Dear Editor,
We accomplished all the comments from the reviewers and now the paper results improved, more clear and understandable. Then, we acknowledge the two Referees for the helpful suggestions.

Please find below the detailed comments and the responses to the reviewers' suggestions.
We hope now the manuscript could meet the reviewers' expectations and then it could be accepted for publication, otherwise we are open to new improvements.

Many thanks for your kind help,
Best regards,

Antonella Senese and Co-authors

Referee #1

General

The paper entitled "A novel integrated method to describe dust and fine supraglacial debris and their effects on ice albedo: the case study of Forni Glacier, Italian Alps" by Azzoni et al. is surely interesting and fits well with the aims of the journal. The paper shows an interesting approach to evaluate the effect of the debris coverage on the albedo and therefore on the energy balance of an alpine glacier. Also the monitoring of the debris coverage changes during the ablation season and the effect of the liquid precipitation on the debris coverage and on the albedo are examined. The proposed methods sound good but on the other hand there some major points and several minor points that the authors should clarify in order to improve the manuscript. At the actual stage I think that the paper could be accepted on TC only in case that the authors improve the manuscript clarifying the obscure points and make all the proposed changes.

Major Points:

Title: In my opinion Title is not correct for two reasons: a) Dust and fine debris are not treated separately in the manuscript so also in the title is enough to state " fine debris" b) The main point is that the authors consider the debris coverage only supraglacial when is known that some or even the major part of the debris cover could be englacial and therefore related also to the glacier dynamic. c) How the authors distinguish supraglacial from englacial debris?

We modified the Title accordingly:
From "A novel integrated method to describe dust and fine supraglacial debris and their effects on ice albedo: the case study of Forni Glacier, Italian Alps**",**
To "A novel integrated method to describe fine debris over a melting glacier surface and to assess its effect on ice albedo: the case study of Forni Glacier, Italian Alps**". In details:**

a) We deleted "dust" accordingly.

b) We also replaced "supraglacial" with "over a melting glacier surface". Actually, with the term "supraglacial" we didn't refer to debris origin but we simply referred to debris on the glacier surface, without any assumption on its origin. This has probably generated misunderstanding.

c) An understanding of how the albedo varies in response to changes in the state of the surface is a central component in modelling ice melt and in describing the climate of the ice-covered regions and the climate in general (see Grenfell, 2011). Moreover, in the recent climate modelling studies, attention is paid to the "ice-albedo feedback" and to its action in modulating the changes in the total energy balance of the analyzed area (Grenfell, 2011). Accordingly, our first issue was to evaluate the impact of fine debris (autochthonous and allochthonous, from both englacial origin and wind transport) on ice albedo thus influencing ablation rates. For this first purpose, analyzing and debating debris origin is negligible. The second issue is to find the main fine debris suppliers since over the last decade darkening phenomena have been observed on the largest part of mountain debris-free glaciers and on Forni Glacier as well. Moreover, the scientific community is already studying black carbon deposition on glacier snow thus suggesting to investigate such phenomenon on glacier ice as well. The second issues is independent from the first one (even if complementary). In fact, a most accurate parameterization of ice albedo taking into account fine debris presence (both autochthonous and

allochthonous) may improve the largest part of ice melt models and this analysis can be performed without describing debris origin. Differently whenever the research aims at mankind impacts on cryosphere (mainly black carbon deposition), it is necessary to distinguish between local debris and wind transported particles. For detecting debris origin and then for achieving the second issue, we performed different analyses (X ray, SEM and EDS) also considering the organic matter and the biological components. We found that for the largest part fine debris showed a local lithology (thus being autochthonous) with a high fraction of organic matter. Only few particles (cenospheres) due to human activities and then wind transported were found.
As regards the third issue, the history of the fine debris we sampled (i.e.. to detect if it came from inner glacier layers or if it was transported and then deposited at the glacier surface by wind), we didn't focus on it. This issue is surely interesting but requires dedicated analyses and then a further and future paper.

Grenfell T.C. (2011) Albedo. In Singh V.P., Singh P. and Haritashya U.K. (eds): Encyclopedia of snow, ice and glaciers. Springer, The Netherlands, 1253 p.

Abstract: It is not well organized, it can be shortened and more focused on the main aims and main results of the paper.

We modified the abstract accordingly:
From "We investigated the characteristics of sparse and fine debris coverage at the glacier melting surface and its relation to ice albedo. In spite of the abundant literature dealing with dust and black carbon deposition on glacier accumulation areas (i.e.: on snow and firn), few studies that describe the distribution and properties of fine and discontinuous debris and black carbon at the melting surface of glaciers are available. Furthermore, guidelines are needed to standardize field samplings and lab analyses thus permitting comparisons among different glaciers. We developed a protocol to (i) sample fine and sparse supraglacial debris and dust, (ii) quantify their surface coverage and the covering rate, (iii) describe composition and sedimentological properties, (iv) measure ice albedo and (v) identify the relationship between ice albedo and fine debris coverage. The procedure was tested on the Forni Glacier surface (northern Italy), in summer 2011, 2012 and 2013, when the fine debris and dust presence had marked variability in space and time (along the glacier tongue and from the beginning to the end of summer) thus influencing ice albedo: in particular the natural logarithm of albedo was found to depend on the percentage of glacier surface covered by debris. Debris and dust analyses indicate generally a local origin (from nesting rockwalls) and the organic content was locally high. Nevertheless the finding of some cenospheres suggests an anthropic contribution to the superficial dust as well. Moreover, the effect of liquid precipitation on ice albedo was not negligible, but short lasting (from 1 to 4 day long), thus indicating that also other processes affect ice albedo and ice melt rates and then some attention has to be spent analysing frequency and duration of summer rainfalls for better describing albedo and melt variability.**",**

To "We investigated the characteristics of sparse and fine debris coverage at the glacier melting surface and its relation to ice albedo. Despite the abundant literature related to dust and black carbon deposition on glacier accumulation areas only few studies on the distribution and properties of fine debris in the ablation zone are available. Furthermore, guidelines are needed to standardize field samplings and lab analyses thus permitting comparisons among different glaciers. We proposed and tested a novel integrated method to describe fine debris occurring at the surface of debris-free glaciers and its impact on ice albedo. We found a linear relation between the percentage of glacier area covered by fine debris and the natural logarithm of ice albedo. The percentage of glacier area covered by fine debris was quantified by applying an innovative semi-automatic approach we developed which is based on high resolution image analysis. We investigated the robustness of this approach through five sensitivity tests. Our procedure was tested on the surface of a wide Alpine valley glacier (the Forni Glacier, Italy), in summer 2011, 2012 and 2013. The results from lab analyses indicate generally a restricted origin of the mineral fraction with a locally high content of organic matter. Nevertheless, some cenospheres were found thus suggesting an anthropic contribution as well. In addition, for a more exhaustive analysis of albedo variability, the effect of water (originating from ice melt and liquid precipitation) was considered as well. It resulted meltwater to occur mostly during the central hours of the day and a short lasting rain influence (from 1 to 4 day long).”

Results: In this sector there are several comments that should be in the Discussion sector. The main point is the validation of the method proposed to estimate the debris coverage and its evolution in the time. Why the authors did not consider to do in the field also another method (i.e. like a visual estimation of the percentage cover) instead to try with some statistical analyses not always clear and probably also auto referential. The other major point is that no statistical significance (p) of the regressions or correlations is presented without this parameter is not possible to verify the statistical meaning of them.

We modified accordingly. In particular, we moved some parts into the Discussion section. Moreover, we quantified the percentage of glacier area covered by fine debris by means of other approaches such as the point intercept and we discussed the results comparing them with the ones estimated through our method. We inserted this part in the Discussions section. In addition, we explained why we chose to vary the gray-scale threshold of 10% (please see further details in the following answers to the Referee comments).
Regarding the statistical significance, as we considered a copious sample (i.e. 51 measurements) and we found a high correlation coefficient (i.e. 0.84), the correlation should be significantly lower than zero. Indeed, we calculated the p value of the correlation coefficient and, as expected, it resulted equal to $9.47e^{-15}$. Nevertheless, it would be more interesting to define the coefficient interval that we found ranging from 0.74 to 0.91 (95% coefficient interval). For a more exhaustive analysis, we also estimated the 99% coefficient interval (i.e. from 0.69 to 0.92).

Discussion: It is too weak, some of the discussion is now mixed in the results sector and no comparison with the results of other methods of debris coverage estimation or with paper regarding the effects of debris coverage and albedo on other glaciers are carried out

We modified accordingly. In particular, we moved some parts that were previously in the Results section, and we performed a deeper analysis on the robustness of our approach in debris quantification (please see further details in the following answers to the Referee comments).

Conclusion: It is too long and it seems more a summary of the activities and of the achieved results than focus only on the main results.

We modified accordingly shortening this section.

Minor Points:

Abstract

Rows 3-6 could be "Despite of the abundant literature related to dust and black carbon deposition on glacier accumulation areas only a few studies on the distribution and properties of fine debris in the ablation areas are available"

We modified accordingly.

Rows 7-11 rewrite as "A new protocol to : (i) sample fine debris on melting glacier surface, (ii) quantify their surface coverage and the covering rate, (iii) describe composition and sedimentological properties, (iv) measure ice albedo and (v) identify the relationship between ice albedo and fine debris coverage.

We modified accordingly.

Introduction

Pag.3173 Delete rows 2-10 "In fact, debris can be found: : :.. is found on actual debris-covered glaciers (see Kirkbride, 2011)."

We modified accordingly.

Pag. 3173 Delete rows 23-2 (3174)

We shortened these sentences. We modified:
From "In spite of this abundant literature dealing with (i) thicker and quite continuous debris layer at the glacier melting surface (this is the case of actual debris covered glaciers and glacier medial moraines), and (ii) fine debris deposition on glacier accumulation areas, the effects of fine (mainly dust) and sparse debris cover at the melting surface of debris-free glaciers (with this term we indicate glaciers not characterized by an extensive and quite continuous debris coverage) are still poorly debated and sometimes underestimated.**",**
To "In spite of this abundant literature, the effects of fine (mainly dust) debris cover at the melting surface of debris-free glaciers are still poorly debated and sometimes underestimated.**"**

Pag. 3174 row 17 Here it is needed to define fine debris and dust because otherwise it is not clear to understand.

We modified accordingly:
From "Supraglacial fine debris and dust consist of mineral and organic fractions.**"**
To "Supraglacial fine debris and dust consist of mineral and organic fractions with a mean diameter lower than 2 mm.**"**

Pag. 3174 row 19 Organic elements not necessarily by bacterial decomposition because also living organism or pollens can be part of the organic components.

