines 33-35 of the manuscript).
We modified the manuscript to include the limitations of our snow grain size measurement method, and we also modified the discussion of the results to remark that snow grain size results might not be as accurate as that from other measurements.

Manuscript Changes

Sect. 2.2, lines 165-168

In the 2017 campaign, a similar in-house developed grid was used (with two scales: 1 mm and 0.5 mm) in combination with a macro lens and a mobile phone digital camera. High-resolution pictures where analyzed later with ImageJ software (Schneider et al., 2012). Snow grains were manually fitted with ellipses; the metric choice was the average of the minor and major axes of the ellipse. The new equipment and methodology introduced in the 2017 campaign allows a more detailed description of the snow samples and a more precise average radius value.

Sect. 3.3, lines 358-361

Regarding snow grain sizes, it is relevant to notice the range of observed average radius. In fresh snow samples from the accumulation zone (sites Acc5-2017 and Acc6-2017) we found an average radius of (151 ± 41) µm, whereas in samples of older firn in the ablation zone (or sub-surface snow/firn in the accumulation zone) we measured values usually around (1000 ± 200) µm. Pirazzini et al. (2015) also used 2D photos, but with a different metric. They suggest that SSK (shortest skeleton branch) is a proxy for "half the width of the shortest particle dimension", which they claim is a better approximation of the optically equivalent snow grain radius. Our metric (see Sect. 2.2) would probably give higher results than SSK, and hence we might have overestimated the optically equivalent snow grain radius. Nevertheless, as we show below in this section, our grain size measurements seem to be good enough to reproduce the measured albedo for fine and coarse snow in SNICARv2.1 snow albedo model.

Sect. 3.3, lines 403-406

In the other hand, comparison between sites with low PM content shows that snow grain size has a remarkable effect, as previously reported (Wiscombe and Warren, 1980; Hadley and Kirchstetter, 2012). Fresh snow with small grain size presents $\alpha_{meas} \approx 0.8$ (sites Acc5-2017 and Acc6-2017), but snow with similar PM content that has aged a few days presents $\alpha_{meas} \approx 0.6$ (site Acc2-2016). Spectral albedo measurements (not available in our field campaigns) would allow to study separately the effect of grain size and LAP content (see for instances measurements of snow specific surface area, SSA, in Carmagnola et al., 2013), to confirm that our grain size measurements are a good estimate of the optically equivalent grain radius.

Sect. 3.3, lines 411-414

Concerning grain size uncertainty (the standard deviation of snow grain radii in each sample), it is clear that the impact on albedo is much larger when PM content is low (sites Acc2-2016, Acc5-2017 and Acc6-2017). For low PM content sites, the effect is comparable to experimental uncertainty, and is relevant both for sites with finer and coarser grain sizes snow. For sites with high content of PM the uncertainty of grain size do not have an appreciable effect. Pirazzini et al. (2015) determined 11% uncertainty in the grain size measurements from 2D photos (due to the subjectivity of the software operators). Although we did not determine such kind of uncertainty in our measurements, we suggest that the reported standard deviation (between 16% and 26% of the average value) is probably larger than the uncertainty of the method. The sensitivity studies showed that the effect on the modeled albedo is lower than 4.5% for clean snow and lower than 0.8% for dirty snow. We believe that this explains the fact that we can reproduce the measured albedo using the estimated grain size together with other snow properties (especially LAP content), even though our grain size estimate might not be as accurate as that obtained by other methods.

Referee comment

Regarding the use of terminology, a reader would benefit from a brief description of the distinction, if any, between LAPs and particulate matter (PM). The abstract begins by stating the relevance of light absorbing impurities in snow studies, however, the results and discussion most frequently refer to PM. Because "LAP" is a well known acronym, I suggest either maintaining the convention used in the literature, or defining PM while also elucidating the reason for the use of "PM" to describe these particular measurements.

