### Response to Reviewer 1 Comments: Evaluation of the CloudSat surface snowfall product over Antarctica using ground-based precipitation radars

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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.

This study evaluates the surface snowfall measured derived by CloudSat by comparing it with the product from ERA and Micro Rain Radar signals over Antarctica. The study brings valuable information to the scientific community to better understand changes in snow cover over Antarctica. It uses a combination of ground instruments, satellite and reanalysis data. It was found that CloudSat does not measure well snowfall because of the lower time resolution of passes of the regional whereas ERA covers the entire continent with 3 hourly outputs. The snowfall measured by the MRR is similar to ERA because it can capture single events as opposed to CloudSat. This study contributes to better understand the evolution of snow cover in Antarctica. Finally, the English and the clarity of some figures should also be improved.

The reviewer is thanked for the review of our manuscript. Improvements regarding the clarity of the figures and the language are discussed in the individual comments below.

1. P.3, line 27-31: It would be useful to explain in an Appendix the choice of the Z-S relationship chosen and how it was compared to other available data used to measure snowfall at each site (other than CloudSat). Also, could you clarify in the manuscript how the 3 sets of data were compared? If I understood correctly they don't provide the snowfall information at the same altitude. For example, it is indicated in the manuscript that the lowest level where the snowfall is estimated by CloudSat is at 1200m and the MRRs is at 300m above ground level. I assumed that ERA snowfall is probably produced at the surface. How these differences affect the results of your study?

We expanded the information regarding the choice of the Z-S relationship for each of the stations. There is now specified which other instruments were available at the stations to measure snowfall amounts and which were used for the derivation of the MRR snowfall rates.

Radar reflectivity measurements were subsequently converted to snowfall rates using relations specifically developed for the MRR at the PE and DDU station. At the PE station, this relation was constructed using information about the snowflake microphysics obtained from a video disdrometer (details in Souverijns et al., 2017), while at the DDU station, the relation was derived based on a weighing gauge, polarimetric radar and snowflake camera (details in Grazioli et al., 2017a).

We decided not to include more information in an appendix section, as the two publications that were cited (i.e. Souverijns et al., 2017; Grazioli et al., 2017a) are fully devoted to the construction of the Z-S relation for the PE and DDU station including a discussion of snowfall amounts measured by the different instruments. A detailed description is available in these publications.

Regarding the comparison of CloudSat, the MRRs and ERA-Interim, it is indeed true that all instruments are measuring at different height levels. 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. ERA-Interim (which is a surface snowfall product) was chosen as this product is currently mainly used for Antarctic-wide surface snowfall estimates. 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.

As such, the main problem is that the lowest bin of the MRR cannot be considered groundtruth and that sublimation can occur between 300m a.g.l. and the surface.

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. (2017b), two models predict an overestimation of 7 % of the cumulative snowfall record at the 300m a.g.l. level compared to the surface.

The vertical profile of precipitation measured by the MRRs is given in Fig. S3 (Fig. R1 in this document) for the three stations for the periods of concurrent measurements with CloudSat. 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. (2017b) 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.



Figure R1: 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 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., 2017b; 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.

Based on Fig. R1, a large discrepancy is detected between MRR snowfall rates at 300m

a.g.l. and 1200m a.g.l.. Despite not being the main goal of this study, the difference is investigated in more detail and a comparison between the MRR snowfall rates at 1200m a.g.l. and CloudSat is executed.

Fig. 6 & 7 from the main paper are reproduced for MRR measurements at 1200m a.g.l. (Fig. S1 & S2 in the Supplement; Fig. R2 & R3 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. R1 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.



Figure R2: (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).

For the MZ station, the same amount of precipitation reduction is obtained as for the PE station (25%; Fig. R2). The vertical profile of total precipitation shows that the layer of maxi-



Figure R3: (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<sup>2</sup> 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 R4: Radar reflectivity spectrum for two snowfall events at the PE station (upper: 24 Feb 2015; lower: 22 Dec 2013).

mum precipitation extends up to 700m after which a sharp decrease is found (Fig. R1). 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. R2). 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., 2017b), 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 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. R2). 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. R3).

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

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

Apart from evaluating the CloudSat snowfall climatology and individual events (obtained at 1200m a.q.l.) with MRR measurements at the level closest to the surface (300m a.q.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., 2017b). 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.

## 2. P.4, Figure 1: Could you add the name of the stations on the map with the acronym used in the text and other figures?

We added the acronym of the stations to the title of each of the DEMs (Figure R5).



Figure R5: Digital Elevation Map of the Antarctic Ice Sheet (Liu et al., 2015) with three insets corresponding to the location of the Micro Rain Radars. Upper: Princess Elisabeth station (PE), right: Mario Zucchelli station (MZ), lower: Dumont D'Urville station (DDU). The inset at the bottom left shows the Micro Rain Radar at the Princess Elisabeth station.

# 3. P.5, line 25, Please double check the guidelines for references. The reference should be (conforme Palerme et al., 2014) instead of (conforme Palerme et al. (2014)).

This is indeed correct. We adapted the reference accordingly. Furthermore, this issue has been adapted in one other place in the manuscript.

..., mainly driven by large-scale circulation (i.e. cyclonic activity in the circumpolar trough; Gorodetskaya et al., 2013, 2014; Souverijns et al., 2018).

### 4. P.6, line 5, How is a snowfall event defined? Were they defined per day or per time period when snow accumulated at the ground (or at the lowest MRR level)?

Regarding the comparison of individual snowfall events detected by both the MRR and CloudSat, events are rigorously defined. As the events need to be detected by both instruments, we are restricted to the CloudSat overpasses. During a CloudSat overpass close by the station, a spatial area within the grid box of 1° latitude by 2° longitude is covered by its track. The distance of this track within the grid box is converted to a time period, i.e. if the track is 130 km long within the grid box and the wind speed at 300m a.g.l. (which is obtained from ERA-Interim reanalysis data over the stations (Dee et al., 2011)) equals 20 km h<sup>-1</sup>, the MRR subsample covers a time period of 6.5 hours. The definition of this comparison period is explained in the result section.

Each of these MRR subsamples however needs to cover a time period to obtain a fair estimate of the temporal uncertainty induced by the CloudSat temporal revisit time. CloudSat has a narrow swath width. During a CloudSat overpass close by the station, a spatial area within the grid box of 1° latitude by 2° longitude is covered by its track (see Sect. 2.2). The distance of this track within the grid box is converted to a time period, i.e. if the track is 130 km long within the grid box and the wind speed at 300m a.g.l. (which is acquired from ERA-Interim reanalysis data over the stations (Dee et al., 2011)) equals 20 km h<sup>-1</sup>, the MRR subsample covers a time period of 6.5 hours.

In order to facilitate the comparison, MRR snowfall rates are calculated by averaging snowfall rates over a time period following the same procedure as in Sect. 3.1. This time period depends on the spatial resolution of the grid and the wind speed at 300m a.g.l.. For example, if the grid has a spatial resolution of 1° latitude by 2° longitude (i.e. with a maximal distance of 130 km between the edges of the grid box) and the wind speed equals 20 km h<sup>-1</sup>, the MRR record is averaged over 6.5 hours. The minimal MRR averaging period is one hour). Using this methodology, one has to assume that the precipitation systems are stationary in time and uniform in space, which is not valid over highly variable topography (see Sect. 2.3). This source of error needs to be considered when comparing both instruments.

# 5. P.7, line 16-26, there are 3 times "in order to get" in the same paragraph. It should be reworded.

We have adapted the paragraph so "in order to get" is limited to the first sentence only.

In order to get an estimate of the uncertainty induced by the low temporal sampling frequency of CloudSat, systematic sampling is applied on the MRR snowfall record (available on the minute time-scale). For the MZ station for example, the revisit time equals approximately 2.1 days. As such, subsamples are extracted from the MRR record with an interval of 2.1 days. Each of these MRR subsamples however needs to cover a time period to obtain a fair estimate of the temporal uncertainty induced by the CloudSat temporal revisit time. CloudSat has a narrow swath width. During a CloudSat overpass close by the station, a spatial area within the grid box of 1° latitude by 2° longitude is covered by its track (see Sect. 2.2). The distance of this track within the grid box is converted to a time period, i.e. if the track is 130 km long within the grid box and the wind speed at 300m a.g.l. (which is acquired from ERA-Interim reanalysis data over the stations (Dee et al., 2011)) equals 20 km h<sup>-1</sup>, the MRR subsample covers a time period of 6.5 hours. On average, this time period equals 7.2, 7.4 and 6.9 hours respectively for the PE, DDU and MZ station. As such, in case of the example for the MZ station, for each bootstrap a subsample of 6.9 hours is extracted every 2.1 days as a means to obtain a correct estimation of the CloudSat temporal uncertainty (Fig. 5).

6. P.8, Figure 3, It is surprising to see that the MRR misses many events detected by ERA. It should be further discussed in the manuscript. Also, a legend should be added to the figure.

We added a discussion of the comparison between ERA-Interim and the MRRs.

For all stations, ERA-Interim reanalysis underestimates the snowfall amount of large events, which has also been observed in Fig. 3, attaining for omission errors similar to CloudSat (see Sect. 3.2). This underestimation is related to the fact that high peaks in snowfall are smoothed out over the grid. Smaller snowfall events are much better captured by ERA-Interim compared to CloudSat (see also Fig. 3 & 4). However, a substantial number of small events are detected in ERA-Interim that were not registered by the MRRs, mainly for PE and MZ station (Fig. 8). This can be related to the topography of the surroundings, leading to localised snowfall, which is gridded to low resolution data products as ERA-Interim and/or other sources as e.g. erroneous erroneous moisture fluxes.

Furthermore, we added a legend to Fig. 3 (Fig. R6 in this document).



Figure R6: Snowfall rates (mm w.e.  $h^{-1}$ ) during March 2016 at the three stations derived from the MRRs (blue bars), the grid box comprising each of the three stations in ERA-Interim reanalysis (green) and the average of the CloudSat overpasses in the grid box (1° latitude by 2° longitude) comprising each of the three stations following the approach of Palerme et al. (2014) (red).

# 7. P.9, Figure 4, Is it possible to do the same figure from ERA and maybe CloudSat? It would be interesting to see how well they compare among each other if possible.

