Authors reply to Reviewer 1

The paper deals with the analysis of two products that use CloudSat data to estimate precipitation rate. These products are then compared to precipitation estimates from model reanalysis data and from some snow depth measurements from 6 surface stations. The paper addresses relevant scientific questions within the scope of this forum.

We thank the reviewer for the straightforward comments: we understood that some key paragraphs of the original manuscript were lacking in clarity, with ambiguities that raised misunderstandings in the reader. We substantially rewrote the Abstract, trying to define better the aim of the paper, and also modified in many parts the discussion of the results and the conclusions, following the reviewer's indications. We address point by point the reviewer's comments below.

Originality (Novelty): Fair

The paper does not really present novel concepts, ideas, tools, or data. It is making use of existing satellite, model, and surface products. The analysis performed is quite standard treatment. The new aspect is the application of this data to the Antarctic. However, the results do not provide any particularly new insight to the treatment of these sources of data. That the CPR on CloudSat can retrieve snowfall rates on a single event temporal scale is not new. Other studies quoted in the references have established this. As an example, the last paragraph of the manuscript reiterates or perhaps confirms the findings of similar studies but offers nothing remarkably original.

We agree with the reviewer that CPR data have been used for many years to infer snowrate at global scale, and the very recent paper of Palerme et al., (2014) used the 2C-SNOW product to compute Antarctic averaged annual snow rate. However, we remark some differences in our work that, in our opinion, make it worth for publication:

1) A global algorithm (KB09) is tuned for Antarctica and applied, discussing the impact of temperature, ground clutter, and Z-S relationship on the results;
2) The first release of 2C-SNOW is dated February 2013, and the team that developed the algorithm is still working to refine the algorithm and test it over remote regions at high latitudes. Any use/intercomparison with other algorithm/data is of interest and can contribute to assess the usefulness of CPR and of 2C-SNOW to depict specific features of precipitation in Antarctica at different temporal scales;
3) We demonstrated that the CPR data, despite the low spatial and temporal sampling, can provide rather detailed information on solid precipitation characteristics that cannot be extracted by no means from the scarce conventional snowfall measurements over Antarctica (i.e. seasonal behavior, impact of physiography, spatial extension of snowfall patterns);
4) The above point is reached by using 2 different algorithms with similar results (in most cases), indicating the CPR usefulness in depicting the main temporal/spatial variability/distribution of Antarctic precipitation. The differences in the results are now more clearly analyzed in relation to the different approaches used (definition of near surface bin, identification of wet snow/liquid precipitation, selection of vertically

continuous clouds, ground clutter correction, choice of Z-S relationship), indicating possible improvements for application of these algorithms over Antarctica and giving the users of the presently available CPR products some suggestions on how to use and interpret snowfall rate estimates over Antarctica;

5) For the first time, we compared snowfall estimate from satellite with ground snow accumulation data. This intercomparison is affected by some shortcomings, but in our opinion, demonstrated, at monthly scale, encouraging results.

We probably did not clearly underlined these topics in the original manuscript, but in the revised form we will put in more evidence the novelty and strengths of the paper, especially in view of the CPR forthcoming mission on the EarthCARE satellite (scheduled in 2017), that will ensure continuity of CPR observations over Antarctica beyond CloudSat.

Scientific Quality (Rigour): Good

The paper does present the information in a straightforward and understandable manner. The scientific methods and assumptions are valid and clearly outlined. The description of data and the calculations are sufficiently complete to be followed and would allow their reproduction by fellow scientists. This is the strength of the paper.

We thank the reviewer for the positive comment: we think that the goal of scientific literature is to provide the scientific community clear tools for progressing in research.

Significance (Impact): Poor

The paper does not really accomplish is stated goal, namely to show how CloudSat in conjunction with other supplementary information can improve the mass balance over Antarctica. Factors that influence this mass balance are discussed and many scientific hurdles identified. The paper claims to evaluating the potentials of CPR for snowfall retrieval in Antarctica – but there is no quantitative evaluation done. Only "possible" explanations that could be applied to evaluations are offered. On balance, there is no significant conclusion reached relative to earlier studies that apply CloudSat information to high latitudes (generally northern hemisphere).

