Response to Reviewer 1 Comments: *How does the ice sheet surface mass balance relate to snowfall? Insights from a ground-based precipitation radar in East Antarctica*

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March 22, 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.

1. The manuscript entitled "How does the ice sheet surface balance relate to snowfall? Insights from a ground-based precipitation radar in East Antarctica" deals with the very important issue of measuring the Surface Mass Balance (SMB) over the Antarctic Ice Sheet. In particular, the goal of this work is to quantify the different terms of the SMB at Princess Elisabeth Station (Antarctica) and investigate the relation between snowfall and accumulation. The manuscript is for sure within the scope of the Journal and gives a systematic and rigorous analysis of the relation between snowfall and the accumulation at the considered site. Of course this work provides good results but many other sites must be analyzed to come to a more general conclusion.

The reviewer is thanked for his comments regarding the manuscript. As noted, the work is only based on results from one site over the Antarctic Ice Sheet and takes advantage of a unique set of instruments, including a precipitation radar and an optical disdrometer, unavailable at other Antarctic stations. We stressed this a bit more clearly in the last section of the conclusion.

Observations for this study were limited to one location over the AIS. As such, results might depend on the local topographical and meteorological conditions. However, as the main conclusions are based on both an analysis of synoptic and local meteorology, deductions of our work are also deemed to be valid at other coastal and escarpment areas of the AIS. Future work should expand the measurements of the individual components of the local SMB to other sites over the AIS, in order to confirm the role of meteorological conditions at other areas including their effect on the local SMB.

2. p.3 l.5-9: "Both drifting snow sublimation and surface sublimation have been quantified for the PE station (Thiery et al., 2012). At the local scale, their significance can be fairly large (e.g. King et al., 2001; Bliss et al., 2011; Gorodetskaya et al., 2015; Grazioli et al., 2017). However, this study mainly focuses on the relation between accumulation / ablation and snowfall. These terms, to-

gether with melt which is only relevant at coastal areas and ice shelves (Lenaerts et al., 2017), are therefore only quantified and not investigated in great depth." * "These terms" in this context seem to refer to accumulation/ablation and snowfall. But I guess those are not the terms the authors don't want to investigate in great depth. The authors probably mean "drifting snow sublimation and surface sublimation" terms, but the sentence should be reworded to be more clear.

The paragraph has been rewritten accordingly. A clear reference to the sublimation terms is added and a sentence was added quantifying the mean annual effect of the sublimation terms over the PE station.

Both surface and drifting snow sublimation have been quantified for the PE station (Thiery et al., 2012). At the local scale, the significance of the processes can be fairly large (e.g. King et al., 2001; Bliss et al., 2011; Gorodetskaya et al., 2015; Grazioli et al., 2017). For the PE station, sublimation was found to remove 10 % of the total precipitation (Thiery et al., 2012). In this study, the focus is mainly on the relation between accumulation / ablation and snowfall. The sublimation terms, together with melt which is only relevant at coastal areas and ice shelves (Lenaerts et al., 2017), are therefore only quantified and not investigated in great depth.

3. p.3 l.10: "The total SMB or snow height" * The SMB is usually measured in unity of mass per surface or mm of water equivalent. If the authors want to link the concept of SMB to the snow height, the connection, although comprehensible, needs to be clarified. The same comment is valid for any time the authors talk about SMB height or height changes (p.3 l.19 or l.23 or p.5 l.24 as an example).

We agree this concept has not been explained well. The Automatic Weather Station (AWS) at the PE station is equipped with an acoustic height sensor, which is capable of measuring snow height changes. In our study, we consider the SMB in units of millimeter water equivalent. In order to convert the height changes measured by the AWS to millimeters of water equivalent, density measurements of snow need to be available. Every summer season, snow density profile measurements are performed in a 1 m snow pit in the close vicinity of the AWS. Each year, the yearly average density of the snow that accumulated since the past year is calculated. Using this density, the height changes measured by the AWS can be converted to water equivalent. This concept is now explained in the introduction and is reformulated at several locations throughout the manuscript, including the caption of Figure 2.

