Author’s response to Benjamin Smith’s Editor Decision

Editor comment

Editor Decision: Publish subject to minor revisions (review by editor) (07 Aug 2020) by Benjamin Smith
Comments to the Author:
There is some sort of a problem with the TC system, and I am not able to see the authors' revised manuscript today. As I'll be out of town next week, I wanted to provide some feedback based on what I can see in the responses to the referees.

Author’s response

We thank the Editor’s decision to publish the revised manuscript. We answer the specific comments and suggestions below.

Editor comment

It looks to me like the authors have done a good job of responding to the referees' comments, and I think the major scientific disagreements have been dealt with well. At the same time, based on the samples of the revised text that are available in the response documents, I suspect that the final manuscript will need some revisions for English and grammar. In particular:
--the response to lines 228-234 has a description of methods in present tense, while all methods should be in past tense

Author’s response

We thank the Editor’s grammar suggestion. We changed all verbs in the mentioned paragraph to the past tense.

Editor comments

--In the abstract, "microscopical" should be "microscopic"
--Lines 29-33: temperature increase -> temperature increases
--Lines 37-44 : "snow grains growth" -> "snow grains' growth" or "growth of snow grains"
--Lines 50-52: should be "online coupling...has"
In the block of supplement text starting with line 34: "placed" should be "located"
... and so on.

Author’s response

We appreciate the Editor’s grammar suggestions. We accepted them all, with exception of the second one. The word “increase” is not used here as a verb but as a noun.

Editor comment

I'm afraid I don't have time for a thorough proof-read of the manuscript, but I'd ask that the authors look carefully at their text with all revisions applied and check the grammar throughout before submitting a final draft. The manuscript is very close!

Author’s response

We thank the Editor’s suggestion. We made several additional grammar or spelling corrections, which are included in the marked-up version of the manuscript at the end of this file. We also improved some of the figure captions to follow more closely the journal guidelines.

Following this response, we include the responses to both reviewers (already posted as Author Comments in the interactive discussion) and a marked-up version of the manuscript.

Author's response to Marius Schaefer's review

Referee comment

General Comments:

The manuscript presents punctual albedo measurements over snow surfaces on different parts of a small glacier in the Northern Patagonian Andes in two consecutive years, together with measurements of physical parameters which could mostly explain the measured albedo variations (like grain size and form and particulate matter content). Then the authors try to reproduce the measured albedos, using a model, which is improved to account for partly cloudy conditions (which were present at least at one of the field days). In a last step the possible influence of the ash content, caused by eruptions of nearby volcanoes, on the total glacier surface mass balance is estimated using a simplified energy balance/mass balance model.

To my point of view the study is original and novel and fits well into the scope of the journal. I think that the significance of the study could be significantly increased by adding some additional data and analysis, which should not be too difficult to obtain and which would allow to better interpret the presented field data and model results:

Author's response

We appreciate the referee's thorough and useful comments to improve the manuscript. Although the suggested additions would increase the significance of the article, some of them are outside the focus of this manuscript. The manuscript already deals with field measurements and models. Including the use of remote sensing data would make it excessively long. We discuss the suggested additions point by point next.

Referee comment

1) Measured surface mass data at stakes: I think that the surface mass balance data measured at stakes were somehow used to interpret the sample obtained form the snow pits (section 3.1, Figure 2) but the detailed data are not indicated. Also in section 2.4 it is stated: "The model was calibrated by surface mass balance measurements performed on a seasonal to annual basis through the year 2016 over Alerce glacier". I would like to know more details about this calibration process. How well could the model reproduce the observed melt and accumulation of snow? Which alpha_firn values fitted best to the observations? The time series of measured surface mass balance could also be helpful for quantifying the impact of the volcanic eruptions on the glacier's surface mass balance.

Author's response

A comprehensive evaluation of the mass balance of Alerce glacier is beyond the scope of this work and it is core of an ongoing manuscript by one of the members of the author team (Lucas Ruiz). We included in Fig. 1 the location of ablation stakes, and in the Supplement (Fig. S4) the location of snow thickness measurements. Detail regarding the process of calibration of the surface mass balance model (SMB model) was added in Sect. 2.4 together with two new figures in the Supplement (Fig S5 and S6) which shows the agreement between modeled and measurements used to calibrate the SMB model and the fitting of the model for two of the ablation stakes close to the albedo sampling locations.

For the hydrological years 2015 and 2016 (during and after the Calbuco eruption) best agreement between measurements and model was achieved using minimum snow albedo values of 0.42-0.38. The range express the difficulty to achieve a straightforward calibration of the different parameters used in enhanced degree-day models. Some parameters counteract each other and minimum RMSEs could be achieved with a variety of parameter combination. Thus, it is also necessary considering surface characteristics at the stakes locations and their distribution across the glaciers, like transient snow lines or extra mass balance measurements through the year.

Manuscript Changes

Lines 228-234:

~~After calibration of the model, $c_0 = -50$ W m^{-2} and $c_1 = 12$ W m^{-2} °C^{-1}.~~ Potential direct solar radiation for all grid cells and days was calculated following Hock (1999). The local surface albedo $\alpha(x,y,t)$ was taken to be constant for bare-ice

surfaces (α_{ice} = 0.34), using most commonly applied literature value (Oerlemans and Knap, 1998; Cuffey and Paterson, 2010), for snow surfaces, α_{snow} was calculated based on the snow aging function proposed by Oerlemans and Knap (1998) with a maximum snow albedo (α_{max}) of 0.8 and a ~~variable~~ minimum snow albedo (α_{min}) adjusted during the calibration procedure. ~~(α_{firn}, table 2)~~.
The model was calibrated in two steps using surface mass balance measurements of year 2016 in Alerce glacier (Supplement, Fig. S4). First, the model is run over the winter period with an initial set of constants (c_0 and c_1) and a guess for the precipitation correction factor C_{pre}. As melt is of minor importance in winter, this run is used to calibrate C_{pre}, that scales D_s for every snow fall event. After a good agreement of measured and calculated winter accumulation is obtained, the model is run over the entire year and the remaining constants are calibrated so that the root-mean-square error between modelled and observed point annual balances is minimized and the average misfit is close to zero (Supplement, Fig. S5 and S6). A random set of snow accumulation and ablation stakes measurements performed through the year and not used to calibrate the model are left apart to validate the results of the surface mass balance model.
We studied ~~G~~glacier-wide mass balance changes for~~between~~ different values of α_{min} ~~α_{firn}~~ (Table 2), which are indicative of the sensitivity of glacier mass balance to a change in albedo that might occur in response to the darkening of the glacier surface.
Supplement, Fig. S4, S5 and S6 (see at the end of this file).

Referee comment

2) I am surprised by the big influence of alpha_firn on the modeled surface mass balance of the glacier. In a "normal" year I would expect to have no firn in the ablation area and the firn of the accumulation area being buried by snow most of the year. How did you initialize the model (regarding presence of snow, firn, ice). Was 2016 a typical year? Probably not since autumn 2016 was exceptionally dry in the region. I would propose to run the model with a few years of "typical" meteorologic data (mean value of several years) and standard firn albedo for model initialization and then start to study the influence of different firn albedos. I think it should be much lower on average.

Author's response

We acknowledge that the use of α_{firn} as a synonymous of minimum snow albedo was not a good choice and give place to confusions. As we stated in Section 2.4, α_{firn} is the minimum albedo that snow could reach using the snow aging function of Oerlemans and Knap (1998). We replaced α_{firn} for α_{min} to avoid any confusion. We agree that if we had only changed the albedo of the firn (the snow accumulated after more than year, for instances), the effect on the surface mass balance would have been much lower.
The model is initiated with a guess snow and firn lines and run for a few days before the evaluated period, which is observational period. to stabilize the surface mass balance to the input data. We have tested different initiation scenarios, to check the sensitivity of the model to initial conditions, and under realistic scenarios, the sensitivity is rather low.
Finally, we agree with the reviewer, 2016 was the driest year since we start the monitoring of the Alerce glacier in 2013.

Manuscript Changes

We replaced α_{firn} for α_{min} throughout the manuscript.

Referee comment

3) Since the albedo measurements are very punctual in time and space, and, as your repeating in the text several times that particulate matter concentration is very variable in time and space, it would be great to get an idea about the significance of your punctual albedo measurements by analyzing for example optical reflectance in satellite images. Images obtained at dates near to your field campaigns could be used for calibration. By this means you could also easily go back until the 2011 Cordon Caulle eruption. Would be great to see how the reflectance of the glacier changed from summer 2011 to 2012. Or from summer 2015 to 2016.

Author's response

Satellite observations are relevant, and we have already look at MODIS products and other remote data for a following article. Although satellite snow reflectance data could be used to evaluate the significance of our punctual surface measurements (albedo measurements, particles content and *snow grain size), Landsat and Sentinel images close to the timing of our measurements are totally or partially cloud covered for Monte Tronador. As we stated in the manuscript cloudiness conditions were challenging and we needed to update SNICAR model to deal with it. Regarding the use of MODIS, although the time resolution allows us to have more images without excessive cloud cover, it spatial resolutions challenges the evaluation against punctual surface measurements. Nevertheless, our preliminary evaluation of MODIS albedo time series of Monte Tronador, shown a decrease in late summer albedo after the Cordon Caulle and Calbuco eruption, with a minimum during the late summer of 2017 (both a combination of the ashes and less snow fallen over the glacier). Nevertheless, as we mention above, these additional analysis would require a considerable amount of space, hence we decided to keep them for another manuscript where we can deal properly with it.*

Referee comment

Technical Comments:

Your abstract is 350 words which is too long (instructions form the journal's web page copied below). Try to reduce! For example you have three introducing sentences. One should be enough! **Research articles** report substantial and original scientific results within the journal's scope. Generally, these are expected to be within 12 journal pages, have appropriate figures and/or tables, a maximum of 80 references, and an abstract of 150–250 words.

Author's response

We thank the referee for the suggestion. We have already reduced the length of the abstract following a suggestion of the Anonymous Referee #1. We present here a further effort of making the abstract more concise.

Manuscript Changes

Abstract

The impact of volcanic ash on seasonal snow and glacier mass balance has been much less studied than that of carbonaceous particles and mineral dust. We present here the first field measurements on Argentinian Andes, combined with snow albedo and glacier mass balance modeling. Measured impurities content (1.1 mg kg−1 to 30 000 mg kg−1) varied abruptly in snow pits and snow/firn cores, due to high surface enrichment during the ablation season and possibly local/regional wind driven resuspension and redeposition of dust and volcanic ash. In addition, we observed a high spatial heterogeneity, due to glacier topography and prevailing wind direction. Microscopical characterization showed that the major component was ash from recent Calbuco (2015) and Cordón Caulle (2011) volcanic eruption, with a minor presence of mineral dust and Black Carbon. We also found a wide range of measured snow albedo (0.26 to 0.81), which reflected mainly the impurities content and the snow/firn grain size (due to aging). We updated the SNICAR snow albedo model to account for the effect of cloudiness on incident radiation spectra, improving the match of modeled and measured values. We also ran sensitivity studies considering 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. Finally, we studied the impact of these albedo reductions in Alerce glacier using a spatially distributed surface mass-balance model. We found a large impact of albedo changes in glacier mass balance, and we estimated that the effect of observed ash concentrations can be as high as a 1.25 meter water equivalent decrease in the glacier-wide annual mass balance (due to a 34 % of increase in the melt during the ablation season).

Referee comment

Detailed Comments:

Page2

Line 26: Patagonian Andes or Wet Andes instead of Southern Andes ? (to be more precise).

Author's response

We agree with the referee that the suggested terms are more precise, we rephrased.

Manuscript Changes

Lines 25-26:

Along the ~~Southern~~Wet Andes (below 35º S latitude), melt is driven by shortwave radiation and sensible turbulent flux (Schaefer et al., 2019).

Referee comment

Line 27: you mean net shortwave ? Albedo is not influencing the oncoming shortwave radiation. I would say summer, since in spring glaciers are mostly snow covered and exhibit high albedos

Author's response

We thank the referee for the comments. Regarding the first comment, we rephrased the sentence in order to make sure the meaning of the sentence is transparent. Regarding the second comment, we agree that the exposure of low albedo layers is much more significant in summer.

Manuscript Changes

Lines 25-29:

The ~~effect of incoming~~ shortwave radiation absorption increases significantly ~~is enhanced~~ during ~~spring and~~ summer, due to the exposure of low albedo areas in their ablation zones, which causes strong, positive feedback that enhances surface melt significantly and shapes the spatial ablation pattern (Brock et al., 2000).

Referee comment

Line 29 – until Page3 Line72: in this section you discuss the influence of light-absorbing impurities on snow albedo. You mention particulate matter, mineral dust, volcanic ash and black carbon). Are all particulate matter light-absorbing impurities? Are mineral dust, volcanic ash and black carbon both particulate matter and light-absorbing impurities? Perhaps order these definitions in an introducing sentence and avoid synonyms (particulate matter = light-absorbing impurities?)

Author's response

We agree with the referee that the original manuscript was not clear enough regarding these definitions, as was also pointed out by Anonymous Referee #1.

Manuscript Changes

*We introduced several changes that are detailed in the **Author's Response to Anonymous Referee #1**, pages 2-4.*

Referee comment

Line 31: produced → producing

Author's response

We thank the referee for the useful phrasing suggestion.

Manuscript Changes

Lines 29-31:

Furthermore, deposition of light-absorbing impurities (LAP; mineral dust, volcanic ash, and black carbon) have a fundamental impact on the melting of glacier and snow-covered areas by increasing the absorption of solar radiation and producinge~~es~~ a regional land-atmosphere feedback

Referee comment

Line 32: "the growth of snow grains is accelerated" explain when and why.

Author's response

We accept the referee's suggestion to further explain this effect. We rephrased two sentences to better explain the direct and indirect effects of LAP on snow.

Manuscript Changes

Lines 29-33:

Furthermore, deposition of light-absorbing impurities (LAP; mineral dust, volcanic ash, and black carbon) have a fundamental impact on the melting of glacier and snow-covered areas ~~by increasing the absorption of solar radiation and produces a regional land-atmosphere feedback~~ (Warren and Wiscombe, 1980; Bond et al., 2013; Molina et al., 2015). LAP decrease snow albedo, increasing solar radiation absorption and thus producing a direct effect on snow melting. But, in addition, the snowpack temperature increase due to the direct effect ~~Along with the enhanced melting due to the darkening of the snow or ice surface,~~ accelerates the growth of snow grains ~~is accelerated~~, which ~~further reinforces snowmelt rates due to~~ produces a further albedo decrease (and thus an additional, indirect impact on snow melting) (Bond et al., 2013; Flanner et al., 2007).

Referee comment

Line 38: "as well as several positive feedbacks" which one?

Author's response

The thorough review by Bond et al. (2013) describes in detail the multiple rapid changes in snow due to LAP deposition (see Fig. 29 of the reference). We added in the text two of the more important feedback processes and refer the reader to the reference.

Manuscript Changes

Lines 37-40:

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), such as the increase in surface concentration of impurities due to enhanced snow melting, or the albedo reduction due to snow grains growth by accelerated snow aging (Bond et al., 2013). More recently, models have included 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).

Referee comment

Line 42: do not understand the sentence. What is a particle metric distribution?

Author's response

We agree with the referee that sentence needs rephrasing. We hope that this new phrasing gives a better, concise description of the main results of the references, and help the reader to find further details therein.

Manuscript Changes

Lines 42-43:

~~More than just one particle metric distribution is necessary to reproduce the spectral snow albedo at all optical wavelengths, especially w~~When the snow has been undergoing heavy metamorphosis processes, a single snow grain size distribution is not enough to reproduce the snow spectral albedo, due to the fact that the largest particles and the thinnest protrusions of the irregular crystals have contributions to the snow reflectance that depend on the wavelength (Carmagnola et al., 2013; Pirazzini et al., 2015)

Referee comment

Line 45: explain broadband albedo

Author's response

We thank the referee's question. We rephrased the sentence to explain more clearly the results in Zhang et al., 2018.

Manuscript Changes

Notably, there has been found that taking into account the amount of LAP~~I~~ in the snow reduces the difference between simulated and measured ~~broadband~~ albedos, specially in the visible range (Zhang et al., 2018).

Referee comment

Line 50: what is "online coupling"?

Author's response

We agree with the referee that the phrase might not be clear for some readers. We use the term "online coupling" to imply that the two models (snow albedo model and atmospheric chemistry model) are run simultaneously and allowing two-way feedback. Other studies use offline coupling, where one of the models (usually, the atmospheric chemistry model) is run first, and the results are used as input for the other model (snowpack model or glacier mass balance model).

Manuscript Changes

Lines 50-52:

"Online" coupling of snow albedo models in global or regional atmospheric chemistry models (where both models are run simultaneously allowing two-way feedback) have been applied to study snow and glaciers interaction with the climate around the globe (Hansen et al., 2005; Flanner, 2013; Ménégoz et al., 2014).

Referee comment

Page3

Lines 67-68: do not understand the sentence starting with "For example ..." Reformulate!

Author's response

We rephrased the sentence.

Manuscript Changes

Lines 67-68:

For example, the albedo reduction ~~for spherical snow grains radii of 100 µm~~ due to BC alone in the north was estimated to be~~is~~ only about 43 % of that for all light-absorbing impurities (assuming spherical 100 µm radii snow grains).

Referee comment

Page4

Line 94: I think the mass balance model is not mentioned in Ruiz et al 2017

Author's response

We thank the referee for noticing the mistake, we corrected the position of the references regarding the Alerce glacier monitoring and we added a new one regarding the mass balance model.

Manuscript Changes

Lines 91-94:

Since 2013 it has been the focus of a glacier mass balance monitoring program by the IANIGLA (Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales; Ruiz et al., 2015, 2017). Seasonal mass balance has been studied every year using the traditional glaciological method of stakes, and snow pits. An enhanced temperature index mass balance model has been developed (Huss et al., 2008; Huss, 2010)~~(Ruiz et al., 2015, 2017)~~ to study the surface mass balance of the glacier.

Referee comment

Page 5:

Line 124: … "with a" … → … with one ...

Author's response

We thank the referee for the useful suggestion.

Manuscript Changes

Upwelling (reflected) and downwelling (direct + diffuse) radiation were measured with ~~a~~one CM5 Kipp & Zonen pyranometer (wavelength range 0.3 µm to 2.8 µm), using two different in-house developed supports in 2016 and 2017 campaigns, logged with a handheld voltmeter.

Referee comment

Line 126: How much W/m² is 0.1mv?

Author's response

For reference, 0.1 mV represents approximately 9.5 W/m^2 for our pyranometer. We did not find relevant to include the conversion factor in the article since we do not report solar irradiances, but only measured albedos (the conversion factor is not relevant for the radiation ratios).

Referee comment

Page 6

Line 166: "High-resolution pictures" … Would be great if you could show them in the supplementary material

Author's response

We added a figure in the Supplement (Fig. S3).

Manuscript Changes

Lines 166-167:

High-resolution pictures (Fig. S3, Supplement) where analyzed later with ImageJ software (Schneider et al., 2012).

Supplement, Fig. S3 (see at the end of this file)

Referee comment

Page 7

Line 173/174 "are decribed in detail in section 3.2" → (Section 3.2)

Line 180: for → of

Author's response

We thank the referee for the useful suggestion.

Manuscript Changes

We adopted the suggested changes.

Referee comment

Page 8

Line 221&228 I could not open the links indicated for the weather stations! Please indicate distance from glacier and elevation for both stations!

Author's response

We thank the referee for noticing the mistake, we corrected the links and added the altitude of the stations.

Manuscript Changes

Line 221:

$P(t)$ was the daily precipitation at Tepual weather station (90 m altitude, ID = 857990; ~~http://www7.ncdc.noaa.gov/~~https://www.ncei.noaa.gov/access/search/data-search/global-summary-of-the-day)

Lines 277-228:

$T(t)$ was taken from the air surface temperature at Bariloche airport weather station (846 m altitude, ID = 877650; ~~http://www7.ncdc.noaa.gov/~~https://www.ncei.noaa.gov/access/search/data-search/global-summary-of-the-day).

Referee comment

Page 9

Line 251/252: on the base of what is this interpretation?

Author's response

The interpretation of the snow/firn layers is based on the observed stratigraphy of the snow column. Snow pits walls and cores were described following common glaciological practices, in terms of layering, grain size and shape, content of PM, density and hardness. Dating of layers or attribution of time windows for each layer was based on the stratigraphic relations between layers and its characteristics. In this case, the layer (242 cm to247 cm) had a high PM concentration, was below a thick, relative low PM content, soft snow layer (interpreted as the snow accumulated during the accumulation season of the hydrological year 2015-2016) and above a harder, coarser grained firn layer (interpreted as the snow of the accumulation season of 2014-2015).

Manuscript Changes

The deepest (242 cm to 247 cm deep) thin, high PM concentration layer ((1970 ± 200) mg kg−1) was interpreted as the surface at end of the ablation season of the hydrological year 2014-15, based on the abrupt change of the density, hardness and grain size of the snow above this layer and the firn found below.

Referee comment

Page 10

Line 262: Abl2-2016 → Abl1-2016?

Author's response

We thank the referee for noticing the mistake

Manuscript Changes

We corrected the mistake in the sampling site name.

Referee comment

Line 264: "These sites ..." which one? Abl3 and Abl4 ? In Abl2 and Abl5 PM content also seems to be quite high!

Author's response

The sentence refers to the sites Abl3-2017 and Abl4-2017, mentioned in the previous sentence, but we changed the sentence to avoid any misunderstanding. The PM content on the surface layer of those sites, (30000 ± 5000) mg kg^{-1} and (12000 ± 2000) mg kg^{-1} respectively, is much higher than that of any other site, due to the reasons explained in the manuscript and in the new section S2 of the Supplement (see response to the next comment). Sites Abl2-2016 and Abl5-2017 had a surface layer of recent snow. Below the surface layer, the PM content of the summer surface layer of site Abl2-2016 was (4400 ± 800) mg kg^{-1}. Site Abl5-2017 presented glacier ice below the surface layer (which was not sampled).