We believe that the Abstract, where the surface mass balance was mentioned with the intention of putting the paper in the broader context, was misleading (in the rest of the manuscript there is no other reference to the mass balance). Surface mass balance computation is not the main goal of the paper, since precipitation can be used also for many other tasks, where the temporal and spatial details are more relevant, such as to support mid to small scale surface and subglacial hydrology, to help in evaluating and refining weather and climate numerical predictions, to study cloud processes, to estimate vertical latent heath exchanges. Moreover, at high latitudes, where ground-based measurements are sparse or unavailable, and where the use of other remote sensing observations for snowfall detection and retrieval is particularly challenging, CPR can provide calibration/validation reference for other estimation techniques based on passive sensors.

The goal of this paper is to show that CPR can be used to retrieve snowfall rates on a wide range of temporal scales and to evidence precipitation characteristics that are not detectable from other conventional instruments or other spaceborne measurements currently available. Quantitative evaluation on the CPR snowfall retrieval has been carried out comparing it with snowfall accumulation at the few ground-based station available, and the ERA-I reanalysis has been used as further comparison to evidence features in the CPR data relative to its temporal and spatial sampling, and to the main assumptions in the two algorithms used in this study.

In the revised version of the manuscript we will modify the Abstract (the modified version of the Abstract is provided 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.

Based also on comment 1) of Reviewer 2 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 figure 5 and 6 accordingly. In particular, we will introduce a new scatterplot between the two satellite estimates according to the different background, considering in both algorithms only CPR profiles with 2 m temperature T(2m) < 0°C (as in KB09), in order to compare annual estimates obtained with the same satellite overpasses and same profiles (see figure 7 below).

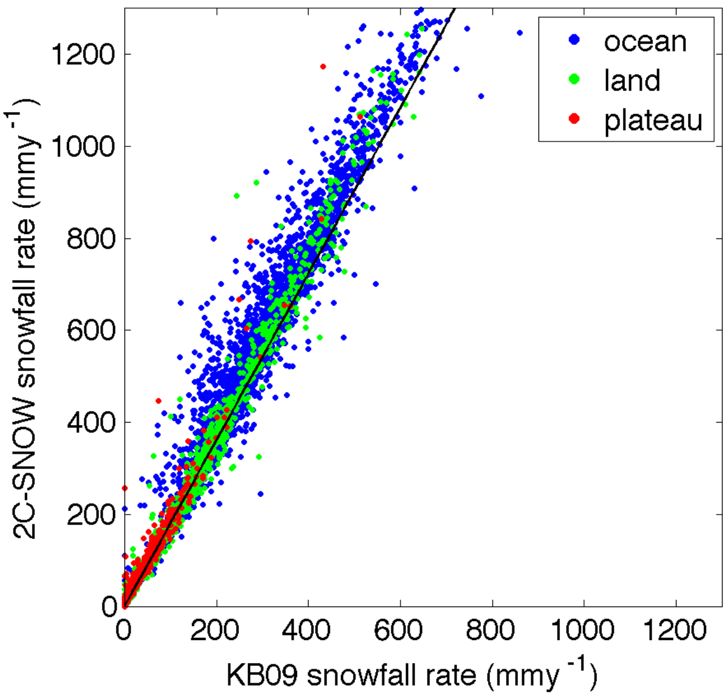


Figure 7

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."

This analysis highlights the negligible impact of other algorithm assumptions (i.e. near surface bin assignment over land or plateau, vertical continuity depth) on the annual values.

Comments within the manuscript such as:

Further studies dedicated to systematic comparisons between different snowfall retrieval algorithms are currently being undertaken …

The systematic comparison between different snowfall algorithms is a rather complex task that would include radiative transfer simulations, cloud physics assumption verification, and a careful analysis of CPR data and products over Antarctica. This is out of the scope of the present Journal and, in our opinion, it would deserve a separate paper. The important points we address here is that, regardless 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.

this comparison is affected by several shortcomings.