We have created the same figure for CloudSat (Fig. R7) and ERA-Interim (Fig. R8).



Figure R7: Seasonal variability of snowfall amounts derived from CloudSat at the three stations.



Figure R8: Seasonal variability of snowfall amounts derived from ERA-Interim at the three stations.

For CloudSat this visualisation does not have much added value due to the lack of observations. Only a limited number of snowfall events are detected over the stations (69, 26 and 47 for the PE, DDU and MZ station respectively). When these are subdivided in seasons, no clear distribution can be deduced due to a lack of large snowfall events.

For ERA-Interim, a similar seasonal cycle is detected compared to the MRR results (compare Fig. R8 & Fig. 4 in the main paper) and no big discrepancies are found. The main difference is the high frequency of small snow storms observed in austral summer (DJF) over DDU compared to results of the MRR. For all stations, ERA-Interim overestimates the frequency of small snowfall events, while underestimating the frequency of large snowfall events. This has also been described and concluded from the results in section 3.3 and Fig. 7 in the main paper. We have added the results of ERA-Interim (Fig. R8) to Fig. 4 in the main paper and included several references to the text referring to this figure.

It is noted that precipitation observations in winter are scarce for the MRR (Sect. 2.3), while interannual precipitation variability can be large. At the PE and MZ stations, snowfall events of highest intensities are limited to the austral spring (SON) and summer season, while during austral winter, lighter snowfall events are recorded in both the MRR and ERA-Interim record. This complies with van Lipzig et al. (2002) in their study of the seasonality of the SMB over Dronning Maud Land. For the DDU station, a larger number of high-intensity snowfall events are observed. Seasonally, at DDU the lowest snowfall amounts are obtained during austral summer, while highest contributions to the total snowfall record are obtained during the other months, confirming the results of Grazioli et al. (2017a). In the ERA-Interim record, the opposite result is obtained, showing a peak in low intensity snowfall events during austral summer. A clear discrepancy in frequencies is observed between the MRR and ERA-Interim snowfall record for all stations. ERA-Interim detects more low-intensity snowfall events, while underestimating the amount of high-intensity storms. This inconsistency is further elaborated in Sect. 3.3.

For all stations, ERA-Interim reanalysis underestimates the snowfall amount of large events, which has also been observed in Fig. 4, attaining for omission errors similar to CloudSat (see Sect. 3.2). This underestimation is related to the fact that high peaks in snowfall are smoothed out over the grid. Smaller snowfall events are much better captured by ERA-Interim compared to CloudSat (see also Fig. 3 & 4).

### 8. P.9, line 9, Should it be Figure 4 instead of Figure 7?

This is indeed a typo. The text has been adapted accordingly.

9. P.10, Figure 5: Add the title of the y-axis on the left column.

We have adapted the figure to increase its readability (Fig. R9 in this document). As we flipped the figure, the names of the stations are now displayed at the top of the figure. Furthermore, the y-axis label has been added.

10. P.11, Figure 6: Add the title of the y-axis. Also, define omission and commission in the figure caption.

The label of the y-axis has been adapted to also include a description. Furthermore, we have added a definition of omission and commission errors to the figure caption (Fig. R10 in this document).

11. P.12, line 8: Delete ")" at the end of the sentence.

This is indeed a typo. The sentence has been adapted accordingly.

### 12. P.12, line 21, should it be "rates" instead of "numbers"?

This is a correct remark of the referee. We have adapted the sentence in order to correctly represent the features described herein.

As the distribution of snowfall rates is skewed towards high intensities (Fig. 4 in the main paper), these snowfall events are missed leading to an underestimation of the total snowfall amount, which is indeed observed for all stations (Fig. 6 in the main paper).

## 13. P.13, line 22 and p.14, Figure 7: The dots on the figure represent each sample of data. Can you indicate how many samples for each dataset used?

The number of samples were added to the figure for each of the stations (Fig. R11 in this



Figure R9: Boxplots showing the uncertainty when applying systematic sampling on the MRR snowfall record (10.000 bootstraps) using different temporal sampling frequencies (x-axis, D denotes days). Total snowfall amounts during collocated periods of MRR and CloudSat measurements (top) and the 95<sup>th</sup> percentile snowfall rate (bottom) are shown. The bottom and top edges of the boxplot indicate the 25-75<sup>th</sup> percentile (dark pink shading), while the whiskers denote the 10-90<sup>th</sup> percentile (light pink shading). The red line denotes the median.

document). Furthermore, we also added the number of samples to Fig. 9 in the main paper (Fig. R12 in this document).

### 14. p.15, Table 1: It could also be a barplot.

We have replaced the table by a bar plot visualisation and added it to the manuscript (Fig. R13 in this document). The table has been moved to the Supplement.



Figure R10: (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). (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).



Figure R11: (first row) Empirical cumulative distribution of MRR and CloudSat snowfall events at a spatial resolution of  $1^{\circ}$  latitude by  $2^{\circ}$  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 R12: Daily snowfall amount comparison between ERA-Interim reanalysis and the MRR.  $R^2$  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 R13: Daily average snowfall amounts (mm w.e.  $day^{-1}$ ) for the concurrent periods displayed in Fig. 2 for the Princess Elisabeth (PE), Dumont D'Urville (DDU) and Mario Zucchelli (MZ) station. CloudSat snowfall amounts are derived for the grid specified by Palerme et al. (2014).

### References

- Chen, S., Hong, Y., Kulie, M., Behrangi, A., Stepanian, P. M., Cao, Q., You, Y., Zhang, J., Hu, J., and Zhang, X.: Comparison of snowfall estimates from the NASA CloudSat Cloud Profiling Radar and NOAA/NSSL Multi-Radar Multi-Sensor System, Journal of Hydrology, 541, 862–872, https://doi.org/10.1016/j.jhydrol.2016.07.047, 2016.
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., and Kobayashi, S.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.
- Gorodetskaya, I. V., van Lipzig, N. P. M., van den Broeke, M. R., Mangold, A., Boot, W., and Reijmer, C. H.: Meteorological regimes and accumulation patterns at Utsteinen, Dronning Maud Land, East Antarctica: Analysis of two contrasting years, Journal of Geophysical Research: Atmospheres, 118, 1700–1715, https://doi.org/10.1002/jgrd.50177, 2013.
- Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M., Neff, W., and van Lipzig, N. P. M.: The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, Geophysical Research Letters, 16, 6199–6206, https://doi.org/10.1002/2014GL060881, 2014.
- Grazioli, J., Genthon, C., Boudevillain, B., Duran-Alarcon, C., Del Guasta, M., Madeleine, J.-B., and Berne, A.: Measurements of precipitation in Dumont d'Urville, Terre Adélie, East Antarctica, The Cryosphere, 11, 1797–1811, https://doi.org/10.5194/tc-2017-18, 2017a.
- Grazioli, J., Madeleine, J.-B., Gallée, H., Forbes, R. M., Genthon, C., Krinner, G., and Berne, A.: Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance, Proceedings of the National Academy of Sciences, 114, 10858–10863, https://doi.org/ 10.1073/pnas.1707633114, 2017b.
- Liu, H., Jezek, K. C., Li, B., and Zhao, Z.: Radarsat Antarctic Mapping Project Digital Elevation Model, Version 2, https://doi.org/http://dx.doi.org/10.5067/8JKNEW6BFRVD, 2015.
- Maahn, M., Burgard, C., Crewell, S., Gorodetskaya, I. V., Kneifel, S., Lhermitte, S., Van Tricht, K., and van Lipzig, N. P. M.: How does the spaceborne radar blind zone affect derived surface snowfall statistics in polar regions?, Journal of Geophysical Research: Atmospheres, 119, 13604–13620, https://doi.org/10.1002/2014JD022079, 2014.
- Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, https://doi.org/ 10.5194/tc-8-1577-2014, 2014.
- Souverijns, N., Gossart, A., Lhermitte, S., Gorodetskaya, I. V., Kneifel, S., Maahn, M., Bliven, F. L., and van Lipzig, N. P. M.: Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations, Atmospheric Research, 196, 211–223, https://doi.org/10.1016/j.atmosres.2017.06.001, 2017.
- Souverijns, N., Gossart, A., Gorodetskaya, I. V., Lhermitte, S., Mangold, A., Laffineur, Q., Delcloo, A., and van Lipzig, N. P. M.: How does the ice sheet surface mass balance relate to snowfall? Insights from a ground-based precipitation radar in East Antarctica, The Cryosphere, 12, 1987–2003, https://doi.org/10.5194/tc-12-1987-2018, URL https://www.the-cryosphere.net/12/1987/2018/, 2018.

- van Lipzig, N. P. M., van Meijgaard, E., and Oerlemans, J.: The spatial and temporal variability of the surface mass balance in Antarctica: results from a regional atmospheric climate model, International Journal of Climatology, 22, 1197–1217, https://doi.org/10.1002/joc.798, 2002.
- Wood, N. B.: Estimation of snow microphysical properties with application to millimeterwavelength radar retrievals for snowfall rate, Ph.D. thesis, Colorado State University, Colorado, URL http://hdl.handle.net/10217/48170, 2011.

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

Niels Souverijns, Alexandra Gossart, Stef Lhermitte, Irina V. Gorodetskaya, Jacopo Grazioli, Claudio Duran-Alarcon, Brice Boudevillain, Christophe Genthon, Claudio Scarchilli and Nicole P.M. van Lipzig

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 Cloud-Sat 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<sup>2</sup> 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).

### References

- Chen, S., Hong, Y., Kulie, M., Behrangi, A., Stepanian, P. M., Cao, Q., You, Y., Zhang, J., Hu, J., and Zhang, X.: Comparison of snowfall estimates from the NASA CloudSat Cloud Profiling Radar and NOAA/NSSL Multi-Radar Multi-Sensor System, Journal of Hydrology, 541, 862–872, https://doi.org/10.1016/j.jhydrol.2016.07.047, 2016.
- Grazioli, J., Madeleine, J.-B., Gallée, H., Forbes, R. M., Genthon, C., Krinner, G., and Berne, A.: Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance, Proceedings of the National Academy of Sciences, 114, 10858–10863, https://doi.org/ 10.1073/pnas.1707633114, 2017.
- Maahn, M., Burgard, C., Crewell, S., Gorodetskaya, I. V., Kneifel, S., Lhermitte, S., Van Tricht, K., and van Lipzig, N. P. M.: How does the spaceborne radar blind zone affect derived

surface snowfall statistics in polar regions?, Journal of Geophysical Research: Atmospheres, 119, 13604–13620, https://doi.org/10.1002/2014JD022079, 2014.

- Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, https://doi.org/ 10.5194/tc-8-1577-2014, 2014.
- Souverijns, N., Gossart, A., Lhermitte, S., Gorodetskaya, I. V., Kneifel, S., Maahn, M., Bliven, F. L., and van Lipzig, N. P. M.: Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations, Atmospheric Research, 196, 211–223, https://doi.org/10.1016/j.atmosres.2017.06.001, 2017.
- Wood, N. B.: Estimation of snow microphysical properties with application to millimeterwavelength radar retrievals for snowfall rate, Ph.D. thesis, Colorado State University, Colorado, URL http://hdl.handle.net/10217/48170, 2011.

### **Evaluation of the CloudSat surface snowfall product over Antarctica using ground-based precipitation radars**

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**Abstract.** In-situ observations of snowfall over the Antarctic Ice Sheet are scarce. Currently, continent-wide assessments of snowfall are limited to information from the Cloud Profiling Radar on board of CloudSat, which has not been evaluated up to now. In this study, snowfall derived from CloudSat is evaluated using three ground-based vertically profiling 24-GHz precipitation radars (Micro Rain Radars; MRRs). Firstly, using the MRRs long-term measurement records, an assessment of

- 5 the uncertainty caused by the low temporal sampling rate of CloudSat (one revisit per 2.1 to 4.5 days) is performed. The 10-90<sup>th</sup> percentile temporal sampling uncertainty on the snowfall climatology varies between 30-40 % depending on the latitudinal location and revisit time of CloudSat. Secondly, an evaluation of the snowfall climatology indicates that the CloudSat product, derived at a resolution of 1° latitude by 2° longitude, is able to accurately represent the snowfall climatology at the three MRR sites (biases < 15 %), outperforming ERA-Interim. For coarser and finer resolutions, the performance drops due to as a result of</p>
- 10 higher omission errors by CloudSat. Moreover, the CloudSat product does not perform well in simulating individual snowfall events. Since the difference between the MRRs and the CloudSat climatology are limited and the temporal uncertainty is lower than current CMIP5 snowfall variability, our results imply that the CloudSat product is valuable for climate model evaluation purposes.

### 1 Introduction

15 The surface mass balance (SMB) of the Antarctic Ice Sheet (AIS) is an important control mechanism in the determination of (future) sea level rise (Gregory and Huybrechts, 2006; Genthon et al., 2009a; Hanna et al., 2013; Ligtenberg et al., 2013; Previdi and Polvani, 2017; Lenaerts et al., 2017). It comprises the sum of snowfall, sublimation / evaporation, melt and blowing snow (van den Broeke et al., 2004). An important component in the SMB of the AIS is snowfall, being the main positive term (Boening et al., 2012). However, snowfall is still poorly constrained in current state-of-the-art climate models and reanalysis

(Genthon et al., 2009b; Bromwich et al., 2011; Palerme et al., 2017; Tang et al., 2018). Tang et al. (2018) indicate a large spread in the annual snowfall amounts of four reanalysis products south of  $60^{\circ}$  S (differences up to 200 mm year<sup>-1</sup>). Furthermore, they point out that these reanalysis products have low correlation with each other and show contrasting trends in historical snowfall amounts. Models of the Fifth Climate Model Intercomparison Project (CMIP5) simulate historical snowfall rates over

5 the AIS ranging from 158 to 354 mm year<sup>-1</sup> (Palerme et al., 2017).

Climate models resolve the different components of the SMB individually. Nevertheless, their evaluation is usually limited to the total SMB (Lenaerts et al., 2012; Wang et al., 2016) as there is a lack of observations of the individual components. For example, snowfall reduced by sublimation is often equated to accumulation records when evaluating climate models. These accumulation records are mainly obtained locally from ice cores and stake measurements (Genthon et al., 2005; Magand et al.,

- 10 2007; Eisen et al., 2008; Favier et al., 2013), while continent-wide estimates of the SMB of the AIS are retrieved from satellite data or the integration of distinct observational records (Vaughan et al., 1999; Velicogna and Wahr, 2006; Medley et al., 2014; Hardy et al., 2017). It is not straightforward to relate snowfall rates to accumulation especially at the local scale, as blowing snow often disturbs these records, making the distinction between transported and precipitated snow challenging (Bromwich et al., 2004; Frezzotti et al., 2004; Knuth et al., 2010; Scarchilli et al., 2010; Gorodetskaya et al., 2015; Gossart et al., 2017;
- 15 Souverijns et al., 2018). Moreover, current observed trends in accumulation are increasing faster than predicted by models (Medley et al., 2018). This stresses the need for reliable snowfall observations over the AIS in order to constrain climate models and to get accurate estimates of the future AIS SMB and sea level rise.

In the last decades, several efforts have been made to get accurate estimates of snowfall over the AIS. However, the amount of observations stays limited. In 2010, the first ground-based Micro Rain Radar (MRR) over Antarctica was installed at the Belgian

20 Princess Elisabeth station (Gorodetskaya et al., 2015). Using disdrometer observations at the surface, a relation between radar reflectivity and snowfall rates was achieved (Souverijns et al., 2017). In 2015, two more MRRs were installed at Dumont D'Urville station (Grazioli et al., 2017a) and Mario Zucchelli station, for which also reliable snowfall rates were obtained.

Apart from ground-based radar measurements, space-borne observations are also a valuable source of information over the AIS. The Cloud Profiling Radar on board of the CloudSat satellite (Stephens et al., 2002) is the first to provide information

- 25 about snowfall on a continental scale over the AIS using the 2C-SNOW-PROFILE product (Wood et al., 2013, 2014). Launched in 2006, it overpasses each location on the AIS within 100 km with a temporal revisit time of seven days or less and has a strong latitudinal dependency (Van Tricht et al., 2016). Palerme et al. (2014) constructed a continental snowfall climatology at a grid of 1° latitude by 2° longitude, including information about the phase and frequency of snowfall. A yearly average snowfall rate of 171 mm year<sup>-1</sup> over the AIS north of 82° S was found, higher than observations of snow accumulation, but
- 30 significantly lower than the CMIP5 ensemble mean (Palerme et al., 2017). Furthermore, the product agrees reasonably well with ERA-Interim reanalysis (Dee et al., 2011) despite the large uncertainties in the retrieval algorithm and the low temporal sampling rate of CloudSat (Palerme et al., 2014)(Palerme et al., 2014; Milani et al., 2018).

Although the CloudSat satellite is the first to offer a continent-wide (north of  $82^{\circ}S$ ) estimation of snowfall over the AIS, the evaluation of this product with ground-based observations of snowfall is still limited (Maahn et al., 2014). In this paper, the

35 CloudSat snowfall product will be compared against observations of the three MRRs that are currently deployed over the AIS.

As a first step, the effect of the low temporal sampling rate of CloudSat on the resulting snowfall climatology is investigated, including an overview of the temporal uncertainty (Sect. 3.1). Next, a climatology is constructed for periods of concurrent observations of the MRRs and CloudSat. The climatology is calculated at different spatial resolutions and evaluated against observations of the three stations. Furthermore, an overview of the discrepancies between CloudSat the CloudSat product and

5 the MRR snowfall rates at the lowest height acquisition level are identified by comparing individual snowfall events (Sect. 3.2). To conclude, a comparison with ERA-Interim reanalysis is performed, currently often used for continent-wide estimates of snowfall over the AIS (Sect. 3.3).

### 2 Material and methods

### 2.1 Ground-based precipitation radars

- 10 Local snowfall measurements by precipitation gauges or disdrometers are hindered in polar regions by the high wind speeds concurring with most snowfall events. Therefore, ground-based precipitation radars have been installed at several Antarctic stations, which attain for an independent view on the snowfall component of the SMB over the AIS. At the moment, there are only three locations over the AIS where the instrument is deployed (Fig. 1): (1) the Belgian Princess Elisabeth (PE) station (71°57' S, 23°21' E; 1392 m-1392m above sea level), located 173 km from the coast, in Dronning Maud Land, north of the
- 15 Sør Rondane mountain chain (a detailed description of the setting can be found in Gorodetskaya et al. (2013)).; (2) the French Dumont D'Urville (DDU) station (66°40' S, 140°01' E; 41 m 41m above sea level), located at the coast of Terre Adélie (a detailed description can be found in Grazioli et al. (2017a)).; and (3) the Italian Mario Zucchelli (MZ) station (74°41' S, 164°07' E; 15 m 15m above sea level), located at the coast of Victoria Land in the Terra Nova Bay area, surrounded closely by high mountain chains the Eisenhower Range mountains (a detailed description can be found in Scarchilli et al. (2010)).
- The precipitation radars deployed at the three stations (MRRs designed by Metek) deployed at the three stations are vertically pointing operating at a frequency of 24 GHz (Klugmann et al., 1996; Peters et al., 2002). As these instruments were originally developed to detect liquid precipitation, operational MRR procedures to derive standard radar variables, as e.g. radar reflectivity, were modified for snowfall using the methodology of Maahn and Kollias (2012), increasing the minimum detectable range to -14 dBz in the lowest measurement bins. Radar reflectivity measurements were subsequently converted
- 25 to snowfall rates using relations specifically developed for the MRR at the PE station (Souverijns et al., 2017) and and DDU station. At the PE station, this relation was constructed using information about the snowflake microphysics obtained from a video disdrometer (details in Souverijns et al., 2017), while at the DDU station(Grazioli et al., 2017a), the relation was derived based on a weighing gauge, polarimetric radar and snowflake camera (details in Grazioli et al., 2017a). For the MRR at the MZ station, no relation has yet been developed. As such, the relation obtained at the DDU station was also applied here, as the
- 30 setting of both stations (located near the coast) can be considered similar.

