Authors reply to Reviewer 2

We thank the reviewer for the sharp comments that forced us to improve the analysis of the results of the two CPR algorithms. Detailed responses to the reviewer's comment and an indication on the action taken on the manuscript are given below.

For the manuscript to be publishable, I think the authors should at least answer the following questions:

1. The difference between KB09 and 2C-Snow is due to (1) temperature threshold for snow, (2) difference in Z-S relation, or (3) difference in surface contamination removal?

We understand the point and we will add a deeper discussion on the discrepancies found on the annual maps among KB09, 2C-SNOW and ERA-I and change the comment to Figures 5 and 6 accordingly. We will also add a new scatterplot between the two satellite estimates according to the different background, after a screening on the 2 m temperature (T(2m) < 0°C), in order to compare annual estimates obtained with the same satellite overpasses and same profiles, and to reduce the impact of melting/liquid precipitation that are not considered by KB09 (see figure 7 below).

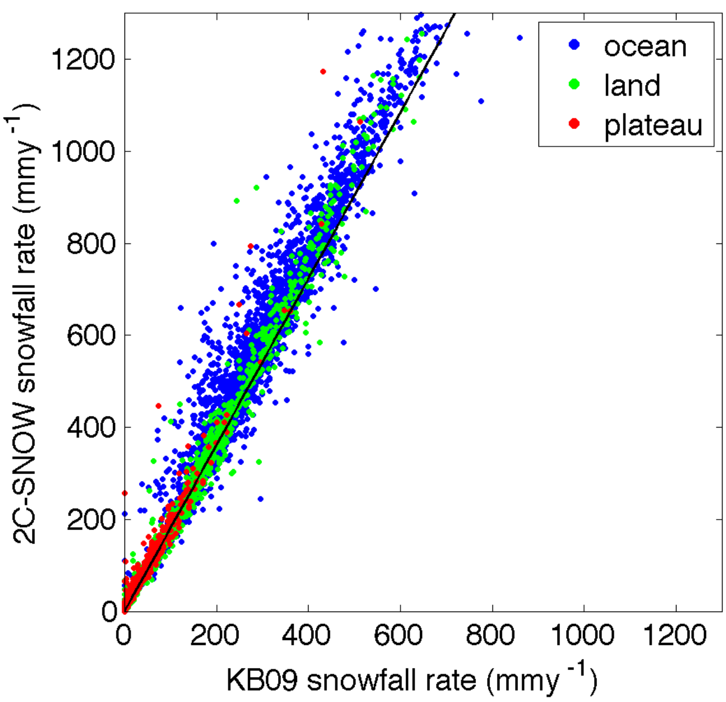

Figure 7

We will add the comment to Figure 7 in the revised version of the manuscript:

"A more direct comparison between KB09 and 2C-SNOW maps is shown in Figure 7, where the two algorithms values are compared for the different backgrounds. An analysis of 2 m temperature (not reported) shows that CloudSat profiles with precipitation and T(2m)>0°C occurred only over Oceans and the extreme Peninsula tip. For this analysis, only observations with T(2m)<0°C are considered, in order to reduce the impact of melting/liquid precipitation that are not considered by KB09 and to compare annual estimates obtained with the same satellite overpasses and same profiles. The high correlation (r = 0.95) evident in Figure 7 points out that on annual scale the main difference between the two retrievals is in the use of the Z-S relationship. The linear relationship holds over the three backgrounds, indicating the lesser impact of other assumptions characterizing the algorithms, such as: determination of near surface bin, vertical cloud continuity, and clutter removal. We remark that for KB09 the Z-S coefficients are fixed for the whole dataset, while for 2C-SNOW they are determined for each profile by the algorithm. Gridpoints classified as "ocean" have higher scatter, due to the higher variability of precipitation structures over the ocean, resulting in a broader range of the Z-S coefficients used by 2C-SNOW. Over the Ocean, KB09 is expected to miss or underestimate shallow precipitation, with respect to 2C-SNOW, due to the higher near surface bin. This results in a distribution of the ocean gridpoints predominantly above the best fit line. Over land, the ground clutter correction is crucial to avoid contamination on annual mean values. KB09 is more conservative, since it screens out reflectivities above 20 dBZ (more likely associated to ground clutter), while the 2C-SNOW retrieval, also applying the ground clutter correction suggested by developers, is still affected by some ground clutter contaminations (see Figure 3, red line). The impact of this residual clutter, however, is negligible at annual scales, as shown in Figure 7, where there is no signal of stationary outliers due to ground clutter."