Manuscript Changes

Lines 264-265:

~~These s~~Sites *Abl3-2017* and *Abl4-2017* had a negative net balance during hydrological year 2016-17, consequently the surface layer presented the highest PM content observed in both campaigns

Referee comment

Line 268: " firn layer from 2015 winter" – how do you know?

Author's response

The layers from sites Abl3-2017 and Abl4-2017 (placed close to each other in the same accumulation pocket, see new Fig. S2 at the end of this file) were identified based on stratigraphic relationships. The dark surface at site Abl4-2017 was the topmost layer of the pocket, but based on the grain size (738 ± 167 μm), density and hardness, we interpreted that all accumulation from 2016 winter had melted. The high PM concentration (12000 ± 2000) mg kg^{-1} was also consistent with the surface enrichment due to melting of snow deposited in more than one hydrological year. The firn below this layer was then identified as the accumulation layer from 2015 winter. In site Abl3-2017, towards the border of the accumulation pocket, the topmost layers described for site Abl4-2017 had also disappeared. Hence, we interpreted that all accumulation from 2015 winter had also melted in this site, and this darkest, surface layer contained most of PM deposited in 2016 and 2015. The firn layer below was interpreted as the accumulation layer from 2014 winter.

Manuscript Changes

Lines 267-270:

In-situ stratigraphy revealed that in *Abl4-2017* site, the high concentration layer was on top of relatively low concentration, firn layer from 2015 winter, which means that, during the 2016-2017 ablation season, all the snow accumulated during 2016 winter was melted. Site *Abl3-2017* presented an even lower net balance, revealing older firn (winter 2014) below the surface high concentration layer. See Sect. S2 in Supplement for additional details on the attribution of layers in sites Abl3-2017 and Abl4-2017.

Supplement, line 34:

S2 Dating of snow/firn layers

Most snow/firn layers sampled during both field campaigns were easily dated, considering that the topmost layer contains the most recent snow and attributing layers below based on PM content, density, hardness and grain size. Topmost layers were identified as:

(1) fresh snow from a recent deposition events, on the accumulation zone, (sites Acc1-2016, Acc2-2016, Acc4-2017, Acc5-2017, Acc6-2017 and Acc7-2017, Fig S2(a)), on an accumulation pocket (site Abl1-2016), or on top of ablation ice (sites Abl2-2016 and Abl5-2017),

(2) end-of-ablation season surface, with high enrichment of PM content (Acc3-2016, Fig. S2 (b)), or

(3) ablation ice (site Abl6-2017).

The only exception were sites Abl3-2017 and Abl4-2017, placed in an accumulation pocket in the ablation zone of the glacier. As can be seen in Fig. S2 (c), site Abl4-2017 corresponded to the topmost layer of the pocket (which disappeared toward the borders of the pocket, site Abl3-2017). However, based on the hardness, density, coarse grain size (738 ± 167 μm) and high surface enrichment (PM content as high as (12000 ± 2000) mg kg^{-1}), we interpreted that this was a firn layer due to negative net accumulation during 2016-2017 hydrological year. The sub-surface firn layer of site Abl4-2017, with a low PM content, was attributed to firn accumulated during 2015 winter. Since those two layers have disappeared in site Abl3-2017, this area was identified as an area with even lower specific mass balance, where all accumulation from 2015-2016 hydrological year had also melted. The PM content, (30000 ± 5000) mg kg$^{-1,}$ is consistent with the expected higher surface enrichment. The sub-surface firn layer was then attributed to accumulation during 2014 winter.

Supplement, Fig. S2 (see at the end of this file)

Referee comment

Line 290/291: "low seasonal humidity" – do you mean variations?

Author's response

We thank the referee for suggesting to clarify this sentence. During summer, snow melting exposes volcanic ash (and mineral dust) deposited in previous years in Monte Tronador and surrounding mountains. During the summer, when humidity is particularly low (such as in 2016 summer), mobility of ash and soil is higher, producing more relevant resuspension events.

Manuscript Changes

Lines 290-294:

The magnitude of resuspension events in Andean Patagonia, a region with strong, persistent westerlies and a dry season with low ~~seasonal~~ relative humidity, is well known. These aeolian remobilization events may produce huge ash clouds that may be even confused with true volcanic plumes, they can remobilize ash tenths of kilometers away (Toyos et al., 2017). In particular, ~~the~~ deposits of volcanic ash that are covered by snow during the winter in the high mountain usually become exposed to remobilization during the summer, travelling through the atmosphere and redepositing over different surfaces due to decrease of wind competence or by adherence of particles on humid surfaces, even at considerably high altitudes.

Referee comment
Page 11
Line 328: "it was dated as winter snow from 2014" – how?
Author's response
The interpretation was based in stratigraphic relationships as discussed for Line 268 comment (above).
Manuscript Changes
One of the samples described under microscope, corresponds to a sub-surface sample from site *Abl3-2017*, ~~it~~ which was ~~dated~~ interpreted as winter snow from 2014, previous to 2015 Calbuco eruption, and approximately 75 % of the observed particles correspond to fine-grained colourless pumiceous ash.

Referee comment
Page 12:
Line 349: "a single measurement" - what does that mean? One voltage reading? How stable is the voltage in time?
Author's response
The sentence means that in 2016 campaign the pyranometer was placed once towards incoming solar radiation and once towards radiation reflected by the snowpack. The voltage was stable during reading (up to the 0.1 mV resolution of the voltmeter), and hence we used the voltmeter resolution as the instrumental uncertainty. In 2017, the higher resolution voltmeter allowed to see changes in voltage readings. As we explain in the manuscript, we believe that this was due both to the higher resolution of the voltmeter and to faster changes in cloudiness.
Manuscript Changes
Lines 349-350:
For the 2016 campaign, the reported measured albedo is a single measurement (registered after voltage reached a stable value) and is informed together with its instrumental uncertainty.

Referee comment
Line 259: SNOW RADIUS!!!
Author's response
We thank the referee for the suggestion.
Manuscript Changes
Lines 359-361:
In fresh snow samples from the accumulation zone (sites *Acc5-2017* and *Acc6-2017*) we found an average snow grain radius of (151 ± 41) µm, whereas in samples 360 of older firn in the ablation zone (or sub-surface snow/firn in the accumulation zone) we measured values usually around (1000 ± 200) µm.

Referee comment
Table1:
Why are there two values for the measured albedo in Abl4?
Why do you present the measured albedo in different lines? Should be always next to the modelled W.Aver?
Author's response
We thank the referee for the comments. For site Abl4-2017, we decided to register two sets of measurements, instead of one single set, due to the observed rapid movements of clouds. The irradiance values were significantly different in both sets, and so were the average albedo values. The second value is similar to the one measured in site Abl3-2017, and both are similar to the modeled value. The coincidence with the modeled value suggests that the sky pictures (taken after both sets of measurements) and cloud cover estimate represent better the sky conditions of the

second set of measurements. Regarding the second comment, we do agree that the measured albedo should be always placed next to the weighted average modeled albedo.

Manuscript Changes

See modified Table 1 at the end of this file

Lines 376-379:

For overcast conditions (*Acc3-2016*, *Abl3-2017* and *Abl4-2017*), the pure diffuse albedo from both models is also similar, and weighted average albedo from SNICARv2.1 is coincident with the pure diffuse albedo. For both models, the diffuse radiation spectrum for overcast conditions is coincident with global solar radiation spectrum (see Fig. 4), which explains the similar results. It must be noticed that for site Abl4-2017, we observed rapid cloud movements, and we decided to register two sets of albedo measurements. The average albedo of the second set is similar to the modeled weighted average albedo and to the measurement for site Abl3-2017. We suggest that this coincidence means that the pictures of the sky above the site (taken after the two sets of measurements) and the estimate of cloud cover based on those pictures represent more accurately the sky conditions during the second set of measurements.

Referee comment

Last column:

could you describe in the methods how you obtain these sensitivities? Are they really always symmetric? I do not understand the uncertainty associated to the concentration of BC? Why is is sometimes 100micrograns/kg and sometimes 20mg/kg.

These numbers have many zeros! Could you better indicate the percentual sensitivity and mark the most important contributor?

Author's response

We thank the referee for the comment. The sensitivity studies were performed modifying one parameter at a time in SINCARv2.1 calculations: for parameter "A", we calculated the albedo values α(A+ΔA), α(A) and α(A-ΔA) (where ΔA stands for the parameter uncertainty reported in the Table 1), keeping all other parameters unchanged. The sensitivities calculated in this way are not always symmetric: we expressed them as single range to make the table easier to read, but we accept the referee suggestion to show that asymmetry. However, we prefer to keep the expression of the observed albedo change (instead of percentage change) to better appreciate which significant figures of the modeled albedo are affected by each estimated sensitivity.

Regarding BC, we were not able to measure (yet) the carbon content of the samples, due to difficulties of equipment availability. We introduced a sensitivity study on BC content since one of the possible limitations of our simulations is the uncertainty regarding other LAP present in the samples aside from volcanic ash. The example value of 100 μg/kg was chosen since is compatible with BC concentrations usually found on glacier surfaces (e.g., Ginot et al. 2014). For sites with higher LAP concentration, 100 μg/kg of BC did not modify the modeled albedo, hence we decided to also calculate the impact of a higher amount of BC (20 mg/kg) to show how high it would need to be to have a similar impact in the albedo.

Manuscript Changes

Table 1:

We corrected the expression of the sensitivities in the last column to show that they are not symmetrical with respect to the parameters uncertainties. We highlighted the most important contributors for each site. See modified Table 1 at the end of this file.

Lines 407-410:

The last column in Table 1 reports the results of sensitivity studies to evaluate the impact on the calculated albedo of the uncertainty in key input parameters. We define the sensitivities as the modeled albedo changes increasing or decreasing one parameter in the same magnitude of its reported uncertainty (identified in Table 1 with a "+" or a "–" sign, respectively), while keeping all other parameters unchanged. ~~The parameters have been modified in ranges allowed by the uncertainty of the input parameters.~~ For each site, we studied PM content and grain size impact, together with other parameters that could be relevant at each site. We highlighted (with bold characters) the higher sensitivities for each site.

Referee comment

Page14.

Line 399: non-additive → non-linear?

Author's response

We thank the referee for the suggestion. We believe that in this context both phrases express almost the same meaning, but we prefer the expression "non-additive" since it remarks the fact that we are talking about the effect on albedo of two separate fractions of LAP.
Manuscript Changes
No changes were introduced.

Referee comment
Page 15
Line414/415: revise sentence starting with: "Volcanic ash ..."
Author's response
We thank the referee for the suggestion.
Manuscript Changes
Lines 414-415:
The uncertainty of ~~V~~volcanic ash content ~~uncertainty~~ does not have a relevant impact for any of the sites, although it is larger for site *Abl4-2017*.

Referee comment
Line 419: what is a thin layer? Give number!
Author's response
We thank the referee for the suggestion. We added a reference to specific samples/sites and their thicknesses to clarify the affirmation.
Manuscript Changes
Lines 419-421:
The impact is maximum for very thin layers, especially when the underlying layer has a significantly different albedo (~~i.e., PM content)~~site *Abl4-2017*, 0.1 cm thick), and its minimum for the thicker layers (sites *Acc5-2017* or *Acc6-2017*, 9 cm thick), or for intermediate thicknesses with high PM content (i.e., low penetration of incident light, site *Abl3-2017*, 0.3 cm thick).

Referee comments
Page 16
Line 442 Albedo and glacier mass balance **model:** up to now only modeled mass balance is analyzed
Line 443 "… glacier wide **modeled** annual and winter **…"**
Author's response
We thank the referee for the suggestions. For the section title, we suggest a different phrasing that we find represents better the content of the section.
Manuscript Changes
Lines 442-444:
3.4 Albedo and modeled impact on glacier mass balance
Table 2 shows the glacier-wide modeled annual and winter mass balance, Equilibrium Line Altitude (ELA) and Accumulation Area Ratio (AAR) for different values of old snow albedo (α_{firn}).

Referee comments
Page 18
Line 510: delete "PM over"
Line 519: delete "major"
Author's response
We thank the referee for the suggestions. Regarding the first comment, we do not agree: our manuscript focus on the impact of PM or LAP on albedo. Hence, we prefer not to delete the phrase. Regarding the second comment, we suggest an additional change that reflects better the intended meaning: the fact that volcanic ash are not only present, but that they represent the major fraction of the collected PM.
Manuscript Changes
Lines 519-521:

The ~~major presence of~~fact that volcanic ash represents the largest fraction of the collected PM in all studied samples indicates that the effect of nearby volcanic eruptions are expected not only immediately after direct deposition, but also many years later, due to surface enrichment and wind resuspension and redeposition.

Referee comment

Line 523/524: please propose how to take account for that

Author's response

We thank the referee for the suggestion. While we do propose how to take account for the spatial heterogeneity of PM distribution at the end of the previous section, we agree that is appropriate to summarize that in the Conclusions as well.

Manuscript Changes

Lines 522-523:

These facts need to be accounted for when studying the effect of snow albedo on glacier mass balance. While the albedo parametrization used in the mass balance model partially accounts for the spatial heterogeneity of PM surface concentration (implicitly), we suggest that in the future it would be useful to couple our mass balance model with an atmospheric model which provides prognosis of PM content and a snow albedo model that includes LAP effect explicitly.

Referee comment

Page 19

Line 525: "We found that rapid changes ..." this is only a problem for your specific set-up. If you are able to measure upwelling and downwelling radiation simultaneously, this is not a problem.

Author's response

We thank the referee for noticing the phrasing mistake. Indeed, we are not describing an inherent problem of albedo measurements but a limitation of our set-up. Using two pyranometers has other instrumental limitations that need to be aknowledged (specially, the need to account for the different sensitivities of the upward and downward sensor; Pirazzini, R., J.Geophys.Res., 109, D20118, 2004).

Manuscript Changes

Lines 525-526:

We found that for our set-up (where the pyranometer must be inverted sequentially to measure upwelling and downwelling radiation) rapid changes in cloudiness hinder the repeatability of albedo measurements and may degrade the comparison with modeled albedo.

Referee comment

Line 530: "… suggesting strategies ..." which strategies are you suggesting? Which were the most important uncertainty?

Author's response

We thank the referee for the suggestion.

Manuscript Changes

Lines 530-533:

The effect of uncertainties of field measurements of snow properties was evaluated for different types of samples (lower or higher LAP~~PM~~ content, grain size, layer thickness, snow density, etc.), suggesting strategies to reduce uncertainty in snow albedo modeling or retrieval of snow properties from measured albedo. We found that snow grain size must be measured more carefully in samples with low volcanic ash content and that the accuracy of layer thickness can be relevant not only for very thin layers (0.1 cm) but also for thicker layers (6 cm) with low ash content. The accuracy of ash content was found to be good enough for reproducing our albedo measurements. However, it was remarked that the presence of small amounts of BC can affect the albedo significantly in samples with low ash content.

Referee comment

Line 534/535: glacier-wide albedo change sensitivity : explain this sensitivities with words or indicate where it was defined.

Author's response

The glacier mass balance sensitivity to albedo change is defined at lines 445-447.

Referee comment

Line 536: how high concentration of volcanic ash do you need for this reduction in SMB?

Author's response

We thank the referee for the question. The mentioned impact on the glacier mass balance was estimated with the minimum snow albedo value of 0.4 (see lines 459-468), which was based on the modeled daily average for site Abl4-2017, with an estimated volcanic ash content of (12000 ± 2000) mg kg^{-1}. However, we have calculated that the modeled albedo for site Acc3-2016 varies only 3.8% for ash contents between 4500 mg kg^{-1} and 10500 mg kg^{-1}. Hence, the 0.4 albedo value can represent a range of sites with high volcanic ash content.

Manuscript Changes

Finally, we suggest that the effect of volcanic ashes in Alerce glacier can be as high as a 1.25 mwe decrease in the glacier annual mass balance or a 34 % of increase in the melt during the ablation season, considering a surface volcanic ash content compatible with that measured in sites Acc3-2016, Abl3-2017 and Abl4-2017.

Referee comment

Figure 1:

could you please show the outline of Alerce glacier in the map and contour of terrain elevation? Would also be nice to have another more zoom-out map to better see the glaciolocial context of Alerce Glacier.

Author's response

We thank the referee for the suggestion. We modified Fig. 1 to include the glacier outline and an inset with a zoom-out.

Manuscript Changes

See modified Fig. 1 at the end of this file.

Referee comment

Figure 2:

what meaning has a white column color?

What do you think: why did you not find the dark layer at 45cm in Acc4 in Acc5?

Author's response

Regarding the first question, white color was not used in the concentration gray-scale, hence white color appears only at the depth where sampling ends (for instance, below 10 cm for site Acc6-2017).

Regarding the second question, we regret that weather conditions did not allow us to continue the snow spit in site Acc5-2017. We believe that the dark layer corresponding to the 2016 summer surface layer was not too far below. This area of the accumulation zone of the glacier has a high specific accumulation variation in very short surface distances.

Referee comment

Figure 4:

what are the units of the Y-Axis?

Diffuse radiation should be less intense than the direct one!

Author's response

We thank the referee for the comment. The spectra shown here are normalized to highlight the difference in their wavelength dependence, hence the Y-Axis has arbitrary units. We have corrected the caption of Fig. 4 as a response to a similar question by Anonymous Referee #1.

Manuscript Changes

*We corrected the caption of Fig. 4, see **Author's Response to Anonymous Referee #1**, pages 6-7.*

Table 1. Measured and modeled snow albedo for six sites (two in 2016 campaign and four in 2017 campaign). For 2016 campaign the measured albedo is a single measurement and is informed together with its instrumental uncertainty. For 2017 campaign, we report the average and the standard error of the average for several repetitions. For modeled albedo, sensitivity to different input parameters is reported, as an estimation of albedo uncertainty.

Site	Surface	α_{meas}	$\alpha_{SNICARv2}$	$\alpha_{SNICARv2.1}$	$\alpha_{SNICARv2.1}$ sens.
Acc2-2016 (accum. zone)	Recent snow		Direct: 0.583	Direct: 0.573	**Grain size: (+)** -0.024 **(-)** $+0.028$
April 12th 2016	Layer: (6 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:47 (UTC - 3)	Grain size: (1000 ± 200) µm		Diffuse: 0.655	Diffuse: 0.748	100 $\mu g\,kg^{-1}$ **BC:** -0.017
Zenith: 51.98°	Snow density: 300 $kg\,m^{-3}$				**Layer thickness: (+)** $+0.010$ **(-)** -0.013
Effective angle: 51.98°	PM: (22.0 ± 0.6) $mg\,kg^{-1}$	0.626 ± 0.011		W.Aver.: 0.590	
Clear Sky	Slope: 0°				
Acc3-2016 (accum. zone)	Dirty summer snow		Direct: 0.435	Direct: 0.445	Grain size: (+) -0.001 (-) $+0.002$
April 12th 2016	Layer: (0.3 ± 0.1) cm				PM content: (+) -0.001 (-) $+0.002$
16:55 (UTC - 3)	Grain size: (1000 ± 200) µm		Diffuse: 0.364	Diffuse: 0.359	20 $mg\,kg^{-1}$ BC: -0.049
Zenith: 66.04°	Snow density: 500 $kg\,m^{-3}$				**Layer thickness: (+)** -0.001 **(-)** $+0.007$
Effective angle: 68.7° to 73.6°	PM: (7800 ± 1500) $mg\,kg^{-1}$	0.257 ± 0.041		W.Aver.: 0.359	Snow density: (+) -0.001 (-) $+0.003$
Overcast sky (approx. 100 % diffuse rad.)	Slope: 11°				% Diff. Rad.: $+0.001$ (89 % diff. rad.)
Abl3-2017 (accum. pocket on abl. zone)	Dirty snow		Direct: 0.374	Direct: 0.381	Grain size: (+) $+0.001$ (-) -0.001
April 3rd 2017	Layer: (0.3 ± 0.1) cm				PM content: (+) $+0.001$ (-) -0.001
13:11 (UTC - 3)	Grain size: (1020 ± 160) µm		Diffuse: 0.360	Diffuse: 0.354	20 $mg\,kg^{-1}$ BC: -0.015
Zenith: 47.57°	Snow density: 500 $kg\,m^{-3}$				Layer thickness: (+) $+0.000\,000\,1$ (-) $-0.000\,002$
Effective angle: 56.5° to 59.9°	PM: $(30\,000 \pm 5000)$ $mg\,kg^{-1}$	0.371 ± 0.011		W.Aver.: 0.356	% Diff. Rad.: (+) $+0.002$ (-) -0.002
Overcast sky (89 % to 95 % diffuse rad.)	Slope: 15°				Effective angle: (+) $+0.001$ (-) -0.001
Abl4-2017 (accum. pocket on abl. zone)	Dirty snow		Direct: 0.379	Direct: 0.384	Grain size: (+) -0.001 (-) $+0.002$
April 3rd 2017	Layer: (0.10 ± 0.05) cm				PM content: (+) -0.004 (-) $+0.006$
13:30 (UTC - 3)	Grain size: (740 ± 170) µm		Diffuse:0.375	Diffuse: 0.368	20 $mg\,kg^{-1}$ BC: -0.050
Zenith: 46.95°	Snow density: 500 $kg\,m^{-3}$				**Layer thickness: (+)** -0.008 **(-)** $+0.031$
Effective angle: 57.1° to 60.1°	PM: $(12\,250 \pm 2050)$ $mg\,kg^{-1}$	0.266 ± 0.008		W.Aver.: 0.368	Snow density: (+) -0.005 (-) $+0.007$
Overcast sky (approx. 100 % diffuse rad.)	Slope: 15°	0.376 ± 0.015			% Diff. Rad.: -0.007 (89 % diff. rad.)
Acc5-2017 (accum. zone)	Recent snow		Direct: 0.788	Direct: 0.778	**Grain size: (+)** -0.012 **(-)** $+0.015$
April 5th 2017	Layer: (9 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:26 (UTC - 3)	Grain size: (150 ± 40) µm		Diffuse: 0.860	Diffuse: 0.910	100 $\mu g\,kg^{-1}$ **BC:** -0.022
Zenith: 48.20°	Snow density: 300 $kg\,m^{-3}$				Layer thickness: (+) $+0.002$ (-) -0.002
Effective angle: 49.4° to 52.3°	PM: (1.28 ± 0.03) $mg\,kg^{-1}$	0.814 ± 0.013		W.Aver.:0.828	% Diff. Rad.: (+) $+0.005$ (-) -0.002
Cloudy sky (34 % to 48 % diffuse rad.)	Slope: 5°				Effective angle: (+) $+0.001$ (-) -0.001
Acc6-2017 (accum. zone)	Recent snow		Direct: 0.786	Direct: 0.776	**Grain size: (+)** -0.013 **(-)** $+0.015$
April 5th 2017	Layer: (9 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:48 (UTC - 3)	Grain size: (150 ± 40) µm		Diffuse: 0.856	Diffuse: 0.905	100 $\mu g\,kg^{-1}$ **BC:** -0.021
Zenith: 49.35°	Snow density: 300 $kg\,m^{-3}$				Layer thickness: (+) $+0.001$ (-) -0.002
Effective angle: 51.0° to 53.9°	PM: (3.9 ± 0.2) $mg\,kg^{-1}$	0.757 ± 0.026		W.Aver.: 0.825	% Diff. Rad.: (+) $+0.004$ (-) -0.002
Cloudy sky (34 % to 48 % diffuse rad.)	Slope: 5°				Effective angle: (+) $+0.001$ (-) -0.001