The MRRs deployed at all stations measure snowfall rate intensity between 300-3000 meters with a vertical height resolution of 100 meters. MRR measurements are available at the minute time scale and are summed to hourly values for most of the applications. It must be noted that the MRR snowfall record is characterised by uncertainties in the radar reflectivity-snowfall



**Figure 1.** Digital Elevation Map of the Antarctic Ice Sheet (Liu et al., 2015) with three insets corresponding to the location of the Micro Rain Radars. Upper: Princess Elisabeth station (PE), right: Mario Zucchelli station (MZ), lower: Dumont D'Urville station (DDU). The inset at the bottom left shows the Micro Rain Radar at the Princess Elisabeth station.

rate relation. At the PE station for example, this uncertainty equals  $\pm 60 \%$  (Souverijns et al., 2017). A similar uncertainty range is obtained for the radar-reflectivity snowfall rate relation obtained at the DDU station (Grazioli et al., 2017a).

### 2.2 CloudSat snowfall climatology

- Apart from ground-based radars, the Cloud Profiling Radar on board of the CloudSat satellite, nadir-looking and operating at 94 GHz, has been used to derive snowfall rate estimates over the AIS (Stephens et al., 2002). The 2C-SNOW-PROFILE product (Wood et al., 2013, 2014) derives snowfall rates from radar reflectivity measurements. The relation between radar reflectivity and snowfall rates is derived using a priori estimates of snow particle size distribution, microphysical and scattering properties (Wood et al., 2013, 2014). The comparison between the ground-based and space-borne radars is facilitated as snowfall rates are derived using similar procedures by the MRRs (Souverijns et al., 2017). Furthermore, as the optimal estimation retrieval
- 10 (Rodgers, 2000) is used to derive the 2C-SNOW-PROFILE product, the relation between radar reflectivity and snowfall rates is variable over the AIS. This is considered important as this relation varies significantly from coastal to inland regions (Souverijns et al., 2017).

The Cloud Profiling Radar of CloudSat has a narrow swath-width (1.7 km by 1.3 km footprint) and provides snowfall rate profiles divided into 150 vertical bins at a resolution of 240 m. In order to remove the effects of ground clutter, the bin closest

15 to the surface that is useful is located at 1200 m 1200 m above ground level. From this data, a snowfall climatology map was created by Palerme et al. (2014) for the AIS by mapping the 2C-SNOW-PROFILE tracks over a grid of 1° latitude by 2° longitude. For each orbit, one snowfall rate value per grid cell that is overpasses by CloudSat is retained, taken as the mean

value of all snowfall rates in this grid cell. At a spatial resolution of  $1^{\circ}$  latitude by  $2^{\circ}$  longitude, the temporal revisit time of CloudSat for each grid cell is five days at maximum (Palerme et al., 2014).

#### 2.3 Comparative analysis

CloudSat provides currently the only continent-wide snowfall product over the AIS. As no ground-based precipitation estimates

- 5 have been available up to now, this product has not been evaluated yet. CloudSat has been operational since 2006. However, due to battery issues, it is not longer able to operate during the night orbit (i.e. at the non-sunlit side of the earth). As such, no snowfall rate measurements are obtained during austral winter season since 2011. The MRR at the PE station was installed in January 2010 and was planned to operate continuously throughout the year. However, due to power cuts at the station, austral winter observations are only available in 2012, limiting the collocated data coverage to the periods of the austral summer (Fig.
- 10 2). Next to this, no field campaign took place during the 2016-2017 austral summer, leaving a data gap of 18 months since May 2016. In total, 928-851 days of collocated measurements of both CloudSat and the MRR are available at the PE station. The MRR at the DDU station was installed in December 2015, operating nearly continuously until present time, leading to 519 days of collocated measurements (Fig. 2). At the MZ station, the MRR is operating continuously since November 2016, after one summer season of measurements in 2015-2016, accounting for 333 days of collocated measurements (Fig. 2). As no full
- 15 year of collocated measurements between CloudSat and the MRRs is available, the comparative analysis will be limited to the austral summer periods (denoted in purple in Fig. 2). Since our main interest lies in the measurement of snowfall at the surface

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 observation and modelling community. As such, the lowest usable measure-

- 20 ment bin of both instruments is considered in the analysis. The data acquisition height difference between CloudSat (1200 m 1200 m a.g.l.) and the MRRs (300 m 300 m a.g.l.) accounts for a typical underestimation of 9-11 an average underestimation of 25 % in total snowfall amount by CloudSat compared to the MRR at the PE station(Maahn et al., 2014), while at ... At the DDU station this equals 13 %, caused by sublimation in these low layers of the atmosphere (Grazioli et al., 2017b)8 % (Grazioli et al., 2017b), while at the MZ station, an underestimation of 25 % is obtained. A discussion on the source of this
- 25 discrepancy in snowfall amount between the 300m and 1200m level can be found in the Supplement (Text S1 and Figs. S1-S3). Furthermore, sublimation persists towards the surface, also influencing the layer between the lowest measurement bin of the MRR (i.e. 300 m 300m a.g.l.) and the surface, where typically an inversion and katabatic flow is present (Grazioli et al., 2017b; 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
- 30 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 300 m 300m of the atmosphere is not considered in this study but needs to be accounted for.



**Figure 2.** Overview of periods with of concurrent CloudSat and MRR measurements for the Princess Elisabeth (PE), Dumont D'Urville (DDU) and Mario Zucchelli (MZ) station denoted in purple. The periods denoted in orange represents other moments when the MRRs were active. Vertical dotted lines denote the start of a year.

Four experiments-analyses will be described in this paper. As a first step, a statistical analysis is executed in order to obtain an overview of the uncertainty caused by the low temporal revisit time of CloudSat (Palerme et al., 2014; Van Tricht et al., 2016). The revisit time of CloudSat equals several days for most of the locations on the AIS. In case a spatial resolution of 1° latitude by 2° longitude is chosen (conform Palerme et al. (2014))(conform Palerme et al., 2014), the revisit time is on average

- 5 4.7 days for the DDU station, 2.5 days for the PE station and 2.1 days for the MZ station. The MRRs achieve snowfall rate estimates on a one-minute temporal resolution. By subsampling from the MRR record during periods of collocated MRR and CloudSat measurements, a similar temporal sampling resolution as CloudSat is obtained, which can be compared to the full MRR record. The systematic sampling technique is applied to the MRR snowfall record (randomly selecting the starting point, while using a fixed periodic interval for subsequent observations; 10.000 bootstraps).
- NextSecond, the total snowfall amounts obtained by CloudSat and the MRRs are calculated for all periods with collocated measurements (Fig. 2). The methodology of Palerme et al. (2014) is used to obtain snowfall rate estimates of CloudSat. The AIS is overlaid by a grid. Each time the CloudSat satellite overpasses a grid cell, one sample is retained by taking the average of all observations within the grid cell. The spatial resolution is fixed in Palerme et al. (2014) at 1° latitude by 2° longitude. However, by varying the spatial resolution of the grid overlaying the AIS (and therefore the distance between the satellite
- 15 overpasses that are taken into account and the MRRs), a different performance is expected. As such, the analysis is performed for several spatial resolutions varying from  $0.1^{\circ}$  latitude by  $0.2^{\circ}$  longitude to  $2^{\circ}$  latitude by  $4^{\circ}$  longitude in steps of  $0.1^{\circ}$  latitude by  $0.2^{\circ}$  longitude.

Apart Third, apart from the total snowfall amount, individual snowfall events recorded by both the MRRs and CloudSat are investigated. Individual CloudSat overpasses in the grid box over the station are averaged and compared to measurements

of the MRRs. This analysis is executed using different spatial resolutions (varying from  $0.1^{\circ}$  latitude by  $0.2^{\circ}$  longitude to  $2^{\circ}$  latitude by  $4^{\circ}$  longitude) in order to investigate the effect of the spatial resolution on the match in surface snowfall amounts.

Lastly, a comparison between the MRRs, CloudSat and ERA-Interim reanalysis (Dee et al., 2011) is executed for the three stations. ERA-Interim reanalysis data is generally considered one of the best reanalysis products regarding snowfall over

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Antarctica, however still very biased (Bromwich et al., 2011; Medley et al., 2013). Notwithstanding the availability of CloudSat and MRR snowfall records, their measurements are not yet assimilated in ERA-Interim reanalysis. As such, all products are independent. Total snowfall amount estimates over the full measurement period will be are compared. Furthermore, the performance of individual event detection of CloudSat the CloudSat product and ERA-Interim reanalysis is investigated.

### 3 Results and Discussion

### 10 3.1 Temporal sampling frequency of CloudSat

Considering the full MRR snowfall record, the precipitation climate over Antarctica is characterised by a limited number of events attaining for large snowfall amounts (Fig. 3 & 4), mainly driven by large-scale circulation (i.e. cyclonic activity in the circumpolar trough; Gorodetskaya et al., 2013, 2014; Souverijns et al., 2018). The snowfall rate distribution is highly skewed to the right towards high precipitation rates and most stations are not characterised by a clear seasonality in snowfall amounts

- 15 (Fig. 4). It is noted that precipitation observations in winter are scarce for the MRR (Sect. 2.3), while interannual precipitation variability can be large. At the PE and MZ station stations, snowfall events of highest intensities are limited to the austral spring (SON) and summer season, while during austral winter, less large lighter snowfall events are recorded in both the MRR and ERA-Interim record. This complies with van Lipzig et al. (2002) in their study of the seasonality of the SMB over Dronning Maud Land. For the DDU station, more a larger number of high-intensity snowfall events are observed. Seasonally, at DDU
- 20 the lowest snowfall amounts are obtained during austral summer, while highest contributions to the total snowfall record are obtained during the other months, confirming the results of Grazioli et al. (2017a). In the ERA-Interim record, the opposite result is obtained, showing a peak in low intensity snowfall events during austral summer. A clear discrepancy in frequencies is observed between the MRR and ERA-Interim snowfall record for all stations. ERA-Interim detects more low-intensity snowfall events, while underestimating the amount of high-intensity storms. This inconsistency is further elaborated in Sect. 3.3.
- 25 Snowfall events over Antarctica (with total precipitation amount of 1 mm w.e. during the course of the event) generally span multiple hours (15 hours on average for the PE station (Souverijns et al., 2018)). This is much shorter than the interval between two overpasses of CloudSat using the resolution of Palerme et al. (2014). This revisit time equals on average 2.5 days for the PE station, 4.7 days for the DDU station and 2.1 days for the MZ station <del>, which is fully determined by their latitudinal location(see Sect. 2.3)</del>. Therefore, snowfall events are often missed (several examples are visible in Fig. 3). In addition, there
- 30 is a strong variability in snowfall rates throughout individual events (see e.g. Fig. 3). One overpass every couple of days is therefore not representative for individual snow storm variability.