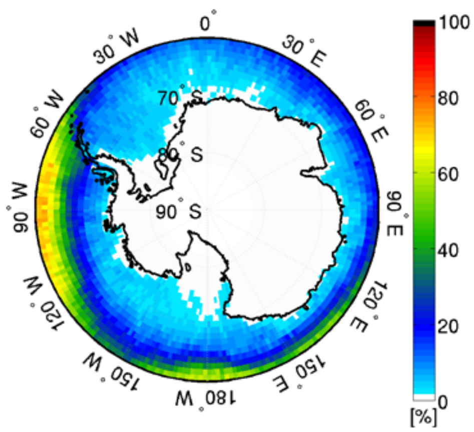
We realized that this sentence was too strong and negative. We reworded to:

"We remark that a number of well known factors (such as blowing snow, diamond dust, etc.) may affect local snow accumulation not related to precipitation from clouds (Knuth et al., 2010; Gorodetskaya et al., 2014), but the relationship between surface measurements and CPR snowfall estimates is found in most cases (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.".

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 show up when comparing observations with such different approaches. This is particularly true for precipitation, given the rapidly varying nature of this field (see Puca et al., 2014; Porcù et al., 2014, among others). Over Antarctica further problems arise, due to scarcity of observations, data quality, and the occurrence of other phenomena (such as blowing snow, and diamond dust), that make the comparison even more challenging.

Further investigation is necessary to assess the effective contribution of wet snowfall or mixed phase to the precipitation.

We made some deeper analysis of the temperature field, showing that the occurrence of wet snow and liquid precipitation is very unlikely over the continent, while is certainly relevant over the Oceans during summer months. We show here the map of the occurrence frequency of T(2m)>0°C. This result will be taken into account in the discussion of Fig. 5 and 6 that will be modified also based on the analysis of the new figure 7 shown above.



However, a direct comparison on single event scale between KB09, 2C-SNOW and ERA-I focused on the solid/liquid discrimination based on temperature thresholds, is not possible given the different nature of CPR products and ERA-I reanalysis (mean snowfall rate vs. 12 hours cumulated snowfall). We will discuss the comparisons of KB09 and 2C-SNOW (for all profiles with T(2m)<0°C) at annual scale, with the introduction of the new scatter diagram, as mentioned above.

This study is not intended for suggesting the best algorithm for precipitation estimation over the Antarctic region, but for:…

In the revised version of the manuscript the sentence reported above will be modified to evidence the goals of this paper, while, we will present as future work the systematic comparison between the two algorithms leading to their optimization for Antarctica.

“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."

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, and the users of the presently available CPR products to critically interpret the snowfall rate estimates over Antarctica.

are exactly the things that need to be carried out to enable this work to be credible.

In our opinion the paper credibility is founded on the results we obtained on: 1) providing annual snowfall maps derived from CPR with two different approaches (KB09 and 2C-SNOW) in quantitative agreement with models (ERA-Interim); 2) explaining the differences in the results on the basis of the assumptions made in the two algorithms (mainly Z-S relation, and to a less extent 2 m temperature threshold and Near Surface Bin selection over ocean); 3) analyzing the seasonal cycle on different surface backgrounds; 4) discussing the impact of moist air lifting over Ocean due to the proximity of the coasts on cloudiness and autoconversion process; 5) showing variability of the typical length of snow patterns; 6) comparing satellite estimates with ground data at monthly and single event scale. Of course, our work leaves many other open questions to be addressed with further research.

The other issue is that many of the things mentioned that are supported by the analysis are just not that significant. Some examples are:

Sec. 3.3 last paragraph: not a compelling argument that the objectives of the paper have been achieved.

We are not sure we understand what the reviewer refers to. The comparison with ADG is carried out "to provide a qualitative measure of the accuracy of the CPR ability to detect snowfall", and it is an attempt to indicate a possible approach to the validation of snowfall rate satellite estimates with some ground reference. We show that good agreement between ground observations and estimates is found at monthly scale, and that at shorter scale it is somewhat lost. However, 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 and the temporal and spatial scale difference of the observed phenomena. More dedicated field campaigns have to be carried out in order to properly "validate" satellite snowfall estimates over Antarctica.