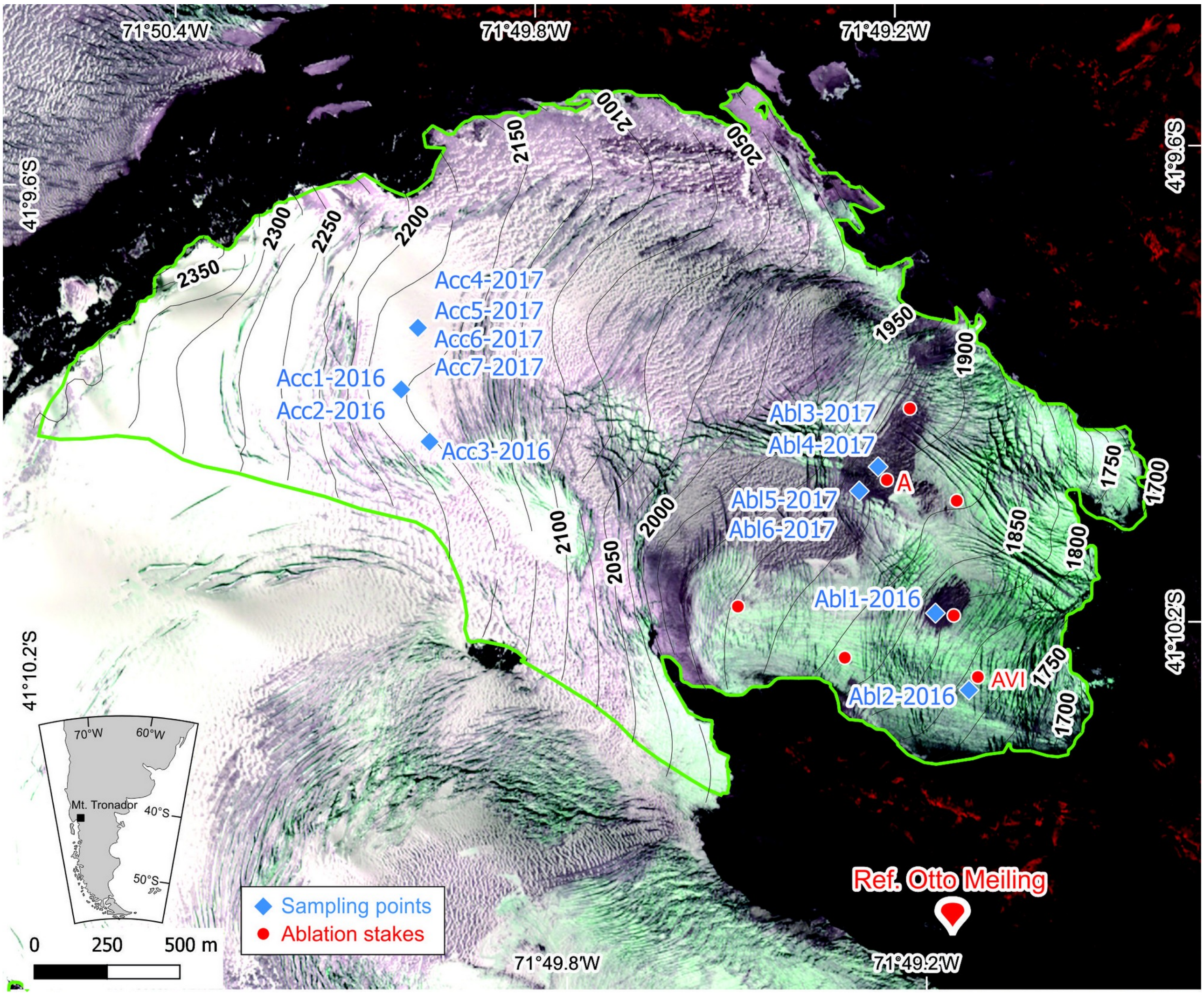
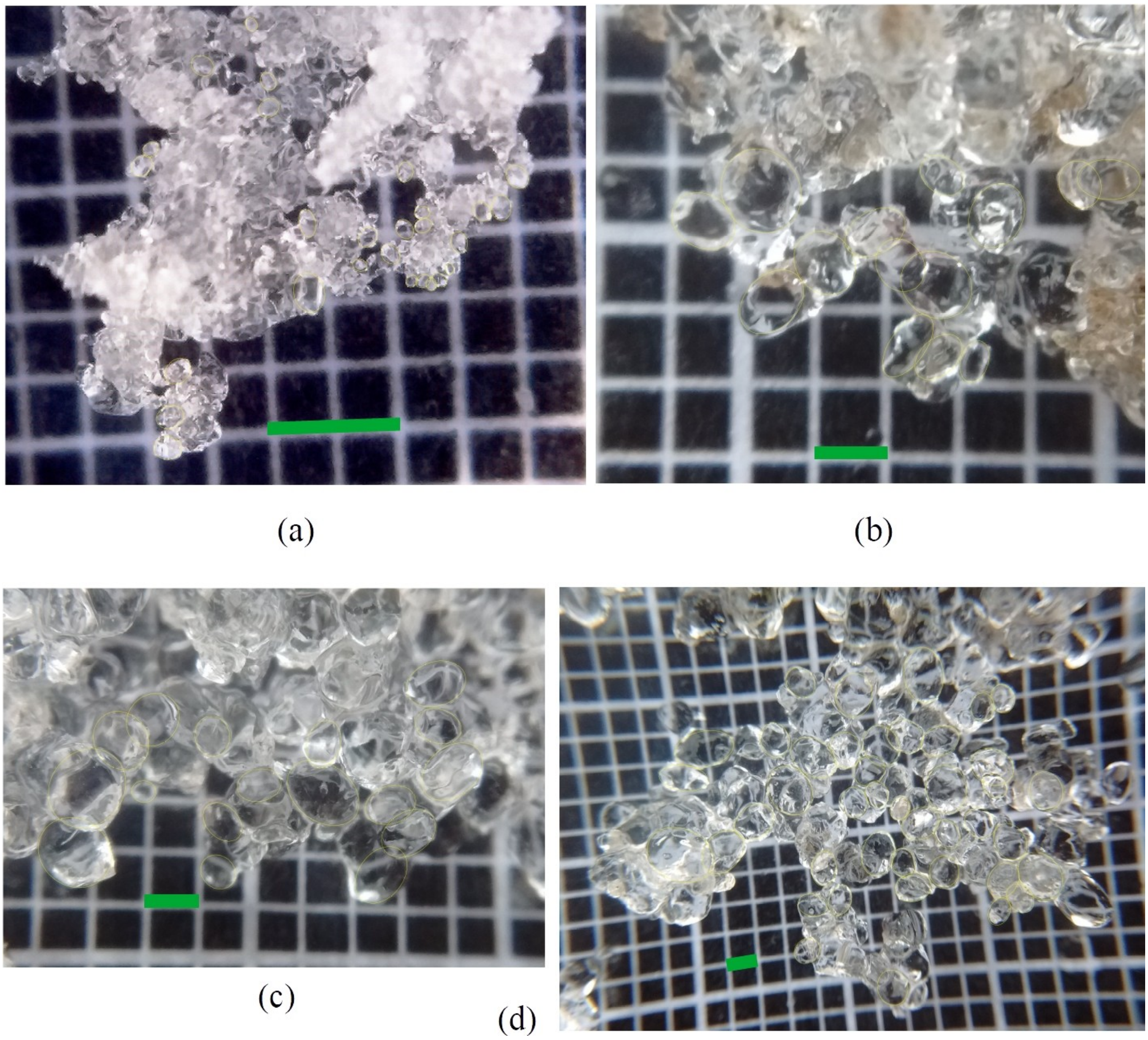


Figure 1. Alerce Glacier (green line represents the outline of the glacier). Labels of contour lines of terrain elevation are expressed in meters above sea level. Sampling points are represented as blue rhombuses. Red circles represent ablation stakes used for mass balance model calibration (model output for labeled ablation stakes is shown at Figure S6). Otto Meiling mountain hut and inset of the location of Monte Tronador in the context of Southern SouthAmerica are represented for reference. Background image: false-color pan-sharpened Pléiades satellite image, 7 March 2012, PGO, CNES-Airbus D & S (Ruiz and others, 2015).

(a) (b)

(c)

Figure S2. Field pictures of sampling sites. (a) General view of the area of the accumulation zone that includes sites Acc1-2016, Acc2-2016, Acc3-2016, Acc4-2017, Acc5-2017, Acc6-2017 and Acc7-2017. (b) Close view of surface of site Acc3-2016 (darkest layer, bottom of the picture), next to recent fresh snow (top of the picture). (c) Accumulation pocket in the ablation area of sites Abl3-2017 and Abl4-2017.



(a) (b) (c) (d)

Figure S3. High resolution macro pictures of snow/firn grains, Alerce glacier, 2017. (a) Surface fresh snow sample, April 2017, site *Acc5-2017.* (b) Surface snow/*firn* sample, attributed approximately to April 2016 (due to negative specific mass balance), site *Abl4-2017*. (c) Sub-surface *firn* sample, attributed to winter 2015, site *Abl4-2017*. (d) Sub-surface *firn* sample, attributed to winter 2014, site *Abl3-2017*. In all pictures the green bar width represents 1 mm.

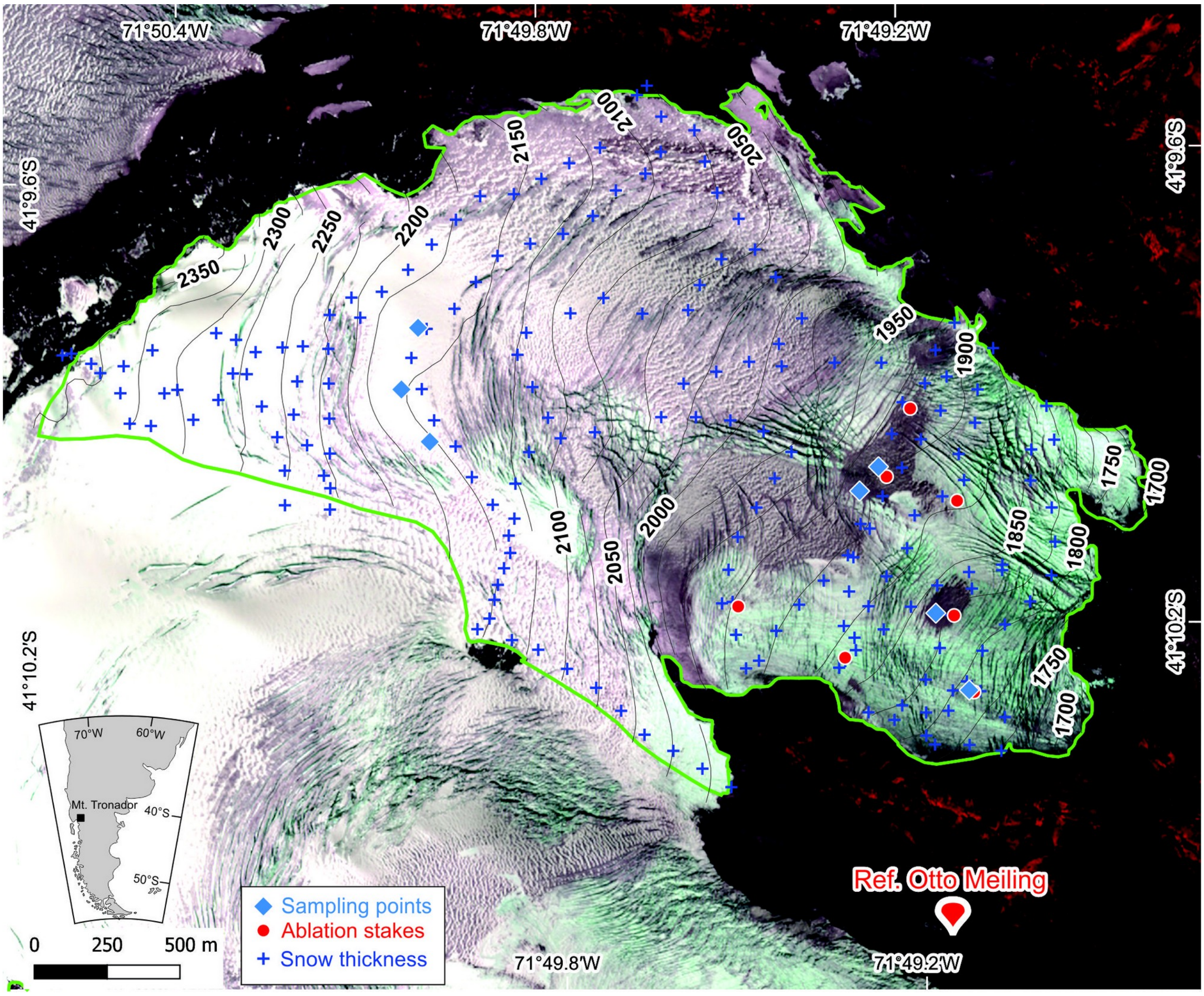


Figure S4. Snow thickness and ablation stakes used for calibration and validation of the mass balance model. Blue rhombuses are albedo and PM sampling points (same as in Fig. 1 of the main article). Background image: false-color pan-sharpened Pléiades satellite image, 7 March 2012, PGO,CNES-Airbus D & S (Ruiz and others, 2015).

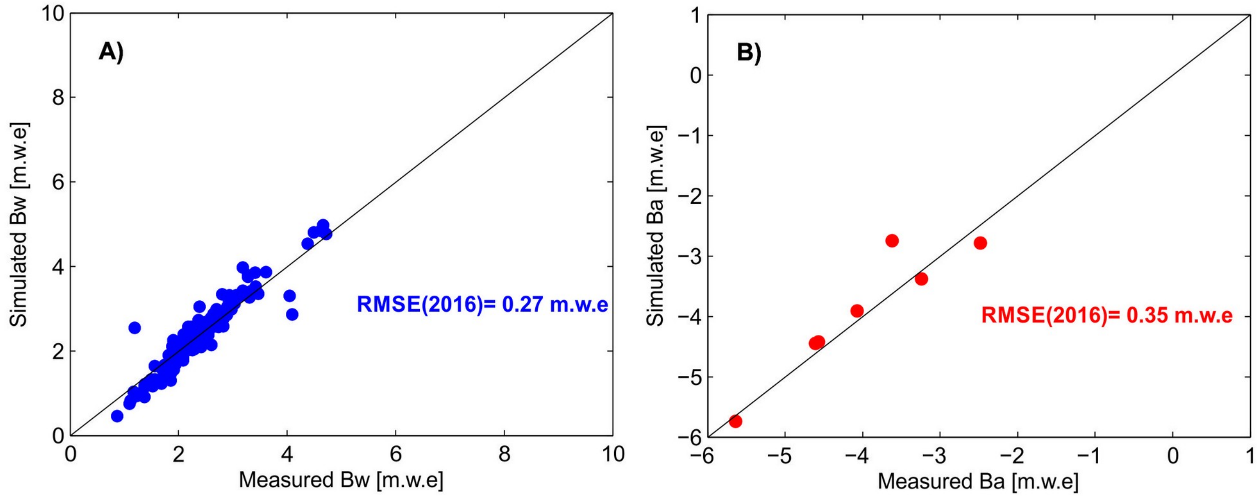


Figure S5. Calibration of the mass balance model with 2016 measurements. (a) First step of the calibration, with winter thickness measurements. (b) Second step of the calibration, with summer specific mass balance measurements (ablation stakes).

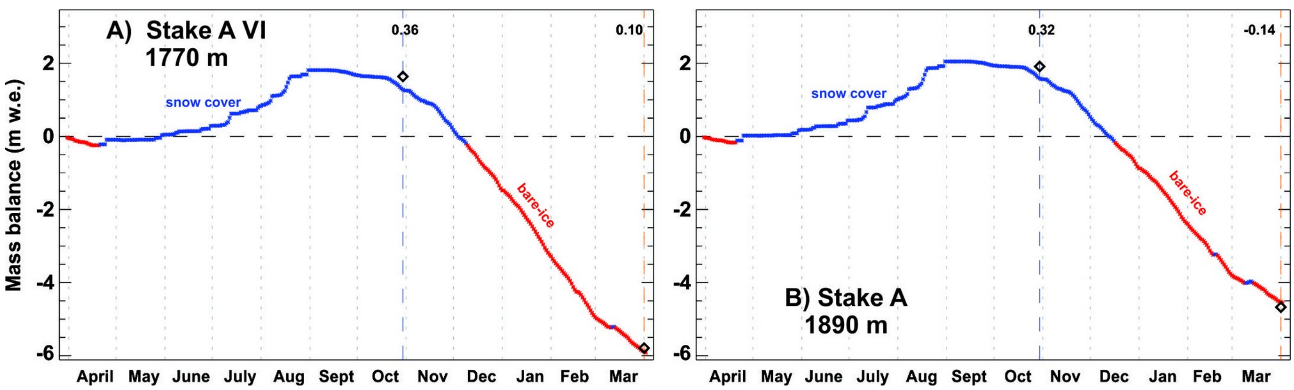


Figure S6. Mass balance model fitting with 2016 measurements for two specific ablation stakes. The residuals between measurements and model it is shown for comparison. Location of (a) stake A VI and (b) stake A are represented in Fig. 1 of the main article.

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, t~~The 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 considering~~on~~ 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 equivalent~~m 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

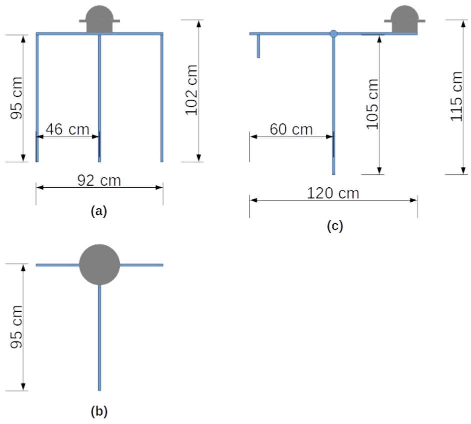


Figure S1. *Details of the pyranometer supports in Fig. 3 of the main text. (a) Side view and (b) top view of the support used in 2016 field campaign. (c) Side view of the support used in 2017 field campaign.*

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.

Measurements and modeling of snow albedo at Alerce Glacier, Argentina: effects of volcanic ash, snow grain size and cloudiness

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[6]Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

Correspondence: Julian Gelman Constantin (juliangelman@cnea.gov.ar)

Abstract. The ~~relevance of light absorbing impurities in snow albedo (and its effects in seasonal snow or~~ impact of volcanic ash on seasonal snow and glacier mass balance ~~) have been under study for several decades. However, the effect of volcanic ash~~ has been much less studied ~~, 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~~than that of carbonaceous particles and mineral dust. We present here the first field measurements on Argentinian Andes, combined with ~~albedo and~~ snow albedo and glacier mass balance modeling~~activities~~. Measured impurities content ($1.1\,\mathrm{mg\,kg^{-1}}$ to $30\,000\,\mathrm{mg\,kg^{-1}}$) varied abruptly in snow pits and snow/~~firn~~ *firn* cores, due to high surface enrichment during the ablation season and possibly local/regional wind driven resuspension and redeposition of dust and volcanic ash. In addition, we observed a high spatial ~~hetereogeneity~~heterogeneity, due to ~~seasonality,~~ glacier topography and prevailing wind direction. ~~Microscopical~~ Microscopic characterization showed that the major component was ash from recent Calbuco (2015) and ~~Cordón~~ Cordón Caulle (2011) volcanic ~~eruption, with~~ eruptions, with a minor presence of mineral dust and ~~Black Carbon~~black carbon. We also found a wide range of measured snow albedo (0.26 to 0.81), which reflected mainly the impurities content and the snow/~~firn~~ *firn* grain size (due to aging). ~~SNICAR model has been updated to model snow albedo taking into account~~ We updated the SNICAR snow albedo model to account for the effect of cloudiness on incident radiation spectra, improving the match of modeled and measured values. We also ran sensitivity studies ~~on the~~ considering the uncertainty of the main measured parameters (impurities content and composition, snow grain size, layer thickness, etc) to ~~assess which field measurements precision can improve the uncertainty of albedo modeling~~detect the field measurements that should be improved to facilitate the validation of the snow albedo model. Finally, we studied the impact of these albedo reductions in Alerce glacier using a spatially distributed surface mass-balance model. We found a large impact of albedo changes in glacier mass balance, and we estimated that the effect of observed ash concentrations can be as high as a ~~1.25 mw e~~ 1.25 meter water equivalent decrease in the ~~glacier-wide annual~~ annual surface mass balance (due to a 34 % of increase in the melt during the ablation season).