We modified accordingly:
From "The organic elements can be originated from bacterial decomposition of organic matter (in situ or outside the glacier), or they can consist of black carbon (e.g.: deriving from fossil combustion and fires), and organic remains in aerosols (Fujita, 2007; Takeuchi et al., 2001; Takeuchi, 2002).**",**
To "The organic elements can be originated from bacterial decomposition of organic matter (in situ or outside the glacier), or they can consist of black carbon (e.g.: deriving from fossil combustion and fires), living organisms, pollens and other vegetal remains and organics contained remains in the aerosols (Fujita, 2007; Takeuchi et al., 2001; Takeuchi, 2002).**"**

Pag. 3174 row 21 the paragraph is debatable because if the fine debris have englacial origin can be originated also by mechanical disintegration of the bedrock below the glacier or by the deformation and weathering processes of the rocks embedded in the ice. In addition, the distance of blowing material can be even much more than hundreds meters depending by wind speed and by the roughness of the area surrounding the glacier.

We modified accordingly:
From "On the one hand the mineral fraction can be locally derived from the weathering of rock outcrops and nunataks or from lateral moraines and debris slopes: in fact, during the summer when warm climatic conditions occur, the dry and unconsolidated materials constituting moraines are easily transported by wind gusts and deposited tens to hundreds of meters away (Oerlemans, 2009).**",**
To "On the one hand, the mineral fraction can be locally derived from the weathering of rock outcrops and nunataks or from lateral moraines and debris slopes: in fact, during the summer when warm climatic conditions occur, the dry and unconsolidated materials constituting moraines are easily transported by wind gusts and deposited also higher than tens to hundreds of meters away, depending by wind speed and by the roughness of the area surrounding the glacier (Oerlemans, 2009). In case of englacial origin, the fine debris can be originated also by mechanical disintegration of the bedrock below the glacier or by the deformation and weathering processes of the rocks embedded in the ice.**"**

Pag 3176 row 22 the sentence "The AWS1 Forni is already… inserted in the SPICE (Solid Precipitation Intercomparison. Should be deleted because it is not relevant for this paper.

In agreement also to the other Referee, we modified accordingly. We added this information in "Acknowledge".

Methods

Pag 3177 row 18 Why 1X1 m The authors should explain why they decide this size and not 0.5X0.5 m or 5x5 m?

We modified accordingly. We added: "At each site we sampled a parcel of area 1m x 1m with the aim at assuring the effectiveness and the repeatability of the measurements. In fact, on the one hand a higher area could entail more time for collecting all the supraglacial materials and consequently a lower number of analysed sites. On the other hand, a smaller area could not really represent the actual features of the site.**"**

Pag. 3178 row 7-10 This sentence is quite confusing. If you have 445 images on 51 sites, means that you selected 1 pictures every 9? Is it correct?

We modified accordingly:
From "From a total of 445 images, we selected one for each measurement site (totally 51): those affected by shadows, deformations, photographic imperfections (e.g. poor exposure, incorrect focus) were excluded from the analysis and only images showing clear differences between bare ice and dust/fine debris-covered ice were considered.**",**
To "We excluded from the analysis the images affected by shadows, deformations, photographic imperfections (e.g. poor exposure, incorrect focus), and for each measurement site (totally 51) we selected the image that better show sharp differences between bare ice and dust/fine debris-covered ice.**"**

Pag. 3178 row 26 Which is the accuracy of d with the resolution of the used images?

We added accordingly: "where the total number of pixel is 6.1×10^6.**"**

Pag. 3179 rows 1-9 Why the authors did not calibrate the images using others method like point intercepts or similar in the field? Normally when someone wants to propose a new protocol should use another system to verify the results of the new one. This is one of the main point that the authors should solve.

The aim of our study is to quantify the fine debris presence through an approach, which provides as thorough as possible data, as the main goal is to find a relation with the surface albedo. Then if the method for the debris quantification is affected by a not negligible error, the resulting relation can not be considered valid. Instead, the method we proposed can give more robust results taking advantage of a very higher resolution (1 pixel corresponds to about 0.6 mm in the field). In order to investigate the possible performance of point intercept method, we selected randomly 10 of our images and superimposed a 10 x 10 cm grid. Then we asked 10 colleagues from our University to estimate the debris coverage. The results, even though in reasonable agreement with our proposed method, show a very high variability between the 10 colleagues, with a general tendency of higher values with respect to the proposed method. As a consequence of the high subjectivity of methods such as the point intercept, we prefer applying the proposed approach.

We modified accordingly the Discussion section:
From "To investigate the robustness of our method to quantify *d* and its sensitivity to changes in the chosen *T*GS, we firstly varied the applied *T*GS values up to ±10% of their initial values (*T*GS−10% and *T*GS+10% respectively, Fig. 7): for example whenever the applied T_{GS} value to discriminate 5 debris from bare ice was 100, we recalculated *d* with 90 ($T_{GS-10\%}$ obtaining $d_{-10\%}$) and with 110 ($T_{GS+10\%}$ obtaining $d_{+10\%}$).**",**
To "As the main goal of this study is to find a relation between percentage of glacier area covered by fine debris and albedo, we looked for an approach for quantifying debris occurrence and distribution able to provide as thorough as possible data. In fact, to obtain an actual relation between fine debris and albedo, the debris distribution data should feature a high accuracy (similarly to albedo data that were acquired with high quality instruments thus featuring high resolution) and be affected by a negligible error. Consequently, we proposed a protocol based on the analysis of high resolution imagery (i.e.: 1 image pixel corresponds to about 0.6 mm in the field) through a semi-automatic approach (only the grey-scale threshold choice is manual, the other steps are automatic ones) to limit the subjectivity in data processing thus obtaining reliable results. To evaluate the

improvements given by our approach, we compared our results with respect to the ones derived from the application of other methods, as the point intercept; we compared the values obtained by a representative sample of people (all geologists) applying the point intercept method on a selection of 10 imagines with values derived from the application of our protocol to the same imagines and it resulted the point intercept to give data affected by a very high variability with a general tendency of overestimation of the debris occurrence and distribution. As a consequence of the high subjectivity of this field approaches, we considered more correct the application of a semi-automatic protocol as the one we developed based on high resolution image analysis. In addition, to investigate the robustness of our method to quantify d and its sensitivity to changes in the chosen T_{GS}, the protocol was carried out by several operators, giving a variability of T_{GS} values lower than the 10%. Then we varied the applied T_{GS} values up to ±10% of their initial values ($T_{GS-10\%}$ and $T_{GS+10\%}$ respectively, Figure 8): for example whenever the applied T_{GS} value to discriminate debris from bare ice was 100, we recalculated d with 90 ($T_{GS-10\%}$ obtaining $d_{-10\%}$) and with 110 ($\mathrm{T}_{GS+10\%}$ obtaining $d_{+10\%}$).**"**

Pag. 3179 row 14 SWin is SWin ?

SWin is the symbol for the incoming shortwave radiation, the SWin and SW_{in} are the same symbol.

Pag. 3179 rows 13-14 Delete the following :This parameter can range from 0 (all the SWin is absorbed by the surface) to 1 (all the SWin 1 is reflected).

We modified accordingly.

Pag. 3180 rows 20-21 why two years with 2 dates and one with three?

Field campaigns on the glacier require generally on the one hand a great organization (e.g. alpine guide, staff member, etc.), and on the other hand, they can be performed only with adequate meteorological conditions. The data we collected are therefore the best we were able to produce given these 2 constrains. As far as the analyses are concerned, we exploit available data as much as possible even though the number of the measurement dates are different among each year.

Pag 3180 rows 26-28 Which was the accuracy of the rain gauge used? If the used rain gauge was not heated why do you use 1.5°C as temperature threshold to consider all the precipitation liquid? In literature also +1 and +2°C were considered so you have to explain and give a citation for justify the limit, but moreover if you have rain gauge measurements why you have to exclude data with temperature below some threshold and not use simply the data collected. Why consider only the days with more than 0.2 mm, is it because this the accuracy of the rain gauge?

We agree with the Referee's comment, and then now we do not use 1.5°C as temperature threshold. Nevertheless, during summertime the air temperatures were always higher than this threshold, then the obtained results remain unchanged.
The model of the pluviometer is DQA035 of LSI-Lastem (unheated sensor). Data sampling frequency is every minute and the data logger (Babuc ABC, LSI-Lastem) records the cumulative values every hour. The threshold to activate the toggle switch of the pluviometer is 0.2 mm of water.
Then we modified accordingly:

From "We considered an actual rainfall any event occurred whenever the hourly air temperature was higher than 1.5°C (Senese et al., 2012a) and featuring an hourly liquid precipitation stronger than 0.2 mm. The precipitation temporal length (i.e. number of rainy days) and amount (i.e. mm of rain) were measured by a rain gauge installed at the AWS1 Forni.**",**
To "Finally, the temporal length (i.e. number of rainy days) and amount (i.e. mm of rain) of liquid precipitation were measured by an unheated pluviometer installed at the AWS1 Forni (DQA035, LSI-Lastem). The liquid precipitation effect was quantified by comparing albedo values before, during and after the occurrence of actual liquid precipitation. In particular, we considered an actual rainfall any event featuring a hourly liquid precipitation higher than 0.2 mm (i.e. the threshold to activate the toggle switch of the rain gauge).**"**

Pag. 3181 row 6 Who decide that 8 samples are enough? Which criteria do you use?

We modified accordingly:
From "First in 2011 the eight samples enabled characterization of the spatial variability of supraglacial debris.**"**
To "First in 2011 the eight samples were collected choosing surfaces with diverse debris grain size and different distances from rock slopes and medial moraines, and these samples were used to characterize the spatial variability of supraglacial debris.**"**

Pag. 3181 row 15 From 2 to 5 cm is more than the double! It is not a real accurate sampling!

Depending on the surface roughness, sometimes it was necessary remove up to 5 cm of ice in order to sample all the fine debris (mainly dust).
Then we modified accordingly:
From "(from 2 to 5 cm deep)**",**
To "(from 2 to 5 cm deep, depending on the surface roughness)**".**

Pag. 3181 rows 7-12 Why sampling was so different every year? C rate what is it, please define?

As explained in a previous comment, field campaigns on the glacier require generally on the one hand a great organization (e.g. alpine guide, staff member, etc.), and on the other hand, they can be performed only with adequate meteorological conditions. The data we collected are therefore the best we were able to produce given these 2 constrains. As far as the analyses are concerned, we exploit available data as much as possible even though the number of the measurement dates are different among each year.
As regard the second comment, we added here the C rate definition: "the fine debris amount reaching the surface over a defined time frame (g day^{-1})**"**

Results

Pag. 3183 row 4 Why the statistical significance (p) is not reported

As we considered a copious sample (i.e. 51 measurements) and we found a high correlation coefficient (i.e. 0.84), the correlation should be significantly lower than zero. Indeed, we calculated the p value of the correlation coefficient and, as expected, it resulted equal to 9.47e^{-15}. Nevertheless, it would be more interesting to define the coefficient interval that we found ranging from 0.74 to 0.91 (95% coefficient interval).

For a more exhaustive analysis, we also estimated the 99% coefficient interval (i.e. from 0.69 to 0.92). This latter is now inserted into the revised manuscript.
Then we modified accordingly:
From "The correlation is 0.84 (the 95% coefficient interval ranging from 0.74 to 0.91)**",**
To "The correlation is 0.84 (the 95% and 99% coefficient intervals ranging from 0.74 to 0.91 and from 0.69 to 0.92, respectively).**"**

Pag. 3183 rows 10-15 Why is necessary to define a completely ice debris-free? It is not really clear and it is also clear that use an indirect measurements of the absence of debris like albedo is not completely correct because albedo of the ice depends also by its structure and roughness.

