Response to Reviewer 2 Comments: *Evaluation of the CloudSat surface snowfall product over Antarctica using ground-based precipitation radars*

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September 4, 2018

For clarifying our answers to the reviewers' comments, the following color scheme is used: comments of the reviewer are denoted in blue, our answers are denoted in black and quotes from the revised text are in green.

Before addressing the comments of the reviewer, it must be noted that during the revision process there was detected that a small part of erroneous MRR data at the PE station was included in the analysis. This erroneous data was recorded during the 2015-2016 austral winter season and was caused by interference from other instruments. It was removed from the sample lowering the period of concurrent data availability of the MRR and CloudSat from 928 to 851 days for the PE station (Fig. 2 in the main paper). This mainly affects Fig. 6 in the main paper where a clear lowering of both the MRR and CloudSat total precipitation amount is observed. However, as the total snowfall amount for both the MRR and CloudSat lowered with an equal amount, results and conclusions are not affected significantly.

The paper explores various parameters of the CloudSat snowfall climatology proposed by Palerme et al. (2014), such as its temporal sampling rate and its spatial resolution. This climatology is evaluated by way of a comparison with observations from three different ground micro-rain radars. It is also compared with ERA-Interim reanalysis, which is designated as a reference in regards with the simulated Antarctic snowfall. The authors conclude that the CloudSat snowfall climatology, at a resolution of 1° latitude by 2° longitude, represents well the snowfall climatology of each MRR site and is more effective than ERA-Interim reanalysis, but cannot be considered for individual snowfall events. The topic of the paper is certainly appropriate for The Cryosphere, and assesses the CloudSat climatology as an effective tool for validating climate models. The manuscript is presented clearly, however, after reviewing this article, I have a few scientific questions that I will explain below.

We thank the reviewer for the review of the manuscript. The specific comments are addressed below.

Page 5, 15th line. It is mentioned that the difference between CloudSat

(1200m a.g.l.) and the MRRs (300m a.g.l) is valued by 9-11%, according to Maahn et al. (2014) at the PE station while at DDU it equals 13%. According to recent studies (such as Grazioli et al. (2017)), coastal areas, such as the DDU and MZ stations are blown by sudden strong katabatic winds. The authors could have compared snowfall rates at the vertical MRR level corresponding to CloudSat first bin. Afterwards they could have evaluated the discrepancies of each MRR between 1200m and 300m a.g.l. by studying their vertical profiles, instead of considering an estimated value of the gap between CloudSat and ground radars.

The goal of this paper is mainly to evaluate the performance of the CloudSat snowfall product as an estimator of the surface snowfall amount, which is the currently the main use of the product in the cryospheric community. This is the reason why we have evaluated the CloudSat product (at 1200m a.g.l.) against the MRRs (300m a.g.l.) as these are the closest observations of snowfall currently available over the AIS. We have clarified our goal in the main text.

The main interest of the paper is to evaluate the CloudSat snowfall product as an estimate of the surface snowfall amount, which is the primary application for both the observing and modelling community. As such, the lowest usable measurement bin of both instruments is considered in the analysis.

The CloudSat snowfall climatology provides very good results compared to MRR total snowfall amount records for all three stations, showing the skill of CloudSat for the estimation of the surface snowfall climatology over the AIS, outperforming ERA-Interim reanalysis.

It is acknowledged that this approach includes several deficiencies. As stated by the reviewer and observed by Maahn et al. (2014) for the PE station and Grazioli et al. (2017) for the DDU station, there can be a large discrepancy between the snowfall rates obtained at the CloudSat and MRR acquisition level. It is therefore appropriate to also investigate these differences in this paper and to not only rely on the results of previous work to gain more insight in the performance of CloudSat and the MRR at the same height acquisition level. As such, part of the analysis was repeated using MRR snowfall rates acquired at the 1200m a.g.l. measurement bin.