In order to get an estimate of the uncertainty induced by the low temporal sampling frequency of CloudSat, systematic sampling is applied on the MRR snowfall record (available on the minute time-scale). For the MZ station for example, the



**Figure 3.** Snowfall rates (mm w.e.  $h^{-1}$ ) during March 2016 at the three stations derived from the MRRs (blue bars), the grid box comprising each of the three stations in ERA-Interim reanalysis (green) and the average of the CloudSat overpasses in the grid box (1° latitude by 2° longitude) comprising each of the three stations following the approach of Palerme et al. (2014) (red). Notice the difference in vertical scale for each of the stations.



Figure 4. Seasonal variability of snowfall amounts derived from the MRRs and ERA-Interim at the three stations. MRR measurements denoted in purple and orange in Fig. 2 are included.

revisit time equals approximately 2.1 days. As such, subsamples are extracted from the MRR record with an interval of 2.1 days. In order to get Each of these MRR subsamples however needs to cover a time period to obtain a fair estimate of the temporal uncertainty induced by the CloudSat temporal revisit time, each of the MRR subsamples needs to cover a time period. CloudSat has a narrow swath width. During a CloudSat overpass close by the station, a spatial area within the grid box of  $1^{\circ}$  latitude by  $2^{\circ}$  longitude is covered by its track (see Sect. 2.2). The distance of this track within the grid box is converted

- <sup>5</sup> of 1° latitude by 2° longitude is covered by its track (see Sect. 2.2). The distance of this track within the grid box is converted to a time period, i.e. if the track is 130 km long within the grid box and the wind speed at  $\frac{300 \text{ m}}{300 \text{ m}}$  a.g.l. (which is obtained acquired from ERA-Interim reanalysis data over the stations (Dee et al., 2011)) equals 20 km h<sup>-1</sup>, the MRR subsample covers a time period of 6.5 hours. On average, this time period equals 7.2, 7.4 and 6.9 hours respectively for the PE, DDU and MZ station. As such, in order to get a correct estimation of the CloudSat temporal uncertainty, in case of the example for the MZ
- 10 station, for each bootstrap a subsample of 6.91-6.9 hours is extracted every 2.1 days as a means to obtain a correct estimation of the CloudSat temporal uncertainty (Fig. 5).

For all stations , generally and as expected, an increase in the uncertainty of the total snowfall amount is observed when decreasing the temporal sampling frequency of data acquisition (Fig. 5). In case less data is available, more uncertain estimates of the total snowfall amount are obtained. For the CloudSat temporal revisit time of Palerme et al. (2014) (2.5 days for the

15 PE, 4.7 days for the DDU and 2.1 days for the MZ station) large uncertainties on the total snowfall amounts are obtained. The



**Figure 5.** Boxplots showing the uncertainty when applying systematic sampling on the MRR snowfall record (10.000 bootstraps) using different temporal sampling frequencies (x-axis, D denotes days). Total snowfall amounts during collocated periods of MRR and CloudSat measurements (lefttop) and the 95<sup>th</sup> percentile snowfall rate (rightbottom) are shown. The bottom and top edges of the boxplot indicate the 25-75<sup>th</sup> percentile (dark pink shading), while the whiskers denote the 10-90<sup>th</sup> percentile (light pink shading). The red line denotes the median.

10-90<sup>th</sup> percentile uncertainty equals [-31 % +10 %] for the PE station, [-37 % +45 %] for the DDU station and [-55 % +36 %] for the MZ station (Fig. 5). Highest uncertainties are found for the DDU and MZ stations. For the DDU station, this can be attributed to the low revisit time of CloudSat. Generally, an increase in uncertainty is observed when lowering the revisit time (Fig. 5). For the MZ station, this might be attributed to the short time period of concurrent observations and/or the highly variable topography of the area surrounding the station (Fig. 1). As such, depending on the location on the ice sheet and revisit time of CloudSat, the temporal uncertainty varies between 30-40 % with lower values for regions towards the southern part of the ice sheet. This uncertainty is lower than current CMIP5 model variability (Palerme et al., 2017), showing the potential of CloudSat for evaluation purposes. Apart from the uncertainty induced by temporal sampling, the CloudSat snowfall product is characterised by high uncertainties (between 1.5 and 2.5 times the snowfall rate (Palerme et al., 2014)). As such, interpretations should still be done with care.

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Apart from considering the uncertainty on the total snowfall amount, also a median total snowfall amount is achieved from the bootstrapping simulations (Fig. 5). Considering the CloudSat temporal resolution, on average the median total snowfall varies compared to the full MRR snowfall record. For the PE station, an overestimation of 4 % was found, while at DDU

and MZ station, a bias of respectively -2 % and +10 % is observed. These biases can be attributed to the skewed distribution of precipitation at the stations, showing the large influence of high precipitation numbers (Fig. 74) and needs to be considered when using the CloudSat climatology for model evaluation of <u>surface</u> snowfall rates over Antarctica, together with the underestimation due to sublimation (Sect. 2.3).

5 Regarding extreme snowfall rates, very high uncertainties are found for typical CloudSat temporal sampling frequencies (Fig. 5) and equals [-21 % +72 %], [-38 % +52 %] and [-43% +108 %] for respectively the PE, DDU and MZ station. Furthermore, also a high variability in the median 90<sup>th</sup> percentile snowfall rate of all bootstrapping simulations compared to the value obtained for the full snowfall record is observed.

#### 3.2 CloudSat total snowfall amount and error identification

- 10 Long-term ground-based snowfall measurements during which concurrent measurements with CloudSat were made, are available for seven austral summer seasons at the PE station, attaining for 928-851 days. During this time period a total number of 952-839 mm w.e. of snowfall was registered , approximately 1.03 by the MRR at 300m a.g.l., approximately 0.99 mm w.e. day<sup>-1</sup>. At the DDU station, concurrent snowfall rate estimates are available for 519 days (three austral summer seasons). A total snowfall amount of 1113 mm w.e. was attained, leading to average snowfall amounts of 2.14 mm w.e. day<sup>-1</sup>. At the
- 15 MZ station, during 333 days, a total of 608 mm w.e. was measured (i.e. 1.83 mm w.e. day<sup>-1</sup>). It should be noted that at the MZ station, snowfall events are often of local origin induced by a mixing of warm coastal air from Terra Nova Bay with cold katabatic winds from the mountains (Carrasco et al., 2003; Sinclair et al., 2010). The average daily snowfall amount at the DDU and MZ station\_stations is approximately double the amount at the PE station. Those two stations are located at the coast of the AIS near sea-level, while the PE station is located 173 km inland at the edge of the Antarctic plateau (Fig. 1). Most of
- 20 the snowfall originating from cyclone activity in the circumpolar trough has already been deposited upstream of the station due to orographic rising of the air masses (Souverijns et al., 2018).

Depending on the maximal distance between the CloudSat overpasses and the stations (i.e. the spatial resolution of the grid covering the AIS), a different number of CloudSat overpasses is available for the construction of the total snowfall amount for each grid cell (see Sect. 2.2). For the PE station, in case we only take CloudSat overpasses close to the station into account,

- 25 i.e. for example a spatial resolution of 0.3° latitude by 0.6° longitude (overpasses within approximately 40 km of the station), only 77 overpasses are available for the calculation of the total snowfall amount in the grid box over the PE station, leading to a temporal revisit time of approximately 12 days (Fig. 6). In case we increase the CloudSat spatial resolution to 2° latitude and 4° longitude (overpasses within approximately 250 km of the station), 726 samples are available, i.e. one sample every 1.3 days.
- 30 Apart from comparing the total snowfall amount detected by both the MRR and CloudSat, individual snowfall events detected by both instruments are investigated. Assuming the MRRs define the ground truth, for each snowfall event detected by both instruments, the average omission (misses by CloudSat) and commission errors (overestimations by CloudSat) are calculated (Fig. 6). In order to facilitate the comparison, MRR snowfall rates are calculated by averaging snowfall rates over a time period following the same procedure as in Sect. 3.1. This time period depends on the the spatial resolution of the grid



Figure 6. (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). (second row) Individual snowfall event error analysis. MRR 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).

and the wind speed at 300 m 300 m a.g.l.. For example, if the grid has a spatial resolution of 1° latitude by 2° longitude (i.e. with a maximal distance of 130 km between the edges of the grid box) and the wind speed equals 20 km h<sup>-1</sup>, the MRR record is averaged over 6.5 hours. The minimal MRR averaging period is one hour). Using this methodology, one has to assume that the precipitation systems are stationary in time and uniform in space, which is not valid over highly variable topography (see Sect. 2.3). This source of error needs to be taken into account considered when comparing both instruments.

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For coarse spatial resolutions, CloudSat underestimates the total snowfall amount compared to the MRR records for each of the three stations (Fig. 6). For these larger spatial scales, CloudSat overpasses are averaged over longer distances. As snowfall amounts are non-stationary, erroneous estimates can be obtained, leading to both omission and commission errors on both the individual event scale as the statistics (Fig. 6). Furthermore, more CloudSat samples are available at higher latitudes

10 (Palerme et al., 2014). As snowfall rates decrease with latitude (and altitude), which is valid for the PE and DDU station, an underestimation of the snowfall amount (high omission errors) at all stations is observed at coarse spatial resolutions (Fig. 6).

This indicates that fine spatial resolutions are preferred in order to obtain more reliable matches between individual events of CloudSat and the MRRs. However, for the finest spatial resolutions, also large omission errors are identified (Fig. 6). Despite the higher accuracy of MRR measurements and CloudSat overpasses that are closer to the stations, the amount of overpasses is too low to capture enough high-intensity snowfall events (Fig. 6). As the distribution of snowfall amounts rates is skewed towards

5 high precipitation numbers intensities (Fig. 4), high-intensity these snowfall events are missed leading to an underestimation of the total snowfall amount, which is indeed observed for all stations (Fig. 6).