Author's response

We agree with the referee that we should stress the difference between both expressions. The gravimetric measurements presented on this manuscript must be attributed to PM deposited on the glacier, because we don't know precisely the fraction of LAP among total PM. Qualitative observations also reported here (field stratigraphies and microscopy observations) suggest that most of collected PM can be attributed to volcanic ash. Quantifying the fraction of ash in collected PM (and/or measure the contributions from 2011 Cordon-Caulle and 2015 Calbuco eruptions) was not amenable. Routine stereo microscope inspection, even at high magnification (up to 80x), did not *allow quantification; only estimates of percentage of dark components was possible due to the fine-grained components. Na_2O, K_2O and SiO_2 content (SEM-EDS) from individual particles helped to distinguish volcanic ash from both eruptions, as exemplified in the manuscript (Fig. 8). In addition, CaO and FeO contents also proved useful to distinguish Cordón Caulle volcanic ash from ash derived from the 2015 Calbuco eruption (not included in the manuscript), but measuring a representative number of particles through SEM is not feasible. Hence, at this moment we can only suggest that most of PM on these samples correspond to volcanic ash, and that is the reason why we used SNICAR's built-in volcanic ash optical properties without further tuning. We know this is not exact, since optical microscopy and SEM microscopy have shown evidence of a minor fraction of mineral dust and black carbon, but we believe our results show that this assumption is a good first order approach to understand snow albedo on the glacier surface. A follow up article will include further chemical characterization of these samples, which has been delayed due to several reasons. We modified the manuscript to introduce a clear distinction between PM and LAP (LAI in our previous version of the manuscript), and we checked that those terms were used consistently through the manuscript.*

Manuscript Changes

- *We replaced the acronym "LAI" by "LAP" throughout the text.*
- *We replaced the acronym "PM" by "LAP" in some paragraphs, to clarify that we refer to the effect of particles that absorb light:*

Sect. 1, lines 73-82:

Here we present the results from two field campaigns developed in the Alerce glacier during April 2016 and April 2017 to assess the bounds of PM deposition impact in the Alerce glacier mass balance. We show in situ albedo measurements and PM concentration values measured on surface and sub-surface snow and firn samples in accumulation and ablation zones of the glacier. Albedo in situ measurements are compared with results from SNICAR snow albedo model (Flanner et al., 2007; He et al., 2018), using measured snow properties and LAP ~~PM~~ content as input data. We present here an improvement of SNICAR's incident radiation spectra (presented as SNICARv2.1), to take into account changes in direct and diffuse solar radiation for partly cloudy skies. We study the effect of nearby volcanic events that occurred in recent years (Puyehue-Cordón Caulle and Calbuco). Finally, the influence of LAP ~~PM~~ on snow/ice albedo on the annual surface mass balance of Alerce glacier is assessed using an enhanced temperature index melt model (Oerlemans, 2001). This study is not only the first field study of the impact of LAP ~~PM~~ in Argentinian glaciers, but also one of the few studies of the long-term impact of volcanic ash on snow albedo.

Sect. 2, lines 93-95:

An enhanced temperature index mass balance model has been developed (Ruiz et al., 2015, 2017) to study the surface mass balance of the glacier. This model is used here to analyze the influence of LAP ~~PM~~, through glacier albedo changes, over the mass balance of Alerce glacier.

Section 2.3, lines 171-173:

Snow density and layer thicknesses were taken as parameters from in-situ stratigraphies. Average snow grain size and shape were obtained from in-situ measurements. LAP ~~PM~~ content was obtained from filters gravimetry.

- *We added two paragraphs to emphasize the difference between PM and LAP, and to further explain the approximation of assuming that all PM is volcanic ash (already mentioned in the original version of the manuscript in Sect. 2.3):*

Sect. 1, line 37:

Atmospheric particulate matter (PM) is diverse in size, chemical composition and optical properties; while most PM reflect a large fraction of the incoming radiation and thus have a cooling effect on the atmosphere, other particles absorb a relevant fraction of the visible radiation (depending on the ratio of their absorption and scattering coefficients) and have a heating effect (Bond et al., 2013). In snow, the term LAP is used to refer to black carbon (BC), mineral dust, volcanic ash and all other particles that totally or partially absorb incident light and hence increase the snow energy absorption. Different snow albedo models have been developed to include the direct effect of ~~Black Carbon (~~BC~~)~~ and other LAP ~~atmospheric particulate matter (PM)~~ as well as several positive feedbacks (Flanner et al., 2007; Koch et al., 2009; Krinner et al., 2006), the effects of non-spherical snow grains (Libois et al., 2013; He et al., 2017), and external/internal mixing of impurities with snow grains (He et al., 2018).