Fig. 6 & 7 from the main paper are reproduced for MRR measurements at 1200m a.g.l. (Fig. S1 & S2 in the Supplement; Fig. R1 & R2 in this document). A lowering of the total MRR snowfall amount is observed for all stations. For the PE station, a 26% decrease in total snowfall amounts is observed. This value is much larger than the number obtained by Maahn et al. (2014) which only found a decrease rate of 11%. The discrepancy between both values can be attributed to the lack of data availability in the study of Maahn et al. (2014). There, only one full year of MRR measurements was available, namely 2012. In 2012, no heavy snowfall events were recorded with precipitation rates exceeding 1 mm/h. In our study, data from 2010-2016 was included. During this longer time period, several large events (> 5 mm/h) were recorded. An overview of the total snowfall amount as a function of height is added to the Supplement (Fig. S3; Fig. R3 in this document). Over the PE station, large snowfall events have the tendency to attribute for large amounts of augmentation in the lowest kilometer of the atmosphere. Furthermore, a distinct number of these large snowfall events have a vertical extent less than 1 km. An example of these types of events are given in Fig. R4. As these events occurred less often in 2012, Maahn et al. (2014) obtained lower values.

For the MZ station, the same amount of precipitation reduction is obtained as for the PE

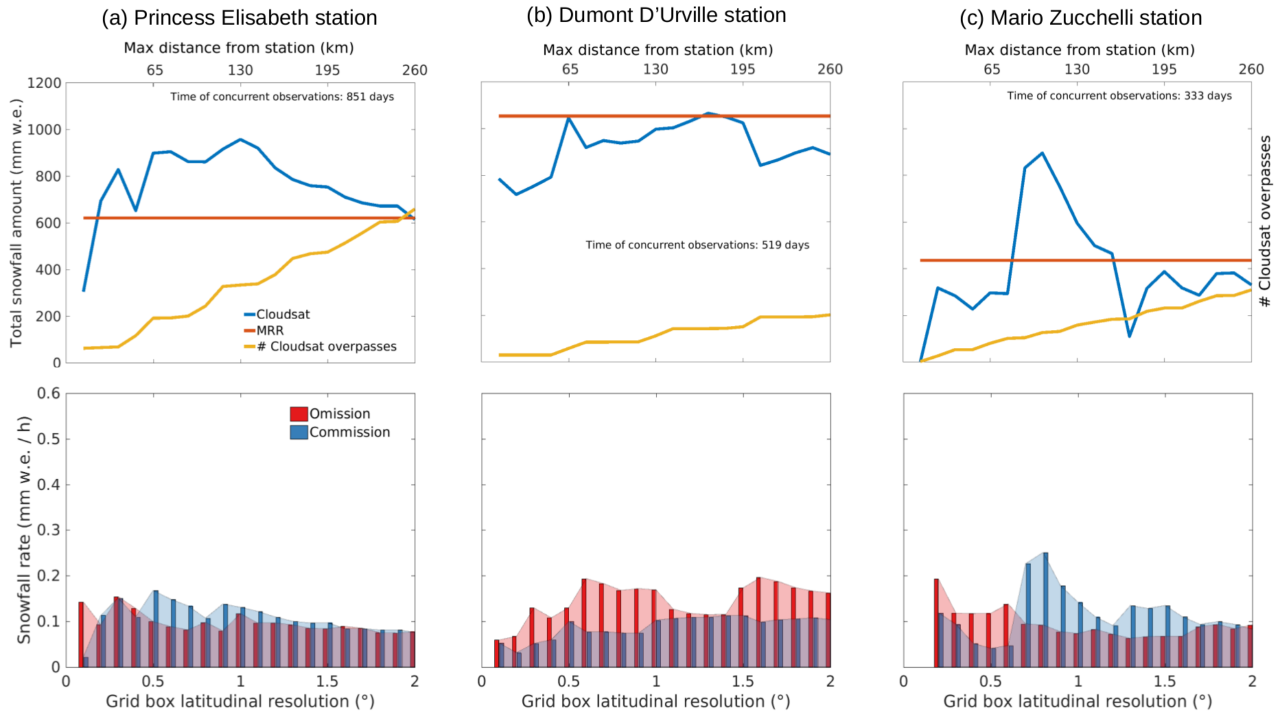

Figure R1: (first row) Overview of the total snowfall amounts for the three stations as observed by CloudSat and the Micro Rain Radars during the periods of collocated measurements (Fig. 2 in the main paper). (second row) Individual snowfall event error analysis. As Micro Rain Radar snowfall rates are