We deleted this part accordingly.

Pag. 3183 row 23 30 events in which period? Why are not reported the rain values of the 30 events?

As we investigated the influence of the rainfall on the ice albedo variability, we considered only the rain events occurring during the ice ablation season. This latter can be deducted analysing albedo and melting data (Senese et al., 2012a). The first one allows to distinguish the presence of a snow cover from a surface featuring bare ice. In fact, glacier ice is characterized by lower albedo values than snow. An example of hourly albedo values calculated from solar radiation fluxes (both incoming and outgoing one) measured by the AWS1 Forni are shown in Fig. 1 (please see below). During 2012 the ice ablation season (red box in the below Fig. 1) ranges from 16th June to 12th October: this period features an albedo lower than 0.4, excluding few snowfall events with a higher reflectivity.

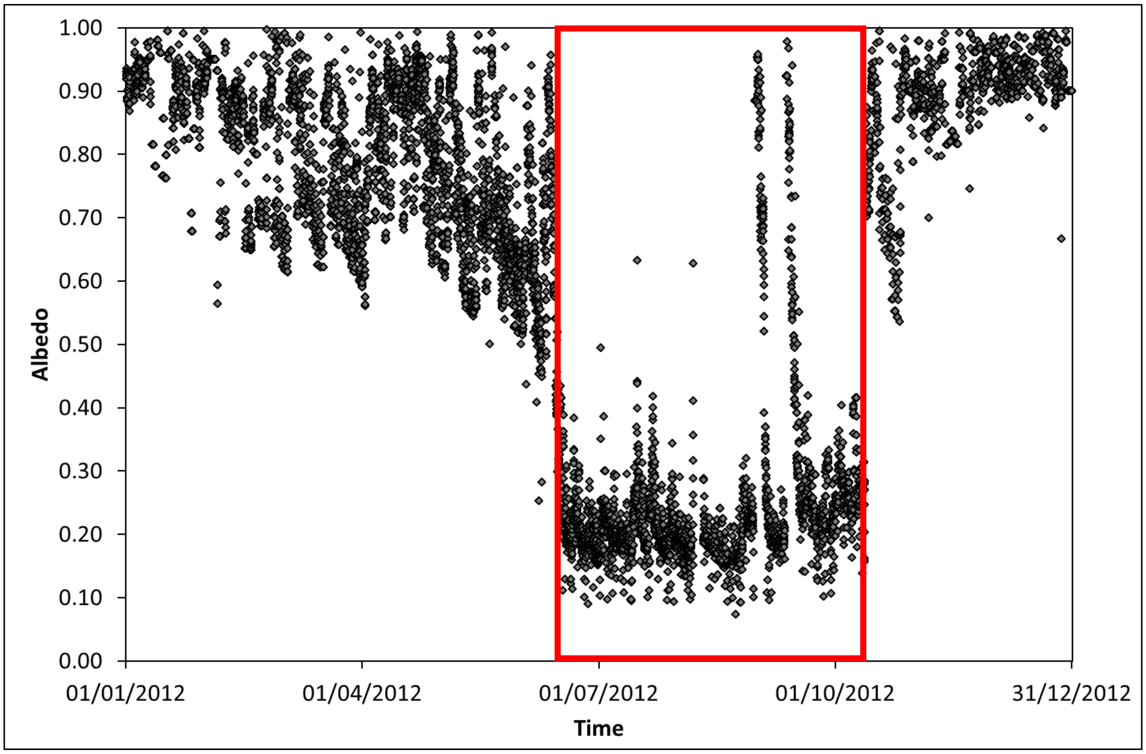

Fig. 1: Hourly albedo values during 2012 calculated from incoming and outgoing solar radiation data measured by the AWS1 Forni. The ice ablation season is marked by the red box.

In addition to albedo values, the melting data are essential in order to set the occurrence of the melting processes at the surface. The snow/ice ablation is quantified applying the energy balance model (for more details please see Senese et al., 2012a, 2012b, 2014). For example, hourly melting values are shown in Fig. 2 (please see below).

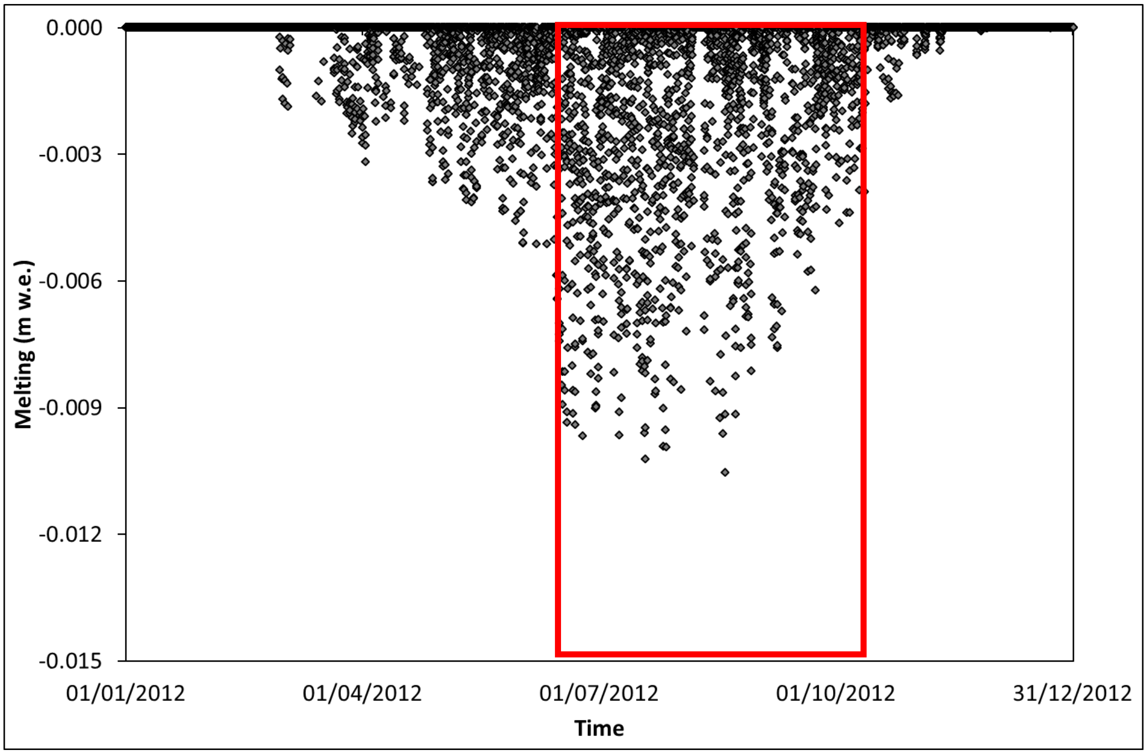

Fig. 2: Hourly melting values during 2012 estimated from the meteorological data and energy fluxes measured by the AWS1 Forni. The ice ablation season (assessed from albedo values) is marked by the red box.

Finally in the Table 1 (please see below) the beginning and the end of each ice ablation season are reported. Regarding the 2013 record, there were no data from 3rd to 13th July. On 3rd July the albedo was equal to about 0.55, thus featuring snow cover, while on 13th July it was equal to about 0.18, thus characteristic of bare ice. Then the 2013 ice ablation season started surely in the timeframe 3rd – 13th July.

Year	**Beginning**	**End**
2011	**14/06/2011**	**06/10/2011**
2012	**16/06/2012**	**12/10/2012**
2013	**3-13/07/2013**	**09/10/2013**

Tab. 1: The beginning and the end of each ice ablation season deducted from albedo and melt data by AWS1 Forni.

Then in agreement also with the second Referee, we analysed the meltwater effect in addition to one led by liquid precipitation. Then we added further information in the Method section and then we modified:
From "Moreover we also analysed the effect of liquid precipitation on glacier albedo variability. In fact the liquid precipitation washes out the finer sediment above glacier ice surface (Oerlemans, 2009) thus changing ice albedo. This water effect was quantified by comparing albedo values before, during and after the occurrence of actual liquid precipitation.**",**

To "In addition to debris, water plays a significant role washing out the finer sediment above glacier ice surface (Oerlemans, 2009) and smoothing the ice surface, thus changing ice albedo. Then, we also analysed the effect of water (derived from melting processes or rainfall) on glacier albedo variability during each ice ablation season from 2011 to 2013. The length of the ice ablation period was investigated coupling albedo and melting data (for more details see Senese et al., 2012a). The occurrence of melting was investigated applying the energy balance model from meteorological data and energy fluxes measured by the AWS1 Forni (for more details regarding the melting model see Senese et al., 2012a; 2012b; 2014). Finally, the temporal length (i.e. number of rainy days) and amount (i.e. mm of rain) of liquid precipitation were measured by an unheated pluviometer installed at the AWS1 Forni (DQA035, LSI-Lastem). The effect of liquid precipitation was quantified by comparing albedo values before, during and after the occurrence of actual liquid precipitation. In particular, we considered an actual rainfall any event featuring a hourly liquid precipitation higher than 0.2 mm (i.e. the threshold to activate the toggle switch of the rain gauge).**"**

Moreover, we added the beginning and the end of each ice ablation season and the rain amount for every event (please see the below Table 2, corresponding to the Table 1 in the revised manuscript).

