Responses to the comments of Referee #1

General Concern

This study investigates changes in the surface albedo of the Zhadang glacier in the southern Tibetan Plateau, a topic of relevance for the special issue that the manuscript was submitted to. Three main issues are explored in this study: (1) trends in the albedo of the glacier during 2001-2010, determined from MODIS satellite observations, (2) the relationship between albedo anomalies and surface mass balance anomalies, and (3) the impacts of black carbon (BC) and dust on the albedo of different parts of the glacier, and under different snow and ice conditions. All of these issues are important and worthy of publication. The discussion of BC and dust impacts is somewhat disconnected from issues (1) and (2), because the in-situ measurements only occurred during July and August of 2012. The study could have been more coherent if the decadal-scale changes in albedo had been linked to changes in dust and BC, but this does not appear possible because of the limited time extent of the ground measurements. Nonetheless, readers will likely be left wondering about the relationship between aerosols and the long-term changes in albedo, and consequently it would be helpful for the authors to comment more on this, perhaps leveraging findings from Ming et al (2012) and others. Such a discussion would help tie the different components of this study together. Aside from this, the issues described below relate mostly to need for justification or more detail on methods.

Re: We would like to thank the anonymous referee for approving the importance of our work and commenting that the work is "a topic of relevance for the special issue that the manuscript was submitted to" and all three issues addressed by our work "are important and worthy of publication".

Zhadang glacier locates very far away from the human settlements, and has no power and accommodation supports. Harshly logistic conditions there do not allow researchers to conduct a long-term in-situ observation to date. Usually, the researchers will choose late springs and summers as the possible campaign time to do some measurements and samplings there. During the melting seasons in some Tibetan glaciers, the reduction of albedo has been related with the deposition of LACs suggested by previous studies (e.g. Ming et al., 2009 in Atmos. Res.; Ming et al., 2012 in ERL; Takeuchi and Li, 2008 in Arctic, Antarctic, and Alpine Research).

In the original ACPD paper, we found a decreasing trend (-0.001 a^{-1}) of the surface albedo in Zhadang glacier during the period 2000-2010, in which the mass balance between 2006 and 2010 is well associated with the variation of albedo. Obviously the albedo decreasing cannot be not primarily attributed to the regional warming which has been sufficiently addressed by many previous studies. However, aside from the warming, the deposition of LACs will also induce surface darkening especially in strong melting seasons, i.e. late spring and summer (See Ming et al., 2009 in Atmospheric Research). It is the very motivation that we conduct this study investigating the variation of surface albedo and the impact of LACs on albedo reduction in various surfaces of the glacier. After collecting more data and adding them into Figure 4, we also found the decreasing trend of surface albedo becomes more robust varying from -0.001 (ACPD) to -0.003 (now) (Fig. S2) and the albedo variations was strongly related with the mass balances between 2006 and 2012.

Most of the revised places are marked in red in the revised manuscript. And English has been improved by Elsevier Workshop.

Issues

1. Why does the MODIS albedo analysis (Figure 4) only extend to 2010? Presumably this could be extended through 2013. (Figure 3 includes 2011 MODIS data). Does the downward trend continue during 2011-2013? Including 2012 MODIS data would also allow a comparison between ASD-measured (in situ) albedo and MODIS albedo, similar

to the comparison between AWS and MODIS albedo that is shown in Figure 3.

Re: Yes, the referee has supposed a very helpful suggestion. Our work was firstly finished in 2012, when the dataset has not been updated to 2012. In the revised paper, we extended the mass balance and MODIS albedo data to 2012, because the dataset of mass balance in 2013 has not been released by the handling institute.

Yes, the decreasing trend of albedo continues to go downward and goes even more negative (-0.003 a^{-1}) than the original one (-0.001 a^{-1}). The revisions have been made in the new Figure 3 and Figure 4.

2. Abstract: Mention that the BC and dust albedo impacts only apply to measurements taken in 2012.

Re: Agree, the statement in the abstract has been revised.

3. p.13111, 11: The "darkening" referred to here probably relates to increasing grain size. I suggest being more precise.

Re: Agree, we revised the statement.

4. p.13111, 26-29: What are these albedo reductions relative to? Are these absolute albedo reductions relative to winter values,

percentages of total impurity-induced albedo reduction, or something different? Please clarify.