Sec. 3.4: effect of coastline: very qualitative and speculative. The length analysis had a difference of 36 km vs 39 km for the two CloudSat algorithms in the seasonal analysis. This was described as "slightly different behaviour". Hardly significant.

As for the impact of coastlines, we will rewrite the discussion, focusing on the effect of coastal areas on the vertical motion of moist air over the Oceans.

The following paragraph will be added to discuss coastal effects.

"The enhancement of the precipitation in proximity of the coast of Antarctica has been widely discussed by many authors. Smith [1979] showed that lifting of lower tropospheric air approaching a steep high obstacle commences well before the ground surface starts to rise. This upstream effect is partly or completely offset by the downwind drift of falling precipitation particles. This means that precipitation may be occurring some distance offshore solely because of the upstream influence of Antarctic topography. Bromwich (1988) pointed out that precipitation over continental areas near sea level and over near-coastal ocean areas is generated by vertical motion fields associated with cyclones and is fed by the water vapor approaching the continent in the eastern sector of maritime lows. Model simulations from Krinner et al. (2007) showed maximum precipitation over coastal Mary Byrd Land, and secondary maxima on the western side of the Antarctic Peninsula, and along the East Antarctic Coast between 110°E and 150°E. All these features are evident in Fig. 7, both for the KB09 and for the 2C-SNOW results, indicating that the interaction with topography acts on both cloud formation process and cloud efficiency in producing snowfall at the ground."

We understand that the paragraph on the snow pattern lengths is difficult to read, and some sentences are not clear. We will reword the paragraph, also introducing a table to complete the analysis and make the discussion more clear.

		ANNUAL	MAM	JJA	SON	DJF
Mean (km)	KB	44.9	43	52.7	48.6	36.2
	SNOW	41.7	38.6	46.4	46.5	35.7
% < 10km	KB	37.5	38.2	35.1	36.0	40.4
	SNOW	41.9	43.7	40.6	39.6	43.2
% 10-100 km	KB	46.9	46.5	47.3	47.5	46.3
	SNOW	43.4	42.2	43.5	44.5	43.7
% >100 km	KB	10.2	9.7	12.6	11.2	7.6
	SNOW	9.2	8.5	10.5	10.4	7.6

The relation between cloud cover and snowfall frequency highlights the impact of coastal orography in enhancing the snowfall occurrence – again hardly significant

We acknowledge that this sentence in the Conclusion section does not adequately report the discussion of Figs. 5 and 7. In the revised version of the manuscript the discussion of Fig.5 and Fig. 7 will be extended to analyze more in detail the impact of the coast and topography in enhancing cloudiness and autoconversion processes leading to precipitation, as indicated in the previous comment to Sec. 3.4.

Presentation Quality: Good

The mathematical formulae, symbols, abbreviations, and units are correctly defined and used. There are no superfluous figures. The number and quality of references is appropriate and gives proper credit to related work.

The overall presentation is well structured and clear generally. However, the abstract is not very concise and could be reworked.

We thank the Reviewer for the positive comment. About the Abstract, we agree. We will completely rewrite the Abstract, making it shorter, more keen and concise. The new abstract is reported at the end of this document.

Specific comments are listed below:

The last two paragraphs of introduction are devoted to previewing results later in the paper. These paragraphs could be reduced as much of it is mentioned later in the paper.

We agree with the reviewer and we will reduce the two last paragraphs, minimizing the references to the work presented in the paper.

Sec 2.1 pg. 147, l 24: more information on the CloudSat data quality flag would be helpful.

We will modify the sentence, better illustrating the quality flag. The sentence in the revised manuscript will read as:

“A data quality flag is also delivered in 2B-GEOPROF (and other CloudSat products), to indicate the presence of corrupted data, and we considered only profiles with the highest quality.”