1 Introduction

~~Glaciers~~ Since 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 (Zemp et al., 2015; IPCC, 2019). Along the ~~Southern Andes~~ Wet Andes (below 35° S latitude), both precipitation decrease and air surface temperature increase have been pointed out as the drivers of the shrinkage of glaciers in the last decades (Dussaillant et al., 2019). Although some processes, like sublimation at the high and cold Dry Andes (37° S to 20° S) or the calving at the outlet glaciers of the Patagonian Ice fields (south of 45° S), could contribute, or be even more critical than melt for the shrinkage of glaciers in some particular cases, ablation is mainly ruled by melt. Along the Southern Andes, melt is driven by shortwave radiation and sensible turbulent flux (Schaefer et al., 2020). The ~~effect of incoming shortwave radiation is enhanced during spring and~~ shortwave radiation absorption increases significantly during summer, due to the exposure of low albedo areas in their ablation zones, which causes strong, positive feedback that enhances surface melt significantly and shapes the spatial ablation pattern (Brock et al., 2000). Furthermore, deposition of light-absorbing impurities (~~LAI;~~ LAP: mineral dust, volcanic ash, and black carbon) have a fundamental impact on the melting of glacier and snow-covered areas ~~by increasing the absorption of solar radiation and produces a regional land-atmosphere feedback (Warren and Wiscombe, 1980; Bond et al., 2013; Molina et al., 2015). Along with the enhanced melting~~ (Warren and Wiscombe, 1980; Bond et al., 2013; Molina et al., 2015). LAP decrease snow albedo, increasing solar radiation absorption and thus producing a direct effect on snow melting. But, in addition, the snowpack temperature increase due to the ~~darkening of the snow or ice surface, the~~ direct effect accelerates the growth of snow grains~~is accelerated, which further reinforces snowmelt rates due to further albedo decrease~~ , which produces a further albedo decrease (and thus an additional, indirect impact on snow melting) (Bond et al., 2013; Flanner et al., 2007). While ~~LAI~~ LAP control the snow albedo mainly in the visible wavelengths (since ice is relatively transparent in the visible band), the snow grain size affects the albedo in the near-infrared (e.g., Hadley and Kirchstetter, 2012; Pirazzini et al., 2015; He and Flanner, 2020). Recently it has been highlighted that the growth of glacier algae could also decrease the albedo (Williamson et al., 2019).

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 atmospheric particulate matter (PM)~~ BC and other LAP as well as several positive feedbacks (Flanner et al., 2007; Koch et al., 2009; Krinner et al., 2006), ~~the~~ such as the increase in surface concentration of impurities due to enhanced snow melting, or the albedo reduction due to the growth of snow grains by accelerated snow aging (Bond et al., 2013). More recently, models have included 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). Although some snow albedo models have been successfully validated for laboratory conditions (Brandt et al., 2011; Hadley and Kirchstetter, 2012), the prediction of snow spectral albedo in environmental conditions is still challenging. ~~More than just one~~

~~particle metric distribution is necessary~~ When the snow has been undergoing heavy metamorphosis processes, a single snow grain size distribution is not enough to reproduce the ~~spectral snow albedo at all optical wavelengths, especially when the~~ snow ~~has been undergoing heavy metamorphosis processes~~ spectral albedo due to the fact that the largest particles and the thinnest protrusions of the irregular crystals have contributions to the snow reflectance that depend on the wavelength (Carmagnola et al., 2013; Pirazzini et al., 2015). Notably, ~~there has been found~~ it has been shown that taking into account the amount of ~~LAI~~ LAP in the snow reduces the difference between simulated and measured ~~broadband albedos~~ albedo, especially in the visible range (Zhang et al., 2018).

Different studies have considered the effect of ~~LAI~~ LAP in snow and ice albedo and its impact on glaciers mass balance or seasonal snow cover, and estimated its radiative forcing (Qian et al., 2015; Skiles et al., 2018). Some studies used point measurements of ~~LAI~~ LAP content (ice cores) together with a snow albedo model to estimate potential melting, using a radiative transfer model to calculate the additional absorbed energy by BC and mineral dust (Ginot et al., 2014; Zhang et al., 2018) or perturbing a glacier mass balance model to include BC forcing (Painter et al., 2013). ~~Online~~ “Online” coupling of snow albedo models in global or regional atmospheric chemistry models ~~have~~ (where both models are run simultaneously allowing two-way feedback) has been applied to study snow and glaciers interaction with the climate around the globe (Hansen et al., 2005; Flanner, 2013; Ménégoz et al., 2014). Although these global or regional atmospheric studies are beneficial to identify ~~LAI~~ LAP sources and dispersion patterns and to compare snow-atmosphere feedback in different regions, the spatial resolution can be inadequate to obtain accurate results in mountain regions (Ménégoz et al., 2014; Qian et al., 2015).

Even though most studies focus on the effect of BC, some include the effect of mineral dust (e.g., Ginot et al., 2014; Skiles and Painter, 2017; Zhang et al., 2018) or even concentrate on mineral dust due to local/regional relevance (e.g., Krinner et al., 2006; Painter et al., 2012; Wittmann et al., 2017). Studies on the effect of volcanic ash concentration on snow albedo are scarcer (e.g., Conway et al., 1996; Brock et al., 2007; Young et al., 2014).

In recent years there has been an increase of measurement and modeling of albedo along the Southern Andes (Rowe et al., 2019). A three-year study (Schmitt et al., 2015) showed that glaciers closer to population centers in the Cordillera Blanca, Peru, have higher surface content of equivalent black carbon (EBC, BC plus other ~~LAI~~LAP, especially dust in this case), up to $70\,\mathrm{ng\,g^{-1}}$ EBC, as compared with remote glaciers (with surface content as low as $2.0\,\mathrm{ng\,g^{-1}}$ EBC). A one-week study successfully connected the decreases in snow broadband albedo with heavy traffic days in the nearby road that connects Argentina and Chile (Cereceda-Balic et al., 2018). A more recent study along the Southern Andes of Chile found a mean albedo reduction due to light-absorbing impurities in the snow, with its corresponding mean radiative forcing increase (Rowe et al., 2019). They conclude that in the north (dusty, vegetation-sparse Atacama Desert), BC plays a smaller role than non-BC, whereas near Santiago and in the south (vegetation-rich), the BC contribution is higher. For example, the albedo reduction ~~for spherical snow grains radii of 100 µm~~ due to BC alone in the north ~~is~~ was estimated to be only about 43 % of that for all light-absorbing impurities (assuming spherical 100 µm radii snow grains). By comparison, these albedo reductions are 53 % and 82 % near Santiago and in southern Chile, where a greater share of light absorption is due to BC. In the Southern Andes of Argentina, the only available information on snow albedo is due to remote sensing (Malmros et al., 2018), and up to now, the impact of volcanic ash and other ~~LAI~~ LAP on Argentinian glaciers mass balance has not been evaluated either.

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~~ *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 ~~PM~~ LAP 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~~in 2011 and Calbuco in 2015). Finally, the influence of ~~PM~~ LAP 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 ~~PM~~ LAP in Argentinian glaciers, but also one of the few studies of the long-term impact of volcanic ash on snow albedo.

2 Site Description and Experimental Methods

Alerce is a small ($2.2\,\mathrm{km}^2$), debris-free, mountain glacier located at Monte Tronador ($41.15°$ S, $71.88°$ W), in the Northern Patagonian Andes. The climate on this region is primarily modulated by the weather disturbance embedded in the mid-latitude westerlies (Garreaud et al., 2009). Weather disturbances and prevailing winds coming from the Pacific Ocean are more frequent and stronger in winter. However, associated frontal precipitation system move over the Patagonian Andes all year round. In this region, the hydrological year ~~is defined from the 1-April to the 31-March of the next year~~begins on April 1st with the accumulation season. 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~~lasts until October 31st, which marks the beginning of the ablation season.

Alerce glacier has an elevation range between $1650\,\mathrm{m}$ to $2400\,\mathrm{m}$ a.s.l. (above sea level), a gentle slope (mean of $10°$), and is exposed to the southeast. Since 2013 it has been the focus of a glacier mass balance monitoring program by the IANIGLA ~~(Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales)~~(Instituto Argentino de Nivología, Glaciología y Ciencias Ambienta . Seasonal mass balance has been studied every year using the traditional glaciological method of stakes ~~,~~ and snow pits. An enhanced temperature index mass balance model has been developed ~~(Ruiz et al., 2015, 2017)~~ (Huss et al., 2008; Huss, 2010) to study the surface mass balance of the glacier. This model is used here to analyze the influence of ~~PM~~LAP, through glacier albedo changes, over the mass balance of Alerce glacier.

In recent years Monte Tronador glaciers have been reached by volcanic ash derived from two volcanic events: (i) Puyehue-Cordón Caulle volcanic complex, which had a long eruption between June 2011 and January 2012 and (ii) Volcán Calbuco, which commenced on April 23rd 2015.

2.1 Fieldwork

In April 2016 and April 2017, besides mass balance measuring, we took snow and ~~firn~~ *firn* samples and we measured surface albedo at Alerce glacier. Figure 1 ~~shown~~ shows the sampling sites at Alerce glacier. We sampled ~~both~~ accumulation and ablation

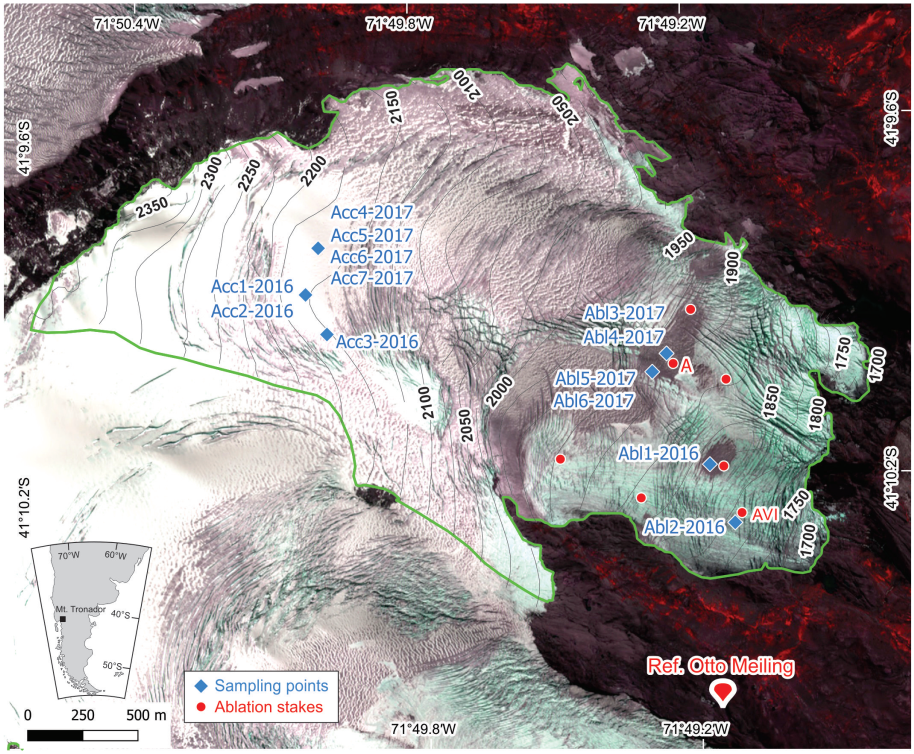

Figure 1. ~~Satellite image~~ Outline of Alerce Glacier~~. Sampling points are represented as blue markers (2017 campaign)~~ , showing the location of sampling sites and ~~red markers~~ ablation stakes used for mass balance model calibration (~~2016 campaign~~model output for labeled ablation stakes is shown in Fig. S6). ~~Green marker represents~~ Labels of contour lines of terrain elevation are expressed in meters above sea level. Otto Meiling mountain hut and inset of the location of Monte Tronador in the context of Southern South America are represented for reference. ~~Copyright~~Background image: ~~Google Earth~~false-color pansharpened Pléiades satellite image, ~~2020~~7 March 2012, ~~CNES/Airbus~~PGO, CNES-Airbus D & S (Ruiz et al., 2015).

zones ~~, and we~~ and looked for similar sampling sites in both campaigns. Otto Meiling mountain hut served both as a base camp for field trips and as a field laboratory for initial processing of the snow samples. April 2016 served as a exploratory campaign. Albedo measurements were improved for the 2017 campaign. We lowered instrumental uncertainty and ~~we~~ used an improved ~~support~~ mounting stand for the pyranometer, which allowed us to evaluate the variability/uncertainty of albedo measurements by repeatedly measuring in the same site. We also improved the measurement of snow grain size distribution. More details are given below. However, the second campaign duration and number of sampling sites were shortened due to poor weather conditions. Nevertheless, relevant results of PM concentration and albedo measurements are presented for the first time for Monte Tronador glaciers.

2.1.1 Snow samples. Filters treatment

Before collecting snow/~~firn~~*firn*/ice samples, we performed ~~a~~ an in situ stratigraphy at each site to identify and date layers. Many of the sampling sites corresponded to the accumulation zone of Alerce glacier or accumulation pockets in the ablation zone. In those sites, we dated seasonal layers of snow/~~firn~~*firn*. The main elements to attribute layers were PM content and hardness of the layers. Figure 2 shows the results of the stratigraphy and PM gravimetry, which are described in detail in ~~Section~~Sect. 3.1. In sampling sites located on the ablation zone, we distinguish glacier ice from recent snow covering the glacier ice.

Most of the samples were taken from snow/~~firn~~ *firn* pits. In the 2016 campaign we also used a snow/~~firn~~ *firn* hand auger to sample a 2.5 m snow/~~firn~~ *firn* core (site *Acc2-2016*, Fig. 2). Samples were melted and filtered in the base camp, and filters were taken to the laboratory for gravimetric determination of PM content and further analysis. Further details are given in ~~Section~~ Sect. S1.1 ~~of~~ in the Supplement.

PM in the filters was described and photographed using a Leica S8APO stereo microscope equipped with a DFC 295 camera. Some samples were also studied by Scanning Electron Microscopy (FEI Quanta 200, equipped with an Edax accessory for energy dispersive X-ray analysis).

2.2 Albedo: measurements and corrections

We performed ~~in-situ~~ in situ albedo measurements in some of the snow sampling sites in both field campaigns. Upwelling (reflected) and downwelling (direct + diffuse) radiation were measured with ~~a~~ one CM5 Kipp & Zonen pyranometer (wavelength range 0.3 µm to 2.8 µm), using two different in-house developed ~~supports~~ mounting stands in 2016 and 2017 campaigns, logged with a handheld voltmeter. The voltmeter used in the 2016 had a reduced precision (resolution of 0.1 mV) that limited the overall accuracy of the albedo measurement (first two rows of Table 1). In the 2017 campaign, a new, more accurate voltmeter was used (resolution of 0.001 mV, accuracy of 0.010 mV), reducing significantly instrumental uncertainty. Further details are given in ~~Section~~Sect. 3.3.

Raw albedo values were corrected to account for the diffuse or reflected light blocked by the operator or the ~~support~~ mounting stand and, for upwelling radiation, the effect of shadows of the sensor and the ~~support~~ stand in the snow surface (Wright et al., 2014; Carmagnola et al., 2013). Further details are given in ~~Section~~ Sect. S1.2 ~~of~~ in the Supplement.

~~**Pyranometer supports and cloudiness effect**~~

2.2.1 Pyranometer mounting stands and cloudiness effect

In the 2016 campaign, we used a fixed ~~support~~ mounting stand with three stainless steel legs (Fig. 3 (a)). It was designed to provide a stable irradiation measurement, with a precise tilt angle (parallel to the snow surface), and to minimize the blocking of incident light. When measuring clear-sky downwelling radiation, this ~~support~~ stand does not block light at all (operators stand 4 m away from the sensor, blocking less than 0.1 % of incoming diffuse radiation). For clear-sky upwelling radiation, the percentage of blocked light is below 0.8 %, and shadows from the equipment represent another 0.4 %. Hence, total correction for upwelling radiation sum up around 1.2 %, affecting around 1 % measured albedo. For cloudy or overcast conditions, due to the sharp changes in cloud cover, incoming radiation varies more quickly than the time needed for assembling/disassembling the pyranometer ~~support~~stand. To proceed faster under these conditions, the measurements were made differently: the sensor was held by two operators, each 0.45 m away from the sensor, without using the ~~support~~ stand legs. Under these conditions 12 % of diffuse downwelling and 9 % of upwelling radiation is blocked by the operators, resulting in an albedo correction of 3.5 %, significantly higher than those obtained for clear-sky conditions.

To overcome the difficulties due to cloudiness, for the 2017 campaign a new ~~support~~ mounting stand was designed. The new lighter design has only one arm and one leg and is carried by one operator, located 1.25 m away from the sensor, and leveled manually with the help of a bubble level (Fig. 3 (b)). This design allows fast and easy alternate downwelling/upwelling radiation measurements, making it possible to assess the variability of albedo under the same sky conditions. For downwelling radiation the operator blocks around 1.1 % of diffuse light. For upwelling radiation, the operator blocks around 1.9 % of light, which, together with shadows of the equipment, brings corrections to a maximum of 2.4 %. Overall albedo corrections vary between 0.8 % and 2.0~~%.~~ %. Additional details on the mounting stands are given in Fig. S1 in the Supplement.

~~**Diffuse and direct radiation fraction**~~

2.2.2 Diffuse and direct radiation fraction

For albedo calculation, the upwelling radiation measurement is used directly from measurements. But for downwelling radiation, direct and diffuse fraction must be distinguished (see Eq. (S1) in the Supplement).

The calculation of the diffuse fraction of downwelling radiation requires to add another measurement with the pyranometer (total downwelling, diffuse downwelling, and total upwelling radiation), and the operation of the accessory to block direct radiation. Fast changes in cloudiness during measurements made it very difficult to assure that all three measurements were performed under the same sky conditions. Therefore, we decided to prioritize that measurements required for albedo calculation (total downwelling and total upwelling radiation) were performed under the same conditions, and thus we dropped the diffuse downwelling radiation measurement. Hence, the diffuse to global radiation ratio $I_{diff\downarrow}/I_{glob\downarrow}$ (needed for albedo measurements corrections and comparison with modeled albedo) had to be estimated differently. We used ~~in-situ~~ in situ observations of cloudiness (or pictures of the sky taken before and after albedo measurements) together with the relations found by Kasten and Czeplak (1980)[eq. 4] to estimate the diffuse radiation ratios, which are presented in Table 1.

~~**Snow/firn grain size**~~

2.2.3 Snow/*firn* grain size

In the 2016 campaign, snow was placed in a crystal grid (with three different scales: 2 mm, 1.2 mm, and 0.6 mm) and average size was determined with a magnifying lens. 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~~ (Fig. S3 in the Supplement) were 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.

2.3 Albedo: modeling

To analyze the different factors affecting measured albedo at each sampling site, we modeled albedo for the same conditions using SNICAR (Flanner et al., 2007; He et al., 2017, 2018). Snow density and layer thicknesses were taken as parameters from ~~in-situ~~ in situ stratigraphies. Average snow grain size and shape were obtained from ~~in-situ measurements. PM~~ in situ measurements. LAP content was obtained from filters gravimetry. Based on ~~in-situ~~ in situ observations and the analysis of microscopy images ~~, are described in detail in Section 3.2~~(Sect. 3.2), we assigned all recollected PM mass to volcanic ~~ashes (in a similar way as previously done in sites where mineral dust represents most of LAI (Krinner et al., 2006; Painter et al., 2012; Wittmann et al.~~ ~~)~~ash (in a similar way as previously done in sites where mineral dust represents most of LAP; Krinner et al., 2006; Painter et al., 2012; Wi . Albedo of the underlying layers was calculated explicitly within the same model, using the properties of those layers.

SNICARv2 (He et al., 2017, 2018) supported only four incident solar spectra: two clear-sky direct solar spectra (one for Summit, Greenland, and one for mid-latitude), and two overcast diffuse spectra (for the same locations). These spectra are used to calculate direct radiation albedo and diffuse radiation albedo, respectively. These are good approximations for clear-sky albedo (where most for the incident radiation is direct, clear-sky solar radiation) or for overcast sky albedo (where most of the radiation is diffuse). In this updated version of SNICAR (referred as SNICARv2.1 throughout the article) we provided an alternative for these spectra for cases when latitude, longitude or altitude differ significantly from those of the provided spectra, or where the sky is partly cloudy.

First, we calculated the clear-sky spectra for the site location and time using SMARTS model (Gueymard, 2001). Then, we calculated the direct and diffuse spectra for overcast or partly cloudy sky following Gueymard (1986, 1987) and Ernst et al. (2016):

$$F_{dir,norm}(\lambda) = \frac{F_{dir,S}(\lambda)}{I_{dir,S}} \tag{1}$$

$$F_{diff,norm}(\lambda) = [1 - N_{pt}]\frac{F_{diff,S}(\lambda)}{I_{diff,S}} + N_{pt}\frac{F_{dir,S}(\lambda) + F_{diff,S}(\lambda)}{I_{glob,S}} \tag{2}$$

I_{dir}, I_{diff}, and I_{glob} are clear-sky direct, diffuse and global solar irradiance (where $I_{glob} = I_{dir} + I_{diff}$), as calculated from SMARTS model. $F_{dir,S}(\lambda)$ and $F_{diff,S}(\lambda)$ are the spectral distributions of clear sky direct and diffuse solar irradiance, also from SMARTS model. $F_{dir,norm}(\lambda)$ and $F_{diff,norm}(\lambda)$ are the normalized spectral distributions of direct and diffuse solar irradiance thus calculated for our sites. The cloud opacity factor N_{pt} is calculated following ~~Ernst et al.~~Ernst et al. (2016):

$$N_{pt} = \frac{\rho - \rho_S}{1 - \rho_S} \tag{3}$$

where ρ and ρ_S are the diffuse to global irradiance ratio for the site and from SMARTS model, respectively.