For intermediate spatial resolutions, reasonable agreements between CloudSat and the MRRs are obtained (Fig. 6). At the PE station, an almost perfect match between snowfall estimates is found for spatial resolutions between  $0.5^{\circ}$  latitude by  $1^{\circ}$  longitude and  $1.2^{\circ}$  latitude by  $2.4^{\circ}$  longitude (differences <10 %). For the DDU station, the underestimation of snowfall

- 10 amounts by CloudSat is limited to 15 % between 0.5° latitude by 1° longitude 1.5° latitude by 3° longitude. These biases fall within the error margins of the temporal sampling uncertainty (Sect. 3.1). The wider range of accurate snowfall estimates for the DDU station can be attributed to their topographic location. The station is located at the coast of the AIS in a smoothly changing topographical area, minimising snowfall differences (Fig. 1). For the PE station, coarser spatial resolutions imply snowfall rates from the Antarctic plateau and the coast to be taken into account. Furthermore, the PE station is located near the
- 15 edge of the Sør Rondane mountain ridge, a highly variable terrain regarding topographic height differences (Fig. 1), leading to a high variability in snowfall rates (Souverijns et al., 2018). For the MZ station, larger differences between the MRR and CloudSat snowfall amount estimates are obtained. This can be attributed to three factors. First, the station is located close to a large mountain ridge, characterised by highly variable snowfall amounts depending on height, which is difficult to capture adequately by a CloudSat single track. Second, mesoscale snowfall events develop at the station through the interaction of
- 20 warm ocean and cold katabatic air (Carrasco et al., 2003; Sinclair et al., 2010). These mesoscale events are easily missed by CloudSat. Third, concurrent measurements are only available for 333 days. As such, the sample of CloudSat observations is small. This attributes for example for the large jump in snowfall amounts which is observed when increasing the grid box resolution from 0.6° latitude by 1.2° longitude to 0.7° latitude by 1.4° longitude (Fig. 6). This step attributed for the addition of two major snowfall events, doubling the total snowfall amount that was detected before within the range of 0.6° latitude by 1.2°
- 25 longitude. In order to erase the influence of single snowfall events, a long-term record of snowfall amounts is indispensable. In Palerme et al. (2014) a grid box width of 1° latitude by 2 ° longitude is used, leading to an accurate estimation of the total snowfall amount based on the analysis above for all three stations. However, for locations close to highly variable topography, erroneous estimates might still be obtained.

For intermediate spatial resolutions, lowest omission errors are observed for all three stations (Fig. 6). However, here, com-30 mission errors are generally higher compared to coarse or fine spatial resolutions. The main difference between intermediate and coarse / fine spatial resolutions is that omission errors approximately equal commission errors. As such, the amount of snowfall that is missed by CloudSat approximately equals the amount of false positive snowfall detections. Consequently, when taking long-term averages of CloudSat snowfall rates, an accurate estimate of the total snowfall amount compared to the MRRs is obtained (Fig. 6). One must understand that the accurate total snowfall amounts obtained by CloudSat can not be

35 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 <u>CloudSat the gridded CloudSat</u> product is not the right tool to investigate individual snowfall events / synoptic events at a single location.

As suchFurthermore, 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 Supplement (Text S1 and Figs. S1-S3).

For observations at the lowest measurement height of both instruments, the spatial resolution of Palerme et al. (2014) (1° latitude by  $2^{\circ}$  longitude) gives an accurate representation of the total snowfall amount for the three stations. In case

- 10 the distribution of snowfall amounts registered by the MRRs and CloudSat is analysed for this spatial resolution, a clear underestimation of extreme snowfall rates by CloudSat is observed for all three locations in both the distribution and when directly comparing individual events (Fig. 7). As stated above, the underestimation of (the frequency of) large events is the main reason for omission errors (Fig. 6). Furthermore, for all stations, CloudSat is found to detect a higher frequency of snowfall events (Fig. 7)(Fig. 7; Chen et al., 2016). These events often attain for low snowfall rates and are not detected by the MRRs.
- 15 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 CloudSat the gridded CloudSat product is not able to capture individual snowfall events adequately at a single location.

#### 20 3.3 Comparison with ERA-Interim reanalysis

The total snowfall amount estimate of CloudSat using the spatial resolution of Palerme et al. (2014) showed reasonable agreement with MRR total snowfall amounts (Fig. 6). Apart from CloudSat, no integrated snowfall product is available over the AIS (north of 82°S), apart from accumulation records, climate model simulations and reanalysis. ERA-Interim reanalysis is often taken as a reference regarding the Antarctic-wide snowfall product, however still strongly biased (Bromwich et al., 2011). An

- 25 assessment of the accuracy of the CloudSat <u>CloudSat as a surface</u> snowfall product compared to ERA-Interim reanalysis is therefore viablerelevant. For the period of concurrent measurements of MRRs and CloudSat, ERA-Interim reanalysis snowfall amounts are extracted and daily average snowfall amounts are calculated (Table 1Fig. 8). As was shown in Sect. 3.2, a reasonable agreement is observed between CloudSat and MRR average snowfall amounts for all stations. Regarding ERA-Interim reanalysis, for both the PE and MZ station, the daily average snowfall amount is underestimated (respectively by 18 % and 45
- 30 %), 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). A detailed bias table can be found in the Supplement (Table S1). At the DDU station, daily radiosoundings are executed which are assimilated in ERA-Interim reanalysis, adding to the performance of this product over the station, explaining its good



**Figure 7.** (first row) Empirical cumulative distribution of MRR and CloudSat snowfall events at a spatial resolution of  $1^{\circ}$  latitude by  $2^{\circ}$  longitude. (second row) Direct comparison between MRR and CloudSat individual snowfall events. R<sup>2</sup> 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.

performance compared to the MRR, even for a derived variable like snowfall. During austral summer, a similar assimilation is conducted at the MZ station. However, here, the performance of ERA-Interim reanalysis snowfall here is still deficient.

Apart from the long-term evaluation, also individual snowfall events can be investigated. For ERA-Interim reanalysis data, daily snowfall amounts are compared with MRR records (Fig. 9). For a fair comparison with CloudSat, the same time frame is

- 5 chosen (Fig. 2). ERA-Interim reanalysis generally achieves better results when simulating individual snowfall events including higher correlations compared to the performance of CloudSat the gridded CloudSat product (Fig. 7). For both the PE and MZ stationall stations, ERA-Interim reanalysis underestimates the snowfall amount of large events, which has also been observed in Fig. 4, attaining for omission errors similar to CloudSat (see Sect. 3.2). However, smaller This underestimation is related to the fact that high peaks in snowfall are smoothed out over the grid. Smaller snowfall events are much better captured
- 10 by ERA-Interim compared to CloudSat (see also Fig. 3 ). For the DDU station, which is located close to the coast, a good agreement for large snowfall events is observed, confirming the results deduced from table 1. However, for this station, commission errors are higher (4). However, a substantial number of small events are detected in ERA-Interim that were not registered by the MRRs, mainly for PE and MZ station (Fig. 9). This can be related to the topography of the surroundings, leading to localised snowfall, which is gridded to low resolution data products as ERA-Interim and/or other sources as e.g.



**Figure 8.** Daily average snowfall amounts (mm w.e.  $day^{-1}$ ) for the concurrent periods displayed in Fig. 2 for the Princess Elisabeth (PE), Dumont D'Urville (DDU) and Mario Zucchelli (MZ) station. CloudSat snowfall amounts are derived for the grid specified by Palerme et al. (2014).



**Figure 9.** Daily snowfall amount comparison between ERA-Interim reanalysis and the MRR.  $R^2$  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.

erroneous erroneous moisture fluxes. For the validation and identification of individual snowfall events, the ERA-Interim reanalysis product therefore however outperforms the CloudSat-derived product.

### 4 Conclusions

The Cloud Profiling Radar on board of the CloudSat satellite is the only instrument from which snowfall rates can be derived over the whole Antarctic Ice Sheet (AIS) at current times (north of 82°S). However, up to now the product has not been evaluated with ground-based observations. In 2010, a Micro Rain Radar (MRR) was installed at the Princess Elisabeth (PE) station in Dronning Maud Land at a distance of 173 km from the coast. In 2015, two more MRRs were set up at the Dumont D'Urville (DDU) and Mario Zucchelli (MZ) station in respectively Terre Adélie and Terra Nova Bay, both located at coastal areas. This paper presents a comparison between these MRRs and CloudSat for periods of concurrent measurements, which is mainly restricted to austral summer periods.

The CloudSat satellite has a temporal revisit time of several days over most of the AIS. Using systematic sampling on the full 5 MRR record and a bootstrapping methodology, it was found that the 10-90<sup>th</sup> percentile uncertainty on total snowfall amounts varies around <u>approximately</u> 30-40 % depending on the latitudinal location of the station. The uncertainty is lower compared to state-of-the-art CMIP5 models, showing the potential of evaluating climate models with this climatology. However, the CloudSat snowfall product is also characterised by high uncertainties due to the relation between radar reflectivity and snowfall rates, which should also be taken into account in the interpretation of this snowfall product. The low temporal sampling

10 frequency does not only impact the uncertainty, but also the median snowfall amount estimate. A variability in the total snowfall amount compared to a continuous record of up to 10 % was observed depending on the station.

The CloudSat total snowfall climatology is highly dependent on the resolution of the grid depending on the spatial resolution of the grid. Choosing a coarse spatial resolution increases the number of samples per grid box, but leads to the inclusion of information from larger distances. Furthermore, in case of coarse spatial resolutions, snowfall amounts are smoothed out,

- 15 more southern precipitation is included and an underestimation of the total snowfall amount is obtained. In case a fine spatial resolution is preferred, more accurate estimations are obtained. However, the amount of CloudSat samples is low. As such, distinct snowfall events are missed, leading again to an underestimation of the total snowfall amount. The best total snowfall amount estimate compared to the MRR records is obtained for spatial resolutions close to 1° latitude by 2° longitude, which equals to the spatial resolution chosen by Palerme et al. (2014) to obtain their snowfall climatology map for the AIS. However,
- 20 the good agreement between the MRRs and CloudSat regarding total snowfall amounts can not be attributed to accurate snowfall rate recordings of CloudSat on an event basis, but rather to the fact that omission errors are compensated equally by commission errors for this spatial resolution.