considered truth, omission errors are defined as an underestimation, while commission errors are an overestimation of snowfall rates by CloudSat. The x-axis denotes different spatial resolutions of the CloudSat climatology (grid box longitudinal resolution = 2 * grid box latitudinal resolution).

station (25%; Fig. R1). The vertical profile of total precipitation shows that the layer of maximum precipitation extends up to 700m after which a sharp decrease is found (Fig. R3). Similar precipitation events as found for the PE station and visualised in Fig. R4 have been observed. This leads to the large difference in precipitation amounts between the 300m and 1200m a.g.l. level.

For the DDU station, a reduction in total snowfall amount of 8 % was observed between the 300 and 1200m a.g.l. level (Fig. R1). This low value can be attributed to the fact that precipitation systems at DDU have a much larger vertical extent and highest precipitation numbers are not limited to the lowest layers. As the augmentation layer extents to higher altitudes, a better agreement of snowfall rates between altitudes of 300m and 1200m a.g.l. is obtained.

These results are now referred to in the main text.

The data acquisition height difference between CloudSat (1200m a.g.l.) and the MRRs (300m a.g.l.) accounts for an average underestimation of 25 % in total snowfall amount by CloudSat compared to the MRR at the PE station. At the DDU station this equals 8 % (Grazioli et al., 2017), while at the MZ station, an underestimation of 25 % is obtained. A discussion on the source of this discrepancy in snowfall amount between the 300m and 1200m level can be found in the Supplement (Text S1 and Figs. S1-S3).

It is remarkable that for the PE and MZ station, the comparison between CloudSat and