The clear-sky direct radiation spectra available in SNICARv2 matches reasonably well SMARTS clear sky direct radiation spectra. ~~In~~ On the other hand, SMARTS clear sky diffuse radiation spectra is very different from diffuse radiation spectra available in SNICARv2 (Fig. 4). The spectral distribution obtained for 95 % cloud fraction for SNICARv2.1 closely matches the diffuse radiation spectra available in SNICARv2, which confirms that the latter was prepared to represent an overcast sky condition. ~~In~~ On the other hand, the spectral distribution obtained for a 50 % cloud fraction differs significantly from both spectra available in SNICARv2, showing a larger contribution from clear sky diffuse radiation (Fig. 4).

Hence, we expect to find a larger impact of our improved incident sun spectra for intermediate cloud cover fractions. For clear sky conditions, direct radiation spectra were already well represented. Even though diffuse radiation spectra were not accounted for, this fact has little impact on the calculated albedo, due to the low diffuse radiation fraction for clear sky conditions. Conversely, for overcast conditions, diffuse radiation spectra were already well represented and neglecting direct radiation fraction has a low impact on albedo calculations.

Using different incident radiation spectral distributions, we obtained the pure direct and diffuse albedo with SNICARv2 and SNICARv2.1 (α_{dir} and α_{diff}). For SNICARv2.1 we also calculated the weighted average albedo, which should be compared to the net measured albedo:

$$\alpha = \rho\alpha_{diff} + (1 - \rho)\alpha_{dir} \tag{4}$$

2.4 Alerce glacier surface mass balance model

To analyze the role of albedo decrease over the surface mass balance of Alerce glacier, we ~~use~~ used a spatially distributed surface mass-balance model (spatial resolution 20 m) driven by daily temperature, precipitation, and potential direct solar radiation (Huss et al., 2008). The model was calibrated by surface mass balance measurements performed on a seasonal to annual basis through the year 2016 over Alerce glacier.

Here we summarize the most relevant model components. Snow accumulation $C_{(x,y,t)}$ for all grid cells (x, y) and all time steps (t) was calculated based on precipitation $P_{(t)}$ occurring below a threshold air temperature of $1.5\,°C$ (Hock, 1999). Accumulation distribution $D_{s(x,y)}$ was inferred based on a spatial distribution pattern derived from winter snow measurements and topographic parameters (slope, curvature) to account for small-scale snow redistribution (Huss et al., 2008; Sold et al., 2016).

$$C_{(x,y,t)} = P_{(t)} C_{pre} D_{s(x,y)} \tag{5}$$

$P_{(t)}$ was the daily precipitation at ~~Tepuel~~ Tepual weather station (90 m altitude, ID = 857990; ~~http~~https://~~www7.ncdc~~www.ncei.noaa.gov/ac The factor C_{pre} allows adjusting precipitation measured at the weather station to the conditions on the glacier.

Snow and ice melt were calculated based on a simplified energy-balance formulation proposed by Oerlemans (2001), where the energy available for melt $\Psi_{d(x,y,t)}$ was defined as follows:

$$\Psi_{d(x,y,t)} = \tau(1-\alpha_{(x,y,t)})I_{(x,y,t)} + (c_0 + c_1 T_{(t)}) \tag{6}$$

where $I_{(x,y,t)}$ is the potential direct solar radiation in $\mathrm{W\,m^{-2}}$, τ is the atmospheric transmission to solar irradiance, $T_{(x,y,t)}$ the air temperature and c_0 and c_1 represent parameters. $T_{(t)}$ was taken from the air surface temperature at Bariloche airport weather station (846 m altitude, ID = 877650; ~~http~~https://~~www7.ncdc~~www.ncei.noaa.gov/~~). After calibration of the model, $c_0 = -50\,\mathrm{W\,m^{-2}}$ and $c_1 = 12\,\mathrm{W\,m^{-2}\,°C^{-1}}$.~~ access/search/data-search/global-summary-of-the-day). Potential direct solar radiation for all grid cells and days was calculated following Hock (1999). The local surface albedo $\alpha_{(x,y,t)}$ was taken to be constant for bare-ice surfaces ($\alpha_{ice} = 0.34$), using most commonly applied literature value (Oerlemans and Knap, 1998; Cuffey and Paterson, 2010), for snow surfaces, α_{snow} was calculated based on the snow aging function proposed by Oerlemans and Knap (1998) with a maximum snow albedo (α_{max}) of 0.8 and a ~~variable~~ minimum snow albedo (~~α_{firn}, table 2) . Glacier-wide mass balance changes between~~ α_{min} adjusted during the calibration procedure.

The model was calibrated in two steps using surface mass balance measurements of year 2016 in Alerce glacier (Fig. S4 in the Supplement). First, the model was run over the winter period with an initial set of constants (c_0 and c_1) and a guess for the precipitation correction factor C_{pre}. As melt is of minor importance in winter, this run was used to calibrate C_{pre}, that scales D_s for every snow fall event. After a good agreement of measured and calculated winter accumulation was obtained, the model was run over the entire year and the remaining constants were calibrated so that the root-mean-square error between modelled and observed point annual balances were minimized and the average misfit was close to zero (Fig. S5 and S6 in the Supplement). A random set of snow accumulation and ablation stakes measurements performed through the year and not used to calibrate the model were left apart to validate the results of the surface mass balance model.

We studied surface mass balance changes for different values of ~~α_{firn}~~ α_{min} (Table 2), which are indicative of the sensitivity of glacier mass balance to a change in albedo that might occur in response to the darkening of the glacier surface.

3 Results and Discussion

3.1 PM concentration on Alerce glacier

PM concentrations in samples obtained in both field campaigns in the accumulation and the ablation zones are depicted in Fig. 2 as a function of pit or core depth. Alternating thin, high PM concentration layers and thick, low PM concentration layers are indicative of the seasonal glacier mass balance of more than one hydrological years, combined with the impact of long-range transported aerosols and the ~~re-suspension and re-deposition~~ resuspension and redeposition of local particles.

Thick and low PM concentration layers ($4.9\,\mathrm{mg\,kg^{-1}}$ to $51\,\mathrm{mg\,kg^{-1}}$, excluding two samples from ablation zone of higher concentration, $(128 \pm 2)\,\mathrm{mg\,kg^{-1}}$ and $(667 \pm 17)\,\mathrm{mg\,kg^{-1}}$) correspond to snow accumulated during ~~autumn and winter (accumulation~~

~~season)~~accumulation season. Meanwhile, thin and high PM concentration layers (with a wide range of concentration, between $(339 \pm 26)\,\mathrm{mg\,kg^{-1}}$ and $(9040 \pm 950)\,\mathrm{mg\,kg^{-1}}$), are related to the surface enrichment of PM content due to the melt of snow during spring and summer (ablation season) or fair-weather melt events during the accumulation season. In the longest snow/~~firn~~ *firn* core (*Acc1-2016*), four high PM concentration layers were recognized. The first one at 3-5 cm deep ~~represent~~ represents the end of the ablation season of the hydrological year 2015-16, with a concentration of $(339 \pm 26)\,\mathrm{mg\,kg^{-1}}$. The next two thin layers with relative high PM concentration at $118\,\mathrm{cm}$ to $120\,\mathrm{cm}$ and $187\,\mathrm{cm}$ to $191\,\mathrm{cm}$ deep ($(365 \pm 26)\,\mathrm{mg\,kg^{-1}}$ and $(410 \pm 20)\,\mathrm{mg\,kg^{-1}}$, respectively), were, on the basis of ~~microscopy analysis (see section~~microscopic characterization (Sect. 3.2), attributed to the resuspension and redeposition of dust and volcanic ash, and also, possible melt events, related to fair-weather events during the accumulation season of the hydrological year 2015-2016. The deepest ($242\,\mathrm{cm}$ to $247\,\mathrm{cm}$ deep) thin, high PM concentration layer ($(1970 \pm 200)\,\mathrm{mg\,kg^{-1}}$) was interpreted as the surface at end of the ablation season of the hydrological year ~~2014-15~~2014-2015, based on the abrupt change of the density, hardness and grain size of the snow above this layer and the *firn* found below. In addition to PM enrichment due to melting, this last layer suffered a direct ash fall event from Calbuco volcano, which erupted on 22-23 April 2015 (Reckziegel et al., 2016).

The same alternating pattern of low and high PM concentration layers was observed at other snow pits in the accumulation zone (*Acc2-2016*, *Acc4-2017* to *Acc7-2017*). At the snow pit *Acc4-2017*, roughly the same location as *Acc1-2016*, the low PM concentration layer between the high concentration layers, is less than $30\,\mathrm{cm}$ thick, which illustrates the strong decrease in direct snow-fall during the accumulation season of the hydrological year 2016-2017. At site *Acc3-2016*, due to the slope of the site, there was no fresh snow accumulation, so it is interpreted as representative of the surface of the accumulation area at the end-of-ablation season.

In the ablation zones we collected samples in two different environments: accumulation pockets (*Abl1-2016*, *Abl3-2017*, *Abl4-2017*) and glacier ice with or without fresh snow on top of it (*Abl2-2016*, *Abl5-2017*, *Abl6-2017*).

The net accumulation layer of ~~*Abl2-2016*~~*Abl1-2016* goes only from $3\,\mathrm{cm}$ to $26\,\mathrm{cm}$ deep. This accumulation pocket completely disappeared in the summer 2016-17. In the 2017 campaign we took two samples in a different accumulation pocket~~(~~. Sites *Abl3-2017* and *Abl4-2017* ~~). These sites~~ had a negative net balance during hydrological year 2016-17, consequently the surface layer presented the highest PM content observed in both campaigns ($(30\,000 \pm 5000)\,\mathrm{mg\,kg^{-1}}$ and $(12\,000 \pm 2000)\,\mathrm{mg\,kg^{-1}}$ respectively), due to the accumulation of PM depositions from several hydrological years (together with the impact of volcanic eruptions). ~~In-situ~~ In situ stratigraphy revealed that in *Abl4-2017* site, the high concentration layer was on top of relatively low concentration, ~~firn~~ *firn* layer from 2015 winter, which means that, during the 2016-2017 ablation season, all the snow accumulated during 2016 winter was melted. Site *Abl3-2017* presented an even lower net balance, revealing older ~~firn~~ *firn* (winter 2014) below the surface high concentration layer. See Sect. S2 in the Supplement for additional details on the attribution of layers in sites *Abl3-2017* and *Abl4-2017*.

The fresh snow at the top of *Abl2-2016* shows slightly higher content of PM than fresh snow sampled on the accumulation zone ($(21.9 \pm 0.6)\,\mathrm{mg\,kg^{-1}}$). In the case of fresh snow on site *Abl5-2017* (with a higher PM content of $(1410 \pm 30)\,\mathrm{mg\,kg^{-1}}$) we could not discard, due to its thin thickness, some contamination with PM from the glacier ice. Glacier ice was highly heterogeneous (relatively pure ice mixed with debris and cryoconite holes), in consequence a substantial variability of PM content over the ice surface was retrieved ($(200 \pm 20)\,\mathrm{mg\,kg^{-1}}$ to ($(4300 \pm 900)\,\mathrm{mg\,kg^{-1}}$).

Figure 5 combines data from both field campaigns and groups PM concentrations according to the attributed date of the layers, but excludes glacier ice samples, which cannot be assigned to an specific year/season. It must be noted that PM content varies over several orders of magnitude ($1.3\,\mathrm{mg\,kg^{-1}}$ to $21.9\,\mathrm{mg\,kg^{-1}}$ on fresh snow, to up to $(30\,000 \pm 5000)\,\mathrm{mg\,kg^{-1}}$ in end-of-summer layers of the ablation zones). As discussed in ~~section~~Sect. 3.3, this is one of the main causes of the albedo values variation.

The alternation of thin and high PM concentration with thick and low PM concentration is partially due to seasonality, as explained above. But in addition to seasonality, there is a large spatial heterogeneity, ~~specially~~ especially during spring/summer ~~(in winter, abundant fresh snow covers the glacier and gives a more homogeneous PM content and albedo distribution, as observed in other glaciers, Brock et al., 2000)~~(in winter, abundant fresh snow covers the glacier and gives a more homogeneous PM content and albe
. The spatial variation is not only between the ablation and accumulation zones of the glacier. The interaction between glacier topography and prevailing winds produce accumulation pockets and windswept ridges, which have contrasted snow accumulation values. These areas of higher and lower accumulation lead to a wide range of spectral albedos. The detailed variations in PM concentrations, and therefore in the albedo, need to be accounted for in a detailed mass balance of the glacier (see ~~section~~ Sect. 3.4).

Field observations on Monte Tronador in 2013 and 2014 confirmed the presence of volcanic ash in the atmosphere, derived from ~~re-suspension~~ resuspension of volcanic ash. The magnitude of resuspension events in Andean Patagonia, a region with strong, persistent westerlies and ~~low seasonal~~ a dry season with low relative humidity, is well known. These ~~events~~ aeolian remobilization events may produce huge ash clouds that may be even confused with true volcanic plumes, they can remobilize ash tenths of ~~kilometres~~ kilometers away (Toyos et al., 2017). In particular, ~~the~~ deposits of volcanic ash that are covered by snow during the winter in the high mountain usually become exposed to remobilization during the summer, ~~travelling~~ traveling through the atmosphere and redepositing over different surfaces due to decrease of wind competence or by adherence of particles on humid surfaces, even at considerably high altitudes.

The 2011 Puyehue-Cordón Caulle eruption produced several ashfall events during the second semester of 2011, by January 2012 explosive activity had declined. As a consequence, thick deposits of tephra with different grain size covered an extended area in Argentina (see Fig. 2, Alloway et al., 2015). Calbuco eruption (April 2015) was active during a shorter period, but due to its location and predominant wind direction also affected Monte Tronador (Romero et al., 2016; Reckziegel et al., 2016).

Direct ash deposition and ~~re-suspension~~ resuspension events can affect the glacier surface in different ways. Continuous, thick layers of ash (few millimeters to few centimeters) have shown to behave as an isolating layer when deposited over snow, in a similar way as in debris-covered glaciers (Brock et al., 2007), which reduces ablation. But on the other hand, a thinner or disperse deposit may have the opposite effect, lowering the surface albedo of the glacier and increasing its melting. The effect of ash (or other PM, for ~~instances~~ instance from biomass burning events) deposition during autumn or winter can extend a few days until the next snow event, which covers the dark surface with the highly reflecting surface of fresh snow (see Fig. 7, Córdoba et al., 2015). But during spring and summer, warmer temperatures and fewer snow events result in an increase of ablation processes over accumulation. Snow melting can flush some of the smaller, hydrophilic PM, but larger particles (or less water-soluble small particles) are concentrated ~~in~~ on the glacier surface (Conway et al., 1996; Xu et al., 2012; Doherty et al., 2013; Li et al., 2017; Skiles and Painter, 2017), producing up to two orders of magnitude of surface enrichment of PM content (Doherty et al., 2016). Resuspension and surface enrichment explain the observed alternating thin, high PM concentration layers and thick, low PM concentration layers. They also impact the spatial variability of albedo on the glacier surface during summer (Fig. 1) (Brock et al., 2000).

3.2 PM characterization

Three main types of particles were identified in samples collected in the field: mineral dust, volcanic ash and crystals derived from ~~ash-fall~~ ashfall events, and carbonaceous particles.

Based on glass morphology, SEM images, and energy dispersive spectroscopy (EDS) microanalysis performed on selected fragments, we were able to identify the presence of volcanic glass derived from Cordón Caulle 2011 (CC) and Calbuco 2015 (Cal) eruptions. Isopach maps for both eruptions (Alloway et al., 2015; Villarosa et al., 2016; Reckziegel et al., 2016) show that Monte Tronador was reached by different plumes from ~~ash fall~~ ashfall events marginally, further confirming that most of the volcanic ash identified in the filters derive from these two recent eruptions. Though both eruptions deposited pumiceous ash east of the Andes in Patagonia, they can be distinguished by petrographic and morphological characteristics of the glass fragments (Fig. 6). CC glass is very fine-grained colourless glass (rhyolitic in composition) while Cal pumice is light to pale brown, clear glass (dacitic to andesitic in composition). SEM images show the presence of irregular glass fragments, with evidence of bubble coalescence, flat or slightly curved platy glass shards that are most probably pieces of broken thin vesicle walls and triangular (in cross section) to Y-shaped particles, which are vesicle walls from the junction of three adjacent vesicles (Fig. 7). EDS analysis of individual fragments of glass from these samples were performed, and were compared with the composition of volcanic glass from samples collected in nearby locations during direct ~~ash-fall~~ ashfall events. Results confirm the presence of glass shards from 2015 Cal and 2011 CC eruptions (Fig. 8). One of the samples described under microscope, corresponds to a sub-surface sample from site *Abl3-2017*, ~~it was dated~~ which was interpreted as winter snow from 2014, previous to 2015 ~~Calbuco~~ Cal eruption, and approximately 75 % of the observed particles correspond to fine-grained colourless pumiceous ash. EDS of individual fragments confirmed that ash on that sample ~~corresponded~~ correspond to CC eruption, as expected.

Another evidence of the presence of volcanic material within the PM collected in the study area are crystals from pyroclastic origin. They are clearly identified as they are partially surrounded by or associated with patches of glass and they are irregular in shape. Crystals that are not directly derived from CC 2011 or Cal 2015 are more or less rounded due to erosion and transport and they exhibit a dull lustre, and they are identified as mineral dust.

Another identified PM component is charcoal, present as black, elongated, brittle fragments. In addition, some of the samples showed evidence of the presence of BC particles, identified by their characteristic shape (carbon spherules of $100\,\mathrm{nm}$ to $200\,\mathrm{nm}$ in aggregates of different morphology). Carbon content by EDS could not be used to confirm the identity of BC particles due to the usage of carbon tape to fix the particles for SEM imaging.

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).

3.3 Albedo: measurements and models

Table 1 shows measured and modeled albedo values for six sites (two from the first field campaign, 2016, and four from the latter, 2017), together with different measured properties of the snow topmost layer and site.

Reported values of measured albedo include shadow corrections, although these corrections were quite small in all cases (below 3.5 % for worst conditions in the 2016 campaign and below 2 % for the 2017 campaign). In some cases (site *Acc3-2016*) the corrections in the measured incoming and reflected radiation are higher (10 to 14 %), but they largely balance out. For the 2016 campaign, the reported measured albedo is a single measurement (registered after voltage reached a stable value) and is informed together with its instrumental uncertainty. It must be noted that for this campaign the reported uncertainty reached values as high as 15 % for worst conditions (low incident radiation and low albedo, as in *Acc3-2016*) or around 2 % for best conditions (clear sky, high albedo). For the 2017 campaign the instrumental uncertainty was lowered by improving the accuracy of the digital multimeter used with the pyranometer, achieving uncertainties lower than 3.5 % (worst conditions) or lower than 1.2 % (best conditions).

Results from the 2017 campaign, obtained using the improved ~~support~~mounting stand, shed light on the reproducibility of albedo measurements. For this campaign, we found that repeated albedo measurements in the same site have a standard deviation corresponding around 5 to 10 % of the average values. This range could be partly due to the leveling of the ~~support~~stand, or to inherent variability of the measurement at these sites (~~specially to~~ especially differences in the solar irradiance for situations with rapid changes in cloudiness).

Regarding snow grain ~~sizes~~size, 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 snow grain radius of (151 ± 41) µm, whereas in samples of older ~~firn~~ *firn* in the ablation zone (or sub-surface snow/~~firn~~ *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. 2.2.3) 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. It must be emphasized here that the developed method for characterizing snow

Table 1. Measured and modeled snow albedo for six sites (two in 2016 campaign and four in 2017 campaign). For 2016 campaign the measured albedo is a single measurement and is informed together with its instrumental uncertainty. For 2017 campaign, we report the average and the standard error of the average for several repetitions. For modeled albedo, sensitivity to different input parameters is reported, as an estimation of albedo uncertainty.