Re: We meant to suggest the albedo reduction was due to the deposition of black carbon and dust. We have revised the statements in the context.

5. p.13113, 18-20: Wording here is unclear. Are these criteria applied by the authors, or are they "built in" to the product? Also, is the QA value binary or is it one of several possible values? If the latter, which threshold was applied?

Re: These criteria are applied by us. QA value is binary, “good” or “bad”. We clarified the statement in the context.

6. p.13114, 7: "mounted in a pistol-shaped unit" - Was this a tripod unit? How was leveling with respect to the normal conducted? Please include more detail here.

Re: The unit is a pistol-shape device that the optical fiber can be fixed inside. The pistol was mounted on the rocker arm of the tripod with a gradienter for levelling. We added these statements in the context.

7. p.13115, 7: "snow size" -> "snow grain size".

Re: Has been revised.

8. p.13115, 12: "Snow grain effective radius is taken as the half of observed snow grain size shown in Table 1" - What is the justification for this factor? More generally, it should be pointed out, either here or in section 2.3, that the measure of grain size determined from a hand lens can be quite different from the optical (effective) measure that is relevant for radiative transfer modeling, and consequently uncertainty in snow grain size translates into substantial uncertainty in modeled albedo impacts of impurities.

Re: We used the method introduced by Aoki et al., (2007) to measure the grain size of snow crystal. The grain sizes are measured using a 25X lens, which is not easy for operating and thus generated quite large uncertainties. So we can only take the median from the diameter range of the grain sizes from a few measurements in an individual sampling.

9. p.13115, 13: "The albedo of the underlying ground is taken as ..., based on observations" - For the radiative transfer modeling, these values should represent the albedo of whatever surface underlies the snow, which for a glacier is usually some sort of ice substrate. Do the "observed" values applied here represent bare glacier albedo or something different? Please clarify.

Re: Yes, the observed values represent the albedo of bare ice after scraping the aged snow off. We have clarified it in the revised context.

10. p.13116, 13: "relative to" -> "related to".

Re: We have revised the mistake.

11. Table 2 includes a useful comparison between modeled and observed albedo, but this is not discussed in the text. It would be helpful to include a brief statistical evaluation of the modeled vs. observed albedo (e.g., RMSE, correlation).

Re: We have added some evaluations of the modeled and observed albedo into the context.

12. Discussion in section 3.2: Tables 2 and A1 indicate that the modeling work assumes thin snowpack (2-5 cm). Although these values are consistent with the measured snow thicknesses (Table 1), this configuration with the SNICAR model implies that impurities contained within the ice beneath the snow do not contribute to the radiative forcing calculations. It is unclear how important this assumption is, but it does contribute to a low bias in the RF estimates. This needs to be acknowledged in the manuscript.

Re: Thanks for the comments. We have addressed this concern in the revised manuscript.

13. Figure 3: Do the AWS measurements extend to 2012? If so, it would be very useful to also include a comparison between AWS and in-situ (ASD) measured albedos.

Re: Yes, the referee #2 also raise this question. We have extended the data of AWS and mass balance to 2012.

14. Figure 5: The caption should mention that these RF estimates represent mid-day RF (when the insolation measurements were conducted) rather than daily-mean RF.

Re: Yes, we have revised it.

Responses to the comments of Referee #2

General Concern

The manuscript entitled "The decreasing albedo of Zhadang glacier on western Nyainqentanglha and the role of light-absorbing impurities" by Qu et al. discussed the influences of LACs (light-absorbing constituents, e.g., BC and dust) on the snow/ice albedo and mass balance of glacier based on in-situ measurements and satellite data. Authors found a good correlation between the decreased glacier mass balance and its surface albedo derived from MODIS. The BC and dust are suggested as two dominant factors driving the glacier albedo reduction. From both the science and societal impact perspectives, Tibetan Plateau is a very sensitive and important region in regulating Asian monsoon and hydrological cycle, which would potentially affect the water resources ecosystem, cryosphere change and even national securities in Asian countries. This study provided some very valuable in-situ measurement data over Zhadang glacier in Tibetan Plateau. While this is an interesting and appropriate topic for ACP, especially this SOAR-TP special issue, the analysis procedure of the data and presentation of the article can be greatly improved. Authors failed to present the data in a context that would logically support the major findings. For example, a good correlation between the glacier mass and surface albedo doesn't necessarily mean it must be the snow/ice impurities that caused the surface darkening. Other factors, such as the warming of atmosphere, no matter from whatever reasons, could reduce the snow surface albedo by increasing the snow gran size thought snow aging process, resulting in a glacier mass lose. The lack of long-term measurements of LACs (impurities) in snow/glacier (so no way to support your conclusion in a stronger way) is a serious flaw in this study. Also the presentation needs to be improved. The paper may need more work in improving the writing by a native English speaker. There are quite several grammatical errors or inappropriate use of English. This reviewer suggests that following comments and suggestions should be addressed before the manuscript can be considered for formally publication in ACP.