Each year, the average density of the snow that has accumulated in the past year is calculated from snow pit measurements at the PE station. Using these average yearly densities (varying between 309-375 kg m^{-3}), snow height changes are converted to changes in the local SMB (water equivalent) (Gorodetskaya et al., 2013, 2015).

Gorodetskaya et al. (2015) showed that snowfall events at the PE station do not necessarily contribute to accumulation or an increase in snow height.

In addition, changes in the local SMB take place without snowfall.

The net local SMB is calculated based on snow height measurements of an AWS and yearly snow density records (see Section 1).

Nevertheless, since the total SMB can be deduced from the AWS (see Section 1), ER_{ds} can be calculated as the residual term after inverting Eq. 1 (Gorodetskaya et al., 2015).

One would therefore expect that snowfall results in accumulation or an increase in height.

4. p.4 l.11: "This instrument is based on a high speed camera and able to obtain detailed information about snowflake microphysics." * "This instrument is based on a high speed camera and is able to obtain detailed information about snowflake microphysics."

The sentence has been adapted accordingly.

This instrument is based on a high speed camera and is able to obtain detailed information about snowflake microphysics (i.e. the particle size distribution).

5. p.4 l.14: "The net local SMB is measured directly by an AWS" * The authors need to explicitly describe or at least mention what kind of instruments are used for a direct measure of SMB. Acoustic height sensors are mentioned but there is no explicit connection with SMB measures.

This comment has been addressed in comment 3. There, we also expanded the description of the instrumentation and methodology to obtain SMB records from AWS snow height measurements. The sentence is repeated here for clarity. We refer also to the material and methods section, where the full approach is discussed.

The net local SMB is calculated based on snow height measurements of an AWS and yearly snow density records (see Section 1).

6. p.5 l.20: "The local SMB constitutes of the sum of different components (Eq. 1), which can be estimated from measurements using the ground-based instrumentation listed in Sect. 2.1" * It would be useful here to summarize what ground-based instrument is used to measure each SMB component.

An overview of the different components is added including the instrumentation that is used to measure each of the components. For a detailed description, we referred to the above sections.

The local SMB is composed of the sum of different components (Eq. 1). Snowfall amounts are measured by a Micro Rain Radar, while the two sublimation terms are calculated based on meteorological data from the AWS (see Section 2.1). The ER_{ds} term is not measured directly at the PE station. Nevertheless, since the total SMB can be deduced from the AWS (see Section 1), ER_{ds} can be calculated as the residual term after inverting Eq. 1 (Gorodetskaya et al., 2015). Its uncertainty is therefore based on the uncertainty of all other components of the local SMB (Eq. 1; Gorodetskaya et al., 2015) and is mainly determined by the uncertainty of the snowfall component at the PE station.

7. p.6 l.4: "(this corresponds to 1 cm of snow when the density of fresh snow equals 100 kg m^{-3})" * The snow height strongly depends on the density of the snowfall particles. In my opinion it is misleading to provide here a general conversion value being the precipitating particles over Antarctica so variable in shape and density.

The conversion of snowfall amounts to height changes is indeed inappropriate and has no added value in this part of the text. It has been removed from this section. See also comment 17 for a clarification of this conversion further in the manuscript.

8. p.6 l.11-12: "These measurements are processed following Gorodetskaya et al. (2013). Snowfall amounts are obtained from the MRR after applying the Ze-SR relation and methodology determined in Souverijns et al. (2017)." * Please provide here a brief description of Gorodetskaya et al. (2013) processing method and some more information about the Ze-S relationship determined by Souverijns et al. (2017). It is not necessary to provide a full description, but at least give to the reader enough information to be able to go on reading and understanding the methodologies without necessarily reading the reference (in my opinion references should provide a full detailed description of what the authors want to say but the text within the manuscript should be descriptive enough to allow a fluent reading). As an example, the Clear Sky Index methodology is briefly described (l.15-16) even if the proper reference is provided.

