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,~~ $\cancel{c_0 = -50\ \mathrm{W\ m^{-2}}}$ ~~and~~ $\cancel{c_1 = 12\ \mathrm{W\ m^{-2}\ ^{o}C^{-1}}}$~~.~~ 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 producing~~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: $(22.0 \pm 0.6)\ mg\ kg^{-1}$	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: $(7800 \pm 1500)\ mg\ kg^{-1}$	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: $(1.28 \pm 0.03)\ mg\ kg^{-1}$	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: $(3.9 \pm 0.2)\ mg\ kg^{-1}$	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

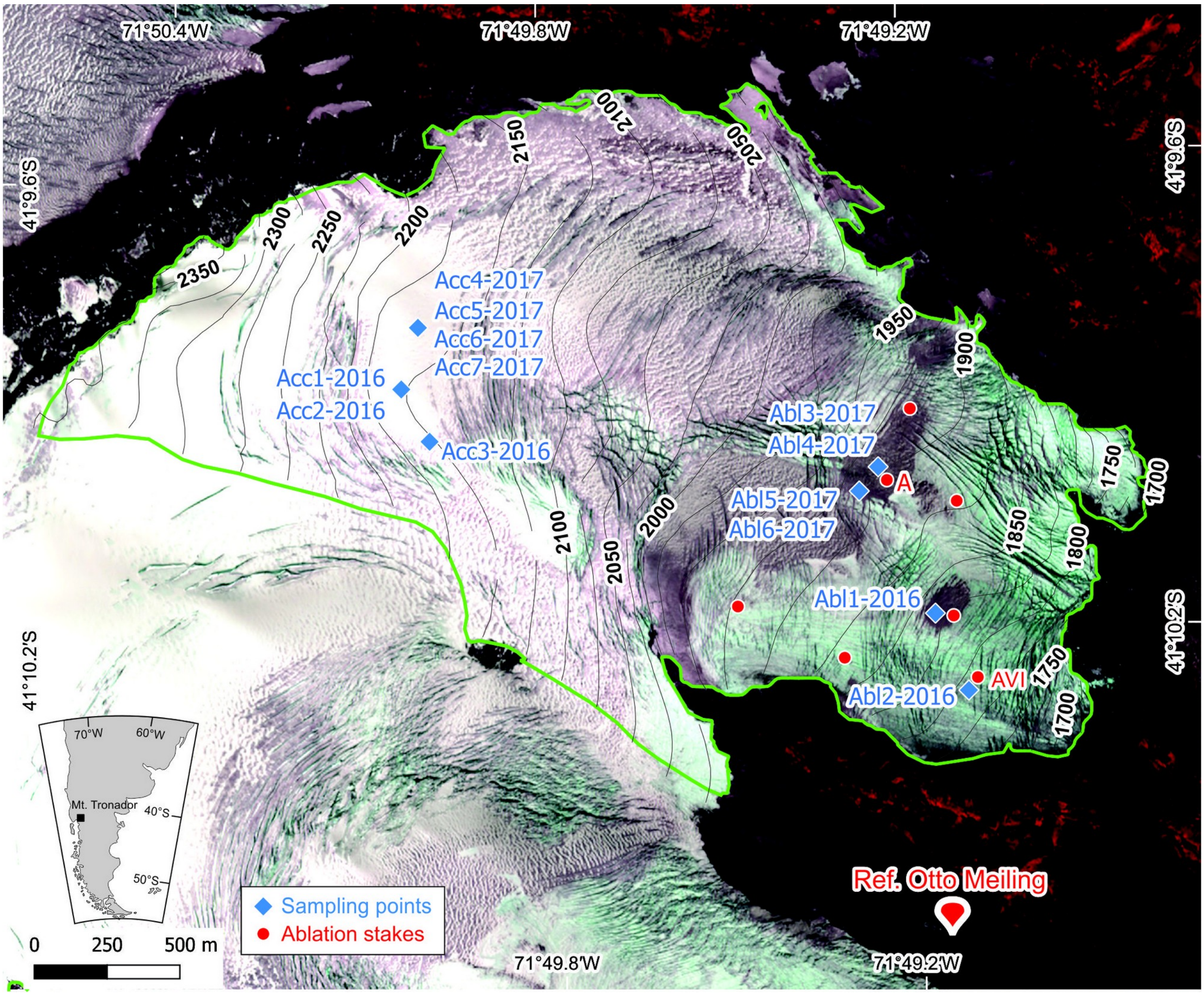

Figure 1. Alerce Glacier (green line represents the outline of the glacier). Labels of contour lines of terrain elevation are expressed in meters above sea level. Sampling points are represented as blue rhombuses. Red circles represent ablation stakes used for mass balance model calibration (model output 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).