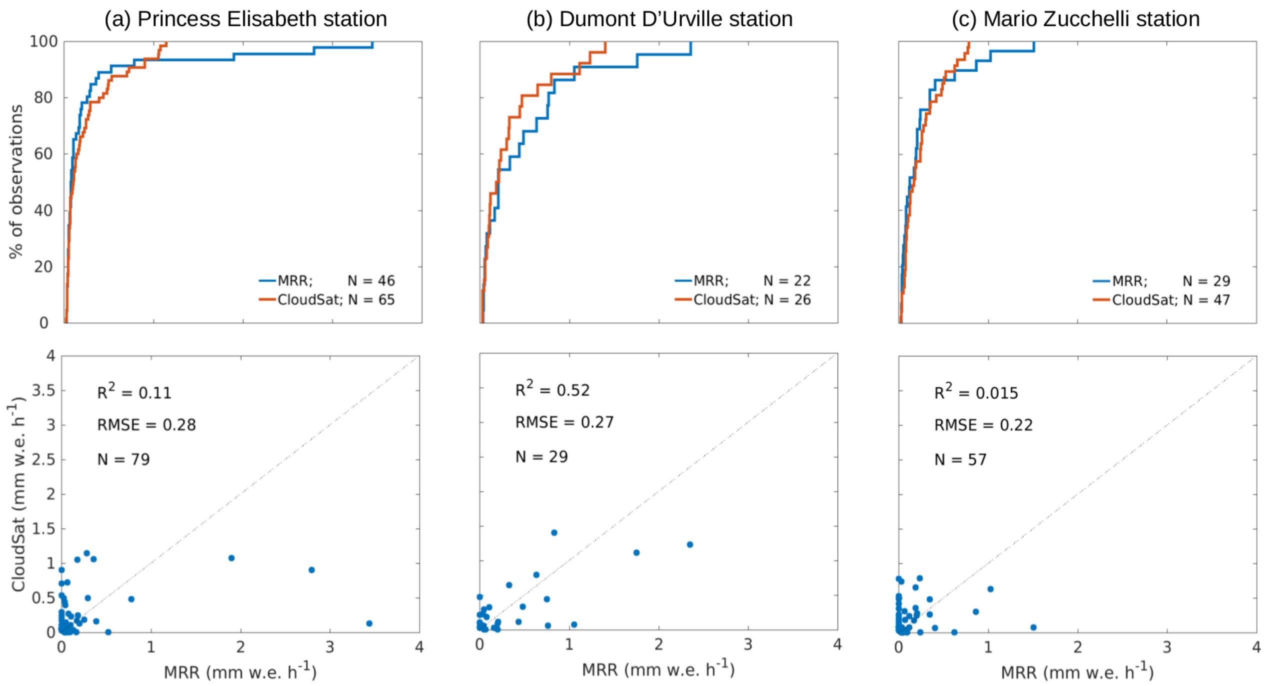

Figure R2: (first row) Empirical cumulative distribution of MRR and CloudSat snowfall events at a spatial resolution of 1° latitude by 2° longitude. (second row) Direct comparison between MRR and CloudSat individual snowfall events. R^2 denotes the adjusted coefficient of determination, RMSE is the root mean square error, N indicates the number of observations, while the thin line is the bisector.

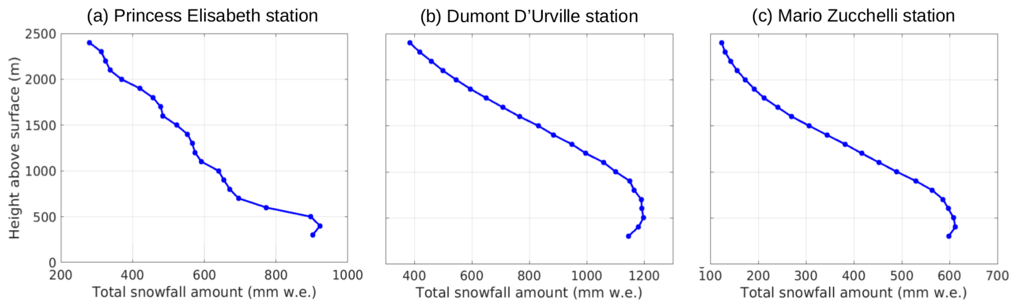

Figure R3: Total snowfall amount as a function of height above ground level as obtained by the MRRs for the periods of concurrent measurements depicted in Fig. 2 of the main paper.

the MRR both measuring at 1200m a.g.l. attributes for less good results compared to MRR measurements at 300m a.g.l. (compare Fig. 6 in the main paper and Fig. R1). This shows that CloudSat overestimates the precipitation amount at 1200m a.g.l. leading to commission errors. CloudSat has a tendency to overestimate the frequency of snowfall events, attributing for the worse performance, even though a better match in the cumulative distribution is obtained (compare Fig. 7 in the main paper and Fig. R2).

Furthermore, the difference in acquisition height between both instruments is not taken into account in the above analysis. In case the MRR measures snowfall rates at the same level as CloudSat (i.e. 1200m a.g.l.), a significant lower amount of snowfall is recorded. As CloudSat is known to overestimate the frequency of small snowfall events (Chen et al., 2016), this can be interpreted as an extra source of commission errors, although a better match in the cumulative distribution is achieved. A thorough discussion on this discrepancy can be found in the Supple-