A description of the processing methods of the measurements is added in the section describing the AWS and the MRR / disdrometer.

The AWS records meteorological variables, such as air temperature, pressure, wind speed and direction, relative humidity and radiative fluxes at 2 meters above the surface. These measurements are processed following Gorodetskaya et al. (2013). Wind speed and directions are recorded by an anemometer at the top of the AWS. Humidity is recorded with respect to water at the top of the AWS and is converted to humidity with respect to ice using the conversion of Anderson (1994). Broadband radiative fluxes are measured using pyranometers and pyrgeometers. All the above parameters are measured with 6-minute resolution and averaged to hourly means. Furthermore, the AWS is equipped with an acoustic height sensor, which measures snow height changes once an hour with an accuracy of 1 cm on an hourly time resolution. A running mean of 24 hours is applied to erase short-term decameter scale variability due to sastrugi movement (Libois et al., 2014). Furthermore, several corrections to remove erroneous data are executed (Gorodetskaya et al., 2011). Apart from this, temporary peaks in the snow height records are excluded from the analysis. In January 2016, a new AWS was set up to replace the one installed in 2009, able to measure snow height changes more accurately. A detailed overview of the specifications of the old AWS including its uncertainty can be found in Gorodetskaya et al. (2013) and of the new AWS in the Supplement (Table S1).

In order to obtain reliable estimates of snowfall rates and their uncertainty, an optical disdrometer (Precipitation Imaging Package Newman et al., 2009) was installed at the PE station. This instrument is based on a high speed camera and is able to obtain detailed information about snowflake microphysics (i.e. the particle size distribution). A correction for the horizontal and vertical displacement of snowfall between the MRR data acquisition level and the surface has been applied (Wood, 2011; Souverijns et al., 2017). Using this information, a relation between radar reflectivity measured by the MRR and snowfall rates was obtained: $Ze{=}18SR^{1.1}$*. Furthermore, a constrain on the uncertainty of the resulting snowfall rates was obtained [-59 % +60 %] (10th-90th percentile) (Souverijns et al., 2017), which is a considerable reduction compared to earlier snowfall rate estimates at the PE station that were retrieved without any information on the snow particle microphysical characteristics (Gorodetskaya et al., 2015).*

9. p.6 l.30: Again, few words about SANDRA optimization algorithm, why did you choose this one instead of another one? Describe at least the main characteristics that made the authors choose it.

A description was added to the SANDRA algorithm including a justification of the choice for this algorithm.

Several algorithms are available to perform a cluster analysis (Philipp et al., 2010). In recent studies, thorough evaluations were performed for each of these algorithms, indicating the best performance regarding circulation clustering for optimisation algorithms over different parts of the world (Huth et al., 2008; Beck and Philipp, 2010; Casado et al., 2010; Souverijns et al., 2016). From these optimisation algorithms, the simulated annealing and diversified randomisation (SANDRA) algorithm was chosen, which is based on k-means clustering (Philipp et al., 2007) as it performed adequately for different applications over the world regarding circulation clustering (Huth et al., 2008; Beck and Philipp, 2010; Casado et al., 2010; Souverijns et al., 2016).

10. p.7 l.3: Describe the Fast Silhouette Index, mentioning also within the text and not only in the S1 fig. caption that low values are good etc.

The sentence has been adapted accordingly.

Using the Fast Silhouette Index, the ability of the SANDRA algorithm to maximise the separability between the members of different circulation patterns, while minimising the variances within each circulation pattern, was investigated (Rousseeuw, 1987). In this study, a total of six circulation patterns was selected. The Fast Silhouette index indicates a local minimum value as a further increase in the total number of circulation patterns shows no significant improvement (i.e. decrease) regarding the classification skill (Fig. S2).