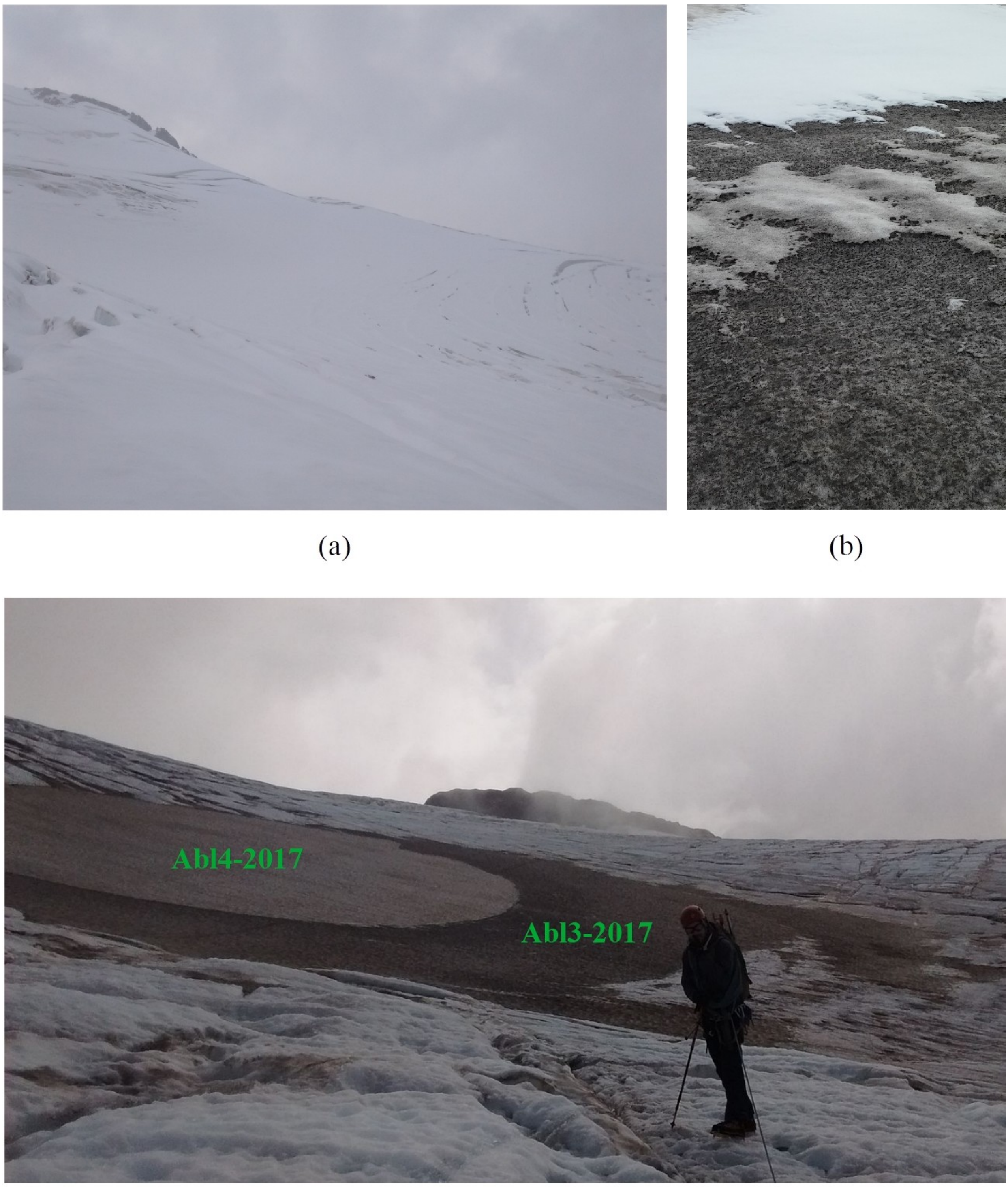

Figure S2. Field pictures of sampling sites. (a) General view of the area of the accumulation zone that includes sites Acc1-2016, Acc2-2016, Acc3-2016, Acc4-2017, Acc5-2017, Acc6-2017 and Acc7-2017. (b) Close view of surface of site Acc3-2016 (darkest layer, bottom of the picture), next to recent fresh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