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 <u>surface</u> snowfall climatology over the AIS, outperforming ERA-

- 25 Interim reanalysis. ERA-Interim reanalysis total snowfall records generally underestimate the MRR snowfall amounts at the PE and MZ station. At the DDU station, a better performance is achieved, which is mainly related to the assimilation in ERA-Interim reanalysis of a daily radiosounding collected at the DDU station. Nevertheless, the assimilation of radiosoundings does not ameliorate the performance of ERA-Interim reanalysis at the MZ station. However, for individual snowfall event identification, ERA-Interim reanalysis outperforms CloudSat the gridded CloudSat product for all stations.
- 30 CloudSat's primary skill is the estimation of the snowfall climatology, offering adequate estimations compared to MRR records and outperforming ERA-Interim reanalysis approximations. However, the CloudSat snowfall climatology is characterised by large uncertainties inherent to the product and the temporal sampling frequency. Apart from that, CloudSat\_the gridded\_CloudSat\_product\_is not advised for the validation of individual snowfall events. For this, ERA-Interim reanalysis achieves better skill. In order to increase confidence in the CloudSat snowfall product at the local scale, more ground-based
- 35 measurements, including scanning radars, are necessary. Furthermore, with the future launch of the EarthCare satellite, year-

round estimates of precipitation will become available again for the AIS, attributing to better precipitation estimates over the continent.

*Data availability.* CloudSat data is freely available via the CloudSat Data Processing Center (http://www.cloudsat.cira.colostate.edu/). Data from the Micro Rain Radar at the Princess Elisabeth station can be obtained from the database on http://www.aerocloud.be. Data from the

5 Micro Rain Radar at Dumont D'Urville station are available at https://doi.pangaea.de/10.1594/PANGAEA.882565, while for the Micro Rain Radar at Mario Zucchelli station, data will be made publicly available as soon as possible (contact person: claudio.scarchilli@enea.it).

Competing interests. The authors declare that they have no conflict of interest.

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### References

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Boening, C., Lebsock, M., Landerer, F., and Stephens, G.: Snowfall-driven mass change on the East Antarctic ice sheet, Geophysical Research Letters, 39, L21 501, https://doi.org/10.1029/2012GL053316, 2012.

Bromwich, D. H., Guo, Z., Bai, L., and Chen, Q.-s.: Modeled Antarctic Precipitation. Part I: Spatial and Temporal Variability, Journal of

Bromwich, D. H., Nicolas, J. P., and Monaghan, A. J.: An Assessment of Precipitation Changes over Antarctica and the Southern Ocean since 1989 in Contemporary Global Reanalyses, Journal of Climate, 24, 4189–4209, https://doi.org/10.1175/2011JCLI4074.1, 2011.

Climate, 17, 427-447, https://doi.org/10.1175/1520-0442(2004)017<0427:MAPPIS>2.0.CO;2, 2004.

Carrasco, J. F., Bromwich, D. H., and Monaghan, A. J.: Distribution and Characteristics of Mesoscale Cyclones in the Antarctic: Ross Sea Eastward to the Weddell Sea, Monthly Weather Review, 131, 289–301, https://doi.org/10.1175/1520-0402(2002)121 c0280.DACOMC5 2.0 CO22 2002

- 10 0493(2003)131<0289:DACOMC>2.0.CO;2, 2003.
  - Chen, S., Hong, Y., Kulie, M., Behrangi, A., Stepanian, P. M., Cao, Q., You, Y., Zhang, J., Hu, J., and Zhang, X.: Comparison of snowfall estimates from the NASA CloudSat Cloud Profiling Radar and NOAA/NSSL Multi-Radar Multi-Sensor System, Journal of Hydrology, 541, 862–872, https://doi.org/10.1016/j.jhydrol.2016.07.047, 2016.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., and Kobayashi, S.: The ERA-Interim reanalysis: configura-

- 15 tion and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.
  - Eisen, O., Frezzotti, M., Genthon, C., Isaksson, E., Magand, O., van den Broeke, M. R., Dixon, D. A., Ekaykin, A., Holmlund, P., Kameda, T., Karlöf, L., Kaspari, S., Lipenkov, V. Y., Oerter, H., Takahashi, S., and Vaughan, D. G.: Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica, Reviews of Geophysics, 46, RG2001, https://doi.org/10.1029/2006RG000218, http://doi.org/10.1029/2006RG000218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1029/2006RG00218, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, http://doi.org/10.1028/20048, h
- 20 //doi.wiley.com/10.1029/2006RG000218, 2008.
  - Favier, V., Agosta, C., Parouty, S., Durand, G., Delaygue, G., Gallée, H., Drouet, A. S., Trouvilliez, A., and Krinner, G.: An updated and quality controlled surface mass balance dataset for Antarctica, The Cryosphere, 7, 583–597, https://doi.org/10.5194/tc-7-583-2013, 2013.
    - Frezzotti, M., Pourchet, M., Flora, O., Gandolfi, S., Gay, M., Urbini, S., Vincent, C., Becagli, S., Gragnani, R., Proposito, M., Severi, M., Traversi, R., Udisti, R., and Fily, M.: New estimations of precipitation and surface sublimation in East Antarctica from snow accumulation measurements, Climate Dynamics, 23, 803–813, https://doi.org/10.1007/s00382-004-0462-5, 2004.
- Genthon, C., Kaspari, S., and Mayewski, P. A.: Interannual variability of the surface mass balance of West Antarctica from ITASE cores and ERA40 reanalyses, 1958-2000, Climate Dynamics, 24, 759–770, https://doi.org/10.1007/s00382-005-0019-2, 2005.
  - Genthon, C., Krinner, C., and Castebrunet, H.: Antarctic precipitation and climate-change predictions: Horizontal resolution and margin vs plateau issues, Annals of Glaciology, 50, 55–60, https://doi.org/10.3189/172756409787769681, 2009a.
- 30 Genthon, C., Magand, O., Krinner, G., and Fily, M.: Do climate models underestimate snow accumulation on the Antarctic plateau? A re-evaluation of/from in situ observations in East Wilkes and Victoria Lands, Annals of Glaciology, 50, 61–65, https://doi.org/10.3189/172756409787769735, 2009b.
- Gorodetskaya, I. V., van Lipzig, N. P. M., van den Broeke, M. R., Mangold, A., Boot, W., and Reijmer, C. H.: Meteorological regimes and accumulation patterns at Utsteinen, Dronning Maud Land, East Antarctica: Analysis of two contrasting years, Journal of Geophysical
  Research: Atmospheres, 118, 1700–1715, https://doi.org/10.1002/jgrd.50177, 2013.
- Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M., Neff, W., and van Lipzig, N. P. M.: The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, Geophysical Research Letters, 16, 6199–6206, https://doi.org/10.1002/2014GL060881, 2014.

Gorodetskaya, I. V., Kneifel, S., Maahn, M., Van Tricht, K., Thiery, W., Schween, J. H., Mangold, A., Crewell, S., and van Lipzig, N. P. M.: Cloud and precipitation properties from ground-based remote sensing instruments in East Antarctica, The Cryosphere, 9, 285–304, https://doi.org/10.5194/tcd-8-4195-2014, 2015.

Gossart, A., Souverijns, N., Gorodetskaya, I. V., Lhermitte, S., Lenaerts, J. T. M., Schween, J. H., Mangold, A., Laffineur, Q., and van

- 5 Lipzig, N. P. M.: Blowing snow detection from ground-based ceilometers: application to East Antarctica, The Cryosphere, 11, 2755– 2772, https://doi.org/https://doi.org/10.5194/tc-11-2755-2017, 2017.
  - Grazioli, J., Genthon, C., Boudevillain, B., Duran-Alarcon, C., Del Guasta, M., Madeleine, J.-B., and Berne, A.: Measurements of precipitation in Dumont d'Urville, Terre Adélie, East Antarctica, The Cryosphere, 11, 1797–1811, https://doi.org/10.5194/tc-2017-18, 2017a.

Grazioli, J., Madeleine, J.-B., Gallée, H., Forbes, R. M., Genthon, C., Krinner, G., and Berne, A.: Katabatic winds diminish pre-

- 10 cipitation contribution to the Antarctic ice mass balance, Proceedings of the National Academy of Sciences, 114, 10858–10863, https://doi.org/10.1073/pnas.1707633114, 2017b.
  - Gregory, J. M. and Huybrechts, P.: Ice-sheet contributions to future sea-level change, Phil. Trans. R. Soc. A, 364, 1709–1731, https://doi.org/10.1098/rsta.2006.1796, 2006.

Hanna, E., Navarro, F. J., Pattyn, F., Domingues, C. M., Fettweis, X., Ivins, E. R., Nicholls, R. J., Ritz, C., Smith, B., Tulaczyk, S., White-

- 15 house, P. L., and Zwally, H. J.: Ice-sheet mass balance and climate change., Nature, 498, 51–59, https://doi.org/10.1038/nature12238, http://www.ncbi.nlm.nih.gov/pubmed/23739423, 2013.
  - Hardy, R. A., Nerem, R. S., and Wiese, D. N.: The Impact of Atmospheric Modeling Errors on GRACE Estimates of Mass Loss in Greenland and Antarctica, Journal of Geophysical Research: Solid Earth, 122, 1–19, https://doi.org/https://doi.org/10.1002/2017JB014556, 2017.
  - Klugmann, D., Heinsohn, K., and Kirtzel, H.-J.: A low cost 24 GHz FM-CW Doppler radar rain profiler, Contributions to Atmospheric
- 20 Physics, 69, 247–253, 1996.
  - Knuth, S. L., Tripoli, G. J., Thom, J. E., and Weidner, G. A.: The influence of blowing snow and precipitation on snow depth change across the Ross Ice Shelf and Ross Sea regions of Antarctica, Journal of Applied Meteorology and Climatology, 49, 1306–1321, https://doi.org/10.1175/2010JAMC2245.1, 2010.