Before a rainy event		During a rainy event			After a rainy event		Albedo increase (%)
Date	**α**	**Date**	**Rain (mm)**	**α**	**Date**	**α**	
Beginning of ice ablation season 2011: 14 Jun 11							
16 Jun 11	0.33	17-18 Jun 11	46.2	0.21	19 Jun 11	0.41	24.2
20 Jun 11	0.31	21-23 Jun 11	33.2	0.21	24 Jun 11	0.31	0.0
24 Jun 11	0.31	25-26 Jun 11	0.6	0.20	27 Jun 11	0.32	3.2
28 Jun 11	0.18	29 Jun 11	15.4	0.18	30 Jun 11	0.20	11.1
3 Jul 11	0.23	4-8 Jul 11	38.6	0.20	9 Jul 11	0.25	8.7
2 Aug 11	0.20	3 Aug 11	10.8	0.19	4 Aug 11	0.24	20.0
31 Aug 11	0.25	1 Sep 11	3.4	0.25	2 Sep 11	0.28	12.0
2 Sep 11	0.28	3-6 Sep 11	63.6	0.24	7 Sep 11	0.29	3.6
7 Sep 11	0.29	8 Sep 11	1.0	0.22	9 Sep 11	0.31	6.9
11 Sep 11	0.22	12 Sep 11	10.8	0.23	13 Sep 11	0.25	13.6
End of ice ablation season 2011: 6 Oct 11							
Beginning of ice ablation season 2012: 16 Jun 12							
19 Jun 12	0.20	20-26 Jun 12	20.0	0.21	27 Jun 12	0.22	10.0
1 Jul 12	0.17	2-7 Jul 12	68.4	0.22	8 Jul 12	0.19	11.8
8 Jul 12	0.19	9-11 Jul 12	28.8	0.19	12 Jul 12	0.23	21.0
12 Jul 12	0.23	13-15 Jul 12	64.6	0.20	16 Jul 12	0.29	26.1
19 Jul 12	0.20	20-22 Jul 12	28.8	0.24	22 Jul12	0.27	35.0
23 Jul 12	0.21	24-25 Jul 12	1.2	0.20	26 Jul 12	0.22	4.8
26 Jul 12	0.22	27-31 Jul 12	27.4	0.20	1 Aug 12	0.23	4.5
2 Aug 12	0.20	3-6 Aug 12	40.0	0.18	7 Aug 12	0.24	20.0
24 Aug 12	0.16	25-26 Aug 12	36.2	0.19	27 Aug 12	0.26	62.5
23 Sep 12	0.22	24-27 Sep 12	93.6	0.23	28 Sep12	0.32	45.4
28 Sep 12	0.32	29 Sep-2 Oct 12	64.4	0.24	3 Oct 12	0.32	0.0
6 Oct 12	0.27	7 Oct 12	1.0	0.23	8 Oct 12	0.30	11.1
End of ice ablation season 2012: 12 Oct 12							
Beginning of ice ablation season 2013: 3-13 Jul 13							
16 Jul 13	0.16	17-24 Jul 13	35.6	0.18	25 Jul 13	0.17	6.3
25 Jul 13	0.17	26 Jul 13	0.2	0.16	27 Jul 13	0.18	5.9
28 Jul 13	0.16	29 Jul 13	4.2	0.15	30 Jul 13	0.23	43.7
30 Jul 13	0.23	31 Jul 13	0.4	019	1 Aug 13	0.25	8.7
6 Aug 13	0.16	7-9 Aug 13	61.2	0.16	10 Aug 13	0.26	62.5
12 Aug 13	0.19	13-15 Aug 13	13.0	0.19	16 Aug 13	0.24	26.3
31 Aug 13	0.18	1 Sep 13	1.0	0.18	2 Sep 13	0.24	33.3
26 Sep 13	0.16	27 Sep 13	1.4	0.15	28 Sep 13	0.24	50.0
End of ice ablation season 2013: 9 Oct 13							
Mean	**0.22**			**0.20**		**0.26**	**21.3**

Tab. 2: Influence of rainfall on surface albedo (α) measured from the AWS1 Forni. In the table are reported the 30 rainy events (and relative rain amount in mm) occurred in 2011, 2012 and 2013 ablation seasons and the albedo values before, during and after every rainfall.

Pag. 3184 rows 16-21 Macrogelivation ? Have the authors some data to say this? Not always macrogelivation is so efficient even in alpine environment. Slope erosion? What does it mean? This material is a product of the rock weathering or of slope erosion? What does it mean recent? The authors have age of the deposits? All these statements seems just some general assumption not suffragated by any data.

We modified accordingly and in particular we deleted "slope erosion" and we replaced "recent" with "active". Then we modified:
From "The lowest value of total organic carbon was found in sample 2, which was collected on a glacier area located close to the flank of the nesting rock walls, a site which receives a high amount of debris originating from macrogelivation and weathering processes. Rock debris coverage here is younger (recent deposition) and unstable, and therefore poorly colonized by supra-glacial organisms. Moreover, the grain-size analysis shows that samples collected at these sites are characterized by coarser sediments, in keeping with their origin, mostly due to slope erosion.**",**
To "The lowest value of total organic carbon was found in sample 2, which was collected on a glacier area located close to the flank of the nesting rock walls, a site which receives a high amount of debris originating from rock weathering processes such as the macrogelivation, which in this area has been reported by Gugliemin and Notarpietro (1997). Rock debris deposits in the area are active and unstable; they are continuously suffering renewal of the surface, therefore poorly colonized by supra-glacial organisms. Moreover, the grain-size analysis shows that samples collected at these sites are characterized by coarser sediments, in keeping with their origin, mostly due to mechanical weathering.**".**

Guglielmin M. and Notarpietro A. (1997). Il permafrost alpino: concetti, morfologia, metodi di individuazione (con tre indagini esemplificative in alta Valtellina). Quaderni di Geodinamica Alpina e Quaternaria, Vol. 5, 117 pp.

Pag. 3185 row 2 Which are the reason to say that it is a particular siderurgic site and not another?

We modified accordingly:
From "These cenospheres can be carried out by a wind contribution probably from siderurgic district at the northern fringe of the Po Plain (c. more than 150 km southward the Forni Glacier), suggesting a limited allochthonous input and a human impact even at the glacier surface.**",**
To "These cenospheres can be carried out by a wind contribution probably from diesel fuel engine or also from siderurgic district at the northern fringe of the Po Plain (c. more than 150 km southward the Forni Glacier), suggesting a limited allochthonous input and a human impact even at the glacier surface.**".**

Moreover in agreement with the other Referee, we deleted accordingly this part in the Discussion section.

Pag. 3185 Row 9 who can say which are the averaged characteristics of the site?

We modified accordingly:
From "From 4 July to 9 September 2012 we found a higher *C*r on sites characterized by coarser dust (i.e. 96 gm^{-2} per day along an entire ablation season) than in the sites featuring finer sediment (i.e. 1 gm^{-2} per day). In the 2013 measures are more representative of the average debris cover condition of the ablation tongue of the glacier. The *C*r value we found is 6 gm^{-2} per day.**",**
To "From 4 July to 9 September 2012 and from 11 July to 4 October 2013 we found a mean C_r equal to 6 g/m^2 per day.**"**

Pag. 3185 Row 26 more rounded shapes normally suggest endoglacial transport not supraglacial!

We modified accordingly:

From "The evolution of the supraglacial debris is also analysed through SEM observations. At the beginning of the melting time frame, the sediment was characterized by sharp and angular clasts; on the other hand, the samples collected in September 2012 featured more rounded shapes, suggesting a supraglacial mass transport.**",**

To "The evolution of the supraglacial debris is also analysed through SEM observations. On the one hand at the beginning of the melting time frame, the sediment was characterized by sharp and angular clasts, thus suggesting a supraglacial mass transport; on the other hand, the samples collected in September 2012 featured more rounded shapes, suggesting an englacial mass transport."

Pag. 3186 Where the comparison between measured albedo are compared with the modelled ones?

We added accordingly a graph showing the measured and modelled albedo values (Fig. 3, see below, corresponding to the Figure 10 in the revised manuscript).

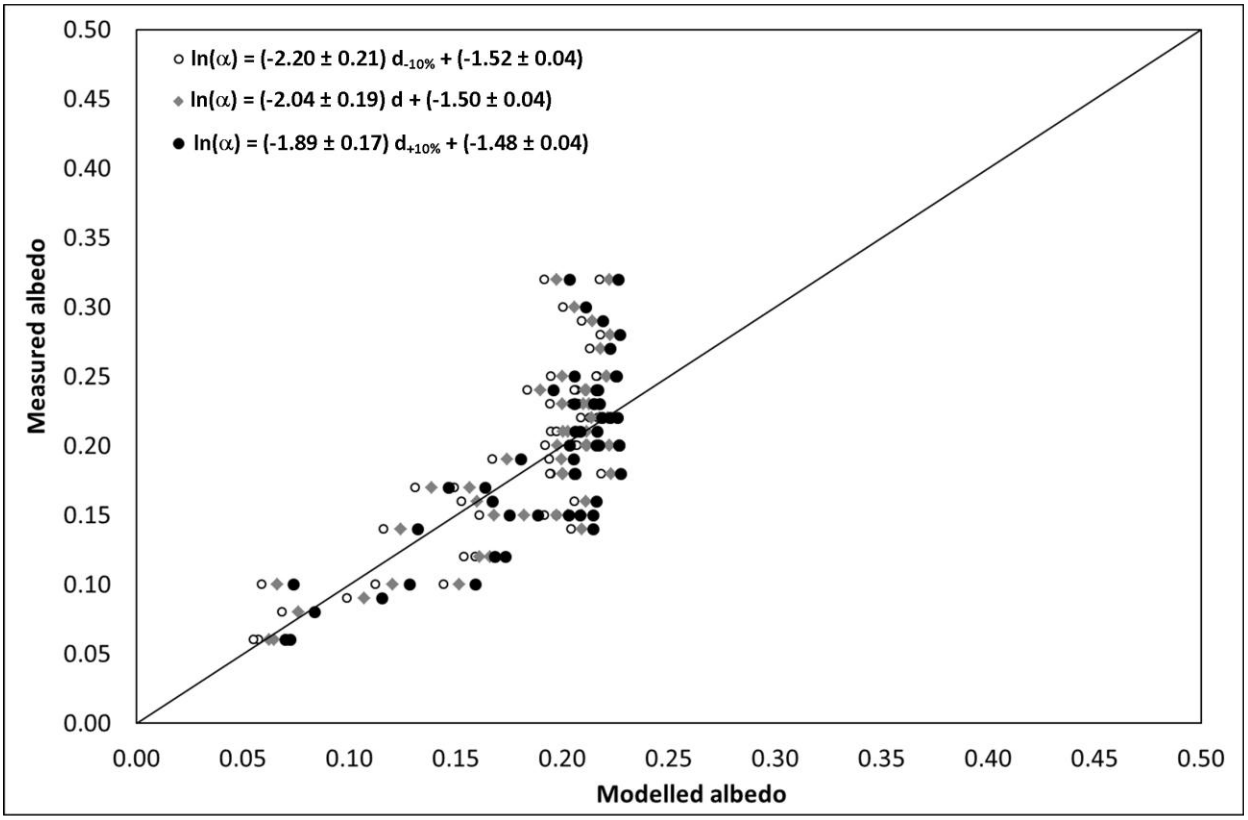

Fig. 3: Comparison between measured and modelled albedo values. The applied equations (please see Table 3 in the revised manuscript) are shown in the legend.

Discussion is partially a repetition of what included in the results section and in general is weaker withouth any comparison with results of relation between glacier and debris cover in other glaciers.

We modified accordingly. In particular, we moved some parts from the Results section into the Discussion one. Moreover, we quantified the surface covered by fine debris by means of other approaches such as the point intercept and we discussed the results comparing them with the ones estimated through our method. In addition, we explained why we chose to vary the gray-scale threshold of 10%.

Conclusion again are too long and more similar to an abstract than to focus on the main results obtained by the study

We modified accordingly.

Reference There are several errors like for example: Aoki et al 2002 is in the text but not in the list and Aoki et al 2006 is in the list but not in the text

We checked the References and modified accordingly.

Referee #2

The authors certainly present a new type of analysis of fine debris on the ice facies of a glacier in Italy. The attempt at combining image analysis techniques with chemical / lab techniques is commendable. However, further implications of the method may be significantly limited by the methods chosen. I have some serious concerns about this paper which I believe need to be addressed in order for this paper to be considered for publication in The Cryosphere.