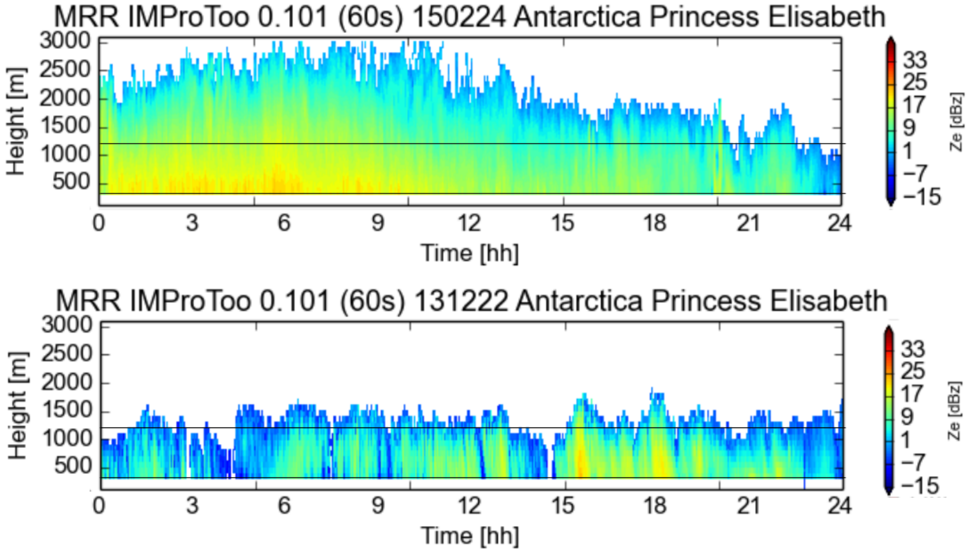

Figure R4: Radar reflectivity spectrum for two snowfall events at the PE station (upper: 24 Feb 2015; lower: 22 Dec 2013).

ment (Text S1 and Figs. S1-S3).

As some interesting new insights are obtained, a text discussing these issues was added to the Supplement.

Apart from evaluating the CloudSat snowfall climatology and individual events (obtained at 1200m a.g.l.) with MRR measurements at the level closest to the surface (300m a.g.l.), an extra comparison is executed by including MRR measurements at 1200m a.g.l.. The higher level of snowfall rate acquisition of the MRR leads to a decrease in the total snowfall amount of 26 %, 8 % and 25 % for respectively the PE, DDU and MZ station compared to measurements at 300m a.g.l. (compare Fig. S1 and Fig. 6 in the main paper). The total snowfall amount as a function of height is visualised in Fig. S3 and is characterised with a typical shape for all stations. Highest snowfall rates are usually obtained a few hundreds meter above the surface. Towards the surface lower values are observed, induced by katabatic winds that cause sublimation (Grazioli et al., 2017). The decrease towards higher altitudes is governed by the vertical extent of the precipitation systems, which are often present only in the lowest layers of the atmosphere (Maahn et al., 2014). For the PE and MZ station, larger discrepancies between the 300m and 1200m a.g.l. level are obtained. This can be attributed to the fact that for these stations, highest precipitation intensities are mainly located below 700m a.g.l., indicating that the vertical extent of the precipitation systems is generally low for these stations (Fig. S3). For the DDU station, precipitation systems usually have a larger vertical extent. Therefore, the steady decrease in snowfall rates for higher altitudes only starts from heights over 1000m a.g.l., attributing for the minor differences in snowfall rates between the 300m and 1200m a.g.l. level for this station.

The lower total amount of snowfall rates obtained at 1200m a.g.l. by the MRRs leads, counter-intuitively, to worse performances compared to the snowfall rates obtained by CloudSat at 1200m a.g.l. for both the PE and MZ station (compare Fig. S1 and Fig. 6 in the main paper). When investigating the cumulative distribution of snowfall rates obtained by both instruments, a better agreement is obtained for both stations compared to the initial assessment using MRR measurements at 300m a.g.l. (compare Fig. S2 and Fig. 7 in the main paper).

