Interactive comment on "The growth of sublimation crystals and surface hoar on the Antarctic plateau" by J.-C. Gallet et al.

Anonymous Referee #3

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General comment.

The paper addresses a very interesting subject, and includes the first attempt to explain the observed diurnal formation and evolution of snow crystals at the surface of a cold snowpack. The method adopted to identify favorable conditions for two different mechanisms of snow grain formation is very interesting, although I think it is partly incorrect and it should be refined. In fact, using the adopted method, the conditions for the formation of sublimation crystals occur around noon, during the warmest hours of the day. The authors do not clearly specify which size or shape the hypnotized sublimation crystals would have, but implicitly assume that they would be similar to surface hoar, and they would raise the surface albedo. This contradicts both their observations (see detailed comments below) and previous results (also from the same site, see Pirazzini (2004)), which show that the minimum diurnal albedo occurs in the early afternoon, during the warmest hours. In my opinion, the authors correctly identified the two mechanisms for the formation of surface snow crystals, but instead of applying the maximum subsurface temperature in the calculation of the criteria to identify near surface super-saturation, they should perhaps look at the magnitude of the subsurface temperature gradient. In am not sure though, it is just an instinctive guess, based on the observation that a fast raise in albedo usually occurs in the late afternoon, when the surface cooling becomes strong. I am afraid that the utilized dataset is too limited, and with a too coarse temporal resolution, to unambiguously support the ambitious goal of the paper, but the authors could still try to revise their method. In conclusion, I invite the editor to accept the paper only if the requested major revision will be done.

We wish to thank referee#3 for her/his comments and will answer below in blue.

The referee raises questions about grain size and shape, surface albedo and growth mechanism. First of all, we would like to stress that grain size is not a variable that we feel should be discussed in detail in this paper. It is not clearly defined, is often observer-dependent (Aoki et al., 2000), and SSA is more adequate to characterize snow grains. In particular, to calculate snow albedo, the variable used is optical grain size, directly related to SSA (Carmagnola et al., 2014;Gallet et al., 2009). Regarding crystal shape, our reply is similar to that to referee #2, and we do not repeat it here in detail. In relation to the detailed comment below which is directly relevant to crystal shape, we do not feel that it is simple to apply the observations of (Pinzer and Schneebeli, 2009) to our case. In that interesting work, the authors subjected crystals to alternating temperature gradients so that a given part of a crystal switched from a sublimation zone to a condensation zone. Condensation at a high rate gives facets while sublimation produces rounded shapes (Colbeck, 1983), and the authors found that the net result was rounded shapes. Here, however, both surface hoar formation and sublimation crystals growth are observed at all times. Therefore, even though the temperature gradients are in opposite directions in both processes, one is lead to expect faceted shapes in all cases. Of course, the picture is not that simple, as growth at low rates can lead to rounded shapes (Colbeck, 1983) and growth at very high rates can lead to rounded dendritic tips (Libbrecht, 2005), but our point is that the nice work of (Pinzer and Schneebeli, 2009) may not be applied easily to our case. We will mention all this is the revised version. Regarding albedo, we show in Figure 8 that the albedo is minimal after noon, in agreement with (Pirazzini, 2004) and with the reviewer's intuition. This is because, as shown in Figure 8, the solar zenith angle (SZA) has a predominant effect on albedo. If snow SSA only is considered, then the albedo should maximize after noon, as shown in Figure 8, but the effect of SZA is overwhelming, so that our work in fact perfectly agrees with the reviewer's view point.
Regarding the issue of surface temperature vs. temperature gradient, the referee does not explain why we should use the temperature gradient rather than the snow temperature. We use the

formalism of Style and Worster (Style and Worster, 2009), which uses the temperature rather than the temperature gradient, and we feel that this gives a sensible interpretation. The effect of the magnitude of the subsurface temperature gradient has also been investigated when the density of the surface layer was changed to a lower value. This showed that the lower the snow density (implying a lower thermal conductivity and therefore a higher temperature gradient), the higher the possibility, theoretically, to observe the formation of sublimation crystals. On the time scale of our experiment, we do agree that more data would have been extremely useful. (Pirazzini, 2004) only presented a 2 days measurements period at Dome C and the observed albedo variations are very small, so that detailed conclusions probably may not be drawn. This author only mentioned that the formation of hoar crystals in the morning and their sublimation during the day due to radiative heating might be the explanation of the daily cycle of snow albedo observed at Dome C. No observations and descriptions of the type of snow crystals at the surface of the snowpack are described by (Pirazzini, 2004).

Finally, (Champollion et al., 2013) observed the same type of structure on top of the snowpack at Dome C and they followed the surface for more than a year using an automatic system to take infrared pictures. They observed hoar crystals in winter but hoar and dendritic-like crystals in summer which comforts our observations. Their Figure 10 shows the main wind patterns during their measurements when hoar crystals are observed and when they are not. They also mentioned that these crystals can disappear within a day. Their Figure 10 c shows the main wind direction responsible for the disappearance of surface hoar, which is around 135 degrees. Looking at available data (ftp://amrc.ssec.wisc.edu/pub/aws/10min/rdr/1997/89890197.r), it happened that the wind was blowing from that particular direction from the 21st to the 23rd of January 1997, a few days before the measurements of (Pirazzini, 2004). Therefore, even if hypothesized sublimation crystals were formed at Dome C in January 1997, they would have disappeared following the observations of (Champollion et al., 2013) and would have not been observed by (Pirazzini, 2004).