Major comments:

1. A major issue that is not addressed by the authors is the prevalence of debris not only deposited from the air but also resident within the ice itself as it emerges to the glacier surface. Indeed, this paper distinguished debris accumulation on snow vs. ice, but much of the debris in the ice will have emerged after being compacted from snow into firn and then ice. This could have paleo implications rather than current ones. Understanding this concentration and providence is important to sort out the variables the authors discuss (including Cr, lithology, etc).

An understanding of how the albedo varies in response to changes in the state of the surface is a central component in modelling ice melt and in describing the climate of the ice-covered regions and the climate in general (see Grenfell, 2011). Moreover, in the recent climate modelling studies, attention is paid to the "ice-albedo feedback" and to its action in modulating the changes in the total energy balance of the analyzed area (Grenfell, 2011). Accordingly, our first issue is to evaluate the role of fine debris (autochthonous and allochthonous, from both englacial origin and wind transport) in modulating ice albedo thus driving ice ablation. In fact, the scientific community is already studying black carbon deposition on glacier snow and they have found an actual impact on snow melt rates thus suggesting to investigate such phenomenon on glacier ice as well. For this first purpose, the most important feature to be measured and analyzed is the present debris distribution at the glacier surface, instead debris origin and history are negligible. The second issue we considered is to find the main fine debris suppliers since over the last decade darkening phenomena have been observed on the largest part of mountain debris-free glaciers. These two issues are independent even if complementary. In fact, the correct parameterization of ice albedo taking into account fine debris presence (autochthonous and allochthonous) may improve the largest part of ice melt models and for several scientists this is the unique information on debris they require. Differently whenever the research is also aimed at mankind impacts on cryosphere (mainly black carbon occurrence), it is necessary to analyze origin and history of debris by distinguishing between local debris and wind transported particles and also considering paleo-implications due to emerging englacial debris. For describing debris origin and history, we performed different analyses (X ray, Scanning Electron Microscope – SEM, and Energy Dispersive Spectrometry - EDS) also considering the organic matter and the biological components. On the one hand, we found that for the largest part fine debris showed a local lithology (thus being autochthonous) with a high fraction of organic matter, and this latter seems very recent (with mesofauna still recognizable and well-conserved also witnessing a very limited transport and compression). On the other hand, we cannot completely exclude that part of the fine debris should come from inner glacier layers. Even with regards to the cenospheres found in the sampled debris (through SEM analysis), we cannot state the exact time of their deposition nevertheless they surely were delivered by diesel fuel engine or by siderurgic factories. In fact the shape of cenospheres differs from the one featured by particles deriving from other processes as stated by Thevenon and Anselmetti (2007), who

through SEM observations demonstrated that charcoal from coal and wood burning are characterized by elongate or prismatic particles.

Nevertheless, it is not so easy to reconstruct debris origin (englacial or wind transported), as the glaciers generally inflict the most extensive array of fracture and abrasion microfeatures (Mahaney, 2011). In addition, from 10% to 20% of grains in glaciers may escape contact with other grains, and hence sojourn in the ice without suffering physical damage. The other 80-90% of glacial grains will exit the system with fractured and abraded surfaces some of which are diagnostic of the glacial environment. Then the glacial grains probably carry the greatest range of deeply embedded microtextures when compared with grains affected by other geologic agents (Mahaney, 2011). This includes the full range of fractures, grooves, and abrasion microfeatures reported by Mahaney (2002), as well as solution-precipitation microfeatures and other coatings that may predate or postdate a glacial episode. Moreover, as some grains (perhaps as many 1 in 5) make the "glacial trip" unscathed by their sojourn in the ice, they carry only microtextures related to previous environments, thus making impossible to detect their origin once found over the glacier surface (Mahaney, 2011). These fragments may carry a record of release from bedrock with unremarkable fracture faces, without the usual grain-to-grain contact on glacial system that produce triangular faceted, sharp-edged grains with moderate to high relief, the latter usually well abraded with a multitude of fractures, grooves, and well-worn abrasion microfeatures. Then these grains record damage that, to a large extent, depends on the thickness of the ice and the distance of transport with temperatures close to pressure-melting (p-melting). While the distance of transport is nearly impossible to compute with total accuracy, it would seem that long-distance transport close to p-melting will yield a triangular faceted quartz grain totally reformed from its original shape and size, and with the greatest damage inflicted on it. No other geological agent is capable of this transformation and none have the damaging effect that glaciers can inflict on quartz and other minerals entrained in the ice. The SEM-EDS (Energy Dispersive Spectrometry) method can be employed to build a database of microtextures, microstructures, and chemical spectra that help to answer questions related to weathering in paleoenvironments as well as generate new ones (Mahaney, 2011). For example, standard databases on precipitates and coatings, information lacking in the Krinsley and Doornkamp (1972) volume, are now frequently used to help solve questions related to weathering of glacial grains (Mahaney, 2002), the coating chemistry offering new insight into wetting depths and paleoleaching in paleosols (Mahaney, 1990), all of which may provide valuable information on preweathering prior to glacial transport (Mahaney et al., 1991) and relative dating of sediments (Mahaney et al., 2009). The 1973 volume on glacial grain surface microtextures, although long out of date, remains a basic reference for researchers interested in the application of the technique since that time. Additional work by Whalley (1978) and Marshall (1987) has added numerous case studies in the microtexture field since that time. Following the new SEM atlas by Mahanney (2002), it is possible to separate till from glaciolacustrine and glaciofluvial grains within the glacial sedimentary environment. Similarly, while it has proved difficult to separate tills genetically (Mahaney et al., 2001), it is possible to generate information related to glacial thickness and differences between warm and cold-based ice (Mahaney et al., 1988), as well as the relative amount of water transport within the glacier system.

Grenfell T.C. (2011) Albedo. In Singh V.P., Singh P. and Haritashya U.K. (eds): Encyclopedia of snow, ice and glaciers. Springer, The Netherlands, 1253 p.

Krinsley D. and Doornkamp J.C. (1973) Atlas of sand grain surface textures. Cambridge, University Press, 91 p.

Mahaney W.C., Vortisch W.A. and Julig P. (1988) Relative differences between glacially crushed quartz transported by mountain and continental ice - Some examples from North America and East Africa. American Journal of Science, 288, 810-826.

Mahaney (1990) Ice on the equator. Ellison Bay, Willaiam Caxton Ltd, 386 p.

Mahaney W.C., Vaikmae R. and Vares K. (1991) Scanning Electron Microscopy of quartz grains in supraglacial debris, Adishy Glacier, Caucasus Mountains, USSR. Boreas, 20, 395-404.

Mahaney W.C., Stewart A. and Kalm V. (2001) Quantification of SEM microtextures useful in sedimentary environmental discrimination. Boreas, 30, 165-171.

Mahaney W.C. (2002) Atlas of sand grain surface textures and applications. Oxford, UK, Oxford University Press, 273 p.

Mahaney W.C., Kalm V., Kapram B., Milner M.W. and Hancock R.G.V. (2009) Soil chronosequence, Humboldt Glacier, northwestern Venezuelan andes. Geomorphology, 10, 99-110.

Mahaney W.C. (2011) Sem analysis of glacial sediment. In Singh V.P., Singh P. and Haritashya U.K. (eds): Encyclopedia of snow, ice and glaciers. Springer, The Netherlands, 1253 p.

Marshall J.R. (1987) Clastic particles. New York, Van Nostrand Reinhold Co., 346 p.

Thevenon F. and Anselmetti F.S. (2007) Charcoal and fly-ash particles from Lake Lucerne sediments (Central Switzerland) characterized by image analysis: anthropologic, stratigraphic and environmental implications. Quaternary Science Reviews, 26, 2631–2643.

Whalley W.B. (ed.) (1978) Scanning Electron Microscopy in the study of sediments. Norwich, GeoAbstracts.

2. While the user-defined threshold is shown to correspond with debris concentrations better than an average threshold, the choice of threshold is largely arbitrary as the user defines it and therefore would be difficult for other users to adopt. More specifically, the choice of threshold to include concentrated clumps of fine debris vs. the ability to quantify the role of fine, distribute, and as-yet-not-consolidated debris is lacking. The threshold in the histogram is shown to be on a non-unique part of the curve – some feature in the histogram (whether a shoulder, valley, etc.) would be more convincing for a transferrable/scalable technique. This is especially true in light of user-acknowledged difficulties with roughness, illumination, water content, etc.

The aim of our study is to quantify the fine debris occurrence and distribution through an approach as detailed as possible, since the main goal is to find an actual relation with surface albedo. Then if the method for the debris quantification is affected by a non-negligible error, the resulting relation can not be considered applicable to predict ice albedo and then to contribute to a better quantification of ice melt. Instead, the semi-automatic method we proposed can give more reliable and accurate results since it is based on the analysis of higher resolution imagery (1 pixel corresponds to about 0.6 mm in the field). In order to investigate the possible performance of other approaches, we applied the point intercept method as well. Then we selected randomly 10 of our images and superimposed a 10 x 10 cm grid. Furthermore, we asked 10 colleagues from our University (all geologists) to estimate the debris coverage. The results, even though in reasonable agreement with our proposed method, show a very high variability between the 10 users, with a general tendency of higher values with respect to the ones derived from the application of our semi-automatic protocol. In addition, with the aim at investigating the robustness of our method and its sensitivity to changes in the chosen T_{GS}, the semi-automatic protocol was carried out by 10 users, giving a variability of T_{GS} values lower than the 10%. For this reason, we varied the applied T_{GS} values up to ±10% of their initial values ($T_{GS-10\%}$ and $T_{GS+10\%}$, respectively). As a consequence of the high subjectivity of methods such as the point intercept, we prefer applying the approach we proposed.

As regards the issue of the different debris aggregation (from concentrated clumps of fine debris to fine, distribute, and as-yet-not-consolidated debris), it was engaged selecting surfaces with different features (please find below some examples of the chosen surfaces, Fig. 4). Moreover, the pictures were always acquired

in the same conditions: central hours of the day, clear sky conditions, and occurrence of melting processes then with meltwater at the surface. In this way, every image is characterized by comparable conditions of roughness, illumination, water content, etc.