11. p.7 l.21: "that surface and drifting snow sublimation (SUs and SUds respectively) are mainly negative." * Saying that they are mainly negative does it mean that they could be also positive? Fig. 2 caption says that they are plotted as ablation terms...

This sentence have been adapted in order to not result in confusion with the caption in Fig. 2.

Furthermore, it can also be noted that surface and drifting snow sublimation (SU_s and SU_{ds} respectively) are both ablation terms.

12. p.7 l.19: "This behaviour is also visible in the ERds" * It should be obvious being the ERds term just a residual term.

This part of the sentence has been removed.

These events occur both with or without snowfall and allows for easy identification of the individual accumulation and ablation events.

13. p.9 l.7: Does the "index" have a name? or a reference?

The index is based on the pressure difference between the PE station and a location northwest of the station where low pressure systems are present attributing for precipitation at the PE station. The location northwest of the station is determined from the results of the cluster analysis (Fig. 3). From the cluster analysis, it was deduced that the higher the pressure difference between both locations, the higher the transport capacity of the station (this can also been seen in Fig. 5b). As this is a site-specific index, it does not have a name or reference. We modified the text so it is emphasised that this index was created by the authors and added a green dot on Fig. 3 in order to denote the locations of the cyclone.

The transport capacity of the cyclone is parametrised by a self-constructed index based on the pressure difference between the PE station and the typical location of the trough northwest of the station (0° E, 62° S, Fig. 3) as these cyclones attribute for the highest snowfall amounts at the PE station.

14. p.11 l.6: "(left side of the graph)" * (left side of the graph - negative pressure difference values)

The text has been adapted accordingly.

In case no cyclone is present NW of the PE station (i.e. negative pressure difference values; left side of the graph), snowfall amounts are generally low.

15. p.11 l.17-18: "Accumulation events are characterised by a larger temporal extent of the cloud structure compared to ablation." * It would be interesting here to report the temporal extent of the cloud structure relative to the snowfall event duration because we would expect the persistence of cloud structures at least during the snowfall event. According to AWS, for SMB+ the temporal extent of the cloud structure is 252% of the snowfall event duration, while for SMB- it is 263%, so higher. Opposite trend for ERAI, with 277% for SMB+ and 243% for SMB-. So, absolutely specking, accumulation events are characterized by a larger temporal extent of the cloud structure, but relatively speaking, some other considerations could be done.

This is a valid comment by the reviewer. The strong link between the temporal extent of the cloud structure and the duration of snowfall has not been considered. This has been clarified in the text and some conclusions are adapted.

It is noted that relatively speaking, the temporal extent of the cloud structure equals on average 260 % of the duration of snowfall for both the accumulation and ablation events using both methods. It is therefore concluded that accumulation events are characterised by a larger temporal extent of the event compared to ablation, which is deduced from both the duration of snowfall and the temporal extent of the cloud structure.

In the previous section, synoptic events with snowfall lead to both accumulation and ablation, depending on the duration of the event (i.e. the duration of snowfall and temporal extent of the cloud structure).

The distinction between accumulation and ablation events during snowfall was correlated to the duration of the event (i.e. the duration of snowfall and the temporal cloud extent).

16. p.12 l.13-14: "From this, the ceilometer was able to detect 486 cm (i.e. the sum of all height changes during events for which blowing snow was detected)" * The ceilometer is not able to detect the snow height, it can detect blowing snow and then the acoustic height sensor can measure the height changes. Please reword the sentence.

This is a correct remark. The statement was adapted.

In total, all 50 snowfall events attained for 542 cm of height changes (both accumulation and ablation; detected by the AWS). During the periods when the ceilometer recorded blowing snow, the AWS detected 486 cm of height changes (i.e. the sum of all height changes during events for which blowing snow was detected), showing the potential of the ceilometer to detect blowing snow during snowfall events.