2. What do the comparison results among ERA-I, KB09 and 2C-Snow tell us, except for saying they are different? Can the authors at least indicate which one is likely more reasonable?

We think that this comment is partially answered by the previous reply. To give a quantitative measure of the differences between the two algorithm we would need a reliable independent measure and perform a "validation". ERA-I is not suitable for this purposes, given the uncertainties related to atmospheric modeling over Antarctica, and the different nature of CPR products and ERA-I reanalysis (mean snowfall rate vs. 12 hours cumulated snowfall). We have used ADG data, with good quantitative agreement in case of monthly mean (POD=0.89, FAR=0.30, CSI=0.64, for KB09, and POD = 0.99, FAR = 0.31, CSI = 0.68 for 2C-SNOW), suggesting that precipitation contributes significantly to the snowfall accumulation variability. The results are more questionable at the event-scale but it has to be remarked that the comparison between instantaneous satellite estimates with ground-based integrated measurements is hindered by several factors, such as the geometry of the observations, the temporal and spatial scale difference of the observed phenomena.

It has to be mentioned that ground validation of satellite estimates of any geophysical parameter is a challenging task, given a number of practical issues that shows up when comparing observations with such different approaches. This is particularly true for precipitation, given the rapidly varying nature of the precipitation fields (see Puca et al., 2014; Porcù et al., 2014). Over Antarctica further problems arise, due to scarcity of observations, their quality, and the occurrence of other phenomena (such as blowing snow, diamond dust…), making the comparison even more challenging. A dedicated campaign should be set up to properly answer to the reviewer request. We remark that neither the KB09, neither the 2C-SNOW are presently optimized for

Antarctica: the developers of 2C-SNOW and KB09 (in collaboration with the first author of this paper) are working in this direction with both algorithms.

The outcomes of this paper will help the developers in tuning the algorithms, for example KB09 developers may consider wet snow, which might have significantly contribution to the snowfall estimates over the ocean, and a lower near surface bin over ocean in order not to miss shallow precipitation. A less conservative ground clutter correction should be applied over land. 2C-SNOW developers could work on ground clutter correction. The suggested procedure to account for ground clutter found in the 2C-SNOW product documentation and applied in the present work, does not completely eliminate the issue (see red line in Fig. 3). Moreover, this paper will help the users of the presently available CPR products to critically interpret the snowfall rate estimates over Antarctica. Both the algorithms are able to identify precipitation features on annual, monthly and single event scale. However, at an annual scale the results are mostly dependent on the Z-S relationship used in the retrieval. Over land and plateau 2C-SNOW shows snowfall mean values similar to ERA-Interim reanalysis and according to this, KB09 underestimates annual mean values by a factor 2. Ground clutter corrections are crucial for annual average values and must be considered in both algorithms. KB09 misses shallow precipitation and it is not a recommended algorithm to be used for shallow precipitation studies.

In the revised version of the manuscript we will add these recommendations in the Conclusions section.

3. The comparison with ADG data (Figs.8 & 9) is confusing. What do these figures exactly mean?

The comparison with ADG data is an attempt to indicate a possible approach to the validation of snowfall rate satellite estimates with some ground reference. Negative difference variations means that the distance between the sensor and the snow surface below have decreased, therefore a snow accumulation is measured, and vice versa. As mentioned, accumulation and depletion of snow level can be due also to many other processes, as indicated in the manuscript and in the literature: this makes our comparison less quantitative, but, in our opinion, still worth to be considered.