Lenaerts, J. T. M., van den Broeke, M. R., van de Berg, W. J., van Meijgaard, E., and Kuipers Munneke, P.: A new, high-resolution surface

- 25 mass balance map of Antarctica (1979-2010) based on regional atmospheric climate modeling, Geophysical Research Letters, 39, L04 501, https://doi.org/10.1029/2011GL050713, 2012.
  - Lenaerts, J. T. M., Ligtenberg, S. R. M., Medley, B., Van de Berg, W. J., Konrad, H., Nicolas, J. P., Van Wessem, J. M., Trusel, L. D., Mulvaney, R., Tuckwell, R. J., Hogg, A. E., and Thomas, E. R.: Climate and surface mass balance of coastal West Antarctica resolved by regional climate modelling, Annals of Glaciology, pp. 1–13, https://doi.org/10.1017/aog.2017.42, https://www.cambridge.org/core/
- 30 product/identifier/S0260305517000428/type/journal{\_}article, 2017.
  - Ligtenberg, S. R. M., van de Berg, W. J., van den Broeke, M. R., Rae, J. G. L., and van Meijgaard, E.: Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model, Climate Dynamics, 41, 867–884, https://doi.org/10.1007/s00382-013-1749-1, 2013.
- Liu, H., Jezek, K. C., Li, B., and Zhao, Z.: Radarsat Antarctic Mapping Project Digital Elevation Model, Version 2, https://doi.org/http://dx.doi.org/10.5067/8JKNEW6BFRVD, 2015.
  - Maahn, M. and Kollias, P.: Improved Micro Rain Radar snow measurements using Doppler spectra post-processing, Atmospheric Measurement Techniques, 5, 2661–2673, https://doi.org/10.5194/amt-5-2661-2012, 2012.

- Maahn, M., Burgard, C., Crewell, S., Gorodetskaya, I. V., Kneifel, S., Lhermitte, S., Van Tricht, K., and van Lipzig, N. P. M.: How does the spaceborne radar blind zone affect derived surface snowfall statistics in polar regions?, Journal of Geophysical Research: Atmospheres, 119, 13 604–13 620, https://doi.org/10.1002/2014JD022079, 2014.
- Magand, O., Genthon, C., Fily, M., Krinner, G., Picard, G., Frezzotti, M., and Ekaykin, A. A.: An up-to-date quality-controlled surface
- 5 mass balance data set for the 90°-180°E Antarctica sector and 1950-2005 period, Journal of Geophysical Research, 112, D12106, https://doi.org/10.1029/2006JD007691, 2007.
  - Medley, B., Joughin, I., Das, S. B., Steig, E. J., Conway, H., Gogineni, S., Criscitiello, A. S., McConnell, J. R., Smith, B. E., van den Broeke, M. R., Lenaerts, J. T. M., Bromwich, D. H., and Nicolas, J. P.: Airborne-radar and ice-core observations of annual snow accumulation over Thwaites Glacier, West Antarctica confirm the spatiotemporal variability of global and regional atmospheric models, Geophysical Research Letters, 40, 3649–3654, https://doi.org/10.1002/grl.50706, 2013.
- Medley, B., Joughin, I., Smith, B. E., Das, S. B., Steig, E. J., Conway, H., Gogineni, S., Lewis, C., Criscitiello, A. S., McConnell, J. R., van den Broeke, M. R., Lenaerts, J. T. M., Bromwich, D. H., Nicolas, J. P., and Leuschen, C.: Constraining the recent mass balance of Pine Island and Thwaites glaciers, West Antarctica, with airborne observations of snow accumulation, The Cryosphere, 8, 1375–1392, https://doi.org/10.5194/tc-8-1375-2014, 2014.
- 15 Medley, B., McConnell, J. R., Neumann, T. A., Reijmer, C. H., Chellman, N., Sigl, M., and Kipfstuhl, S.: Temperature and snowfall in western Queen Maud Land increasing faster than climate model projections, Geophysical Research Letters, 45, 1472–1480, https://doi.org/10.1002/2017GL075992, http://doi.wiley.com/10.1002/2017GL075992, 2018.
  - Milani, L., Kulie, M. S., Casella, D., Dietrich, S., L'Ecuyer, T. S., Panegrossi, G., Porcù, F., Sanò, P., and Wood, N. B.: CloudSat snowfall estimates over Antarctica and the Southern Ocean: An assessment of independent retrieval methodologies and multi-year snowfall analysis,
- 20 Atmospheric Research, https://doi.org/10.1016/j.atmosres.2018.05.015, http://linkinghub.elsevier.com/retrieve/pii/S0169809517310682, 2018.
  - Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, https://doi.org/10.5194/tc-8-1577-2014, 2014.
  - Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Climate Dynamics, 48, 225–239, https://doi.org/10.1007/s00382-016-3071-1, 2017.
  - Peters, G., Fischer, B., and Andersson, T.: Rain observations with a vertically looking Micro Rain Radar (MRR), Boreal Environment Research, 7, 353–362, 2002.
    - Previdi, M. and Polvani, L. M.: Impact of the Montreal Protocol on Antarctic surface mass balance and implications for global sea level rise, Journal of Climate, 30, 7247–7253, https://doi.org/10.1175/JCLI-D-17-0027.1, 2017.
- 30 Rodgers, C. D.: Inverse methods for atmospheric sounding: Theory and practice, World Scientific, 2000. Scarchilli, C., Frezzotti, M., Grigioni, P., De Silvestri, L., Agnoletto, L., and Dolci, S.: Extraordinary blowing snow transport events in East Antarctica, Climate Dynamics, 34, 1195–1206, https://doi.org/10.1007/s00382-009-0601-0, 2010.

Sinclair, K. E., Bertler, N. A. N., and Trompetter, W. J.: Synoptic controls on precipitation pathways and snow delivery to high-accumulation ice core sites in the Ross Sea region, Antarctica, Journal of Geophysical Research, 115, D22 112, https://doi.org/10.1029/2010JD014383,

35 http://doi.wiley.com/10.1029/2010JD014383, 2010.

10

25

Souverijns, N., Gossart, A., Lhermitte, S., Gorodetskaya, I. V., Kneifel, S., Maahn, M., Bliven, F. L., and van Lipzig, N. P. M.: Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations, Atmospheric Research, 196, 211–223, https://doi.org/10.1016/j.atmosres.2017.06.001, 2017.

Souverijns, N., Gossart, A., Gorodetskaya, I. V., Lhermitte, S., Mangold, A., Laffineur, Q., Delcloo, A., and van Lipzig, N. P. M.: How does the ice sheet surface mass balance relate to snowfall? Insights from a ground-based precipitation radar in East Antarctica, The Cryosphere, 12, 1987–2003, https://doi.org/10.5194/tc-12-1987-2018, https://www.the-cryosphere.net/12/1987/2018/, 2018.

Stephens, G. L., Vane, D. G., Boain, R. J., Mace, G. G., Sassen, K., Wang, Z., Illingworth, A. J., O'Connor, E. J., Rossow, W. B., Durden,

- 5 S. L., Miller, S. D., Austin, R. T., Benedetti, A., and Mitrescu, C.: The cloudsat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation, Bulletin of the American Meteorological Society, 83, 1771–1790, https://doi.org/10.1175/BAMS-83-12-1771, 2002.
  - Tang, M. S. Y., Chenoli, S. N., Samah, A. A., and Hai, O. S.: An assessment of historical Antarctic precipitation and temperature trend using CMIP5 models and reanalysis datasets, Polar Science, 15, 1–12, https://doi.org/https://doi.org/10.1016/j.polar.2018.01.001, https://
- 10 //www.sciencedirect.com/science/article/pii/S1873965217300981, 2018.
  - van den Broeke, M. R., Reijmer, C. H., and Van de Wal, R. S. W.: A study of the surface mass balance in Dronning Maud Land, Antarctica, using automatic weather stations, Journal of Glaciology, 50, 565–582, https://doi.org/10.3189/172756504781829756, 2004.
  - van Lipzig, N. P. M., van Meijgaard, E., and Oerlemans, J.: The spatial and temporal variability of the surface mass balance in Antarctica: results from a regional atmospheric climate model, International Journal of Climatology, 22, 1197–1217, https://doi.org/10.1002/joc.798,
- 15 2002.
  - Van Tricht, K., Lhermitte, S., Gorodetskaya, I. V., and van Lipzig, N. P. M.: Improving satellite-retrieved surface radiative fluxes in polar regions using a smart sampling approach, The Cryosphere, 10, 2379–2397, https://doi.org/10.5194/tc-10-2379-2016, 2016.
  - Vaughan, D. G., Bamber, J. L., Giovinetto, M., Russell, J., and Cooper, A. P. R.: Reassessment of Net Surface Mass Balance in Antarctica, Journal of Climate, 12, 933–946, https://doi.org/10.1175/1520-0442(1999)012<0933:RONSMB>2.0.CO;2, 1999.
- 20 Velicogna, I. and Wahr, J.: Measurements of time-variable gravity show mass loss in Antarctica, Science, 311, 1754–1756, https://doi.org/10.1126/science.1123785, 2006.
  - Wang, Y., Ding, M., van Wessem, J. M., Schlosser, E., Altnau, S., van den Broeke, M. R., Lenaerts, J. T., Thomas, E. R., Isaksson, E., Wang, J., and Sun, W.: A comparison of Antarctic ice sheet surface mass balance from atmospheric climate models and in situ observations, Journal of Climate, 29, 5317–5337, https://doi.org/10.1175/JCLI-D-15-0642.1, 2016.
- 25 Wood, N. B.: Estimation of snow microphysical properties with application to millimeter-wavelength radar retrievals for snowfall rate, Ph.D. thesis, Colorado State University, Colorado, http://hdl.handle.net/10217/48170, 2011.
  - Wood, N. B., L'Ecuyer, T. S., Bliven, F. L., and Stephens, G. L.: Characterization of video disdrometer uncertainties and impacts on estimates of snowfall rate and radar reflectivity, Atmospheric Measurement Techniques, 6, 3635–3648, https://doi.org/10.5194/amt-6-3635-2013, 2013.
- 30 Wood, N. B., L'Ecuyer, T. S., Heymsfield, A. J., Stephens, G. L., Hudak, D. R., and Rodriguez, P.: Estimating snow microphysical properties using collocated multisensor observations, Journal of Geophysical Research Atmospheres, 119, 8941–8961, https://doi.org/10.1002/2013JD021303, 2014.