Site	Surface	α_{meas}	$\alpha_{SNICARv2}$	$\alpha_{SNICARv2.1}$	$\alpha_{SNICARv2.1}$ **sens.**
Acc2-2016 (accum. zone)	Recent snow		Direct: 0.583	Direct: 0.573	**Grain size: (+)** -0.024 **(-)** $+0.028$
12 April 2016	Layer: (6 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:47 (UTC - 3)	Grain size: (1000 ± 200) µm		Diffuse: 0.655	Diffuse: 0.748	100 µg kg^{-1} **BC:** -0.017
Zenith: 51.98°	Snow density: 300 kg m^{-3}				**Layer thickness: (+)** $+0.010$ **(-)** -0.013
Effective angle: 51.98°	PM: (22.0 ± 0.6) mg kg^{-1}	0.626 ± 0.011		W.Aver.: 0.590	
Clear Sky	Slope: 0°				
Acc3-2016 (accum. zone)	Dirty summer snow		Direct: 0.435	Direct: 0.445	Grain size: (+) -0.001 (-) $+0.002$
12 April 2016	Layer: (0.3 ± 0.1) cm				PM content: (+) -0.001 (-) $+0.002$
16:55 (UTC - 3)	Grain size: (1000 ± 200) µm		Diffuse: 0.364	Diffuse: 0.359	20 mg kg^{-1} BC: -0.049
Zenith: 66.04°	Snow density: 500 kg m^{-3}				**Layer thickness: (+)** -0.001 **(-)** $+0.007$
Effective angle: 68.7° to 73.6°	PM: (7800 ± 1500) mg kg^{-1}	0.257 ± 0.041		W.Aver.: 0.359	Snow density: (+) -0.001 (-) $+0.003$
Overcast sky (approx. 100 % diffuse rad.)	Slope: 11°				% Diff. Rad.: $+0.001$ (89 % diff. rad.)
Abl3-2017 (accum. pocket on abl. zone)	Dirty snow		Direct: 0.374	Direct: 0.381	Grain size: (+) $+0.001$ (-) -0.001
3 April 2017	Layer: (0.3 ± 0.1) cm				PM content: (+) $+0.001$ (-) -0.001
13:11 (UTC - 3)	Grain size: (1020 ± 160) µm		Diffuse: 0.360	Diffuse: 0.354	20 mg kg^{-1} BC: -0.015
Zenith: 47.57°	Snow density: 500 kg m^{-3}				Layer thickness: (+) $+0.0000001$ (-) -0.000002
Effective angle: 56.5° to 59.9°	PM: (30000 ± 5000) mg kg^{-1}	0.371 ± 0.011		W.Aver.: 0.356	% Diff. Rad.: (+) $+0.002$ (-) -0.002
Overcast sky (89 % to 95 % diffuse rad.)	Slope: 15°				Effective angle: (+) $+0.001$ (-) -0.001
Abl4-2017 (accum. pocket on abl. zone)	Dirty snow		Direct: 0.379	Direct: 0.384	Grain size: (+) -0.001 (-) $+0.002$
3 April 2017	Layer: (0.10 ± 0.05) cm				PM content: (+) -0.004 (-) $+0.006$
13:30 (UTC - 3)	Grain size: (740 ± 170) µm		Diffuse:0.375	Diffuse: 0.368	20 mg kg^{-1} BC: -0.050
Zenith: 46.95°	Snow density: 500 kg m^{-3}				**Layer thickness: (+)** -0.008 **(-)** $+0.031$
Effective angle: 57.1° to 60.1°	PM: (12250 ± 2050) mg kg^{-1}	0.266 ± 0.008		W.Aver.: 0.368	Snow density: (+) -0.005 (-) $+0.007$
Overcast sky (approx. 100 % diffuse rad.)	Slope: 15°	0.376 ± 0.015			% Diff. Rad.: -0.007 (89 % diff. rad.)
Acc5-2017 (accum. zone)	Recent snow		Direct: 0.788	Direct: 0.778	**Grain size: (+)** -0.012 **(-)** $+0.015$
5 April 2017	Layer: (9 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:26 (UTC - 3)	Grain size: (150 ± 40) µm		Diffuse: 0.860	Diffuse: 0.910	100 µg kg^{-1} **BC:** -0.022
Zenith: 48.20°	Snow density: 300 kg m^{-3}				Layer thickness: (+) $+0.002$ (-) -0.002
Effective angle: 49.4° to 52.3°	PM: (1.28 ± 0.03) mg kg^{-1}	0.814 ± 0.013		W.Aver.:0.828	% Diff. Rad.: (+) $+0.005$ (-) -0.002
Cloudy sky (34 % to 48 % diffuse rad.)	Slope: 5°				Effective angle: (+) $+0.001$ (-) -0.001
Acc6-2017 (accum. zone)	Recent snow		Direct: 0.786	Direct: 0.776	**Grain size: (+)** -0.013 **(-)** $+0.015$
5 April 2017	Layer: (9 ± 1) cm				PM content: (+) -0.001 (-) $+0.001$
14:48 (UTC - 3)	Grain size: (150 ± 40) µm		Diffuse: 0.856	Diffuse: 0.905	100 µg kg^{-1} **BC:** -0.021
Zenith: 49.35°	Snow density: 300 kg m^{-3}				Layer thickness: (+) $+0.001$ (-) -0.002
Effective angle: 51.0° to 53.9°	PM: (3.9 ± 0.2) mg kg^{-1}	0.757 ± 0.026		W.Aver.: 0.825	% Diff. Rad.: (+) $+0.004$ (-) -0.002
Cloudy sky (34 % to 48 % diffuse rad.)	Slope: 5°				Effective angle: (+) $+0.001$ (-) -0.001

grains for the 2017 campaign allows us to measure the size distribution and to assess the relevance of different grain shapes (when necessary). It has been shown that the shape of the snow grains can significantly affect snow albedo (Libois et al., 2013; He et al., 2017). Except for fresh snow (snow less than one day old), where it is possible to still distinguish crystal fragments, in both campaigns the observed snow/~~firn~~ *firn* grains were rounded. This is related with the temperate climate at Monte Tronador, where snow temperature is above $-5\,^{\circ}\mathrm{C}$ and the temperature gradient is low. Also, the presence of meltwater within the snow layers enhance the rate at which grains become rounded, because the grains melt first at their extremities. Finally, the average grain size increases because the smaller grains tend to melt before the larger ones ~~(Cuffey and Paterson, 2010)~~ (Flanner and Zender, 2006). Hence, we assumed spherical grains for all modeled albedo calculations.

Table 1 also reports modeled albedo results for each site. Results of the updated model (SNICARv2.1) were calculated with the direct and diffuse spectra estimated for the specific sky conditions, as detailed in ~~section~~Sect. 2.3. The weighted average of pure direct and pure diffuse radiation albedos represents the net albedo of snow for total incident radiation. For comparison, results from SNICARv2 with the available standard spectra (mid-latitude clear-sky direct radiation spectrum or overcast sky diffuse radiation spectrum) are presented. As expected, for clear-sky conditions (site *Acc2-2016*) the pure direct albedo from SNICARv2 is similar to the weighted average from SNICARv2.1. The pure diffuse albedo from both models differ significantly, but the fraction of diffuse radiation is very low, and hence its contribution to net albedo is also low. For overcast conditions (*Acc3-2016*, *Abl3-2017* and *Abl4-2017*), the pure diffuse albedo from both models is also similar, and weighted average albedo from SNICARv2.1 is coincident with the pure diffuse albedo. For both models, the diffuse radiation spectrum for overcast conditions is coincident with global solar radiation spectrum (see Fig. 4), which explains the similar results. It must be noticed that for site *Abl4-2017*, we observed rapid cloud movements, and we decided to register two sets of albedo measurements, The average albedo of the second set is similar to the modeled weighted average albedo and to the measurement for site *Abl3-2017*. We suggest that this coincidence means that the pictures of the sky above the site (taken after the two sets of measurements) and the estimate of cloud cover based on those pictures represent more accurately the sky conditions during the second set of measurements. Finally, partly cloudy skies (sites *Acc5-2017* and *Acc6-2017*) are the main reason for the development of SNICARv2.1. For these cases, pure direct and pure diffuse albedo differ much more than the associated uncertainties, and pure diffuse albedo from SNICARv2.1 also differs from that from SNICARv2. These differences are also evident from the comparison between the diffuse radiation spectra for partly cloudy skies developed for SNICARv2.1 and the diffuse spectra for overcast skies used in SNICARv2 (Fig. 4). For these sites, SNICARv2 cannot give a good approximation. For *Acc5-2017* SNICARv2.1 weighted average albedo seems a good approximation of the measured albedo. For *Acc6-2017*, measured albedo is lower than pure direct and pure diffuse albedo, so both models give higher estimates for this site. As discussed below in this section, the effect of the diffuse radiation fraction does not seem to be the main source of this disagreement.

The updated model reproduces quite well the main features of the measured albedo (with a larger discrepancy for sampling site *Acc3-2016*). One of the most important parameters affecting albedo is PM content: the measurements with lower albedo values ($\alpha_{meas} < 0.4$) correspond to sites with the highest PM content (*Acc3-2016*, *Abl3-2017* and *Abl4-2017*), whereas the remaining sites have much lower PM content (fresh snow) and $\alpha_{meas} > 0.6$. It must be noted that for high PM content, a further increase in particle content does not significantly affect the albedo: our simulations for site *Acc3-2016*, with $(7800 \pm 1500)\,\mathrm{mg\,kg^{-1}}$ of PM match closely those for sites *Abl3-2017* and *Abl4-2017*, with $(30\,000 \pm 5000)\,\mathrm{mg\,kg^{-1}}$ and $(12\,250 \pm 2050)\,\mathrm{mg\,kg^{-1}}$ of PM, respectively. The same effect is noticed when simulating the impact of the possible presence of BC on snow. For sites with low PM content, an increment of $100\,\mathrm{\mu g\,kg^{-1}}$ of aged BC has a relevant impact on modeled albedo (between -0.017 and -0.022 for the studied sites). However, for sites with higher PM content, much higher BC concentrations were needed in order to observe a relevant effect in modeled albedo (for a $20\,\mathrm{mg\,kg^{-1}}$ increment of BC, we calculated an effect of -0.015 to -0.050 in calculated albedo). Ginot et al. (2014) have already reported simulation results for Mera Glacier, Nepal, that showed that the effect of dust and BC content on albedo and potential melting of snow are non-additive. Our results show that for site *Acc3-2016* $20\,\mathrm{mg\,kg^{-1}}$ of BC represent a lowering of -0.049 of albedo for snow containing $7800\,\mathrm{mg\,kg^{-1}}$ of volcanic ash, but the impact increases to -0.057 if the snow contains only $6300\,\mathrm{mg\,kg^{-1}}$ of volcanic ash (which is possible due to the uncertainty in gravimetric PM content).

~~In~~ On 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 instance 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.

The last column in Table 1 reports the results of sensitivity studies to evaluate the impact on the calculated albedo of the uncertainty in key input parameters. ~~The parameters have been modified in ranges allowed by the uncertainty of the input parameters~~ We define the sensitivities as the modeled albedo changes increasing or decreasing one parameter in the same magnitude of its reported uncertainty (identified in Table 1 with a "+" or a "–" sign, respectively), while keeping all other parameters unchanged. For each site, we studied PM content and grain size impact, together with other parameters that could be relevant at each site. We highlighted (with bold characters) the higher sensitivities for each site.

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~~ size snow. For sites with high content of PM the uncertainty of grain size ~~do~~ does not have an appreciable effect. ~~Volcanic ash contentuncertainty~~ 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 estimates might not be as accurate as that obtained by other methods.

The uncertainty of volcanic ash content does not have a relevant impact for any of the sites, although it is larger for site *Abl4-2017*. However, as previously mentioned, the presence of BC (not yet quantified in these samples) could have a more relevant impact on albedo. For instance, it could explain the difference between measured and modeled albedo for site *Acc6-2017*, and the difference with site *Acc5-2017*.

Regarding the impact of the uncertainty of layer thickness, the results show that several factors determine the relevance of this parameter. The impact is maximum for very thin layers, especially when the underlying layer has a significantly different albedo (~~i.e., PM content~~site *Abl4-2017*, 0.1 cm thick), and its minimum for the thicker layers ~~,~~ (sites *Acc5-2017* or *Acc6-2017*, 9 cm thick), or for intermediate thicknesses with high PM content (i.e., low penetration of incident light, site *Abl3-2017*, 0.3 cm thick). The impact of uncertainty of snow density was not studied in detail, but the impact is inverse to that of the thickness of the layer. Hence, we report only the moderate impact of snow density uncertainty for site *Abl4-2017*.

The impact of the uncertainty of the diffuse to global irradiance ratio is moderate but appreciable, which emphasizes the relevance of measuring the ratio on the field. Finally, the impact of the uncertainty of the incidence angle is low, and not appreciable for this range of experimental albedo uncertainty.

Another possible reason for disagreement between modeled and measured albedo, especially for aged snow, is surface roughness. Millimeter scale surface roughness due to snow aging ~~have~~ has shown to reduce albedo, especially in the infrared region, due to multiple reflections in the cavities (Pirazzini et al., 2015). Computer simulations have studied the parameters that determine the magnitude of the effect of sastrugi (centimeter-scale roughness) on albedo (Zhuravleva and Kokhanovsky, 2011). Quantification of the impact of surface roughness of snow in measured albedo is out of the scope of this work, but it must be remarked that in sites with higher PM content, ~~which has been under~~ where there has been longer snow metamorphosis processes (*Acc3-2016*, *Abl3-2017* and *Abl4-2017*), ~~presented~~ we observed higher surface roughness.

Literature values of snow albedo ~~depend mainly~~ mainly depend on the PM content. Two other studies that found snow albedo ranges similar to our measurements are connected with local/regional transport of dust (Painter et al., 2012; Wittmann et al., 2017). Young et al. (2014) modeled the direct deposition of volcanic ash from Redoubt volcano 2009 eruption on Arctic snow, finding similarly high albedo reductions. Sicart et al. (2001) also found a similar albedo range at Zongo glacier, but their lower values of albedo are not attributed to PM surface enrichment but to very thin snow layers over dirty ice.

Recent studies in Chilean Andes measured or modeled small reductions on snow albedo, due to traffic related BC (Cereceda-Balic et al., 2018) or to a combination of urban BC and dust from desert regions (Rowe et al., 2019). Similarly, studies on Mera Glacier, Nepal (Ginot et al., 2014), and at several sites ~~at~~ on the Tibetan Plateau (Zhang et al., 2018) found small albedo reductions due to BC and dust, and almost negligible effects of impurities in Greenland (Carmagnola et al., 2013; Wright et al., 2014).

3.4 Albedo and modeled impact on glacier mass balance

Table 2 shows the ~~glacier-wide~~ modeled annual and winter surface mass balance, Equilibrium Line Altitude (ELA) and Accumulation Area Ratio (AAR) for different values of old snow albedo ($\cancel{\alpha_{firn}}\alpha_{min}$). Figure 9 shows the change in cumulative ~~glacier-wide~~ surface mass balance and ablation and the annual mass balance elevation gradient for the different values of

$\cancel{\alpha_{firn}}\alpha_{min}$. The mass balance sensitivity to albedo change, defined as the change in ~~glacier-wide~~ surface mass balance per 0.1 of $\cancel{\alpha_{firn}}$ α_{min} decrease is around of $-0.6\,\mathrm{mw\,e/yr}$ and $-0.07\,\mathrm{mw\,e/yr}$, for annual and winter mass balance, respectively (Table 2). ~~Firn albedo or old snow albedo have~~ Aged snow albedo has a considerable effect on the surface mass balance of Alerce glacier (Fig. 9 A) increasing the amount of melt during the ablation period, from almost 2.4 m w.e. to more than 4.6 m w.e. when $\cancel{\alpha_{firn}}$ α_{min} is decreased from 0.7 to 0.3 (Fig. 9 B). Although the accumulation of the glacier does not change (the amount of precipitation for the different run test is the same) there is a decrease in the winter (accumulation) mass balance due to the albedo effect over ablation episodes at the begging of the accumulation season (Fig. 9, Table 2). The decrease in the ~~old snow albedo had~~ aged snow albedo α_{min} has an impact all over the glacier, decreasing the surface mass balance at all elevation range. Other glaciological parameters related to the surface mass balance of the glacier, like the ELA or AAR also seems to be profoundly impacted with the decrease of albedo, with a total increase of ELA of $250\,\mathrm{m}$ and a decrease of AAR of more than 50 % when the old snow albedo changes from 0.7 to 0.3. Nevertheless, since both ELA and AAR ~~depends~~ depend on the hypsometry of the glacier the ~~change~~ changes do not increase constantly.

Table 2. Albedo values for ice (α_{ice}), old snow (firn, α_{min}) and fresh snow (α_{max}) used for the sensitivity study of Alerce glacier-wide mass balance to change in the albedo. The winter and annual glacier-wide surface mass balance, ELA and AAR for each simulation is presented.

α_{ice}	α_{min}	α_{max}	Wint. MB (m w.e.)	Annu. MB (m w.e.)	ELA (m)	AAR (%)
0.35	0.3	0.8	3.32	-1.28	2165	22.30
0.35	0.4	0.8	3.4	-0.69	2125	34.6
0.35	0.5	0.8	3.48	-0.08	2055	50.3
0.35	0.6	0.8	3.55	0.56	1935	70.5
0.35	0.7	0.8	3.61	1.22	1915	78.8

To give physical meaning to the albedo values presented in Fig. 9 and Table 2, we can use as a reference the daily-averaged albedo values modeled with SNICARv2.1 for some of the sampling sites in Table 1.

The $\alpha_{max} = 0.8$ used in the mass balance model is equivalent to the daily average of 0.805 for clear-sky conditions, 0.803 for overcast sky, and 0.835 for 33 % of cloudiness, modeled for fresh ~~recent snow ,~~ snow with very low PM content at site *Acc5-2017*. The $\cancel{\alpha_{firn} = 0.6}$ $\alpha_{min} = 0.6$ scenario in Table 2 is similar to the daily average of 0.612 for clear-sky conditions, 0.605 for overcast sky, and 0.637 for 33 % of cloudiness, modeled for ~~recent~~ aged snow with low PM content (*Acc2-2016*). Although it represents intermediately aged snow, it can serve as an example of a ~~firn~~ snow/*firn* surface with low PM content, a situation where no ash fall occurred at Monte Tronador. The $\cancel{\alpha_{firn} = 0.4}$ $\alpha_{min} = 0.4$ scenario in Table 2, is similar to the modeled daily average of 0.407 for clear-sky conditions, 0.368 for overcast sky, and 0.382 for 33 % of cloudiness of the ~~firn~~ *firn* with very high PM content (*Abl4-2017*). These values are ~~representatives of the firn~~ representative of the snow/*firn* albedo during summer for the years 2016 and 2017. The other scenarios are used to depict intermediate or more extreme situation and to analyze the role of albedo change in the surface mass balance of the glacier.

Our ~~α_{firn}~~ α_{min} analysis allows us to estimate the impact of volcanic ash on the surface mass balance of Alerce glacier. In absence of volcanic eruptions, if we assume that other local or regional PM sources (mineral dust, biomass burning, etc.) do not affect significantly fresh snow albedo, it is expected that the summer ~~α_{firn}~~ α_{min} over glacier surface is similar to ~~$\alpha_{firn} = 0.6$~~ $\alpha_{min} = 0.6$ scenario. Although we could not sample summer ~~firn~~ *firn* layers previous to 2015 Cal eruption to test this hypothesis, this first order assumption would mean, that volcanic ash ~~are~~ is responsible for a $1.25\,\mathrm{mwe}$ decrease in the ~~glacier-wide annual~~ annual surface mass balance (or a 36 % increase in summer ablation), if we compared the ~~$\alpha_{firn} = 0.6$ and $\alpha_{firn} = 0.4$~~ $\alpha_{min} = 0.6$ and $\alpha_{min} = 0.4$ scenarios.

Although more sampling of ~~firn~~*firn*/snow layer and further chemical analysis on the samples are needed to confirm that the decrease of albedo is only due to the effect of volcanic ash, we have shown that PM content (and hence ~~α_{firn}~~α_{min}) varies largely over the glacier surface. Taking into account these spatiotemporal changes in albedo for glacier mass balance models is a defying task. Defining a low number of representative regions over the glacier surface is not an easy task, due to the already mentioned high heterogeneity. In addition, it would be difficult to regularly measure PM content (and/or albedo) on those regions, due to the distances and path conditions on the glacier. Regional atmospheric models could be of help in predicting deposition of volcanic ~~ashes~~ash, mineral dust, BC and other PM. But the spatial scale of those models ($\geq 1\,\mathrm{km}$) is too coarse to capture to reproduce the spatial variation of the albedo over the glacier.

These challenges have been acknowledged in literature, and several approaches have been followed to estimate snow/ice melting. The simplest approaches have used measured or modeled albedo changes together with measured or modeled solar radiation to estimate melting, without taking into account spatial heterogeneity (in surface temperature, PM concentration, etc) (Ginot et al., 2014; Zhang et al., 2018). For Mera glacier, Ginot et al. (2014) calculate that BC and dust are responsible of approximately 26 % of total melting. Zhang et al. (2018) do not report the effect on melt rates but only the impact on seasonal snow cover duration, and hence the results are not easy to compare with ours. Painter et al. (2013) used a glacier mass balance model similar to ours, but introducing temperature anomalies (due to BC radiative forcing) to estimate mass balance changes. They used several approximations to postulate BC concentrations over the glaciers based on limited ice cores. Their results are difficult to compare to ours due to the different approach, they analyze general mass balance trends over two centuries. ~~Flanner et al. (2007) and Ménégoz et al. (2014)~~ Flanner et al. (2007) and Ménégoz et al. (2014) used emission inventories and general circulation models to study deposition of BC (and mineral dust, in the latter work) and its radiative forcing. The spatial resolution of their simulations make difficult the comparison with field PM concentration measurements, and hinder the accuracy of quantitative mass balance calculations (Ménégoz et al., 2014; Qian et al., 2015). Young et al. (2014) used modeled ash deposition, SNICAR and a restricted degree-day radiation balance. They found melt rates between 140 % and 320 % higher than for pure snow, although the low spatial resolution of the simulations ($\approx 18\,\mathrm{km}$) may affect the precision of the results. ~~Vionnet et al. (2012)~~ Vionnet et al. (2012) used the detailed snow model CROCUS implemented on the soil model SURFEX to study the snowpack on the Grandes Rousses mountain range in the French Alps . They used a high resolution DEM ($150\,\mathrm{m}$) together with meteorological forcing from interpolation of SAFRAN atmospheric reanalysis. They main weakness is that at that moment CROCUS did not explicitly treated PM in snow (it was only implicitly included in ~~the~~ their parametrization of snow albedo changes with snow aging).

There are also some examples on literature that studied the coupling of meteorological models with glacier or snowpack models. Different authors studied climate feedback effects on Karakoram glaciers (Collier et al., 2013) and in the Svalbard glaciers (Aas et al., 2016), and the snowpack in Antarctica (Vionnet et al., 2012). The authors suggest that the next steps would be to couple a regional atmospheric model with the ability of prognosis of PM deposition ~~(such as Ménégoz et al. (2014))~~ (such as Ménégoz et al., 2014) with a high resolution glacier mass balance model ~~(such as ours or CROCUS implementation on SURFEX (Vionnet et al., 2012))~~(such as ours or CROCUS implementation on SURFEX, Vionnet et al., 2012), and including explicit treatment of PM effect on snow albedo ~~(such as SNICAR or recent CROCUS implementations (Tuzet et al., 2017))~~(such as SNICAR or recent CROCUS implementations Tuzet et al., 2017).

4 Conclusions

Our study combines field ~~observation and modeling activities to analysis~~ measurements and modeling to analyze the role of PM over the albedo of Alerce glacier in Monte Tronador.