The main reason for the overestimation of CloudSat snowfall rates compared to MRR snowfall rates at 1200m a.g.l. is therefore attributed to the much higher frequency of snowfall events detected in CloudSat (Chen et al., 2016), leading to high commission errors. In the comparison at 300m a.g.l., this overestimation of the frequency of snowfall events was compensated by the higher snowfall rates registered by the MRR (omission errors; Fig. 7 in the main paper), which is not the case at 1200m a.g.l. (Fig. S2). For the DDU station, the frequency of snowfall event detection is approximately equal, explaining the better performance for this station.

Page 5, 20th line. The difference in snowfall rate between the first bin of the MRRs and the surface is not considered in this study. It has been simulated by ECMWF IFS (Grazioli et al., 2017) that 35% of the snowfall is sublimating in the lower kilometer of the atmosphere over the Nov-2015 to Oct-2016 period, where the surface is lower than 1 km above sea level. By studying the average vertical profiles of each MRR over their corresponding periods of observation, can the authors establish a trend from this sublimation to the surface, quantify it and estimate its effect on their ground snowfall estimations?

It is indeed noted that the lowest bin of the MRR cannot be considered ground-truth and that significant amounts of sublimation can occur between 300m a.g.l. and the surface. This is a drawback of the study which needs to be considered by the reader.

For the PE station, the amount of sublimation between the lowest measurement bin of the MRR and the surface was calculated using the height correction of Wood (2011), by extrapolating the trend in the lowest MRR vertical levels towards the surface to account for horizontal displacement and sublimation. This resulted in an average decrease of radar reflectivity of 1.66 dBz in case sublimation was detected in the lowest bins of the MRR (Souverijns et al., 2017) and would lead to an overestimation of the snowfall rate by 29 %. As this correction was only applied during events with a clear sublimation signal (approximately 15 % of the precipitation events), the impact on the total snowfall amount is limited.

For the DDU station, three model simulations have been performed simulating the vertical profile of precipitation. Based on the results of Fig. 2 of Grazioli et al. (2017), two models predict an overestimation of 7 % of the cumulative snowfall record at the 300m a.g.l. level compared to the surface.

As the reviewer suggests, it is possible to extrapolate the trend from the lowest measurement bins towards the surface using a similar approach as applied in (Wood, 2011; Souverijns et al., 2017). This leads to an overestimation of 14 % of the total snowfall amount at 300m a.g.l. compared to the surface for the PE station, 9 % for the DDU station and 7 % for the MZ station. These numbers are in line with the results of Souverijns et al. (2017); Grazioli et al. (2017) for the PE and DDU station respectively discussed also above. The difference in numbers for the PE station between this study and Souverijns et al. (2017) can be attributed to the fact that different time periods are studied.

The description of sublimation in the lowest layers of the atmosphere is expanded in the main text.

Furthermore, sublimation persists towards the surface, also influencing the layer between the lowest measurement bin of the MRR (i.e. 300m a.g.l.) and the surface, where typically an inversion and katabatic flow is present (Grazioli et al., 2017; Souverijns et al., 2017). The amount of *sublimation in the lowest 300m of the atmosphere can be calculated by extrapolating the vertical trend in snowfall rates towards the surface following the approach of Wood (2011) leading to an overestimation of the snowfall rate at 300m a.g.l. of 14 %, 9 % and 7 % for respectively the PE, DDU and MZ station compared to the surface. One must note that sublimation increases the saturation level of the atmosphere, negatively influencing future sublimation. Therefore, the method of Wood (2011) might overestimate the amount of sublimation. The discrepancy in the lowest 300m of the atmosphere is not considered in this study but needs to be accounted for.*

Page 13, 27th line. When the authors mention that "CloudSat is not able to capture individual snowfall events adequately at a single location", I think the authors should be more specific about that assertion. Indeed for specific precipitation cases, when the satellite overpasses a station closely, if the ground-radar and the CloudSat radar are properly calibrated and their Ze-Sr relations well-established, they should capture a similar precipitation rate.