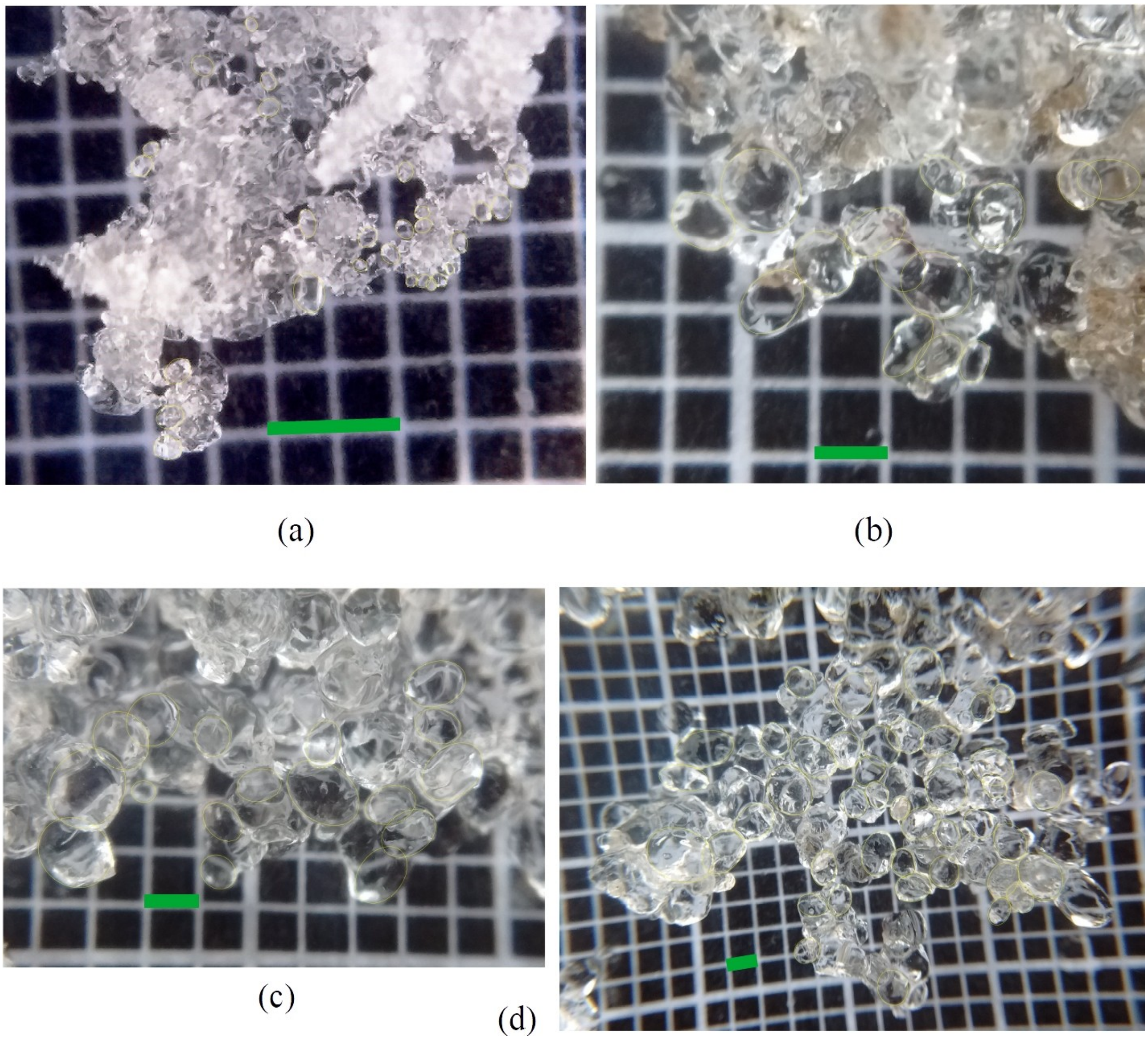

Figure S3. High resolution macro pictures of snow/firn grains, Alerce glacier, 2017. (a) Surface fresh snow sample, April 2017, site *Acc5-2017.* (b) Surface snow/*firn* sample, attributed approximately to April 2016 (due to negative specific mass balance), site *Abl4-2017*. (c) Sub-surface *firn* sample, 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.