PM content of the samples varied in a wide range, from lowest to highest: fresh snow ($1.1\,\mathrm{mg\,kg^{-1}}$ to $21.9\,\mathrm{mg\,kg^{-1}}$), old winter snow/~~firn~~ *firn* ($4.9\,\mathrm{mg\,kg^{-1}}$ to $51\,\mathrm{mg\,kg^{-1}}$, except ~~from~~ for some samples from ablation zone), and thin, darker layers with contribution of local/regional resuspension of dust/~~ashes~~ ash ($365\,\mathrm{mg\,kg^{-1}}$ to $410\,\mathrm{mg\,kg^{-1}}$) or with high PM enrichment due to spring and summer ablation ($339\,\mathrm{mg\,kg^{-1}}$ to $9040\,\mathrm{mg\,kg^{-1}}$, reaching even $12\,250\,\mathrm{mg\,kg^{-1}}$ to $30\,000\,\mathrm{mg\,kg^{-1}}$ in the ablation zone). ~~Microscopical~~ Microscopic characterization of PM showed that the major component on snow and ~~firn~~ *firn* layers after 2014 and also glacier ice surface is volcanic ash, not only from the recent Calbuco eruption (2015), but also from the Cordón Caulle eruption (2011). Minor contributions of mineral dust and ~~Black Carbon~~ black carbon were also detected.

The ~~major presence of volcanic ash~~ fact that volcanic ash represents the largest fraction of the collected PM in all studied samples ~~indicate~~ indicates that the effect of ~~nearby~~ volcanic eruptions are expected not only ~~immediately~~ immediately after direct deposition, but also many years later, due to surface enrichment and wind resuspension and redeposition. The spatial and temporal distribution of PM is highly heterogeneous, due both to seasonality and to the combination of glacier topography and prevailing wind direction. These facts need to be accounted for when studying the effect of snow albedo on glacier mass balance. While the albedo parametrization used in the mass balance model partially accounts for the spatial heterogeneity of PM surface concentration (implicitly), we suggest that in the future it would be useful to couple our mass balance model with an atmospheric model which provides prognosis of PM content and a snow albedo model that includes LAP effect explicitly.

The measured snow albedo also varied in a wide range (0.26 to 0.81), similar to that of other glaciers with dust ~~of volcanic concentrations in~~ or volcanic ash concentration in the same order of magnitude. We found that for our set-up (where the pyranometer must be inverted sequentially to measure upwelling and downwelling radiation) rapid changes in cloudiness hinder the repeatability of albedo measurements and may ~~difficult~~ degrade the comparison with modeled albedo. Nevertheless, comparison of measured and modeled snow albedo showed a good match, and illustrates the effect of PM content and composition (i.e., BC versus dust or volcanic ash), snow grain size, layer thickness, and cloudiness on snow albedo. To evaluate the latter, we updated the SNICAR snow albedo model ~~,~~ to accurately represent the effect of cloudiness on direct and diffuse solar spectra (SNICARv2.1). This update improved considerably the match of measured and modeled albedo for partially cloudy sky conditions. The effect of uncertainties of field measurements ~~of snow properties~~ was evaluated for different types of samples~~(lower or higher PM content, grain size, layer thickness, snow density, etc.),~~ , suggesting strategies to reduce uncertainty in snow albedo modeling or retrieval of snow properties from measured albedo. We found that snow grain size must be measured more carefully in samples with low volcanic ash content and that the accuracy of layer thickness can be relevant not only for very thin layers ($0.1\,\mathrm{cm}$) but also for thicker layers ($6\,\mathrm{cm}$) with low ash content. The accuracy of ash content was found to be good enough for reproducing our albedo measurements. However, it was remarked that the presence of small amounts of BC can affect the albedo significantly in samples with low ash content.

We showed that ~~glacier-wide~~ surface mass balance is highly sensitive to ~~firn or old snow albedochanges~~the parametrization of aged snow albedo. We find a glacier-wide albedo change sensitivity of around ~~of~~ $-0.6\,\mathrm{mwe/yr}$, mostly due to ~~a~~ higher ablation during spring and summer. Finally, we suggest that the effect of volcanic ~~ashes~~ ash in Alerce glacier can be as high as a $1.25\,\mathrm{mwe}$ decrease in the glacier annual mass balance or a 34 % of increase in the melt during the ablation season, considering a surface volcanic ash content compatible with that measured in sites *Acc3-2016*, *Abl3-2017* and *Abl4-2017*. Nevertheless, a more accurate calculation of volcanic ash impact would take into account the amount of other regional or local sources of PM present on the glacier in absence of such volcanic eruptions, which cannot be estimated with the results of the field campaigns reported in this article.

To the best of our knowledge, this work is the first study of PM content and snow albedo on Argentinian glaciers. Our results highlight the need of ~~considering appropriately~~ appropriately considering the effect of volcanic eruptions on snow albedo and glacier mass balance even years after the eruption events. We suggest possible future steps to improve prognosis ability and mass balance accuracy, using a combination of measurements and modeling.

Code and data availability. The complete set of field measurements are available from the corresponding author on reasonable request. The code of SNICAR v2.1 is available online at https://github.com/EarthSciCode/SNICARv2.git

Author contributions. JGC, LD and LR designed the field campaigns. HB designed and built the mounting stands for albedo measurents. JGC and FB collected and filtered the snow samples and performed the albedo measurements, with assistance of LR and his team. JGC performed the gravimetry of filters and corrected albedo measurements. JGC updated SNICAR code in collaboration with CH. JGC performed modeling related to solar incident spectra and SNICAR snow albedo. VO and GV characterized PM on the filters by binocular microscopy, SEM and EDS. LR performed the modelling of glacier mass balance. JGC, LD and LR prepared the manuscript, with contributions of VO, GV and CH.

Competing interests. The authors declare that they have no conflict of interest.

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References

Aas, K. S., Dunse, T., Collier, E., Schuler, T. V., Berntsen, T. K., Kohler, J., and Luks, B.: The climatic mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere–glacier mass balance model, The Cryosphere, 10, 1089–1104, https://doi.org/10.5194/tc-10-1089-2016, https://www.the-cryosphere.net/10/1089/2016/, 2016.

Alloway, B. V., Pearce, N. J. G., Villarosa, G., Outes, V., and Moreno, P. I.: Multiple melt bodies fed the AD 2011 eruption of Puyehue-Cordón Caulle, Chile, Scientific Reports, 5, 17 589, https://doi.org/10.1038/srep17589, http://www.nature.com/articles/srep17589, 2015.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D. M., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D. T., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, Journal of Geophysical Research: Atmospheres, 118, 5380–5552, https://doi.org/10.1002/jgrd.50171, http://dx.doi.org/10.1002/jgrd.50171, 2013.

Brandt, R. E., Warren, S. G., and Clarke, A. D.: A controlled snowmaking experiment testing the relation between black carbon content and reduction of snow albedo, Journal of Geophysical Research, 116, D08 109, https://doi.org/10.1029/2010JD015330, http://doi.wiley.com/10.1029/2010JD015330, 2011.

Brock, B., Rivera, A., Casassa, G., Bown, F., and Acuña, C.: The surface energy balance of an active ice-covered volcano: Villarrica Volcano, southern Chile, Annals of Glaciology, 45, 104–114, https://doi.org/10.3189/172756407782282372, 2007.

Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurement and parameterisation of albedo variations at Haut Glacier d ' Arolla , Switzerland, Journal of Glaciology, 46, 675–688, https://doi.org/10.3189/172756506781828746, 2000.

Carmagnola, C. M., Domine, F., Dumont, M., Wright, P., Strellis, B., Bergin, M., Dibb, J., Picard, G., Libois, Q., Arnaud, L., and Morin, S.: Snow spectral albedo at Summit, Greenland: Measurements and numerical simulations based on physical and chemical properties of the snowpack, Cryosphere, 7, 1139–1160, https://doi.org/10.5194/tc-7-1139-2013, 2013.

Cereceda-Balic, F., Vidal, V., Moosmüller, H., and Lapuerta, M.: Reduction of snow albedo from vehicle emissions at Portillo, Chile, Cold Regions Science and Technology, 146, 43–52, https://doi.org/10.1016/j.coldregions.2017.11.008, https://linkinghub.elsevier.com/retrieve/pii/S0165232X17302070, 2018.

Collier, E., Mölg, T., Maussion, F., Scherer, D., Mayer, C., and Bush, A. B. G.: High-resolution interactive modelling of the mountain glacier–atmosphere interface: an application over the Karakoram, The Cryosphere, 7, 779–795, https://doi.org/10.5194/tc-7-779-2013, https://www.the-cryosphere.net/7/779/2013/, 2013.

Conway, H., Gades, A., and Raymond, C. F.: Albedo of dirty snow during conditions of melt, Water Resources Research, 32, 1713–1718, https://doi.org/10.1029/96WR00712, 1996.

Córdoba, G., Villarosa, G., Sheridan, M. F., Viramonte, J. G., Beigt, D., and Salmuni, G.: Secondary lahar hazard assessment for Villa la Angostura, Argentina, using Two-Phase-Titan modelling code during 2011 Cordón Caulle eruption, Natural Hazards and Earth System Sciences, 15, 757–766, https://doi.org/10.5194/nhess-15-757-2015, https://www.nat-hazards-earth-syst-sci.net/15/757/2015/, 2015.

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

Doherty, S. J., Grenfell, T. C., Forsström, S., Hegg, D. L., Brandt, R. E., and Warren, S. G.: Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow, Journal of Geophysical Research: Atmospheres, 118, 5553–5569, https://doi.org/10.1002/jgrd.50235, 2013.

Doherty, S. J., Hegg, D. A., Johnson, J. E., Quinn, P. K., Schwarz, J. P., Dang, C., and Warren, S. G.: Causes of variability in light absorption by particles in snow at sites in Idaho and Utah, Journal of Geophysical Research, 121, 4751–4768, https://doi.org/10.1002/2015jd024375, 2016.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P., and Ruiz, L.: Two decades of glacier mass loss along the Andes, Nature Geoscience, pp. 1–7, https://doi.org/10.1038/s41561-019-0432-5, http://www.nature.com/articles/s41561-019-0432-5, 2019.

Ernst, M., Holst, H., Winter, M., and Altermatt, P. P.: SunCalculator: A program to calculate the angular and spectral distribution of direct and diffuse solar radiation, Solar Energy Materials and Solar Cells, 157, 913–922, https://doi.org/10.1016/J.SOLMAT.2016.08.008, https://www.sciencedirect.com/science/article/pii/S0927024816302999, 2016.

Flanner, M. G.: Arctic climate sensitivity to local black carbon, Journal of Geophysical Research Atmospheres, 118, https://doi.org/10.1002/jgrd.50176, 2013.

Flanner, M. G. and Zender, C. S.: Linking snowpack microphysics and albedo evolution, Journal of Geophysical Research, 111, D12 208, https://doi.org/10.1029/2005JD006834, http://doi.wiley.com/10.1029/2005JD006834, 2006.

Flanner, M. G., Zender, C. S., Randerson, J. T., and Rasch, P. J.: Present-day climate forcing and response from black carbon in snow, Journal of Geophysical Research: Atmospheres, 112, D11 202, https://doi.org/10.1029/2006JD008003, http://dx.doi.org/10.1029/2006JD008003, 2007.

Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J.: Present-day South American climate, Palaeogeography, Palaeoclimatology, Palaeoecology, 281, 180–195, https://doi.org/10.1016/j.palaeo.2007.10.032, 2009.

Ginot, P., Dumont, M., Lim, S., Patris, N., Taupin, J.-D., Wagnon, P., Gilbert, A., Arnaud, Y., Marinoni, A., Bonasoni, P., and Laj, P.: A 10 year record of black carbon and dust from a Mera Peak ice core (Nepal): variability and potential impact on melting of Himalayan glaciers, The Cryosphere, 8, 1479–1496, https://doi.org/10.5194/tc-8-1479-2014, http://www.the-cryosphere.net/8/1479/2014/, 2014.

Gueymard, C.: Une paramétrisation de la luminance énergétique du ciel clair en fonction de la turbidité, Atmosphere-Ocean, 24, 1–15, https://doi.org/10.1080/07055900.1986.9649237, http://www.tandfonline.com/doi/abs/10.1080/07055900.1986.9649237, 1986.

Gueymard, C.: An anisotropic solar irradiance model for tilted surfaces and its comparison with selected engineering algorithms, Solar Energy, 38, 367–386, https://doi.org/10.1016/0038-092X(87)90009-0, https://www.sciencedirect.com/science/article/pii/0038092X87900090, 1987.

Gueymard, C. A.: Parameterized transmittance model for direct beam and circumsolar spectral irradiance, Solar Energy, 71, 325–346, https://doi.org/10.1016/S0038-092X(01)00054-8, 2001.

Hadley, O. L. and Kirchstetter, T. W.: Black-carbon reduction of snow albedo, Nature Climate Change, 2, 437–440, https://doi.org/10.1038/nclimate1433, 2012.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Genio, A. D., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, Journal of Geophysical Research, 110, D18 104, https://doi.org/10.1029/2005JD005776, http://doi.wiley.com/10.1029/2005JD005776, 2005.

He, C. and Flanner, M.: Snow Albedo and Radiative Transfer: Theory, Modeling, and Parameterization, in: Springer Series in Light Scattering (Volume 5), edited by Kokhanovsky, A. A., pp. 67–133, Springer, Cham, https://doi.org/10.1007/978-3-030-38696-2_3, http://link.springer.com/10.1007/978-3-030-38696-2_3, 2020.

He, C., Takano, Y., Liou, K.-N., Yang, P., Li, Q., and Chen, F.: Impact of Snow Grain Shape and Black Carbon–Snow Internal Mixing on Snow Optical Properties: Parameterizations for Climate Models, Journal of Climate, 30, 10 019–10 036, https://doi.org/10.1175/JCLI-D-17-0300.1, http://journals.ametsoc.org/doi/10.1175/JCLI-D-17-0300.1, 2017.

He, C., Flanner, M. G., Chen, F., Barlage, M., Liou, K.-N., Kang, S., Ming, J., and Qian, Y.: Black carbon-induced snow albedo reduction over the Tibetan Plateau: uncertainties from snow grain shape and aerosol–snow mixing state based on an updated SNICAR model, Atmospheric Chemistry and Physics, 18, 11 507–11 527, https://doi.org/10.5194/acp-18-11507-2018, https://www.atmos-chem-phys.net/18/11507/2018/, 2018.

Hock, R.: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation, Journal of Glaciology, 45, 101–111, https://doi.org/10.3189/s0022143000003087, 1999.

Huss, M.: Mass balance of Pizolgletscher, Geogr. Helv., 65, 80–91, https://doi.org/10.5194/gh-65-80-2010, https://gh.copernicus.org/articles/65/80/2010/, 2010.

Huss, M., Bauder, A., Funk, M., and Hock, R.: Determination of the seasonal mass balance of four Alpine glaciers since 1865, Journal of Geophysical Research, 113, F01 015, https://doi.org/10.1029/2007JF000803, http://doi.wiley.com/10.1029/2007JF000803, 2008.

IPCC: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, https://doi.org/https://www.ipcc.ch/report/srocc/, 2019.

Kasten, F. and Czeplak, G.: Solar and terrestrial radiation dependent on the amount and type of cloud, Solar Energy, 24, 177–189, https://doi.org/10.1016/0038-092X(80)90391-6, 1980.

Koch, D. M., Menon, S., Del Genio, A., Ruedy, R., Alienov, I., and Schmidt, G. A.: Distinguishing Aerosol Impacts on Climate over the Past Century, J. Climate, 22, 2659–2677, https://doi.org/10.1175/2008JCLI2573.1, http://dx.doi.org/10.1175/2008JCLI2573.1, 2009.

Krinner, G., Boucher, O., and Balkanski, Y.: Ice-free glacial northern Asia due to dust deposition on snow, Climate Dyn., 27, 613–625, https://doi.org/10.1007/s00382-006-0159-z, http://dx.doi.org/10.1007/s00382-006-0159-z, 2006.

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., and Zanettin, B.: A chemical classification of volcanic rocks based on the total alkali-silica diagram, Journal of Petrology, 27, 745–750, https://doi.org/10.1093/petrology/27.3.745, 1986.

Li, X., Kang, S., He, X., Qu, B., Tripathee, L., Jing, Z., Paudyal, R., Li, Y., Zhang, Y., Yan, F., Li, G., and Li, C.: Light-absorbing impurities accelerate glacier melt in the Central Tibetan Plateau, Science of the Total Environment, 587-588, https://doi.org/10.1016/j.scitotenv.2017.02.169, 2017.

Libois, Q., Picard, G., France, J. L., Arnaud, L., Dumont, M., Carmagnola, C. M., and King, M. D.: Influence of grain shape on light penetration in snow, The Cryosphere, 7, 1803–1818, https://doi.org/10.5194/tc-7-1803-2013, 2013.

Malmros, J. K., Mernild, S. H., Wilson, R., Tagesson, T., and Fensholt, R.: Snow cover and snow albedo changes in the central Andes of Chile and Argentina from daily MODIS observations (2000–2016), Remote Sensing of Environment, 209, 240–252, https://doi.org/10.1016/J.RSE.2018.02.072, 2018.

Ménégoz, M., Krinner, G., Balkanski, Y., Boucher, O., Cozic, A., Lim, S., Ginot, P., Laj, P., Gallée, H., Wagnon, P., and others: Snow cover sensitivity to black carbon deposition in the Himalayas: from atmospheric and ice core measurements to regional climate simulations, Atmos. Chem. Phys., 14, 4237–4249, 2014.

Molina, L. T., Gallardo, L., Andrade, M., Baumgardner, D., Borbor-Córdova, M., Bórquez, R., Casassa, G., Cereceda-Balic, F., Dawidowski, L., Garreaud, R., Huneeus, N., Lambert, F., McCarty, J., Mc Phee, J., Mena-Carrasco, M., Raga, G. B., Schmitt, C. G., and Schwarz, J. P.:

Pollution and its impacts on the South American Cryosphere (PISAC), Earth's Future, 3, 345–369, https://doi.org/10.1002/2015EF000311, 2015.

Oerlemans, J.: Glaciers & Climate Change, CRC Press, Exton (PA), 1 edition edn., 2001.

Oerlemans, J. and Knap, W. H.: A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland, Journal of Glaciology, 44, 231–238, https://doi.org/10.3189/s0022143000002574, 1998.

Painter, T. H., Skiles, S. M., Deems, J. S., Bryant, A. C., and Landry, C. C.: Dust radiative forcing in snow of the Upper Colorado River Basin: 1. A 6 year record of energy balance, radiation, and dust concentrations, Water Resources Research, 48, https://doi.org/10.1029/2012WR011985, http://doi.wiley.com/10.1029/2012WR011985, 2012.

Painter, T. H., Flanner, M. G., Kaser, G., Marzeion, B., VanCuren, R. A., and Abdalati, W.: End of the Little Ice Age in the Alps forced by industrial black carbon, Proceedings of the National Academy of Sciences, 110, 15 216–15 221, https://doi.org/10.1073/pnas.1302570110, http://www.pnas.org/content/110/38/15216.abstract, 2013.

Pirazzini, R., Räisänen, P., Vihma, T., Johansson, M., and Tastula, E.-M.: Measurements and modelling of snow particle size and shortwave infrared albedo over a melting Antarctic ice sheet, The Cryosphere, 9, 2357–2381, https://doi.org/10.5194/tc-9-2357-2015, https://www.the-cryosphere.net/9/2357/2015/, 2015.

Qian, Y., Yasunari, T. J., Doherty, S. J., Flanner, M. G., Lau, W. K. M., Jing, M., Wang, H., Wang, M., Warren, S. G., and Zhang, R.: Light-absorbing Particles in Snow and Ice : Measurement and Modeling of Climatic and Hydrological impact, Advances in Atmospheric Sciences, 32, 64–91, https://doi.org/10.1007/s00376-014-0010-0.1., 2015.

Reckziegel, F., Bustos, E., Mingari, L., Báez, W., Villarosa, G., Folch, A., Collini, E., Viramonte, J., Romero, J., and Osores, S.: Forecasting volcanic ash dispersal and coeval resuspension during the April–May 2015 Calbuco eruption, Journal of Volcanology and Geothermal Research, 321, 44–57, https://doi.org/10.1016/j.jvolgeores.2016.04.033, http://linkinghub.elsevier.com/retrieve/pii/S0377027316300762, 2016.

Romero, J. E., Morgavi, D., Arzilli, F., Daga, R., Caselli, A., Reckziegel, F., Viramonte, J., Díaz-Alvarado, J., Polacci, M., Burton, M., and Perugini, D.: Eruption dynamics of the 22-23 April 2015 Calbuco Volcano (Southern Chile): Analyses of tephra fall deposits, Journal of Volcanology and Geothermal Research, 317, 15–29, https://doi.org/10.1016/j.jvolgeores.2016.02.027, http://dx.doi.org/10.1016/j.jvolgeores.2016.02.027, 2016.

Rowe, P. M., Cordero, R. R., Warren, S. G., Stewart, E., Doherty, S. J., Pankow, A., Schrempf, M., Casassa, G., Carrasco, J., Pizarro, J., MacDonell, S., Damiani, A., Lambert, F., Rondanelli, R., Huneeus, N., Fernandoy, F., and Neshyba, S.: Black carbon and other light-absorbing impurities in snow in the Chilean Andes, Scientific Reports, 9, 4008, https://doi.org/10.1038/s41598-019-39312-0, http://www.nature.com/articles/s41598-019-39312-0, 2019.

Ruiz, L., Berthier, E., Masiokas, M., Pitte, P., and Villalba, R.: First surface velocity maps for glaciers of Monte Tronador, North Patagonian Andes, derived from sequential Pléiades satellite images, Journal of Glaciology, 61, 908–922, https://doi.org/10.3189/2015JoG14J134, 2015.

Ruiz, L., Berthier, E., Viale, M., Pitte, P., and Masiokas, M. H.: Recent geodetic mass balance of Monte Tronador glaciers, northern Patagonian Andes, Cryosphere, 11, 619–634, https://doi.org/10.5194/tc-11-619-2017, 2017.

Schaefer, M., Fonseca-Gallardo, D., Farías-Barahona, D., and Casassa, G.: Surface energy fluxes on Chilean glaciers: measurements and models, The Cryosphere, 14, 2545–2565, https://doi.org/10.5194/tc-14-2545-2020, https://tc.copernicus.org/articles/14/2545/2020/, 2020.