Section 3.2, lines 339-342:

The predominance of volcanic glass in the collected PM indicates the need to take into account the effect of volcanic ash in the albedo of seasonal snow and glaciers of the region, which can be frequently affected by volcanic eruptions. It must be emphasized that ash from CC and Cal eruptions was observed in most of the samples, not only in layers dated immediately after the eruptions, but also many years after direct deposition.

Field stratigraphy together with these microscopy results suggest that we can study the effect of LAP on snow albedo considering that all PM content can be attributed to LAP (and more specifically, to volcanic ash). Further chemical studies will be performed on the PM samples to refine the representation of LAP in the snow albedo model, since optical properties can be very different for BC, mineral dust, volcanic ash, etc. (the ratio of light absorption to light scattering at different wavelengths depends on particle size, shape, and chemical composition).

Referee comment

Although I found Sect. 3 to be well written, I recommend the following technical corrections regarding mostly the other sections and figures:

1. *Abstract (lines 1–4):* Background could be refined, perhaps by moving one or two of the sentences into Sect. 1, to quickly introduce the present work.

Manuscript Changes

Abstract, lines 1-4:

The relevance of light absorbing impurities in snow albedo (and its effects in seasonal snow or glacier mass balance) have been under study for several decades. However, tThe effect of volcanic ash in snow albedo (and its impact in seasonal snow and glacier mass balance) has been much less studied than that of other light absorbing impurities such as carbonaceous particles and mineral dust. , and most articles studied only the effect of thick layers after direct deposition. There is also a knowledge gap in field measurements of seasonal snow and glaciers of the southern Andes, that only recently has started to be filled. We present here the first field measurements on Argentinian Andes, combined with albedo and mass balance modeling activities.

Referee comment

2. *Abstract (line 6):* “during ablation” → “during the ablation”
3. *Abstract (line 9):* “from recent...eruption, with minor” → “from the recent...eruptions, with a minor”
4. *Abstract (lines 11–12):* “SNICAR model has been updated to model snow albedo taking into account” → “We updated the SNICAR model to account for”

Author’s response

We thank the referee for the useful grammar/phrasing suggestions.

Manuscript Changes

We adopt all changes suggested by the referee.

Referee comment

5. *Abstract (line 14):* This part seems like an important component of this study, yet, it took me two or three times to understand the meaning of this sentence. Perhaps “which field measurements precision” can be rephrased to improve the readability.

Author’s response

We agree with the referee regarding the readability of the sentence, we rephrased it.

Manuscript Changes

Abstract, line 14:

We also ran sensitivity studies consideringon the uncertainty of the main measured parameters (impurities content and composition, snow grain size, layer thickness, etc) to detect the field measurements that should be improved to facilitate the validation of the snow albedo model.to assess which field measurements precision can improve the uncertainty of albedo modeling.

Referee comment

6. *Abstract (line 17):* “m we” → “m snow water equivalent (SWE)”

Author’s response

We thank the referee’s suggestion, but we believe that both abbreviations for the snow water equivalence are widely used. We do agree that it needs to be defined in the abstract, and also in the main text.

Manuscript Changes

Abstract, line 17

1.25 meter water equivalentm we decrease

Sect. 3.4, line 447

−0.6 meter water equivalent per year (m w.e./yr)

Referee comment
7. *Sect. 1 (line 20):* I like this opening, but the first sentence needs to begin with "Since" or "Because."
Author's response
We agree with the referee's suggestion.
Manuscript Changes
Abstract, line 20
Since ~~G~~glaciers are highly sensitive to climate fluctuations, their unprecedented retreating rates observed during the last decades represent one of the most unambiguous signals of climate change

Referee comments
8. *Sect. 1 (line 29):* It's probably better to use the term "light-absorbing particles (LAP)" (Skiles et al., 2018).
9. *Sect. 1 (line 38):* What is the distinction between LAP and atmospheric particulate matter?
Author's response
See response and changes in the discussion regarding PM and LAP above in this file.
Referee comments
10. *Sect. 1 (line 44):* "there has been found" → "it has been shown"
11. *Sect. 2 (lines 88-89):* "the hydrological year is defined from the 1-April to the 31-March of the next year. The accumulation season last from 1-April to 31-October and the ablation season from 31-October to the 31-March of the next year." → "the hydrological year begins on April 1st with the accumulation season. The accumulation season lasts until October 31st, which marks the beginning of the ablation season."
Author's response
We thank the referee for the useful grammar/phrasing suggestions.
Manuscript Changes
We adopt all changes suggested by the referee.