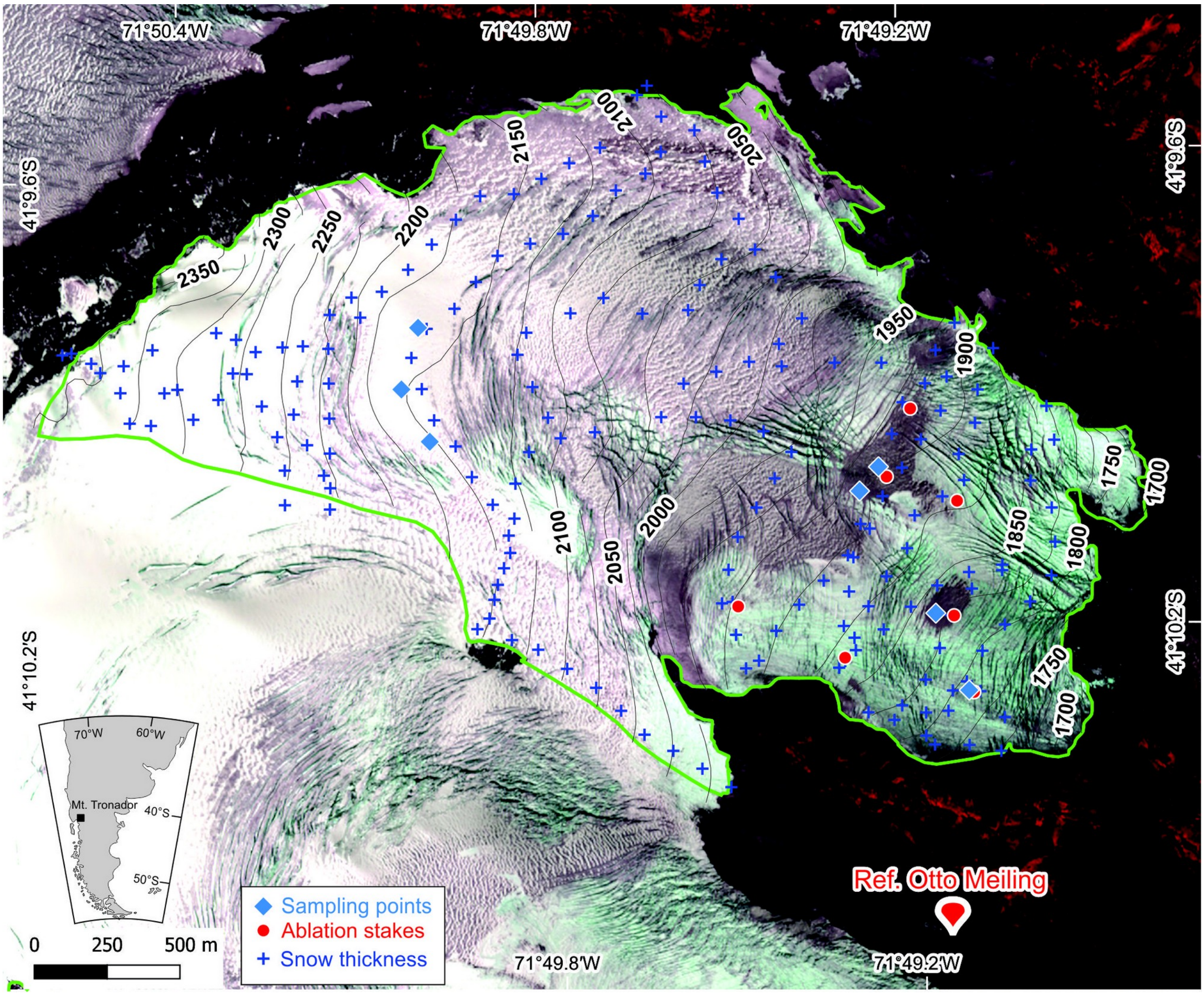

Figure S4. Snow thickness and ablation stakes used for calibration and validation of the mass balance model. Blue rhombuses are albedo and PM sampling points (same as in Fig. 1 of the main article). Background image: false-color pan-sharpened Pléiades satellite image, 7 March 2012, PGO,CNES-Airbus D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