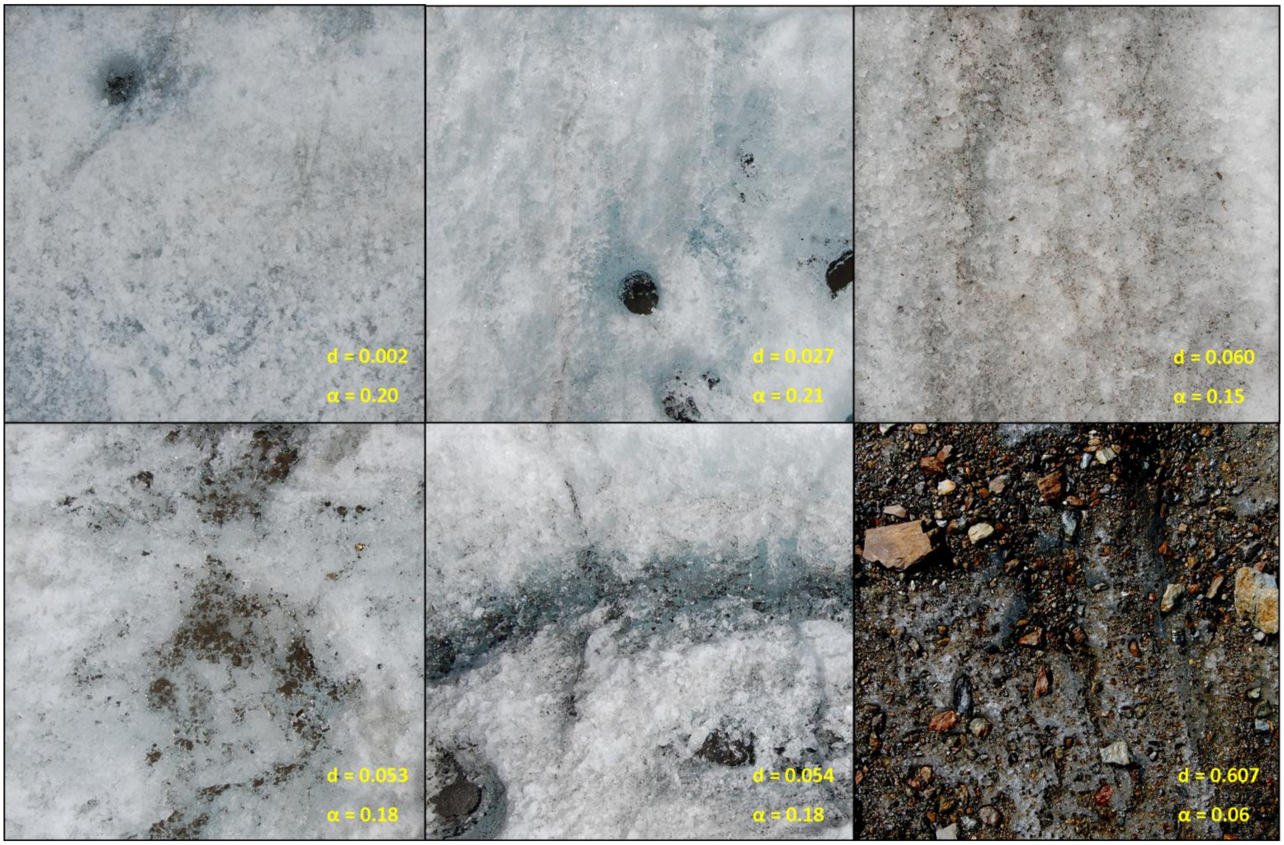

Fig. 4: Some examples of investigated glacier surfaces. Albedo (α) values derived from measured incoming and outgoing solar fluxes, and debris cover ratio (d) by the application of our semi-automatic image analysis.

In addition, we performed a further test applying as T_{GS} the most frequent grey tone (please see the top of the curve in Fig. 5c below, corresponding to the new Fig. 9c in the revised manuscript). With this threshold some pixels with ice and not with debris are selected as debris-covered ones thus overestimating the d value (49.78% instead of the actual value of 9.96%, please see Fig. 5d below). In fact, the most frequent grey tone could correspond to a tonality featured by the ice, probably covered by a thin water film (please see Fig. 5a below).

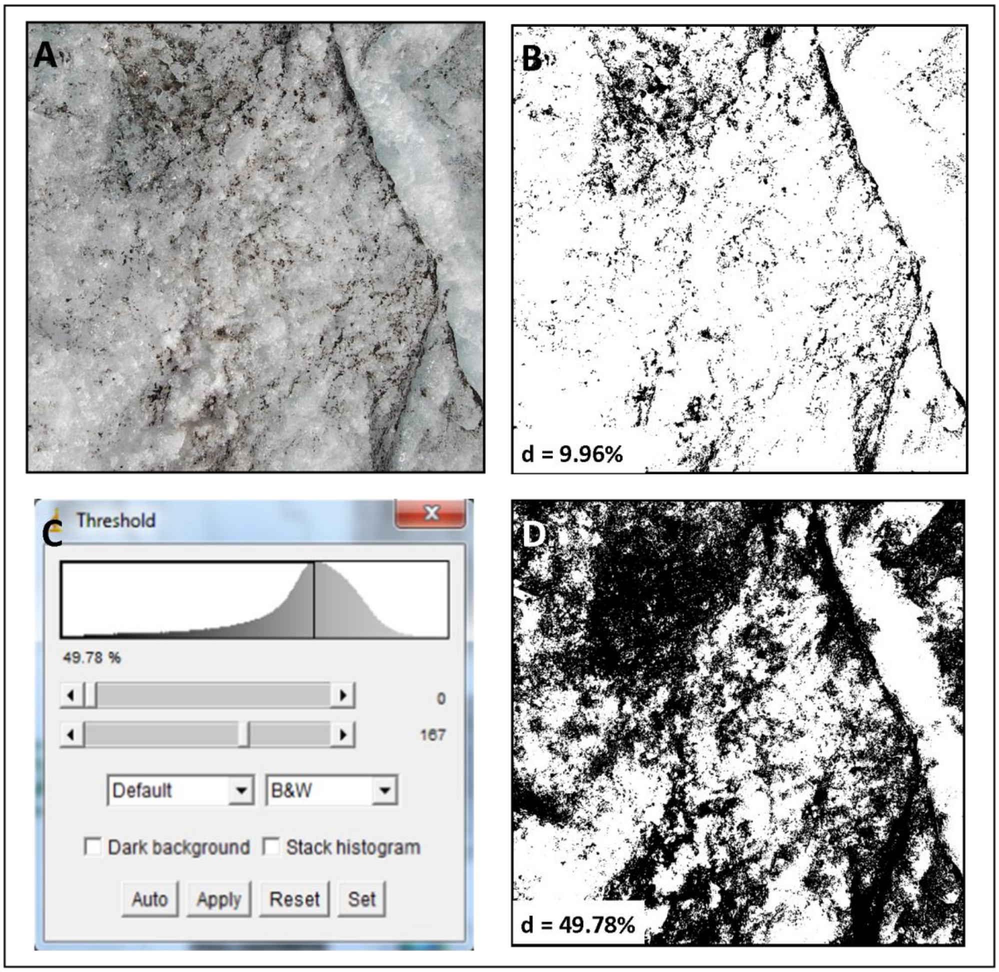

Fig. 5: Comparison between the application of the threshold chosen correctly by the user (B) and the one corresponding to the most frequent grey tone (D) deducted by the frequency distribution curve (C). The relative *d* values are shown (B and D). In A the analyzed surface is shown.

Then we investigated the robustness of our image analysis approach with five sensitivity tests: i) the application of other field methods, such as the point intercept, providing a high variability in the results and a general overestimation, ii) the comparison between the T_{GS} values estimated by numerous users obtaining a variability lower than the 10%, iii) the variation of the selected threshold (T_{GS}) up to ±10% for each image, iv) the application as T_{GS} of the most frequent grey-scale value (i.e. the top of the curve in Figure 3c in the revised manuscript), selecting as debris also the pixel with clean ice, and v) the application of a unique threshold ($T_{GS\text{-}AVE}$) obtained by averaging all the chosen T_{GS}.

3. The authors include consideration of liquid precipitation in their albedo discussion, but do not address the significant role that melt plays on the albedo of the surface. Quantity of melt and quality of the ice surface drainage are crucial to understanding the albedo and therefore the ability to correlate albedo and debris concentrations. E.g. see Pope & Rees 2014 in the International Journal of Earth Observation and Geoinformation for reflectance spectra of "dry ice", "wet ice" and different debris type surfaces in the ablation zone of glaciers in

Iceland and Svalbard. Casey et al. 2012 in The Cryosphere also includes a consideration lithological remote sensing, as well.

Our study was carried out during the ice ablation season, then when the meltwater is present quite constantly over the glacier tongue surface. Moreover, the available equipment does not allow an exhaustive analysis regarding the influence of meltwater and of drainage on albedo variability. Nevertheless, we are able to investigate the possible meltwater presence by means of energy budget computation (for more details regarding the melting model, please see Senese et al., 2012a, 2012b, 2014). In particular, we coupled the hourly albedo values (measured by the permanent automatic weather station, AWS1 Forni) with the melt values (estimated by the energy balance). For example, some days of the ice ablation season during 2012 are shown in Figure 6 (please see below, in the revised manuscript it is the new Figure 6). It resulted that in correspondence of a higher ablation rate the ice albedo decreases. This can be due to a lower reflectivity of the water respect to the ice (i.e. equal to 0.05-0.10, Hartmann, 1994). Moreover whenever the melting processes are not so intense (e.g. on 20/06/2012) the albedo decreasing is not so marked. Anyway in general the water occurs during the central hours of the day when the melting processes are more intense.

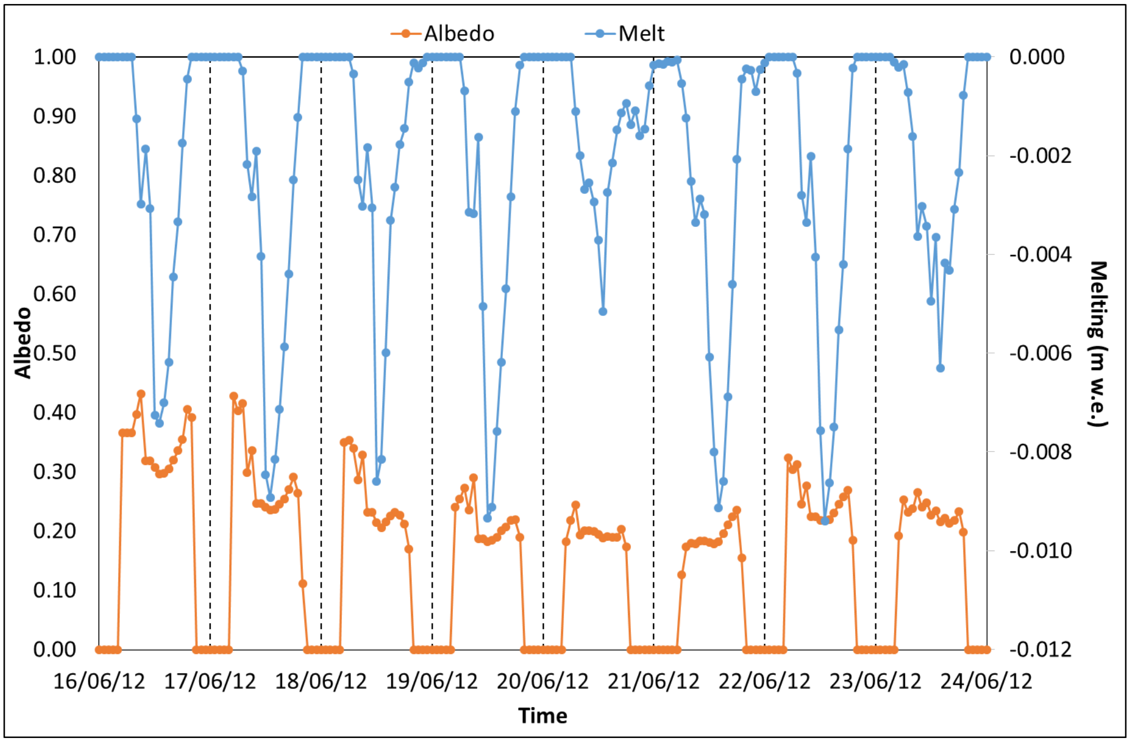

Fig. 6: Comparison between the albedo values measured by AWS1 Forni (red line) and the melting amount (blue line) estimated by the energy balance model.