Re: We would like to thank the anonymous referee for approving the importance of the work and commenting that the work "provided some very valuable in-situ measurement data over Zhadang glacier in Tibetan Plateau" and "is an interesting and appropriate topic for ACP, especially this SOAR-TP special issue". We also think the kind but critical comments from the referee are very helpful to improve the interpretation and presentation further. To improve the English presentation, the manuscript has been submitted to and revised by the Elsevier language editing service. Considering the main points raised by the referee in the beginning of the report have been included in the major and minor comments, we will address the issues raised by the comments item by item in follow.

Most of the revised places are marked in red in the revised manuscript.

Major Comments

1. Surface albedo inferred from satellite measurements have typical errors of a few percent, the bias could be even larger in mountainous area like Tibetan Plateau, so a signal of reduced or increased albedo will be difficult to detect. So how you can detect the albedo trend or change shown in Figure 4 is significant and reliable? The inference of albedo from a nadir radiance measurement can be biased low because of undetected thin clouds, multiple reflectance in the mountains or blowing snow altering the angular reflectance pattern (Warren, 2013). But even if the albedo could be measured perfectly from satellite, its attribution would be ambiguous because of the vertical variation of snow grain size, absorbing aerosol in the atmosphere above the snow, and especially because of sub pixel heterogeneity of the thin and patchy

snow cover of the treeless regions. The spectral signature of thin snow resembles that of BC in snow. For these reasons, Warren (2013) suggests that attempts to use satellite remote sensing to estimate the variability of albedo by BC are unlikely to be successful. Authors suggested a downward trend of albedo in Zhadang glacier as shown in Figure 4. However, it would appear an upward trend if last two years of data are removed. This is a critical issue that should be more carefully addressed.

Re: There are some literatures already discussing the possible usage of MODIS albedo data in mountainous regions, which are properly cited in this study. Warren (2013) suggested that it is unlikely to detect the impact of black carbon on snow albedo by remote sensing, which has been properly addressed in the method section. Particularly in our study, we did some validation work on MODIS albedo data using the observation data measured by the sensors mounted on automatic weather station on the saddle of Zhadang glacier. We collected more mass-balance and MODIS-albedo data on Zhadang glacier during the period 2010-2012 and added them into Figure 3 and 4. The linear relationship in Figure 3 between MODIS and observational albedo data becomes more statistically significant than that in the previous ACPD paper (Fig. S1). And we also found the decreasing trend of surface albedo becomes more robust varying from -0.001 (ACPD) to -0.003 (now) (Fig. S2) and the albedo variations were strongly related with the mass balances between 2006 and 2012.

2. To justify the validity of using MODIS data to look at the trend or variability of glacier albedo, authors tried to use in-situ AWS albedo data to evaluate the MODIS albedo data, see Figure 3. This figure shows an overall positive correlation between these two datasets, but also a remarkable scattering and discrepancy can be seen. Especially, if the 5 points at lower albedo end are removed, the correlation would be much smaller. The in-situ AWS observation

is point measurement but the MODIS albedo represents an average of 500x500 m2 pixel, which could contribute to the discrepancy, especially over mountainous area with complex terrain like Zhadang. This part of discussion should be more carefully revised.

Re: Yes, as pointed out by the referee, the linear relationship in Figure 3 is not very convincible in the ACPD paper, because the data points are more concentrated in the up-right corner. However, after adding MODIS and observed albedo data in 2010-2012, the linear relationship is much more robust (Fig S1).