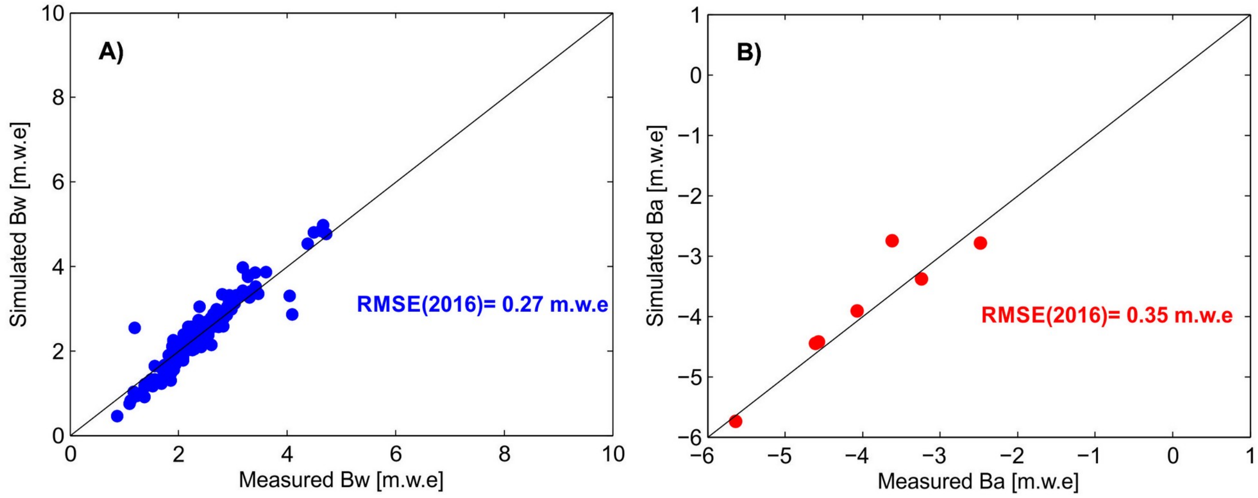

Figure S5. Calibration of the mass balance model with 2016 measurements. (a) First step of the calibration, with winter thickness measurements. (b) Second step of the calibration, with summer specific mass balance measurements (ablation stakes).

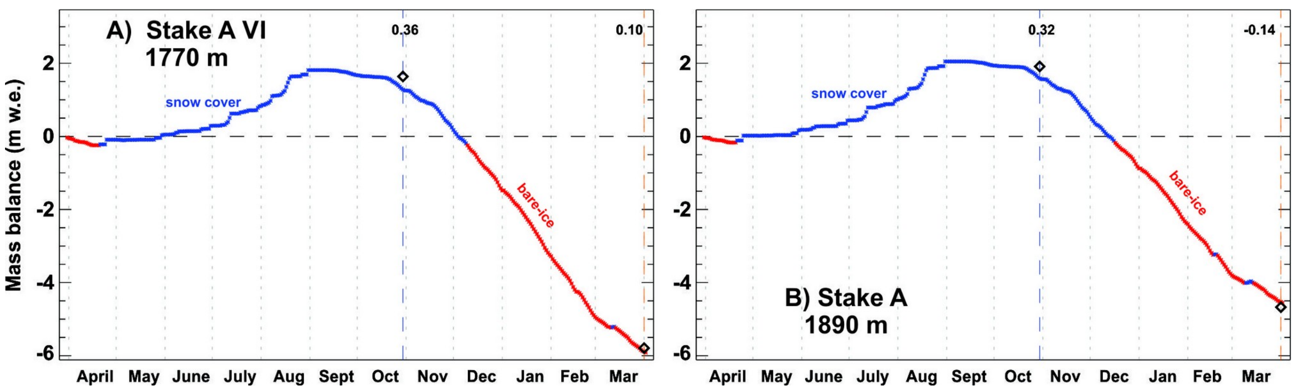

Figure S6. Mass balance model fitting with 2016 measurements for two specific ablation stakes. The residuals between measurements and model it is shown for comparison. Location of (a) stake A VI and (b) stake A are represented in Fig. 1 of the main article.