I missed the point of this paper. In the conclusion, it says that the intention of the paper is not to identify the best algorithm, but ... However, I am wondering what else a comparison paper is supposed to do. In my opinion, it should give an indication that "this algorithm gives a more reasonable result" although conditions may be added, such as "at such location, during such season, over such time/spatial scale, etc". Otherwise, doesn’t it mean that the comparison has zero impact?

What we address here is the capability of CPR data to reproduce some relevant characteristics of snowfall over Antarctica. These characteristics include: annual accumulation rates, relation between snowfall and cloud cover, seasonal impact on snowfall rate over different backgrounds, typical length of snowfall patterns.

We analyze the results and explain the differences and similarities in relation to the main assumptions in the two algorithms. We provide comparisons also with independent snowfall rate estimates and accumulation measurements (i.e. ERA-I and ADG) at different temporal scales. The important points we address here is that, regardless of the algorithm used, the CPR data provide a reliable picture of the precipitation structures over Antarctica both at a single event scale, and at monthly and seasonal scale. At the annual scale, for all types of surfaces, the most important assumption is the Z-S relationship, while other assumptions (i.e., Near Surface Bin, vertical cloud continuity) are less relevant. A definitive algorithm intercomparison is a rather complex task that would include radiative transfer simulations, cloud physics assumption and a careful analysis of CPR data and products over Antarctica. This is surely out of the scope of the present Journal and, in our opinion, it would deserve a separate paper.

We remark that neither the KB09, neither the 2C-SNOW are presently optimized for Antarctica. Both the considered algorithms are under refinement and future modifications are expected in new releases: we are confident that our work contains useful results to help such refinements (as indicated in the comment n.2).

In the revised version of the manuscript we will modify the Abstract (the revised abstract is reported at the end of this document), as well as some introductory parts and the conclusions, to better illustrate the aims and the results of the paper, and, we will also add further analysis of the results (for example, comment to Figure 7 above).

Revised Abstract:

"Precipitation is a key geophysical parameter in understanding the Antarctic climate and in many other applications such as surface and subglacial hydrology, surface mass balance, weather and climate numerical prediction refinement and testing, cloud processes and latent heath budget studies. However, the particular environmental conditions of the Continent make it difficult to measure directly the snowfall rate, from both ground based instruments and passive space-borne sensors. A significant improvement in the study of solid precipitation over Antarctica is possible by using active space-borne instruments: the Cloud Profiling Radar (CPR), on board the low earth orbit CloudSat satellite, measures the vertical profile of reflectivity at 94 GHz providing narrow vertical cross sections of the atmosphere along the satellite track. Two years of CloudSat data over Antarctica are analyzed and converted in water equivalent snowfall rate, by using two different algorithms.

The aim of this work is to show that, after accounting for the characteristics of precipitation and the effect of surface on reflectivity in Antarctica, the CPR can be used to retrieve snowfall rates on a wide range of temporal scales. Furthermore, the CPR, despite its limited temporal and spatial sampling capabilities, is able to evidence precipitation characteristics difficult to study from conventional ground-based instruments. The differences in the results obtained with the two CPR algorithms evidence critical aspects in the approaches used that need to be carefully taken into account when interpreting snowfall rate estimates over Antarctica.

The results are analyzed in terms of annual/monthly averages and instantaneous values: annual snowfall maps are compared with ERA-Interim reanalysis showing overall agreement, and differences related to the main assumptions in the two algorithms. The effects of coastal areas in

enhancing precipitation rates and cloud precipitation efficiency are recognized, showing also a significant seasonal signal. A comparison with snow accumulation ground measurements shows consistency with the CPR retrievals: all the retrieved snowfall episodes correspond to an increase of snow accumulation at the ground, while several episodes of increase of snow stack height are not related to significant retrieved snowfall rate, likely indicating the local contribution of blowing snow. The results show that CPR data provide rather detailed information on solid precipitation characteristics (i.e., seasonal behavior, impact of physiography, and spatial extension of snowfall patterns) that cannot be extracted from the scarce conventional snowfall measurements over Antarctica."