3. Authors failed to present the data in a context that would logically support the major findings. For example, a good correlation between the glacier mass and surface albedo doesn't necessarily mean that it must be snow/ice impurities that caused the surface darkening. Other factors, such as the warming of atmosphere, no matter from whatever reasons, could increase the snow grain size (through snow aging process) thus reduce surface albedo, resulting in a glacier mass lose. The lack of long-term measurements of LACs in snow/glacier is a serious flaw in this study. This reviewer would suggest more measurement data that can link the snow albedo and impurities should be added in this study to support your conclusions.

Re: The linear relationship between MODIS albedo in the Zhadang glacier and mass balance records is good between 2006 and 2010, and even better after extending the data to 2012. And the relationship is associated with the more and more negative mass balances and lowering surface albedo of the glacier. Besides the warming of the atmosphere, we would like to investigate the impact of LACs on the melting of the glacier in different surface conditions. Summer is the best season that can provide strong melting and frequent snow falls. That's why we did the sampling and in-situ observations. We will input this explanation into the context in order to avoid the further confuse. The measured air temperature in the upper area of the Zhadang glacier during the period 2008 to 2012 does not show increasing trend, but a slight decreasing trend (revised Fig. 4), which does not support that regional warming induces glacier-surface darkening.

Minor Comments

1. Page 13131, Figure 5. How did you calculate the RF driven by BC and dust in the S-I condition? I think the SNICAR model only applies to the impurities in snow rather than glacier.

Re: In S-I condition, bare ice denotes the strongly melting surface with wet snow. Actually, it is still a snow surface, which has been showed in the photo (Fig. 2).

2. Page 13112, line 14. “Dust” -> “dust”.

Re: This has been revised.

3. Page 13113, line 4-5. “The surface conditions are typical in alpine glaciers all around the year” means those conditions are typical all the time in Tibetan too?

Re: These conditions are typical in Tibetan glaciers in summers, which has been addressed in the context with proper citations.

4. Page 13116, line 3-4. The albedo increases with elevation, could it also due to lower BC and dust contained in the snow/ice?

Re: The concentrations of BC and dust in higher snow are indeed lower with higher albedo. Thanks to the referee, we did not mention the point in the context. Now we have properly addressed it.

5. Page 13116, line 17-18. N=6? Or 5?

Re: Originally in the ACPD paper, it should be "5". Now, it should be "7" after adding into two-year data.

6. Page 13116, line 23-26. The BC is accumulates greatly in aged snow/ice, so the concentration in the S-I condition is much higher than the ice core records or fresh snow. The BC concentration in aged snow should not be directly compared with the BC concentrations in ice core or fresh snow.

Re: We have deleted the comparison.

7. In calculation of albedo using SNICAR, please make sure the "MAC scaling factor (experimental)" is not MAC. In SNICAR model, the factor of BC in broadband is 1. If the authors just input "11" in the "factor (experimental)", that'll make the results of albedo reduction higher.

Re: This is a mistake. We re-calculated the results setting the MAC scaling factor (experimental) as 1, which did not alter the results much. The new results were showed in the revised Table 2.

8. Page 13114, line 10, at sites A and B, it was bare ice. So when sampling, the ice just been picked up? Or chop one piece off from the bare ice? I suggest making the sampling procedure clear.

Re: In site A and B, the glacier was covered by aged snow showed in the photo of Fig. 2. We have made it clear in the revised manuscript.

9. Page 13114, line 18, "clean hands-dirty hands", what that means?

Re: In short, "clean hands-dirty hands" means the one whose hands are collecting sampling won't touch any other material that may contaminate snow samples. We have addressed the issue in the revised manuscript.

10. Page 13126, Table A1. “10. Dust concentration (ppm, 5.0–10.0m diameter)” How get the dust grain size (5.0-10.0 um in diameter)? The concentration is based on the different weights of filters before and after filtration? How get the dust diameter?

Re: Yes, the dust concentrations are based on the different weights of filters before and after filtration. Dust grain sizes in Zhadang glacier can be visually measured by simple ways such as a ruler. Thus we chose the largest scale provided by the on-line SNICAR as its diameter.

11. Reference format and arrangement should be corrected.

Re: This has be revised.

12. The paper may need more work in improving the writing by a native English speaker. There are quite several grammatical errors or inappropriate use of English.

Re: The manuscript has been edited for language by Elsevier language editing service.

13. Introduction: the first paragraph seems too long.

Re: The original paragraph has be divided into several parts properly.