Referee comments
12. *Fig. 1 (caption):* It might be good practice to include the term "true color" in the description to indicate that the image is intended to reproduce a natural color rendition.
13. *Fig. 2 (caption):* It might be good practice to indicate that the grayscale used is logarithmic.
Author's response
We thank the referee for the useful suggestions.
Manuscript Changes
Fig. 1 caption:
Figure 1. True color ~~S~~satellite image of Alerce Glacier. Sampling points are represented as blue markers (2017 campaign) and red markers (2016 campaign). Green marker represents Otto Meiling mountain hut. Copyright: © Google Earth, 2020, CNES/Airbus
Fig. 2 caption:
Figure 2. PM concentration (grayscale) as a function of pit depth for different sampling sites. Notice that the grayscale is logarithmic. Top panel: accumulation zone. Bottom panel: ablation zone. α symbol is used to highlight sites with concurrent albedo measurements. In sample *Abl2-2016*, the top rectangle corresponds to the average PM content of the first two layers (fresh snow and end-of-summer dark layer).

Referee comment
14. *Sect. 2.2 (line 125):* Please provide additional details of the "in-house developed supports" in order to improve the reproducibility of results.
Author's response
We added a Figure at the Supplement to provide additional construction details on the supports.
Manuscript Changes
Sect 2.2, line 150
Additional details on the supports are given in Fig. S1 in Supplement.
Supplement, Fig. S1

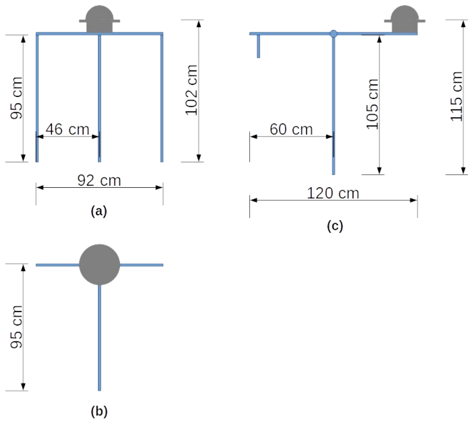

Figure S1. *Details of the pyranometer supports in Fig. 3 of the main text. (a) Side view and (b) top view of the support used in 2016 field campaign. (c) Side view of the support used in 2017 field campaign.*

Referee comments

15. *Sect. 2.2 (line 127):* "In the 2017 a" → "In the 2017 campaign, a"

16. *Sect. 2.2 (subsection headings):* Are these subsection headings supposed to be numbered (i.e., 2.2.1, 2.2.2, and 2.2.3)?

Author's response

We agree with the referee's suggestions.

Manuscript Changes

We adopt the referee's suggestions.

Referee comment

17. *Sect. 2.2 (line 153):* Equation (S1) has now been referred to twice. Should it be included in the main text?

Author's response

We believe that the details of the albedo measurements corrections (including Eq. S1) are not needed in the main text.

Manuscript Changes

We did not find the need to introduce any changes.

Referee comment

18. *Sect. 2.3 (line 189):* Is $I_{glob} = I_{dir} + I_{diff}$, or something else? Perhaps this can be more clearly described in Sect. 2.2.

Author's response

Yes, $I_{glob} = I_{dir} + I_{diff}$, as usually defined, but we accept the suggestion to remark that in the manuscript.

Manuscript Changes

Sect. 2.3 (line 189)

Idir, *Idiff* , and *Iglob* are clear-sky direct, diffuse and global solar irradiance (where $I_{glob} = I_{dir} + I_{diff}$), as calculated from SMARTS model.

Referee comment

19. *Fig. 4*: If the vertical axis represents a normalized, dimensionless quantity, please indicate so. Otherwise, please provide the meaning of the vertical dimension. Also, the right-most part of the figure (horizontal axis) appears clipped.

Author's response

We thank the referee for the comment. The plotted distributions are indeed normalized, we modified the caption to make that clear. We corrected the clipping of the image to show the last horizontal axis label correctly.