Schmitt, C. G., All, J. D., Schwarz, J. P., Arnott, W. P., Cole, R. J., Lapham, E., and Celestian, A.: Measurements of light-absorbing particles on the glaciers in the Cordillera Blanca, Peru, The Cryosphere, 9, 331–340, https://doi.org/10.5194/tc-9-331-2015, http://www.the-cryosphere.net/9/331/2015/, 2015.

Schneider, C. A., Rasband, W. S., and Eliceiri, K. W.: NIH Image to ImageJ: 25 years of image analysis, https://doi.org/10.1038/nmeth.2089, 2012.

Sicart, J. E., Ribstein, P., Wagnon, P., and Brunstein, D.: Clear-sky albedo measurements on a sloping glacier surface: A case study in the Bolivian Andes, Journal of Geophysical Research, 106, 31 729–31 737, https://doi.org/10.1029/2000JD000153, 2001.

Skiles, S. M. and Painter, T. H.: Daily evolution in dust and black carbon content, snow grain size, and snow albedo during snowmelt, Rocky Mountains, Colorado, Journal of Glaciology, 63, 118–132, https://doi.org/10.1017/jog.2016.125, 2017.

Skiles, S. M., Flanner, M., Cook, J. M., Dumont, M., and Painter, T. H.: Radiative forcing by light-absorbing particles in snow, https://doi.org/10.1038/s41558-018-0296-5, 2018.

Sold, L., Huss, M., Machguth, H., Joerg, P. C., Leysinger Vieli, G., Linsbauer, A., Salzmann, N., Zemp, M., and Hoelzle, M.: Mass Balance Re-analysis of Findelengletscher, Switzerland; Benefits of Extensive Snow Accumulation Measurements, Frontiers in Earth Science, 4, https://doi.org/10.3389/feart.2016.00018, http://journal.frontiersin.org/Article/10.3389/feart.2016.00018/abstract, 2016.

Toyos, G., Mingari, L., Pujol, G., and Villarosa, G.: Investigating the nature of an ash cloud event in Southern Chile using remote sensing: volcanic eruption or resuspension?, Remote Sensing Letters, 8, 146–155, https://doi.org/10.1080/2150704X.2016.1239281, https://www.tandfonline.com/doi/full/10.1080/2150704X.2016.1239281, 2017.

Tuzet, F., Dumont, M., Lafaysse, M., Picard, G., Arnaud, L., Voisin, D., Lejeune, Y., Charrois, L., Nabat, P., and Morin, S.: A multilayer physically based snowpack model simulating direct and indirect radiative impacts of light-absorbing impurities in snow, Cryosphere, 11, https://doi.org/10.5194/tc-11-2633-2017, 2017.

Villarosa, G., Outes, V., Delménico, A., Beigt, D., Cottet, J., Toyos, G., Horwell, C. J., Damby, D. E., Najorka, J., Arretche, M., Wilson, T., and Stewart, C.: Impacts after the 2015 Calbuco eruption in Argentina and their relation to tephra deposit characteristics and climatic variables, in: Cities on Volcanoes 9, Puerto Varas, Chile, 2016.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J.-M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geoscientific Model Development, 5, 773–791, https://doi.org/10.5194/gmd-5-773-2012, https://www.geosci-model-dev.net/5/773/2012/, 2012.

Warren, S. G. and Wiscombe, W. J.: A Model for the Spectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols, J. Atmos. Sci., 37, 2734–2745, https://doi.org/10.1175/1520-0469(1980)037<2734:AMFTSA>2.0.CO;2, http://dx.doi.org/10.1175/1520-0469(1980)037<2734:AMFTSA>2.0.CO;2, 1980.

Williamson, C. J., Cameron, K. A., Cook, J. M., Zarsky, J. D., Stibal, M., and Edwards, A.: Glacier Algae: A Dark Past and a Darker Future, Frontiers in Microbiology, 10, https://doi.org/10.3389/fmicb.2019.00524, https://www.frontiersin.org/article/10.3389/fmicb.2019.00524/full, 2019.

Wiscombe, W. J. and Warren, S. G.: A Model for the Spectral Albedo of Snow. I: Pure Snow, J. Atmos. Sci., 37, 2712–2733, https://doi.org/10.1175/1520-0469(1980)037<2712:AMFTSA>2.0.CO;2, http://dx.doi.org/10.1175/1520-0469(1980)037<2712:AMFTSA>2.0.CO;2, 1980.

Wittmann, M., Groot Zwaaftink, C. D., Steffensen Schmidt, L., Guðmundsson, S., Pálsson, F., Arnalds, O., Björnsson, H., Thorsteinsson, T., and Stohl, A.: Impact of dust deposition on the albedo of Vatnajökull ice cap, Iceland, The Cryosphere, 11, 741–754, https://doi.org/10.5194/tc-11-741-2017, https://www.the-cryosphere.net/11/741/2017/, 2017.

Wright, P., Bergin, M., Dibb, J., Lefer, B., Domine, F., Carman, T., Carmagnola, C., Dumont, M., Courville, Z., Schaaf, C., and Wang, Z.: Comparing MODIS daily snow albedo to spectral albedo field measurements in Central Greenland, Remote Sensing of Environment, 140, 118–129, https://doi.org/10.1016/j.rse.2013.08.044, http://dx.doi.org/10.1016/j.rse.2013.08.044, 2014.

Xu, B., Cao, J., Joswiak, D. R., Liu, X., Zhao, H., and He, J.: Post-depositional enrichment of black soot in snow-pack and accelerated melting of Tibetan glaciers, Environmental Research Letters, 7, 014 022, https://doi.org/10.1088/1748-9326/7/1/014022, 2012.

Young, C. L., Sokolik, I. N., Flanner, M. G., and Dufek, J.: Surface radiative impacts of ash deposits from the 2009 eruption of Redoubt volcano, Journal of Geophysical Research: Atmospheres, 119, 387–11, https://doi.org/10.1002/2014JD021949, http://doi.wiley.com/10.1002/2014JD021949, 2014.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L. E., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. a., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, Journal of Glaciology, 61, 745–762, https://doi.org/10.3189/2015JoG15J017, 2015.

Zhang, Y., Kang, S., Sprenger, M., Cong, Z., Gao, T., Li, C., Tao, S., Li, X., Zhong, X., Xu, M., Meng, W., Neupane, B., Qin, X., and Sillanpää, M.: Black carbon and mineral dust in snow cover on the Tibetan Plateau, The Cryosphere, 12, 413–431, https://doi.org/10.5194/tc-12-413-2018, https://www.the-cryosphere.net/12/413/2018/, 2018.

Zhuravleva, T. B. and Kokhanovsky, A. A.: Influence of surface roughness on the reflective properties of snow, Journal of Quantitative Spectroscopy and Radiative Transfer, 112, 1353–1368, https://doi.org/10.1016/J.JQSRT.2011.01.004, https://www.sciencedirect.com/science/article/pii/S002240731100015X, 2011.

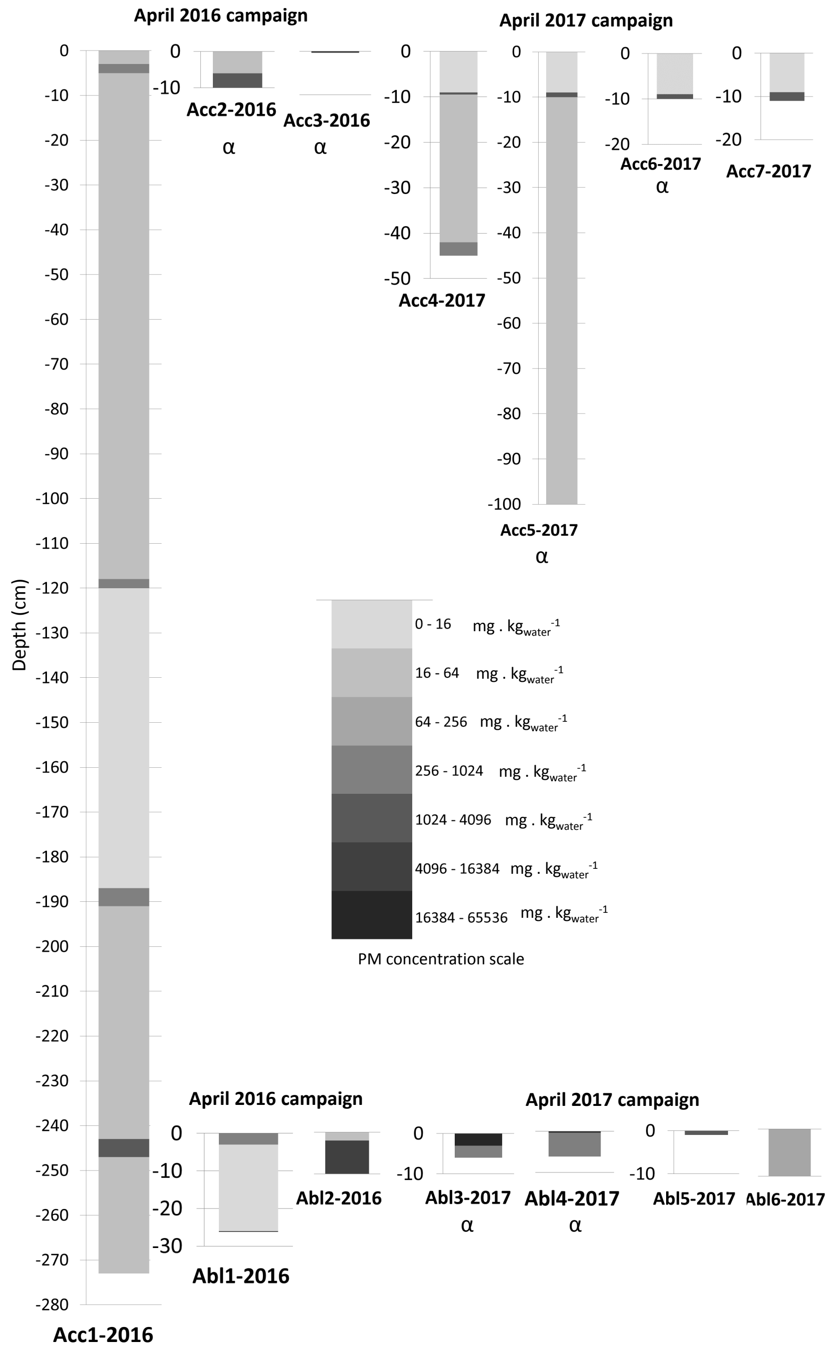

Figure 2. PM concentration (grayscale) as a function of pit depth for different sampling sites. Notice that the grayscale is logarithmic. Top panel: accumulation zone. Bottom panel: ablation zone. α symbol is used to highlight sites with concurrent albedo measurements. In sample *Abl2-2016*, the top rectangle corresponds to the average PM content of the first two layers (fresh snow and end-of-summer dark layer).

(a) (b)

Figure 3. Albedo measurement equipment. (a) ~~support~~ Mounting stand used in the 2016 campaign. (b) ~~support~~ Mounting stand used in the 2017 campaign. The presence of the ~~support~~ stand and the observer is taken into account to correct the albedo measurement through the angles θ and ϕ and Eq. (S1) and (S2) in the Supplement.

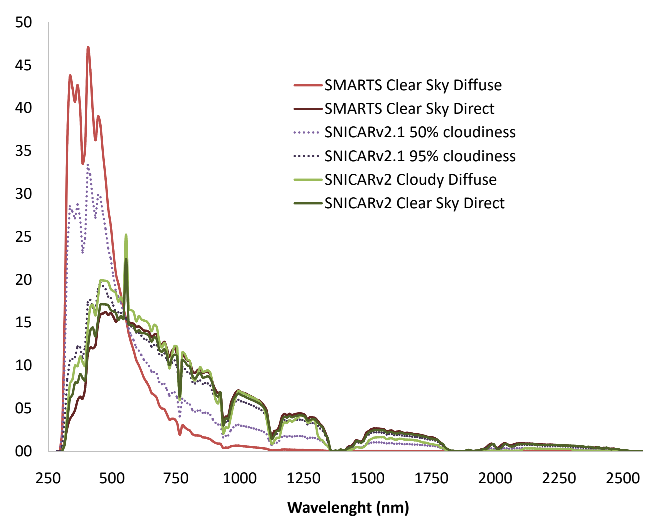

Figure 4. Different normalized spectral distributions of sun radiation for SNICAR snow albedo model. SNICARv2 included two spectra for mid-latitude locations: one for overcast conditions~~(light green line)~~, and one for clear sky conditions. SNICARv2.1 allows calculation of diffuse spectra for partly cloudy conditions (~~dark green line~~50% and 95% cloud fraction are shown as examples). 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).~~

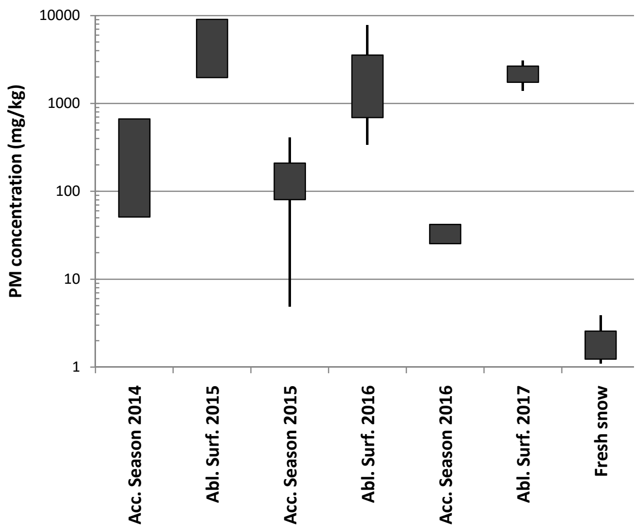

Figure 5. Seasonal range of PM concentration found on snow/~~firn~~ *firn* samples. For accumulation season, the values represent the mean PM concentration in thick, low PM layers of snow/~~firn~~*firn*. For ablation season the values represents the surface PM concentration at the end of the season. 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 ~~an~~ a specific year/season. Fresh snow represent snow fallen a few days before field campaigns of 2016 or 2017.

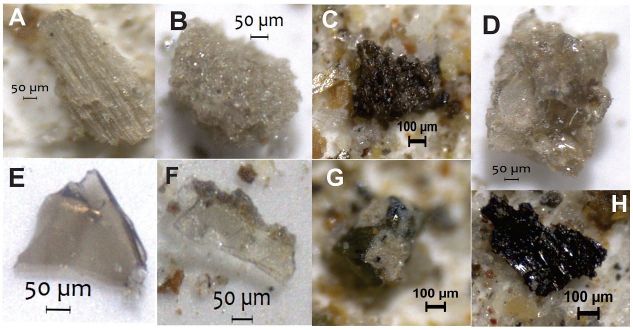

Figure 6. Stereo microscope images of juvenile glass fragments from ash fall events identified in the filters. Different morphologies are shown: A: Colourless glass fragment with elongate, thin, pipe-shaped vesicles (2017 end-of-summer dark layer, site *Acc7-2017*); B: Colourless pumice (surface ablation ice, site *Abl6-2017*). C: Dark brown fragment of vesicular glass (2017 end-of-summer dark layer, site *Acc7-2017*). D: Glass fragments with smooth, round surfaces formed by surface tension within still-molten, vesiculating droplets suggesting highly vesicular interior (2017 end-of-summer dark layer, site *Acc7-2017*). E and F: Two flat, tan glass shards derived from broken vesicle walls. Left: Y-shaped fragment formed where three bubbles were in close proximity (surface ablation ice, site *Abl6-2017*). Right: flat glass plate formed by the fragmentation of walls that enclosed large elongated, flattened vesicles as those shown above (fresh snow on top of ablation ice, site *Abl5-2017*). G: Pyroxene crystal with two patches of colourless glass with tiny dots of magnetite (2016 end-of-summer dark layer, site *Acc4-2017*). H: planar piece of charcoal with subtle striated surface texture and brilliant luster.

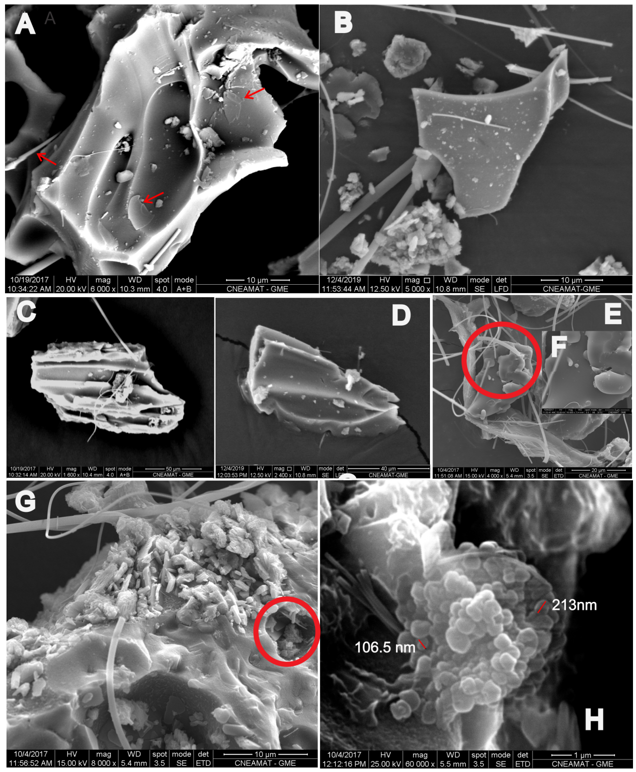

Figure 7. Scanning Electron Microscopy images of samples collected on Alerce glacier. A: irregular glass fragment with low vesicularity, evidence of bubble coalescence, and small, flat, platy, very thin glass shards indicated by red arrows, loosely adhering to the grain surface. These tiny fragments are remnants of burst vesicle walls. B: glass fragment with smooth surface. C: glass fragment, with remnant of parallel pipe vesicles, notice the thin vesicle walls. D: Y-shaped glass fragment, remnant of a partially broken pumiceous pyroclast with elongated parallel bubbles. E: glass fragment with smooth surface. F: closeup of the glass fragment in E, showing in detail the smooth surface. G: portion of a vitric pyroclast with loose material on its surface (adhering dust), mostly tiny glass fragments, and a vesicle indicated by a red circle which contains small particles. H: closeup of the vesicle filling in G, showing an aggregate of carbon spherules of $100\,\mathrm{nm}$ to $200\,\mathrm{nm}$ corresponding to ~~Black Carbon~~ black carbon (BC) particles.

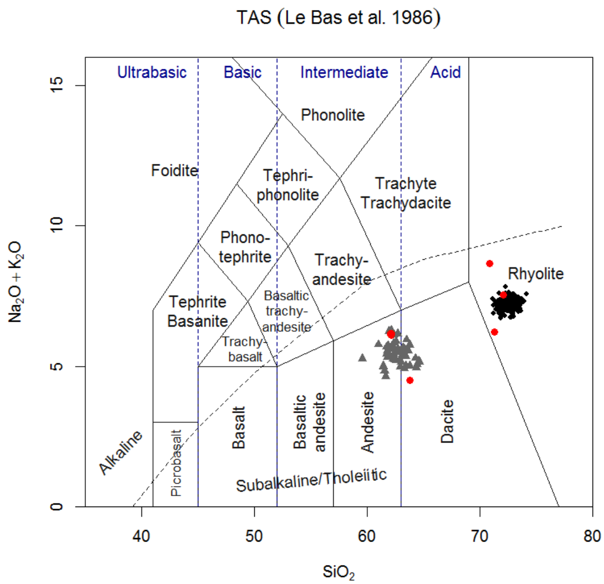

Figure 8. Classification diagram TAS (Le Bas et al., 1986). Major element compositions of glass shards from the AD 2015 Calbuco eruption acquired by electron microprobe analyses (LAMARX, Córdoba, Argentina) from samples collected during direct ashfall events in Junín de los Andes and Paso Cardenal Samoré, Argentina (Villarosa et al., 2016) and from the AD 2011 Puyehue-Cordón Caulle eruption acquired by electron microprobe (EMP) analysis, samples collected in San Carlos de Bariloche, Villa La Angostura and Paso Cardenal Samoré, Argentina (Alloway et al., 2015). Red circles: EDS analyses from PM samples from the studied area. Glass shards derived from Puyehue-Cordón Caulle (black circles) are rhyolitic in composition while glass from Calbuco eruption (grey triangles) is andesitic to dacitic in composition.

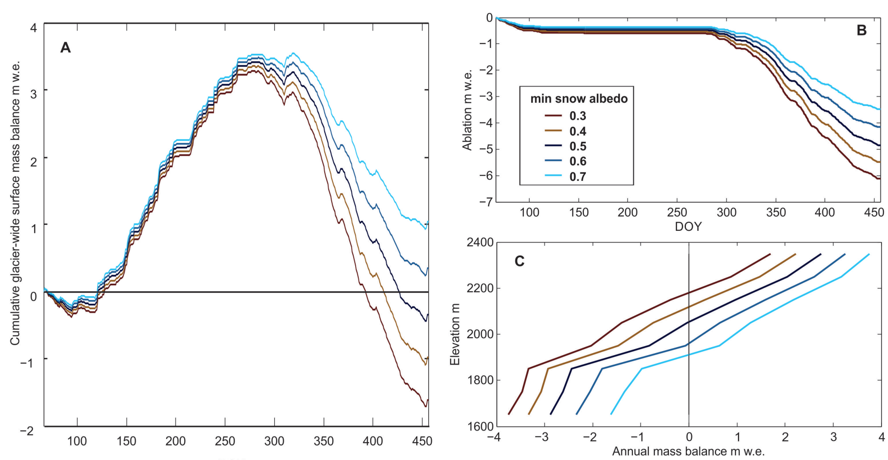

Figure 9. Sensitivity of Alerce ~~glacier-wide~~ surface mass balance to change in albedo of ~~old~~ aged snow~~or firn~~. A) cumulative ~~glacier-wide~~ surface mass balance, B) cumulative melt and C) mass balance gradient of Alerce glacier for the different ~~albedo~~α_{min} values.