17. p.12 l.16-17: "During all snowfall events, a total amount of 230 mm w.e. (approximately 230 cm in case fresh snow density equals 100 kg m^{-3}) was registered by the MRR, which is lower than the height changes recorded by the AWS (542 cm). This indicates the importance of the continuous movement of snow during snowfall events." * Without any information about snow density, the conversion of 1 mm w.e. to 1 cm cannot be considered realistic. PIP information should be used case by case to convert the w.e. to height and only after comparing the results to AWS measures. On the contrary, if in this work density information are used somehow for the conversion, it should be reported in the manuscript. Without clarifying this point, any conclusion made from this comparison cannot be considered reliable.

This is a valid statement. Information about the density of snowfall at the PE station can be retrieved from the optical disdrometer (Precipitation Imaging Package) following the approach of Tiira et al. (2016). However, since we do not have precipitation gauge measurements at PE station, we are bound to the relation between particle diameter and snow density retrieved in Tiira et al. (2016). Over the PE station, the median diameter of the snow particles equals 0.7 mm. Using Eq. 14 of Tiira et al. (2016), a mean density of 323 kg m^{-3} is obtained. Secondly, each year, the average density of the snow that has accumulated in the past year is calculated from snow pit measurements at the PE station. Here, yearly average snow densities varying between 309-395 kg m^{-3} are obtained. The last method is preferred as these consist of measurements obtained at the PE station. Whenever a conversion between snow heights and water equivalent is needed, the yearly snowfall densities measured in the snow pit are used.

During all snowfall events, a total amount of 230 mm w.e. was recorded. Based on yearly density measurements in the uppermost layers of the snow pack, yearly average values between 309-395 kg/m^3 are reported. This results in 58-75 cm accumulation at the surface if no other processes are at play. This is significantly lower than the total height changes recorded by the AWS during all snowfall events (542 cm).

18. p.15 l.14: "The ceilometer was only able to detect 274 cm" * Again, the ceilometer detects the blowing snow, not the snow height.

Following comment 16, we also adapted this sentence.

When the ceilometer detected blowing snow, only 274 cm of height changes were detected by *the AWS, indicating that the blowing snow layer only has a limited vertical extent and that the transport of snow is restricted to shallow layers close to the ground during these type of events.*

19. p.16 l.5: "both accumulation as ablation" * "and" or "as well as".

This sentence was removed from the original manuscript.

20. p.16 l.7: "The distinction between accumulation and ablation events during snowfall was attributed to the duration of the event and the temporal cloud extent" * I would say "was related" or "we found a correlation between..." instead of "was attributed".

The sentence has been adapted accordingly.

The distinction between accumulation and ablation events during snowfall was correlated to the duration of the event (i.e. the duration of snowfall and the temporal cloud extent).

21. Supplement p.3 l.21: "influenced".

The sentence has been adapted.

In circulation type 1 (C1) the Antarctic circumpolar trough is clearly visible showing a high pressure bulge over Dronning Maud Land.

22. Fig.4a: "Wind rose showing the speed and direction of the snowfall events" * "Wind rose showing the speed and direction of the wind during snowfall events".

The sentence has been adapted accordingly.

Wind rose showing the hourly speed and direction of the wind recorded by the AWS during snowfall events detected by the MRR.

23. Fig. 5a: It is difficult to appreciate lines color differences, I would suggest to change the colorscale. Moreover, a legend describing the different lines would be useful.

We have adapted the figure in order to improve readability. At first, a zoom to the Southern ocean north of Dronning Maud Land is made. The marker sizes of the line are enlarged in order to easier detect differences between the different lines. We choose to keep the colors as a sequential colorscheme is useful for denoting air parcels with different starting heights. We clarified the differences between the trajectories in the figure by stating that each line represents a different height and adapted the caption of the figure.

Backtrajectories for the snowfall event of the 17th of December 2011 at the Princess Elisabeth station for different heights (start at 06 UTC). The red dot denotes the location of the Princess Elisabeth station, while the line shows the time the snowfall event arrived at the station.

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