Then we modified accordingly the Method section:

From "Moreover we also analysed the effect of liquid precipitation on glacier albedo variability. In fact the liquid precipitation washes out the finer sediment above glacier ice surface (Oerlemans, 2009) thus changing ice albedo. This water effect was quantified by comparing albedo values before, during and after the occurrence of actual liquid precipitation. We considered an actual rainfall any event occurred whenever the hourly air temperature was higher than 1.5 C (Senese et al., 2012a) and featuring an hourly liquid precipitation stronger than 0.2 mm. The precipitation temporal length (i.e. number of rainy days) and amount (i.e. mm of rain) were measured by a rain gauge installed at the AWS1 Forni.**”,**

To “In addition to debris, water plays a significant role as well, washing out the finer sediment above glacier ice surface (Oerlemans, 2009) and smoothing the ice surface thus changing ice albedo. Then we also analysed the effect of water (derived from melting processes or rainfall) on glacier albedo variability during each ice ablation season from 2011 to 2013. The ice ablation period length was investigated coupling albedo and melting data (for more details see Senese et al., 2012a). The melting occurrence was investigated applying the energy balance model from meteorological data and energy fluxes measured by the AWS1 Forni (for more details regarding the melting model see Senese et al., 2012a; 2012b; 2014). Finally, the temporal length (i.e. number of rainy days) and amount (i.e. mm of rain) of liquid precipitation were measured by an unheated pluviometer installed at the AWS1 Forni (DQA035, LSI-Lastem). The liquid precipitation effect was quantified by comparing albedo values before, during and after the occurrence of actual liquid precipitation. In particular, we considered an actual rainfall any event featuring a hourly liquid precipitation higher than 0.2 mm (i.e. the threshold to activate the toggle switch of the rain gauge).**”**

In addition, we modified also the Results section:

From “Regarding the impact of liquid precipitation on supraglacial fine debris and ice albedo, we report in Table 1 the mean daily albedo values before, during and after rainfall events.**”,**

To “Regarding the impact of water on fine debris over the glacier surface and then on ice albedo, we considered melting processes and rainfall occurrence during each ice ablation season from 2011 to 2013. The beginning and the end of each ice melting period are shown in Table 1. Regarding the 2013 record, there are no data from 3rd to 13th of July. On 3rd July the albedo was equal to about 0.55, thus featuring snow cover, and on 13th July equal to about 0.18, thus characteristic of bare ice. Then the 2013 ice ablation season started surely in the timeframe 3rd – 13th July. Analysing melt and albedo data it resulted that in correspondence of a higher ablation rate the ice albedo decreases (Fig. 6). Differently whenever the melting processes are not so intense (e.g. on 20/06/2012, see Fig. 6), the albedo decreasing is not so marked. In general, we can deduce that the water occurs during the central hours of the day when the melting processes are more intense. The decreasing in albedo values is due to a lower reflectivity of water respect to ice (i.e. equal to 0.05-0.10, Hartmann, 1994). In fact Pope and Rees (2014) reported a lower reflectance featured by wetter icy surfaces than dry ones. This trend is found also analysing liquid precipitation. In particular we report in Table 1 the mean daily albedo values before, during and after rainfall events.**”**

4. The writing style of the paper presents the paper as largely anecdotal and exploratory in sampling. A tighter “argument” and presentation of the analysis in the paper would greatly improve the readability of the manuscript and allow the reader to place it within a larger research context.

We modified accordingly the manuscript, in particular the Results, the Discussion and the Conclusions sections.

5. The authors astutely finish the paper by attempting to link their conclusions to more widely applicable remote sensing techniques. However, the study methods would frankly be very ill-suited to remote sensing application for two main reasons. One, there is no demonstrated link between the point measurements on the authors and actual satellite imagery. The greatly inhomogeneous nature of the glacier surface makes this important to demonstrate. Two, even sub-meter spatial resolution available in some commercial imagery would be an order of magnitude higher than the resolution in the images acquired in this study. The mixing in each pixel would be unable to distinguish the level of debris studied here. As such, a sub-pixel (spectral) mixing approach would be *necessary for this study to be considered for upscaling. Although it is important to be able to define meaningful implications (especially for publication in The Cryosphere), in this conclusion, the authors reach too wide.*

We modified accordingly:

From “In conclusion, this methodological approach is applied to a very small scale (parcel of 1 m x 1 m), nevertheless it could be extended to a larger scale. For instance, the image analysis can be performed on higher resolution imagery such as orthophotos (for Lombardy Alps available with pixel resolution of 0.5 m x 0.5 m) or satellite imagery (featuring a resolution of 3-5 m or better). This improvement and the jump of scale will permit to distribute ice albedo once the debris properties are analysed and the relationship between albedo and debris ratio is known.**“,**

To **“**In the future it will be interesting investigating whether the approach presented in the paper can be performed on remotely sensed material such as high resolution orthophotos (for Lombardy Alps available with pixel resolution of 0.5 m x 0.5 m) or satellite imagery (featuring a resolution of 3-5 m or better). This would permit distributing ice albedo, given that debris can be reasonably estimated for the entire glacier.**”**

Directed comments:

p3173, l19-22: Dust and black carbon are also of extensive Interest in the Arctic and Greenland. Extensive references by Dumont, Benning, Stibal, Anesio, Lutz, etc. would be appropriate here. Also, it would seem that a consideration of the role of ash as a fine particulate present in the Arctic (Iceland, Alaska, etc.) would be meaningful, too.

We added accordingly: “In addition, Dumont et al. (2014) found that the Greenland springtime darkening since 2009 stems from a widespread increase in the amount of light-absorbing impurities in snow, as well as in the atmosphere. Regarding previous studies, Clarke and Noone (1985) found that the black carbon deposition entailed an Arctic snow albedo reduction of 1–3% in fresh snow and of another factor of 3 as the snow ages. Hansen and Nazarenko (2004) modeled this decreased albedo in Arctic snow and sea ice and found this resulted in a hemispheric radiative forcing of +0.3 W m^{-2}, which may have had a substantial impact on the Northern Hemisphere climate in recent decades.**”**

Dumont M., Brun E., Picard G., Michou M., Libois Q., Petit J-R., Geyer M., Morin S. and Josse B. (2014): Contribution of light-absorbing impurities in snow to Greenland’s darkening since 2009. Nature Geoscience, 7, 509-512.

Clarke A. D. and Noone J. (1985): Measurements of soot aerosol in Arctic snow. Atmos. Environ., 19, 2045-2054.

Hansen J. and Nazarenko L. (2004): Soot climate forcing via snow and ice albedos. Proceedings of the National Academy of Sciences U.S.A., 101, 423-428.

P3174, l3: correct to “In this contribution, we show the result from our research devoted to quantifying fine: : :”

We modified accordingly.

P3175, last paragraph: In the major comments, Pope & Rees was referenced. We studied spectral responses of different ash/debris cover types, and so a standardized method to sample debris may in fact be helpful as a complement.

We added accordingly: “Recently, Pope and Rees (2014) investigated the spectral responses of different ash/debris cover types over Midtre Lovénbreen (Svalbard) and Langjökull (Iceland).**”.**

P3175, last line: “research” should be singular (“researches” is a verb conjugation, never a pluralized noun”

We modified accordingly.

P3176, last paragraph: none of the AWS network information is needed in the text.

We modified accordingly. We added this information in “Acknowledge”.

P3177, L8: should be “: : :we performed 51 field measurements in total on the: : :”

We modified accordingly.

P3179, L11: Brock likely is not the best citation here. Use something like Schaepman-Strub et al 2006 to be more specific about what “albedo” means in this case.

We modified accordingly:
From “The albedo (α) is defined as the broadband hemispherically averaged reflectance in approximately the spectral range 0.3–2.8 µm (Brock et al., 2000) and depends on solar elevation, cloudiness, presence of liquid water, crystal structure, ice surface conditions and the presence or absence of coverage (rock debris, dust, organic matter, etc.).**”,**
To “The bihemispherical reflectance (BHR), generally called albedo (α), is defined as the ratio of the radiant flux reflected from a unit surface area into the whole hemisphere to the incident radiant flux of hemispherical angular extent (Schaepman-Strub et al., 2006) in approximately the spectral range 350-3000 nm (Grenfell, 2011). The albedo is an apparent optical property. This means that it depends on the angular distribution and spectral composition of the ambient radiation field as well as on the inherent optical properties, which depend only on the structural and optical properties of the medium (Grenfell, 2011), then it is important to consider solar elevation, cloudiness, presence of liquid water, crystal structure, ice surface conditions and the presence or absence of materials at the surface (rock debris, dust, organic matter, etc.).**”.**

P3180, last paragraph: When considering the effect of liquid precipitation, it would seem to me that not just the physical action of washing needs to be considered –indeed, if some debris is being removed, where it is then going? Are the authors sure that it is not concentrating on the glacier surface? Also, the role that water plays in internal reflections is important – see Gardner and Sharp for a physical model.

We modified accordingly the Method section: in addition to the washing out effect, we considered also that the run off is able to smooth the ice surface decreasing the roughness and thus increasing the reflectivity.
In addition we added in the Results section the study performed by Gardner and Sharp (2010): "Also following Gardner and Sharp (2010), the liquid water ponding on the surface of glaciers and sea ice can greatly reduce shortwave albedo and increase transmittance by reducing the number of air-ice boundaries that exist near the ice surface**."**

Section 3.3 - Note to editor: I don't have a background in sedimentological analysis and so cannot comment on the specifics of their analysis. Although the scraping, etc does make some sense to me: : : Although scraping could slightly change the surface routing of water, which wouldn't be independent

Generally with the aim at investigating the fine debris features, the upper glacier layer can be removed mechanically or thermally. Then on the one hand, we can scrape the glacier surface with a cleaned chisel or we can cut a block of ice by a chainsaw (e.g. Zapf et al., 2013). On the other hand, we can melt the upper layer of the glacier ice surface by means of a blowtorch and collect the meltwater mixed with fine debris. Nevertheless in our study the sampling was performed always after i) measuring albedo and ii) quantifying the debris cover ratio, thus the sampling method did not affect the obtained relation between d and α.

Zapf A.,A. Nesje, S. Szidat, L. Wacker, M. Schwikowski (2013) ^{14}C measurements of ice samples from the Juvfonne Ice Tunnel, Jotunheimen, Southern Norway - Validation of a ^{14}C dating technique for glacier ice. Proceedings of the 21st International Radiocarbon Conference edited by A.J.T. Jull and C. Hatté. Radiocarbon, Vol 55, Nr 2–3, 2013, p 571–578.