Manuscript Changes

- *We corrected the clipping of the image.*
- *Fig. 4 caption:*

Figure 4. Different normalized spectral distributions of sun radiation for SNICAR snow albedo model. SNICARv2 included two spectra for mid-latitude locations: one for overcast conditions (light green line), and one for clear sky conditions (dark green line). SMARTS diffuse (light red line) and direct (dark red line) clear sky spectra for one of our sampling sites are represented for comparison. Dotted lines represent spectra for partly cloudy conditions (SNICARv2.1).

Referee comment

20. *Fig. 5*: The box-and-whisker plot demonstrates the distribution of measurements nicely when *N* >2. Does this mean that boxes represent standard deviations even when *N* = 2? If this is the case, perhaps a bar chart displaying the minimum and maximum values would be a more consistent portrayal of seasonal ranges, since standard deviations are better for estimating the variance of a distribution with a larger number of samples.

Author's response

We thank the referee for drawing the attention on this plot. We agree that standard deviation is more relevant for N >> 2, but even so we believe in this case box-and-whiskers plot gives more information than a bar chart. For cases with N > 2 (four of the plotted seasonal ranges) the plot allows showing the range where most data fall, together with the extreme values (which in some cases are far away form standard deviation, e.g. Acc. season 2015). For N=2 (the three remaining seasonal ranges), the standard deviation is equal to half the separation between the minimum and maximum value, and hence the plot shows the minimum and maximum values. We modified the figure's caption to stress this fact, so the plot can be easily interpreted.

Manuscript Changes

- ***Fig. 5 caption:***

Figure 5. Seasonal range of PM concentration found on snow/firn samples. For accumulation season, the values represent the mean PM concentration in thick, low PM layers of snow/firn. For ablation season the values represents the surface PM concentration at the end of the season. The box encompasses one standard deviation of data, and whiskers represent minimum and maximum values (when N >2). Notice that for seasonal layers with only two measurements, the box represents those two values (coincident with the definition of standard deviation for N = 2). The plot includes data from both field campaigns, and excludes ablation ice samples, which cannot be assigned to a specific year/season. Fresh snow represent snow fallen a few days before field campaigns of 2016 or 2017.

Referee comment

21. *Sect. 3.3 (line 368):* Although Cuffey and Paterson (2010) have written a standard textbook for glaciology, it would be nice to include a more accessible, primary reference that demonstrates this phenomenon.

Author's response

We took the referee suggestion and found a different reference regarding the phenomenon.

Manuscript Changes

~~Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, Academic Press, 4th editio edn., https://doi.org/10.1016, 2010.~~

Flanner, M. G., and Zender, C. S.: Linking snowpack microphysics and albedo evolution, Journal of Geophysical Research, 111, D12208. https://doi.org/10.1029/2005JD006834, 2006

Referee comment

22. *Sect. 3.3 (line 403):* "In the other hand" → "On the other hand"

Author's response

We thank the referee for the useful grammar suggestion.

Manuscript Changes

We adopt the change suggested by the referee.

Referee comment
23. *Sect. 3.4 (AAR):* Definition of accumulation area ratio? If it is the accumulation area to ablation area ratio, why are the values in m?

Author's response

We thank the referee for noticing the mistake in the units of the Accumulation Area Ratio (the ratio of the glacier's accumulation area to its total area). The numbers are correct but they are a percentage.

Manuscript Changes

Table 2 header

α_{ice}	α_{firn}	α_{max}	Wint. MB (m w.e.)	Annu. MB (m w.e.)	ELA (m)	AAR (% ~~m~~)

Referee comments
24. *Fig. 9:* The prefix "glacier-wide" is technically redundant, as "surface mass balance" is considered a surface area-integrated quantity. When referring to it as a local quantity, however, it can be stated as "specific surface mass balance." Also, the units on the axes labels should be in parentheses.
25. *Sect. 4 (line 510)* "observation and modeling activities to analysis" → "measurements and modeling to analyze"
26. *Sect. 4 (line 512):* No need for a paragraph break here.
27. *Sect. 4 (line 526):* "may difficult" → "may degrade"
28. *Sect. 4 (line 529):* Remove the comma.
29. *Sect. 4 (line 534):* "glacier-wide" → "surface" (see comment 24)

Author's response

We thank the referee for the useful grammar/phrasing suggestions.

Manuscript Changes

We adopt the changes suggested by the referee.