Sec 2.1.1 pg. 149,l 18-24: long awkward worded sentence. Split into 2 or 3 separate sentences.

Agreed. We will split the sentence in 2, that in the revised manuscript it will read as:

“The number of such contaminated bins is very low (around 10^{-5} of the total), but screening them out is important because they could result in very high snowfall rate, with an impact on the mean precipitation values. Within the OP, the correction due to the screening of these bins is around 0.37% over the whole Antarctic region (below 60 S), but it increases to 3.53% if we consider only the land below 2000 m where the ground clutter contamination is expected to influence more the reflectivity values.”

And also we’ll modify the similar sentence on page 150 (lines 19-24) in the original manuscript, that will be:

“As for the KB09 algorithm, the number of bins affected by ground clutter is not very high (also in this case only 10^{-5} of total profiles within the OP), but enough to affect mean snowfall rate values.

The annual mean snowfall rate decreases 1.3% over the total Antarctic region, but more than 9.6% if we consider only the grounded ice sheet below 2000m where the ground clutter contamination is expected to be higher”

Sec. 2.1.2 pg. 152, l 6: seems strange to include station 08915 in the monthly analysis as well (Fig. 9).

We agree on this comment and removed station 08915 from the monthly analysis, considering also its negligible impact on the results.

Figures 4, and 8, and results in Table 2 and 3 (slightly changed) have been modified accordingly,

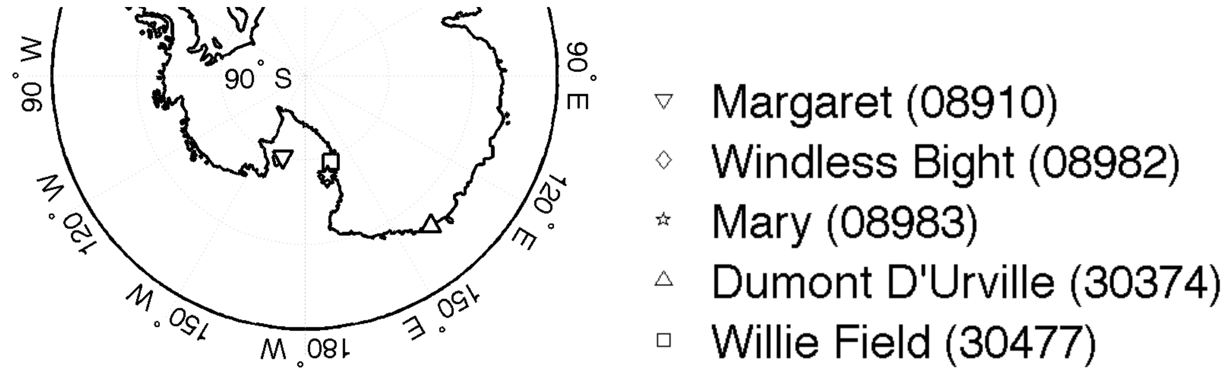


Figure 4

KB09	Monthly mean snowfall rate >0	Monthly mean snowfall rate =0
Distance difference <0	67	9
Distance difference >=0	29	11

Table 2

SNOW	Monthly mean snowfall rate >0	Monthly mean snowfall rate =0
Distance difference <0	75	1
Distance difference >=0	34	6

Table 3

I suggest replacing the term rain gauges with precipitation gauges.

Agreed.

Sec 3.1 pg 154 l 13-25: very poor, ambiguous worded paragraph.

This paragraph will be rewritten, taking into account the better analysis of the differences between KB09 and 2C-SNOW maps, as indicated in a previous comment on Significance.

Sec 3.1 pg 154 l 17: define “significant”.

We will replace “significant” with “marked”.

In the discussion of Tables 1, 2, and 3, listing standard skills scores like CSI could reduce the wording in the text and make the results more discernible.

Agreed. We will introduce a table (Table 4) with a list of scores such as POD FAR and CSI to improve the clarity of the discussion

	2C-SNOW	KB09
POD	0.99	0.89
FAR	0.31	0.30
CSI	0.68	0.64

Table 4

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. "