Detailed comments.

p 5978, section 3.2: the authors discuss the two mechanisms responsible for the daily crystal formation at the surface: nocturnal condensation and diurnal sublimation. The authors should more clearly relate these grain generating mechanisms to the observed grain typologies described in section 3.1: (1) clusters of crystals with sharp, dendride-like outgrowths, 2) faceted crystals, and 3) faceted-round crystals. Or, at least, the authors should clarify which snow grain characteristics (faceted shape, sharp outgrowths?) they associate to the hypothesized crystal formation mechanisms, and why. p. 5978, second paragraph: the observed SSA relevant variations are named as event I.1 and I.2 (increases) and D.1 and D.2 (decreases) in the text, but they are not evidenced or marked as such nor in Figure 2 neither in the rest of the paper. These relevant variations should be put in evidence in Figures 2 and 8, and, above all, they should be referred to in the final discussion and used as a basis for it.

Thank you for this remark. We will clarify this in the revised version, as outlined above and in the response to reviewer #2. However, there are limitations to what can be stated and concluded, because of the difficulties in observing growth in complex crystal clusters. We will nevertheless do our best to provide a reasonable relationship between observed crystal shape and growth mechanism, but some speculation will be inevitable. We will also add the events on Figures 2 and 8.

p. 5984, lines 3-4: “Between 18 January 14:30 and 19 January noon, the SSA increase due to the growth of sublimation crystals. . .” The authors probably refer to the hypothesized sublimation growth occurring on 19 January around noon. If the correct time of the observation on 19 Jan is 11:30 (as in Table 1) and not around 15:00 (as in Figure 2 and 8, see my comment for those Figures), then most probably the observed SSA raise was due to early morning formation of surface hoar crystals (in correspondence of the coldest surface temperatures), possibly preceded by a 18-Jan-late-afternoon formation of sublimation crystals (in correspondence of still warm subsurface temperatures and strong surface cooling).

Thank you very much for that observation, we apologize for that. The correct time is 11:30 as mentioned in Table 1. The rise is due to the formation of sublimation crystals in the morning and until noon on the 18th of January as presented in Figure 6. We never mention that sublimation crystals would form in the late afternoon and our calculations showed that even by modifying the snow density to enhance the temperature gradient and moving the warmest point 1 cm below the snow surface, sublimation crystals never form after 15:00 local time.

p. 5985, paragraph from line 3 to 11: the authors explain that sublimation crystals can be identified as surface hoar if only looking at the crystal appearance. What is then the difference between the two types of crystals? Is there some physical basis to conclude that the two hypothesized formation mechanisms produce similar crystals? The authors should compare their results with the observations of Pinzer and Schneebeli (Pinzer, B. R., and M. Schneebeli (2009), Snow metamorphism under alternating temperature gradients: Morphology and recrystallization in surface snow, Geophys. Res.Lett., 36, L23503, doi:10.1029/2009GL039618), which revealed the lack of facets in grains that underwent to strong temperature gradients.

We will clarify the description of the theoretically shape that are expected but again, as the processes are complex and continuous, crystals are clusters formed by a variety of shapes. As mentioned above, we do not think that it is simple to apply the work of (Pinzer and Schneebeli, 2009) to our case, as conditions are very different.

Figure 2, 4 and 7: Time in x-axis should be labelled in a clearer way (for instance, with more tick marks and shorter labels, showing hours without day and month).

Sorry for that, we will improve the quality of the figures.

Figure 2 (a) and 8: the temporal coordinates of SSA and snow density do not correspond to those marked in Table 1: on 19 Jan 2009, the data marked at 11:30 in Table 1 appear located around 15:00 in Figure 2(a). Albedo time series in Figure 8 corresponds to the SSA time series of figure 2(a) and therefore does not follow Table 1. This is not a small detail, as the corrected figures (supposing that Table 1 is correct) would more clearly show a drop in SSA and albedo during the warmest hours of the day (between 11-11:30 and 14:30-17:00) on both 18 and 19 January, contradicting the main thesis of the paper, which claims that the strong subsurface heating occurring at midday induces a growth of sublimation crystals that increases SSA and albedo.

Regarding the Figure, as mentioned above, this is a mistake of our part and we do apologize for that. It will be corrected. Regarding the drop in SSA and albedo, we believe this can be explained. When sublimation crystals start forming in the day, the growth of small crystals result in an increase in SSA. Subsequently, these small crystals keep growing and become large. Since for all shapes SSA is inversely proportional to size, the growth of crystals translates into a drop in SSA. This process also explains why dendritic frost flowers have a much lower SSA than dendritic snow crystals, as frost flowers are much larger, as explained in detailed by (Domine et al., 2005). As shown in Figure 8, a drop in SSA does not necessarily translate into a drop in albedo, as the increasing solar zenith angle has a prevailing effect over the decreasing SSA.

Figure 4: please show the same time interval as in Figure 2 and Figure 8.

Thank you, it will be modified.

Figure 7: symbols are too small, they can hardly be identified. Color and symbols in the figure’s legend do not correspond to the description in the figure’s caption (probably, in the caption, red should be light blue, and green should be red, right?)

We will improve the quality of Figure 7. The captions are correct. Blue denotes when the density has been modified and lowered with the warmest temperature 1 cm below the surface so that we are in the configuration of the highest possibility to form sublimation crystals and therefore to reach regime VI more often. Red is with the field density, a higher value so that the temperature gradient is lowered compared to the blue experiment and we reach regime VI less often. The caption have been corrected accordingly.

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