P3182, Line 21: "Image analysis yielded 51 d values ranging: : :"

We modified accordingly.

P3182, Line 22: "radiometer varied from 0: : :."

We modified accordingly.

P3182, Line 24:"are" instead of "result" Also "A" plot, not "The" plot.

We modified accordingly.

*—Fig 5 does give *some(comfidence, but also that the user is just doing something. To help "make it match"*

As observed by the Referee, for low values of debris cover ratio, the correlation appears less accurate. This can be due to the occurrence of other influencing parameters that become dominant whenever debris is poor or quite absent (i.e. d<0.1). Among the most important factors, bubble and other air inclusions modulate the volume scattering and then albedo (see Mullen and Warren, 1988); moreover Grenfell (2011) reported ice inhomogeneities (also at a microscale) to be significant in determining albedo. Nevertheless these other factors become negligible whenever the debris cover ratio is higher than 0.1.
Then we added accordingly: "For low values of debris cover ratio, the correlation appears less accurate. This can be due to the occurrence of other influencing parameters that become dominant whenever debris is poor or quite absent (i.e. d<0.1). Among the most important factors, bubble and other air inclusions modulate the volume scattering and then albedo (see Muller and Warren, 1988); moreover Grenfell (2011) reported ice inhomogeneities (also at a microscale) to be significant in determining albedo. Nevertheless these other factors become negligible whenever the debris cover ratio is higher than 0.1.**"**

Mullem P.C. and Warren S.G. (1988) Theory of the optical properties of lake ice. J. Geophys. Res., 93(D7), 8403-8414.

P3183, last paragraph regarding precipitation: You take into account "liquid precipitation" but do you take into account liquid on the glacier's surface as a result of melt (e.g. days above vs. below freezing) / surface drainage? What about change in ice water content (even from rain) which would be expected due to the difference in spectral irradiance regarding relative amount of light in different wavelengths.

Please see the answer to the previous Referee comment (the third one).

P3184: regarding local source of rock dust – Presumably the regional geology is all quite similar, and so understanding whether the dust was local to the glacier valley as opposed to a few valleys over, or even more distal (but still in a similar geological province) is not possible?

In order to investigate the lithological features of the studied area, we analyzed the geological maps of Sheet 024 – Bormio (http://www.isprambiente.gov.it/Media/carg/24_BORMIO/Foglio.html) and of Sheet 41 – Ponte di Legno (http://www.isprambiente.gov.it/Media/carg/41_PONTE_DILEGNO/Foglio.html). In the Forni Glacier area the main lithology is represented by metamorphic rocks, mostly micaschist rich in quartz, muscovite, chlorite and sericite. On the one hand, outside the Forni Glacier basin at a distance of about 8 km northward (in Sheet 24 – Bormio), there is a lithological and tectonic discontinuity (namely the Zebrù Line). Therein, micaschist are in contact with carbonate-bearing sedimentary rocks (i.e. dolomite). On the other hand, at a distance of about 18 km toward the South the Adamello Pluton (i.e. an intrusive igneous rock) is found. As the X-ray diffraction analysis indicated that our samples from the Forni Glacier are enriched with quartz, muscovite, chlorite and sericite, we concluded that the debris was originated within the Forni Glacier basin, in an area of radius lower than 8 km, thus confirming the local origin.

P3185, lines 12-13: This sentence makes no grammatical sense and I'm sorry I can't understand what it is trying to say. One questions the rate of debris cover addition, but also how a disturbed area would become homogenized, but the importance of the sentence is unclear.

We modified accordingly:
From "As at the each field survey the parcels were not distinguishable from glacier areas nearby, the development of debris coverage resulted occurring at a fast rate."**,**
To "Immediately after each sampling, the cleaned 1 m^2 parcel can be clearly distinguished from the glacier areas nearby. Nevertheless, at the following survey the sampled parcel can not be identified. This suggests that the development of debris coverage resulted occurring at a fast rate.**"**

P3186: While the attempt to include error bars by varying d 10% is appreciated, I don't think this addresses the real issue of error in the method. It is that the selection is restricted only to obvious, concentrated dust. As discussed above, this means that the study is limited to particular kinds of fine debris and also that it not repeatable for another user in the same way as it is for these authors.

We modified accordingly. In particular we investigated the robustness of our image analysis approach with five sensitivity tests: i) the application of other field methods, such as the point intercept, providing a high variability in the results and a general overestimation, ii) the comparison between the T_{GS} values estimated by numerous users obtaining a variability lower than the 10%, iii) the variation of the selected threshold (T_{GS}) up to ±10% for each image, iv) the application as T_{GS} of the most frequent grey tone (i.e. the top of the curve in Figure 3c in the revised manuscript), selecting as debris also the pixel with clean ice, and v) the application of a unique threshold ($T_{GS\text{-}AVE}$) obtained by averaging all the chosen T_{GS}. Moreover during field campaigns we selected 51 sites featuring different debris aggregation (from concentrated clumps of fine debris to fine, distribute, and as-yet-not-consolidated debris).

P3187: Your discussion does not include the role of melt-albedo feedback processes, whether positive (melt -> concentration -> darkening -> more melt) or negative (melt -> runoff -> lightening -> less melt).

Please see the answer to the previous Referee comment (the third one).

P3187: This discussion also addresses the fact that there are spatial and temporal inhomogeneities in the distribution of debris and in glacier albedo. This is already a well-understood conclusion. For this paper to make a more meaningful contribution to the literature, more insight regarding controls on these distributions (as opposed to their presence) would be necessary. The sampling design will be important in these considerations.

In according also to the other Referee, we deleted this part.

P3187 L 9: Starting here, perhaps this is more conclusion rather than still discussion as it repeats earlier discussed material.

We modified accordingly.

Figure 1: the AWS location (black star) doesn't appear be consistent in the map vs the image relative to the glacier terminus. The shading indicating moraines and nunataks also do not appear to be consistent between the image and the map.

We modified accordingly.

Figure 7: plotting in a bar graph in that way implies some meaning to the x-axis of the measurements. Perhaps better to plot in a meaningful order or use a different kind of plot (histogram, etc.)

We modified accordingly. In particular, we explained what is shown in x-axis and we ordinated the samples in a crescent order. Please see the below Fig. 7 (corresponding to Fig. 8 in the revised manuscript).

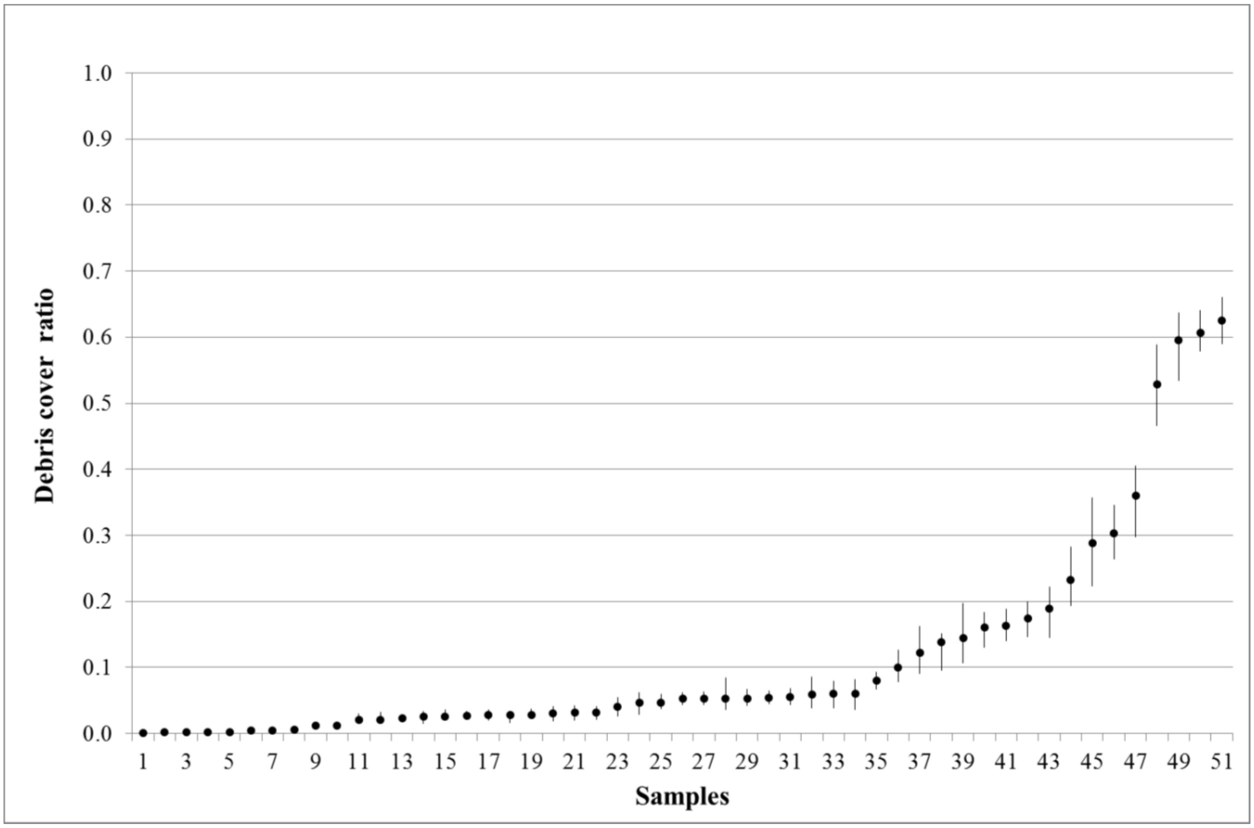

Fig. 7: Values of debris covered ratio (d) from 51 measurements performed in 2011, 2012 and 2013 ablation seasons (black dots). The vertical bars indicate the $d_{+10\%}$ and $d_{-10\%}$ values.

Figure 8: dAVE depends as much on the image collection (exposure, camera model, etc.) as anything else, that its subjective nature precludes its future use as a threshold for others to be able to use. Also, it appears like the correlation may be driven by a small number of almost-outliers (around d > 0.5). These paired considerations need to be addressed to make the inclusion of an average threshold more compelling (or, limit the scope and define that consideration of the average is only to demonstrate the utility of the user-defined threshold).

The pictures were acquired in the same conditions: central hours of the day, clear sky conditions, and occurrence of melting processes then with water at the surface. In this way every images is characterized by similar proprieties of roughness, illumination, water content, etc.
Nevertheless, we modified accordingly:
From "Moreover we also tested the method using a unique threshold value. For this attempt we applied $T_{\mathrm{GS\text{-}AVE}}$ (i.e. 92) obtained averaging all the 51 T_{GS} values thus obtaining 51 d_{AVE} values.**",**
To "Moreover we also tested the utility of the user-defined threshold using a unique value. For this attempt we applied $T_{GS\text{-}AVE}$ (i.e. 92) obtained averaging all the 51 T_{GS} values thus obtaining 51 d_{AVE} values.**"**