This is a correct remark by the reviewer. As both the MRRs and CloudSat apply the same detection principle, are well-calibrated and have well-established Ze-SR relations, both instruments are expected to record similar snowfall rates when operating over the exact same area. This was recently shown to be the case for a number of exact overpasses between CloudSat and the MRRs at the PE and DDU station (presentation Florentin Lemonnier at POLAR2018 conference in Davos: `Wed_8_AC-2_746`: Comparison Between Cloudsat and In-situ Radar Snowfall Rates in East Antarctica). In this work we showed that individual snowfall events cannot be captured by CloudSat when averaging over a spatial domain (i.e. a grid of 1° latitude by 2° longitude). This does not apply to very close overpasses as noted by the reviewer and has been clarified throughout the text.

In the abstract there is referred to the CloudSat product (gridded): *Moreover, the CloudSat product does not perform well in simulating individual snowfall events.*

Introduction: *Furthermore, an overview of the discrepancies between the CloudSat product and the MRR snowfall rates are identified by comparing individual snowfall events (Sect. 3.2).*

Material and methods: *Furthermore, the performance of individual event detection of the CloudSat product and ERA-Interim reanalysis is investigated.*

Results and discussion: *One must understand that the accurate total snowfall amounts obtained by CloudSat can not be attributed to the fact that the satellite is recording correct individual snowfall quantities for each grid box, but to the fact that omission and commission errors cancel each other out. Consequently, it can be concluded that the gridded CloudSat product is not the right tool to investigate individual snowfall events / synoptic events at a single location.*

Results and discussion: *As the CloudSat domain spans several tens of kilometers at a resolution of 1° latitude by 2° longitude, it often detects small snowfall events near the station. The detection of these small-scale snowfall events is the main contributor to commission errors compared to the MRRs at this spatial resolution (Fig. 6). In addition, the direct comparison between individual events detected by the MRRs and CloudSat shows a large spread and low correlation (Fig. 7). This indicates again that the gridded CloudSat product is not able to capture individual snowfall events adequately at a single location.*

Results and discussion: *For the validation and identification of individual snowfall events,* *the ERA-Interim reanalysis product however outperforms the CloudSat-derived product.*

Conclusions: *However, for individual snowfall event identification, ERA-Interim reanalysis outperforms the gridded CloudSat product for all stations.*

Conclusions: *Apart from that, the gridded CloudSat product is not advised for the validation of individual snowfall events.*

Page 14, 1st line. ERA-Interim reanalysis provides surface snowfall. Is it relevant to compare this surface product with 1200m a.g.l and 300m a.g.l observations? Do you take into account the effects of the low level sublimation processes on the first bin CloudSat and the first bin MRR measurements?

As noted in the previous comments, both the CloudSat snowfall climatology achieved at 1200m a.g.l. and the observations from the MRR at 300m a.g.l. do not represent the surface snowfall amount. The goal of the paper is to evaluate the CloudSat snowfall product as an estimator of ground-based precipitation. As such it is necessary to compare with products that provide surface snowfall rates (as ERA-Interim).

In the comparison with the MRR, one needs to take into account the overestimation of snowfall amounts that is obtained from measuring at the 300m a.g.l. level. compared to the surface, which accounts for 14 %, 9 % and 7 % for respectively the PE, DDU and MZ station. In the manuscript it is clarified to take into account this discrepancy between the 300m a.g.l. level and the surface and to clarify that the goal is to evaluate the performance of CloudSat for ground-based precipitation amounts.

An assessment of the accuracy of CloudSat as a surface snowfall product compared to ERA-Interim reanalysis is therefore viable.

Regarding ERA-Interim reanalysis, for both the PE and MZ station, the daily average snowfall amount is underestimated (respectively by 18 % and 45 %), while for the DDU station, ERA-Interim reanalysis outperforms the CloudSat snowfall estimate (bias is limited to 6 %). Here, one must take into account that the MRR measurements slightly overestimate the surface snowfall product (see Sect. 2.3).

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